DESIGN AND OPTIMIZATION OF POWER GENERATION SYSTEM USING SOLAR PHOTOVOLTAIC MODULES AT KYAMBOGO UNIVERSITY

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A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN ADVANCED MANUFACTURING SYSTEMS ENGINEERING OF KYAMBOGO UNIVERSITY

OCTOBER, 2025

DECLARATION

I **Kiguli Godfrey**, declare that this dissertation is wholly the result of my own independent study and personal endeavors and has never been submitted, in whole or in part, to any academic institution for any kind of academic award. According to established academic standards and ethical guidelines, all notions, ideas, information, or labor that came from other authors and were included into this dissertation have been properly attributed and acknowledged.

Signature…………………………………. Date…………………………………

APPROVAL

This dissertation has been developed under the supervision of the undersigned academic supervisors and it is due for approval.

Signature ……………………………..…. Date …………………………….

Al- Mas Sendegeya, PhD

Signature…………………...…………. Date …………………………….

Dr. Kizito Mubiru Paul

DEDICATION

I dedicate this dissertation to my dear mother Ms. Namutebi Rose, my spouse Nasoozi Florence, my sisters, my brothers, all friends, clan members ,my children Nalunkuma Rose, Nakiyingi Reyan and Kalyesubula Roman for the inspiration, prayers, support and encouragement throughout my pursuit for education. I hope this achievement will fulfill the dream they envisioned for me.

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LIST OF SYMBOLS AND ABBREVIATIONS

AB	Administration Block
AC	Alternating Current
CF	Capacity Factor
CTF	Central Teaching Facility
DC	Direct Current
DNI	Direct Normal Irradiation
GCPV	Grid Connected Photovoltaic
GHI	Global Horizontal Irradiation
GNSS	Global Navigation Satellite System
GUI	Graphics User Interface
IoT	Internet of Things
MPSLB	Multi-Purpose Science Laboratory Building
NASA	National Aeronautics And Space Administration
NDPIII	National Development Plan III
NPA	National Planning Authority
PR	Performance Ratio
S/N	Serial Number
SAPV	Stand Alone Photovoltaic
SD	Solar Data
SDGs	Sustainable Development Goals
TD	Temperature Data
TS	Time Series
TTB	Teacher Technical Building
UN	United Nations
USD	United States Dollar

NPV	Net Present value
PBP	Pay back period
IRR	Internal rate of return
LCOE	Levelized cost of energy

ABSTRACT

The transition to renewable energy is critical in addressing the challenges of fossil fuel depletion, rising energy costs, and climate change. Solar photovoltaic (PV) technology offers a viable and sustainable alternative, but its performance is highly dependent on site-specific installation parameters such as tilt angle, azimuth orientation, and environmental conditions. This study focused on the design and optimization of a solar PV power generation system at Kyambogo University, Kampala, by utilizing underutilized parking lots as potential sites for solar canopies. The research employed a mixed-methods approach involving site selection, shading analysis, and system modeling. Three canopy designs were developed using AutoCAD, and their performance was simulated with MATLAB/Simulink and RETScreen software to optimize tilt and azimuth configurations. Historical solar irradiance and temperature data (2018–2024) from NASA databases were analyzed to assess system performance under local climatic conditions. The results revealed that a tilt angle of 0° with a south-facing azimuth produced maximum output; however, a 15° tilt was adopted to enhance panel self-cleaning and structural durability with minimal energy losses. The optimized 80-panel system demonstrated consistent energy generation trends, confirming the feasibility of integrating PV infrastructure into university facilities. An economic analysis based on Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and Payback Period (PBP) indicated that the proposed system is both financially viable and environmentally sustainable. The findings highlight the potential of leveraging existing infrastructure to meet institutional energy needs while contributing to Uganda’s renewable energy goals and the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy).

Keywords: Solar PV, Tilt Angle, Azimuth Orientation, Energy Optimization, Economic Viability, Kyambogo University

CHAPTER ONE: INTRODUCTION

1.1 Background

Due to rising demand, the depletion of fossil resources, and increased global warming brought on by carbon emissions, energy supply is a significant issue in the modern world (Lehloka et al., 2020). As the world moves toward advanced manufacturing systems with automation, real-time data analytics, and cyber-physical integration, high levels of sustainability, resilience, and energy reliability are required. These technologies are being used more and more in research-based infrastructures, educational institutions, and manufacturing sectors (Smith & Doe, 2021). The energy supply, especially in areas with limited access to reasonably priced, sustainable power, continues to be a significant barrier to achieving the full potential of intelligent, adaptive systems (Rathour et al., 2024).During the COVID-19 pandemic, the globe was hit by a serious global energy crisis, which was made worse in February 2022 by the Russian Federation's invasion of Ukraine. Energy costs soared to their highest levels in 2022, both in Europe and globally.

According to the International Energy Agency, 90% of the increase in electricity prices in 2022 was due to rising fossil fuel prices, with over half of this increase coming from fossil gas prices alone. All energy-consuming industries saw significant inflationary effects from the price increase, which drove families into poverty, forced enterprises to reduce output, and slowed economic growth overall. This is due to the fact that energy drives all economic activity and can impact the cost of everything from food to apparel to smartphones.(REN21. 2023).Another threat is the ever-rising population of the world and mass urbanization in developing and developed countries have caused challenges to the power sectors (Umer et al., 2019).It is anticipated that worldwide energy consumption will double by 2050 due to the economy's and population rapid growth, posing increasingly serious energy-related difficulties than they currently do (Cai et al., 2023).

The world has experienced a massive industrial expansion in a number of industries in recent years, which has increased demand for energy (Alkalbani & Guangul, 2021). Fossil fuels are too costly for emerging nations due to their constantly rising prices. The amount of sunshine that reaches the earth in less than two hours is enough to meet the annual energy needs of all the economies in the world. Even though solar energy is abundant, just a small percentage of the world's current energy supply is generated by converting sunlight into forms of useful energy. (Kumari, 2024).Solar power is inexhaustible compared to other sources like fossils (Profile, 2021).Installing photovoltaic (PV) systems has become significant globally since they are a safe, clean, and environmentally beneficial energy source. The high initial cost of PV systems in comparison to traditional energy sources is a disadvantage, a lot of research is being done on optimizing PV systems to maximize the amount of PV modules, storage battery capacity, inverter capacity, and tilt angle of the PV array(Khatib et al., 2012).

Temperature and the amount of solar radiation that strikes the PV module plane are two of the variables that affect the modules' capacity to produce electricity. The ideal tilt angle for capturing the most solar energy on the PV module plane is determined by PV power designers. It becomes challenging to guarantee optimal solar radiation collection because the amount of sunlight at any given place changes throughout the year, particularly when the tilt angle is fixed. As a result, some PV power plants use sun tracking systems to guarantee that the solar panels are always aligned at the ideal tilt angle. The strategy increases the PV power system owner's investment and maintenance expenses.(Elijah George et al., 2020). The future of Uganda's climate is also anticipated to put an increased burden on its water resources.

Warmer temperatures will speed up evapotranspiration, decreasing the advantages of more rainfall, even if it is predicted that precipitation would increase in some areas of Uganda. The region's water supply and hydropower output are all expected to suffer from more frequent and severe droughts (Climate Risk Profile-Uganda:, 2020).

A number of countries have pledged to reach net-zero carbon emissions by 2050 (International Energy Agency, 2021).The National Energy Policy for Uganda 2023 focuses increasing energy efficiency and promoting the use of alternative sources of energy (International & Agency, 2023). The utilization of electricity from renewable sources is growing. Solar energy and its associated systems are the best option for sustainable development. There are social, environmental, and financial advantages to installing PV systems in parking lots. (Iringová & Kovacic, 2021). Kyambogo University has parking spaces which are potential sites for solar PV installation as shown in figures 1.1 and 1.2 but they are not fully utilized. Energy is necessary to power Kyambogo University's lecture halls, offices, workshops, labs, outdoor areas, and street lighting. However, street lighting is the main use of solar energy at the moment, which covers only a small portion of the university's facilities. Utilizing existing parking lots, for solar energy production is important for solar power generation using photovoltaic (PV) modules. As a result, the institution would be able to provide clean, sustainable energy to more university facilities.

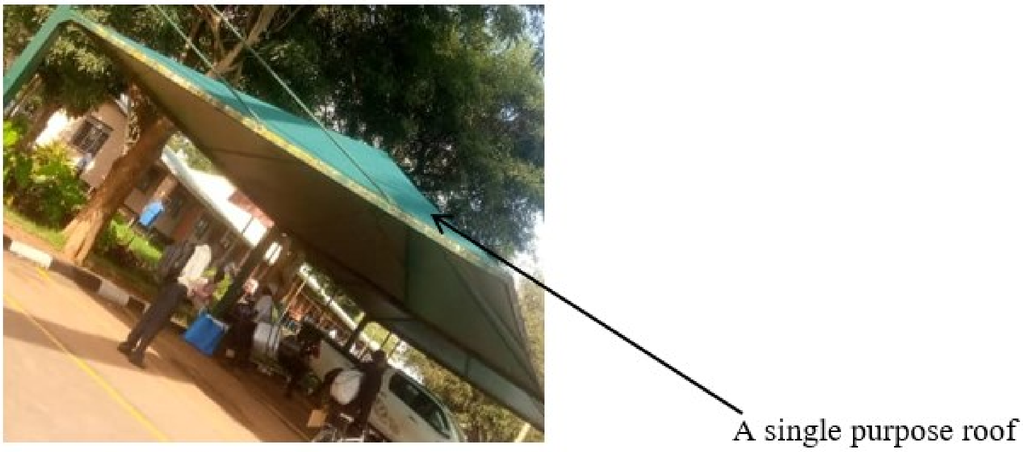


Figure 1.1: Available Carport at Kyambogo University

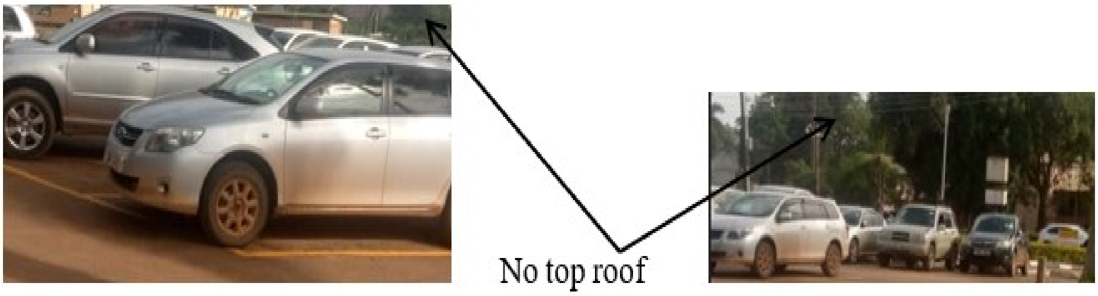


Figure 1.2: Designated Car Parking Space at Kyambogo University

1.2 Problem Statement

Energy sustainability and reliability are seriously threatened by the depletion of fossil fuels, rising global energy consumption, and the negative effects of carbon emissions, especially in industries like sophisticated manufacturing that rely on reliable, high-quality power. Even with the growing trend towards automated and data-driven smart manufacturing systems, areas like Uganda still struggle with structural energy infrastructure constraints. There are many parking lots at Kyambogo University, the institution which promotes manufacturing and engineering education, but they are not being used to their full potential as locations for decentralized energy solutions. Despite providing a practical, clean, and scalable energy source, solar photovoltaic (PV) technology is extremely sensitive to installation parameters including tilt angle and azimuth orientation as well as environmental factors. The institution's ability to create and illustrate integrated energy solutions for adaptive production systems is limited by the lack of optimum PV systems on these underutilized surfaces. Thus, by developing energy systems that improve dependability, affordability, and environmental performance, this study tackles the technical difficulty of optimizing solar PV installation at Kyambogo University and eventually contributes to resilient, energy-efficient manufacturing infrastructure.

1.3 Research Objectives

1.3.1 Main objective

To design and optimize power generation system using solar photovoltaic modules at Kyambogo university

1.3.2 Specific objectives

i. To identify and evaluate a potential site for photovoltaic system installation for optimum energy output based on solar irradiance, shading analysis and site accessibility at Kyambogo University.

ii. To develop the 3D models of photovoltaic systems using Auto card software and select the best for optimum energy output for the selected site.

iii. To enhance the performance of the developed photovoltaic systems through simulation of parameters (tilt angle, azimuth orientation, solar irradiance and PV panel type) using MAT Lab and RET screen software.

iv. To determine the economic viability of the optimized system using standard financial evaluation methods ((NPV, IRR, LCOE and PBP).

1.4 Research questions

i. What is the most suitable site for photovoltaic system installation at Kyambogo University when evaluated based on solar irradiance, shading analysis, and accessibility?

ii. What are the 3D models of photovoltaic systems can be developed using AutoCAD software, and which model offers the best configuration for optimum energy output at the selected site?

iii. How do variations in tilt angle, azimuth orientation, solar irradiance, and PV panel type influence the performance of photovoltaic systems, and how can these parameters be optimized using MATLAB and RET Screen?

iv. What is the economic viability of the optimized photovoltaic system based on financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and Payback Period (PBP)?

1.5 Scope of the Study

This study was restricted to Kyambogo University's design and optimization of solar photovoltaic (PV) systems incorporated into carport canopies. In particular, energy generation was the main area of focus. Using sophisticated tools like AutoCAD, MATLAB, and RETScreen, the research was conducted by choosing the best parking locations, thoroughly simulation of PV canopy structures in three dimensions, simulating performance under various tilt and azimuth orientations, and evaluating the economic feasibility. Although the study doesn't cover the PV system's actual construction or installation, it offered a thorough technical and financial feasibility framework that can guide future deployment. Geographically, the study was limited to Kyambogo University, and in-depth assessments were carried out at specific parking location that had been judged appropriate for solar integration. In order to simulate the energy generation performance of the suggested system, the time scope included temperature and solar irradiance data from 2018 to mid-2024.Furthermore; the scope excludes hybrid or standalone off-grid configurations and is limited to grid-connected PV systems.

1.6 Significance of the Study

This work makes a substantial contribution to the development of renewable energy applications in educational institutions, especially in sub-Saharan Africa, where problems with energy supply continue to exist. The study offers a paradigm for sustainable energy integration that may be used to other institutions dealing with comparable energy dependability problems by concentrating on the design and optimization of solar photovoltaic (PV) systems. The study improves technical knowledge of how solar performance can be affected by site selection and panel orientation. The use of simulation programs like MATLAB and RET Screen provides a scientific foundation for maximizing energy output by optimizing system parameters including tilt angle, azimuth orientation, and PV module arrangement. Economically, the study assesses the return on investment and cost-effectiveness of solar PV systems using recognized financial indicators such as Payback Period (PBP), Levelized Cost of Energy (LCOE), Internal Rate of Return (IRR), and Net Present Value (NPV).

These observations are helpful to institutional decision-makers who are looking for evidence-based recommendations about investments in energy infrastructure. Additionally, the study supports both national and global sustainability objectives, such as the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy) and Uganda's National Development Plan III. The research encourages dual-purpose infrastructure that offers both vehicle shelter and clean energy generation by utilizing underutilized parking lots.

1.7 Justification of the Study

Most of the vehicles at Kyambogo University are parked in open places for longer hours where sun rays and rainfall directly hit them. The available carport canopies at the administration building are developed unit-purposely to provide shading of vehicles. This does not add value to the institution which crippling with periodical utility costs e.g. electricity bills. Besides considering only shading of vehicles it is paramount to address the issue of energy generation as the technologies for this are already available and mature. The project is timely as it addresses the institutional goal of serving the community by demonstrating appropriate technology. Also the project is meeting the national development agenda and supports the UN SDG7.2 where utilization of sustainable energy for development is considered.

1.8 Conceptual Framework

The conceptual framework illustrated the logical structure that guided the study. It connected the problem, objectives, and methodology by outlining the variables that influenced the design and optimization of solar PV systems at Kyambogo University. The framework supported systematic analysis by identifying cause-effect relationships between independent, dependent, and intervening variables, leading to the expected research outputs.

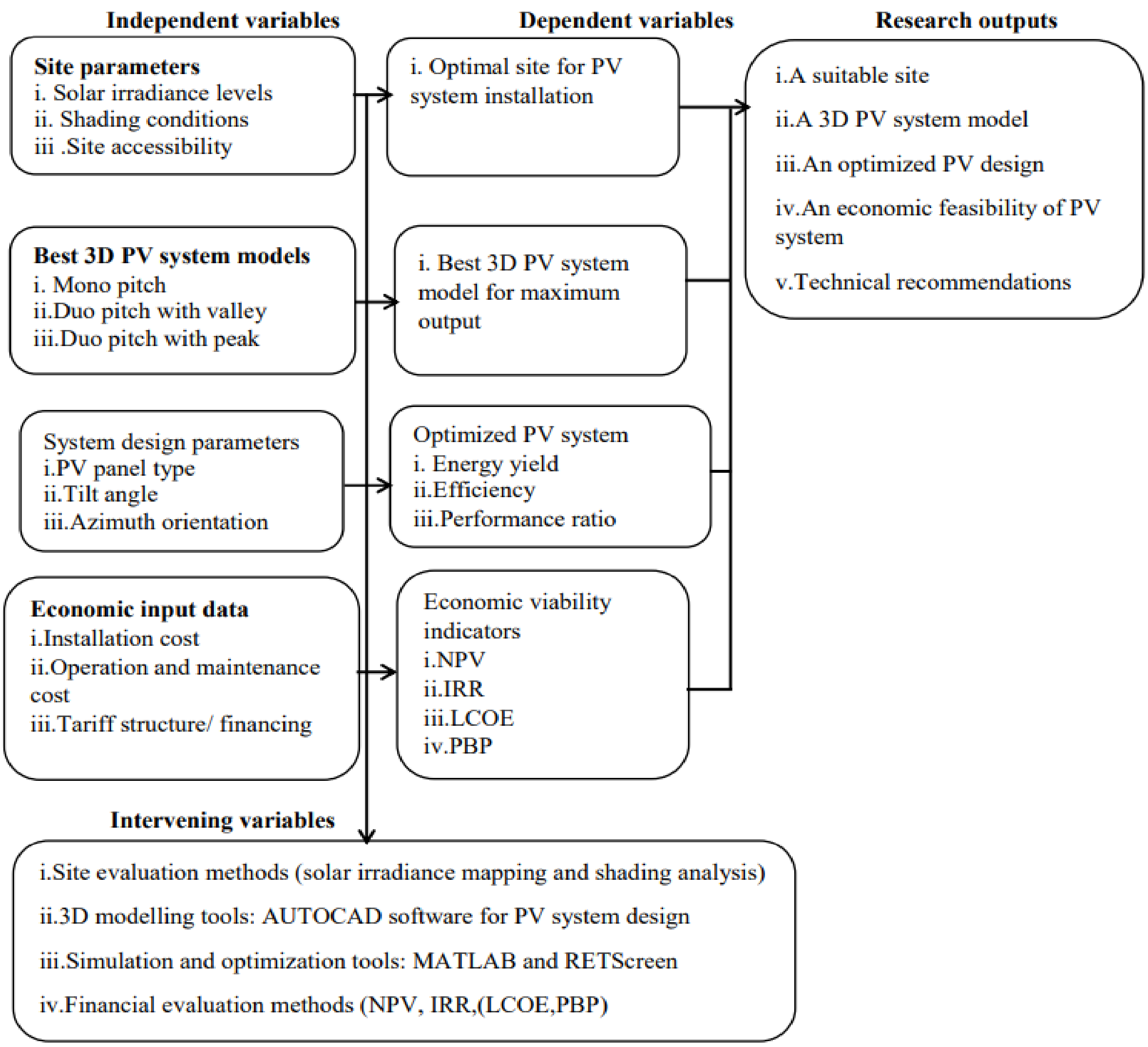


Figure 1.3:Conceptual Framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter highlights the different existing studies on potential sites which are suitable for the optimum power output, different 3D designs for the photovoltaic systems, Parameters for Optimization power output from photovoltaic systems and economic viability of the photovoltaic systems.

2.2 Site Selection for PV installation

The location of solar photovoltaic (PV) power plants has a significant impact on their long-term sustainability, economic feasibility, and technical efficiency. Environmental, climatic, socioeconomic, and infrastructure issues are among the many elements that must be thoroughly assessed in order to choose the best location (Ns, 2021; Şenlik, 2017). According to Deveci et al. (2021), location analysis is a crucial phase in PV deployment since site factors have a direct impact on energy yield and project viability. The combination of Multi-Criteria Decision-Making (MCDM) tools and Geographic Information Systems (GIS) has been a significant methodological development in this field. By facilitating the spatial analysis and weighting of many parameters, such as slope, land availability, solar irradiance, closeness to transmission lines, and accessibility to road networks, these methods expedite the decision-making process (Heo et al., 2021; Akay, 2025).

GIS-based frameworks reinforce their importance in designing sustainable energy systems by supporting evidence-based planning and improving adaptability across various climatic zones. Accessibility of the location and the closeness of infrastructure can lower capital and operating expenses considerably from an economic standpoint. Research indicates that being close to existing transmission infrastructure lowers line losses and grid integration costs, while being close to transportation networks minimizes logistics costs related to equipment supply and plant maintenance (Srikanth & Sajja, 2023). Therefore, in order to balance cost-effectiveness and energy efficiency, infrastructure factors must be incorporated into site study. When it comes to PV siting, climate is still the most important consideration. Since higher radiation levels immediately result in higher energy yields, solar irradiance is the primary factor influencing plant output (Nebey et al., 2020). However, system performance is also impacted by other environmental factors as wind speed, dust collection, and ambient temperature. PV modules normally function best between 25 and 45°C; temperatures outside of this range hasten module deterioration and lower conversion efficiency.

Dust deposition reduces irradiance capture and raises maintenance needs, while high wind speeds and shadowing also cause structural stress and energy losses (Sharma & Singh, 2018). Recent studies highlight the need for a comprehensive approach to site selection, acknowledging the interconnectedness of technological, financial, and environmental considerations. For example, if the location is prone to high humidity, frequent dust storms, or grid inaccessibility, the system's long-term dependability may be jeopardized, even though high sun irradiation may suggest strong generation potential. In order to maximize project siting and guarantee sustainable energy production, integrated assessment frameworks that incorporate mapping of solar resources with environmental and infrastructure restrictions are essential (de Luis-Ruiz et al., 2024).

2.2.1. Solar Geometry

The position of the sun and the geometric relationships between a plane and the beam solar radiation incident mainly depends on latitude. Latitude is the location on the planet in terms of north or south. The equator is defined by zero degrees(Equator, n.d. 2020)

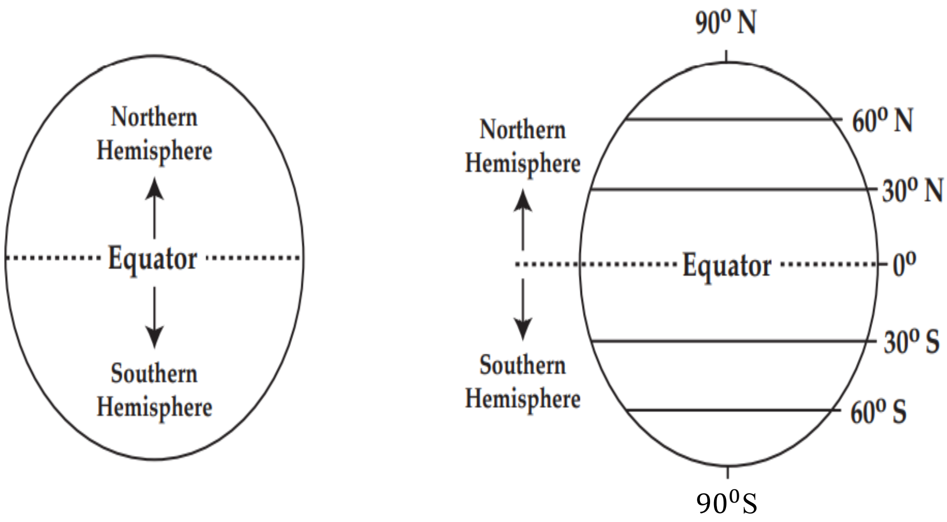


Figure 2.1: Equator and hemispheres (Equator, n.d.2020)

2.2.2 Positions of Earth and the Sun

The various places on Earth shift in regard to the Sun as the planet revolves on its axis. Twelve hours later, a city on Earth that faces the Sun at midday will turn to face away from it. Sunrise, sunset, day, and night are caused by the locations of the Sun and Earth over a 24-hour rotation. Half of the Earth is always facing the Sun, and the other half is facing away from it. The glow of the Sun illuminates the side that faces it. On that side of the world, it is daytime. The portion of the Earth that faces away from the Sun is dark at the same moment. On that side of the world, it is nighttime. (Capitaine & Bizouard, 2019).

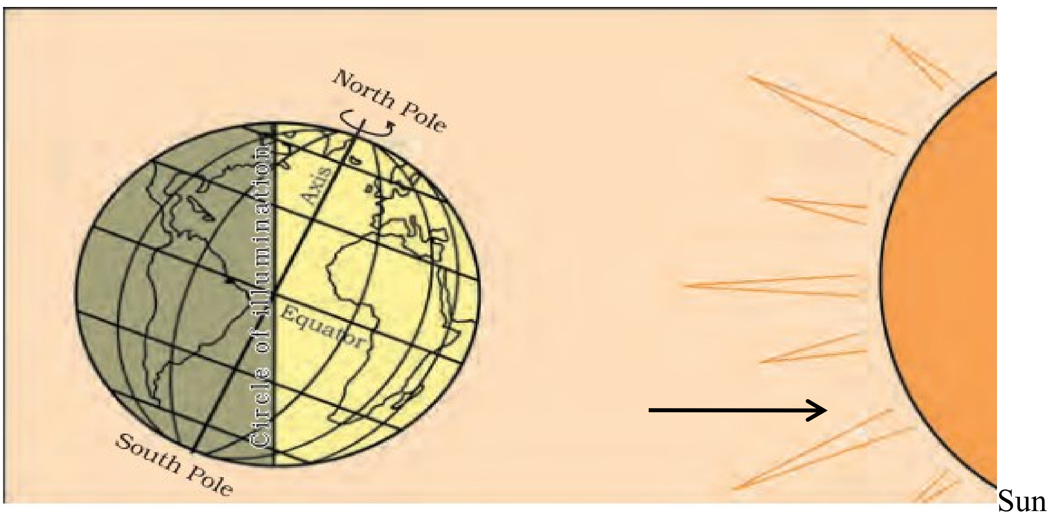


Figure 2.2: Day and night on the Earth due to rotation (Of & Earth, 2023)

2.3 Designs for the PV system installation

This highlighted the possible designs of roofs which have been used for solar pv installations in various locations.

2.3.1 Mono pitch Canopy

This type of a canopy has a single surface slope, with same slope angle at a given time as shown in the figure 2.3. For optimum shading of the cars , rooftop should range from 5° to 10° ,beyond this angle, it makes visual impacts and reduces shade to cars (Umer et al., 2019)

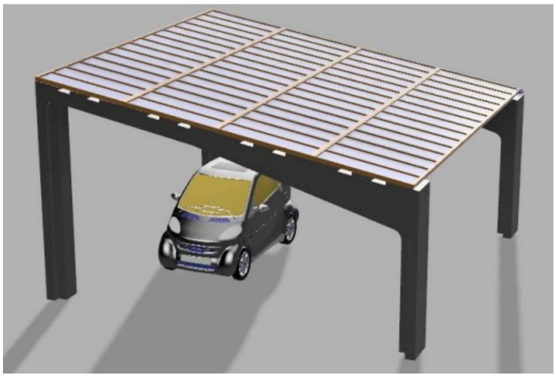


Figure 2.3: Mono pitch Canopy (Benedetti et al., 2020)

2.3.2 Duo pitch Canopy

For this design, two rows of roofs face each other in the south and north, forming a valley between the rows as shown in figure 2.4. The south-facing row of photovoltaic modules has an azimuth angle of 180°, whereas the north-facing modules have an angle of 360° north (Umer et al., 2019)

Figure 2.4: Duo pitch Canopy (Khoso et al., 2022)

2.3.3 Barrel-Arch Canopy

The curved design of a barrel-arch canopy has varying tilt angles at each point as shown in figure 2.5. The photovoltaic modules in this roof canopy are arranged as follows; the first row has an azimuth angle of 360° north at a tilt angle of 10°, the middle row has a tilt angle of 0°, and the last row has an azimuth angle of 180° south at a tilt angle of 10° (Umer et al., 2019).

Figure 2.5: Barrel-Arch Canopy (Khoso et al., 2022)

2.4 Optimization of the PV systems

Numerous soft wares are available for modeling and simulation of solar PV modules to optimize various parameters (Vinod et al., 2018).

2.4.1 PVsyst software

The PVsyst software was created in Geneva and it aids in calculating how PV systems operate. In addition to calculating the energy produced by the PV module, this program aids in system design and configuration. The output is predicated on the size system simulation and mostly relies on the PV system's geographic location (Teja et al., 2021).It is the most popular simulation software for designing and calculating fundamental solar system considerations. This software aids in the evaluation of output parameters by updating the weather information for the chosen area. The PVsyst provides monthly information on the chosen location's temperature, wind speed, diffuse irradiance, and global irradiance. The Sun's trajectory, which offers details on losses that take place over the course of a year, is also provided based on this data. The simulation software's output includes specific energy, performance ratio, and total energy generated. These findings can be used to compute the PV array and PV system's energy yield, capacity factor, and efficiency.(Navothna & Thotakura, 2022).

The PVsyst software was used to construct a fixed PV system as shown in figure 2.6 to produce 11.4kWh to fulfill the average electrical power demands of household consumption in Bangladesh. A 3kW solar PV plant mounted on a rooftop for 8.1kWh/day of residential load use was examined using the program. The PV panels produce 4172 kWh of accessible AC electricity annually, and when the daytime power requirement is satisfied, 1871 kWh of excess energy is fed into the grid (Islam, 2022).

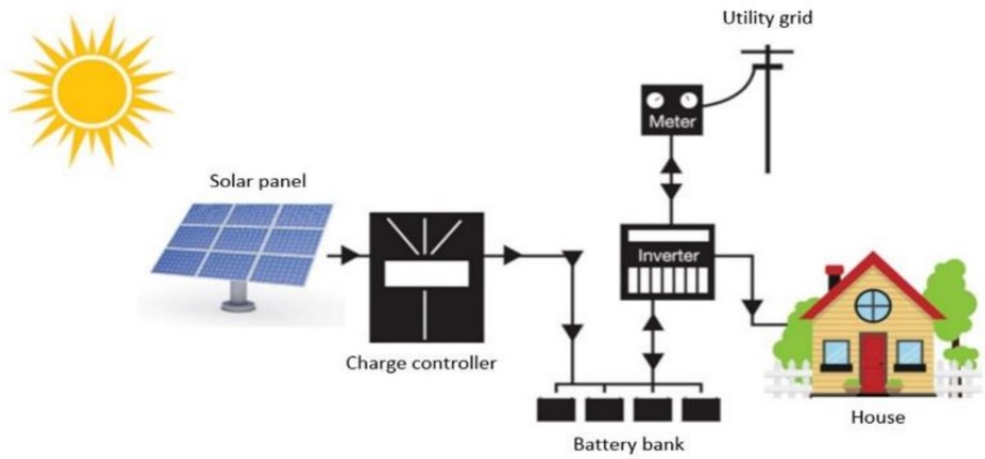


Figure 2.6: Arrangement of PV grid connected solar system (Islam, 2022)

Three key critical metrics for a stand-alone PV system were studied in India using PVsyst software: solar yield, performance ratio, and system losses. According to the figures collected, the energy given to the user was 781.13 kWh, which was somewhat less than the energy produced, while the energy available through the solar panel was 1015.2 KWh. Based on the analysis and simulation result using PVsyst software, it was concluded that the optimum tilt angle for fixed PV module installation is 5 degrees throughout the year (Mohamed et al., 2022).

2.4.2 Overview of HOMER Pro

In order to identify the most economical and effective choice, HOMER Pro can be used to assess and contrast different micro grid designs, such as renewable energy sources, energy storage and management systems, converters, grids, and conventional generators. Additionally, it provides the opportunity to conduct sensitivity analysis. It may also be used to perform a thorough financial and environmental analysis, which involves figuring out the internal rate of return, net present value (NPV), and other financial parameters(International energy agency, 2024).Remote communities, islands, military installations, colleges, and commercial and industrial establishments are just a few of the places where the software can be used. There are various license choices for this program depending on the applications (Kavuma, 2022).

2.4.3 Tilt and Azimuth angles

The tilt angle of photovoltaic (PV) panels plays a crucial role in determining the amount of solar radiation captured at the module surface. The orientation of PV systems with respect to the horizontal plane significantly influences both their efficiency and energy output. As the tilt angle changes, the effective solar radiation received on the panel surface varies accordingly, directly affecting the total amount of electricity generated. Therefore, precise determination of the optimal tilt angle is essential to maximize incident solar radiation and enhance overall system performance (Sado & Hassan, 2021).

Effective solar radiation, defined as the portion of irradiation that contributes to useful energy generation, is highly dependent on the tilt angle of PV modules (Aksoy et al., 2023). Both tilt and azimuth angles are critical design parameters that collectively determine the total energy yield of a PV system (Božiková et al., 2021). Research has shown that optimal tilt angles are not fixed but rather vary according to the seasonal and monthly trajectories of the Sun (Ibrahim & Aljanabi, 2024).

Geographical latitude is another determinant of tilt angle selection, as it dictates the solar radiation intensity at a given location. Solar energy capture generally improves when the panel orientation is perpendicular to incoming radiation, which often corresponds to aligning the tilt angle approximately with the site's latitude (Sumitaa et al., 2024; Mansour et al., 2021). Thus, proper alignment of PV panels with respect to location-specific tilt and azimuth angles is vital for achieving maximum power output (Krishna et al., 2021).

In addition to tilt optimization, the azimuth angle substantially influences annual energy production. A misaligned azimuth orientation can lead to significant reductions in system efficiency, whereas proper alignment enhances long-term energy yield (Dhimish & Silvestre, 2019). However, in equatorial regions where solar irradiance is relatively stable throughout the year, azimuth angle selection may be guided by non-irradiance factors such as structural constraints, land use efficiency, or load consumption patterns, with minimal impact on total energy generation (Correa-Guamán et al., 2025).

2.4.4 Environmental parameters

The performance and efficiency of photovoltaic (PV) modules are highly sensitive to environmental conditions such as temperature, humidity, wind speed, shading, dust accumulation, soiling, and solar irradiance (Kumar et al., 2018). Among these factors, temperature is particularly critical due to its strong and direct influence on PV system efficiency (Temperature et al., 2017). Since not all incident solar energy is converted into electricity, a significant portion is dissipated as heat, which raises the module temperature. Elevated temperatures increase the electrical resistance of the semiconductor material, thereby reducing the module's conversion efficiency (Shaik et al., 2025). Furthermore, prolonged exposure to high temperatures accelerates material degradation, contributing to thermal decay and a shortened lifespan of PV cells (Karaca & Yaver, 2024).Variations in irradiance also play a decisive role in PV performance. A reduction in solar irradiance leads to a decline in both output current and voltage, whereas an increase in cell temperature typically results in a marginal rise in current but a substantial reduction in voltage (Adeeb et al., 2019).

2.4.5 PV Solar Technologies

Solar photovoltaic (PV) panels, also referred to as solar electric panels or PV modules, consist of an array of interconnected photovoltaic cells mounted within a protective framework. These panels harness sunlight as an energy source to generate direct current (DC) electricity, forming the fundamental building block of solar energy systems (Khoso et al., 2022). At the core of this process is the photovoltaic effect, defined as the direct electronic conversion of solar radiation into electrical energy at the atomic level of semiconductor materials (Johnson & Ogunseye, 2017).

PV systems are generally categorized into two main types: grid-connected and standalone configurations. In grid-connected systems, the PV generator supplies electricity directly to the utility grid, with energy either consumed on-site or exported depending on demand and generation levels. Conversely, standalone photovoltaic (SAPV) systems operate independently of the grid and are typically deployed to meet localized energy requirements at or near the site of application (Alsadi & Khatib, 2018).

The choice of PV cell technology is a critical design consideration that directly influences system performance under varying climatic conditions. Monocrystalline silicon cells, while highly efficient, exhibit reduced performance in excessively hot climates, making them more suitable for cooler environments. In contrast, polycrystalline silicon cells offer greater adaptability, performing reliably in both cold and hot regions, thereby enhancing their suitability for diverse applications (Mohammed & Alibaba, 2019).

2.5 Economic viability of PV installation projects

Solar photovoltaic (PV) technology has been widely recognized as both a technically and economically viable option for electricity generation (Aboagye et al., 2020). A key driver of PV adoption globally is the continuous decline in generation costs, which has positioned solar as one of the most competitive renewable energy technologies (Leewiraphan et al., 2024). Beyond cost considerations, solar energy is acknowledged as a sustainable resource that offers cleaner, more reliable, and environmentally secure alternatives to conventional fossil-based power systems, thereby supporting long-term energy security for future generations (Jaiswal et al., 2019).

The deployment of PV systems has also demonstrated economic feasibility within institutional settings, where energy cost savings and sustainability goals are increasingly prioritized (Asnawi et al., 2024). However, the economic dimension remains a critical factor in determining the viability of any proposed solar installation. A rigorous economic analysis provides decision-makers with essential insights regarding investment feasibility, payback periods, and long-term cost-effectiveness (Sami, 2019). Such analyses are commonly embedded within comprehensive feasibility studies, which involve a systematic assessment of technical, financial, and operational parameters. Each component of the feasibility assessment requires specialized methodologies to ensure accurate and reliable evaluation outcomes (Group, 2024).

2.6 Summary of literature review

Globally, much research work has been done on design and optimization of solar energy using PV modules. Quite a number Centre on installation parameters, environmental parameters, PV technologies, this has taken place in many different countries apart from Uganda in particular Kyambogo University. This is the gap this paper intended to fill. It was the authors' opinions to use the available parking spaces in Kyambogo University to optimize and design a carport PV canopy. Table 2.1 shows the summary of previous researchers, work done and identified gaps.

Table 2.1: Summary of Gaps in Literature

S/N	Authors	Tittle	What was done	Gaps
1	A. Iringova and M. Kovacic(2021)	Photovoltaic system design and optimization in a parking garage (University of Zilina, Slovakia)	Comparison of the overall amount of electricity produced by various PV panel technologies	Only one orientation (south) was taken into consideration in the investigation
2	Anurag Shrivastava(2018)	Assessment of a standalone PV system's solar energy capacity and performance using PVSYST at Karunya Institute of Technology (India)	PVSYST was used to evaluate the performance and solar energy capacity of a standalone PV system.	Did not simulate various azimuth angles
3	Lehloka.M, CletusSwart .A and Hertzog. P(2020)	Verifying the ideal tilt angle for photovoltaic modules in South Africa's Highveld for the summer	Investigated the ideal tilt angle for installing fixed-axis photovoltaic modules.	Considered one season yet energy is needed every day throughout the year
4	Rubaiyet Binte Nazmul(2019)	Finding the Best Angle for Bangladeshi Solar Panels in Dhaka to Get the Most Irradiation	Determined the ideal solar panel angle for each of the 365 days. If any angle is maintained constant for 365 days, the total sun irradiation was also determined.	The study considered tilt angle only and neglected azimuth angle
5	Sahib.N.Abdul-wahid(2020)	Tilt Angle's Impact on Solar Panel Output	The study examined various tilt angles for the installation of solar PV modules during the course of the year.	Azimuth orientations were not considered
6	Jae Heo (2021)	Solar Photovoltaic Power-Plant Site Selection for Infrastructure Planning	evaluation of the site selection for photovoltaic (PV) plants, using spatial analysis and geographic information system (GIS)	Did not conduct study of shading structures like trees, buildings and dust accumulate from highway
7	Semih Sami Akay(2025)	Investigating Land Suitability for PV Farm and Existing	identified the most suitable areas for the	Temperature impact on PV energy

		Sites Using a Multi-Criteria Decision Approach in Gaziantep	establishment of PV farms in Gaziantep	generation was not considered in site selection
8	Muhammet Deveci, Umit Cali, Dragan Pamucar (2021)	Evaluation criteria for site selection of solar photovoltaic (PV) projects using fuzzy logarithmic additive estimation of weight coefficients	Determined the degree of importance of criteria affecting site selection of solar photovoltaic (PV) projects using a decision-making model.	Temperature impact on PV energy generation was not fully analyzed in site selection
9	Y.M. Srikanth, Satish Sajja (2023)	Optimal site selection for establishing solar power plant based on solar radiation using GIS	Selected an ideal location to establish a solar power plant in the district of Anantapur using GIS with sun radiation data.	Temperature was not considered for site selection for solar power plant
10	Muharrem Hilmi Aksoy (2023)	Impact of Tilt Angle on The Performance of The Photovoltaic Systems for Different Row Spacing	Examined the performance values and economic feasibility of PV systems using various panel row spacing and tilt angles	Azimuth orientation was not considered in the study

CHAPTER THREE: METHODOLOGY

3.1 Introduction

The methods used to achieve the respective research objectives have been explained and the tools in collecting data on solar radiations from review studies have been presented. The criteria for assessing the designs of existing PV carport canopies, technical design principles and performance evaluation, and the methods employed in analysis of the experimental results have also been highlighted.

3.2 Research Approaches

A mixed research method was used, it combined both the elements of quantitative research and qualitative research approaches to answer research questions. This helped to provide a more complete picture than standalone quantitative or qualitative studies however the research was more quantitative than qualitative.

3.3 Site Selection

As indicated in table A.1, Kyambogo University has numerous buildings with parking spaces that range in size and capacity. The availability of the parking space was verified by visiting each of these buildings. For the goal of obtaining sufficient space for PV installation, the study concentrated on buildings with a minimum of twenty parking spaces. On each location, the slots were physically counted in accordance with their portions, and the ratios are displayed in table 3.1. The aggregate of the ratios from the various parking sections determines the overall number of slots on each site.

Table 3.1: Kyambogo University parking sites with at least twenty parking slots

S/N	Location	Ratios of parking slots at different sites	Total number of slots
1	AB	8:6:7:8:17	44
2	MPSLB	6:4:10:20	40
3	CTF	18:4:13:14:8:8	65
4	TTB	16:16:21:20:19	92
5	Faculty of education	No parking slots seen	20
6	Faculty of special needs and rehabilitation	No parking slots seen	20
7	Department of mechanical and production engineering	No parking slots seen	30
8	Barclays library	No parking slots seen	45
9	Engineering workshop	10:8:6	24

3.3.1 Tools used for site selection included the followings

i. Tape measure, this was used to get the size of the length and width of the site which was later multiplied to determine the area.

ii. Auto card software was used for making various drawings

iii. Google earth pro was used to extract the images of the sites

iv. Compass was used to identify the direction and the movement of the sun at the site.

3.4 Proposed Designs

Three designs of solar PV module installations roofs were proposed which included single slope, double slope with a crest at the highest points of the roof and double slope with a valley between the lowest points of the roof. The three proposed designs were further evaluated to select the using the following tools;

i. Literature review was used to evaluate the merits and demerits of the three designs

ii. Auto card software was used to generate 3D structural drawings for visualization and technical assessment.

iii. Mathematical evaluation was used to determine the number of PV modules to fit on the designed roof.

3.5 Optimization of the developed photovoltaic systems

The optimization of the photovoltaic system was done by considering installation, environmental and technology parameters. The installation parameters were azimuth and tilt angles and these were simulated using RET screen. MATLAB and Simulink were used to simulate the environmental parameters (solar irradiance and temperature).After simulation, sizing was also performed to guide on equipment specification selection.

3.5.1 Simulation of installation parameters of the PV Modules.

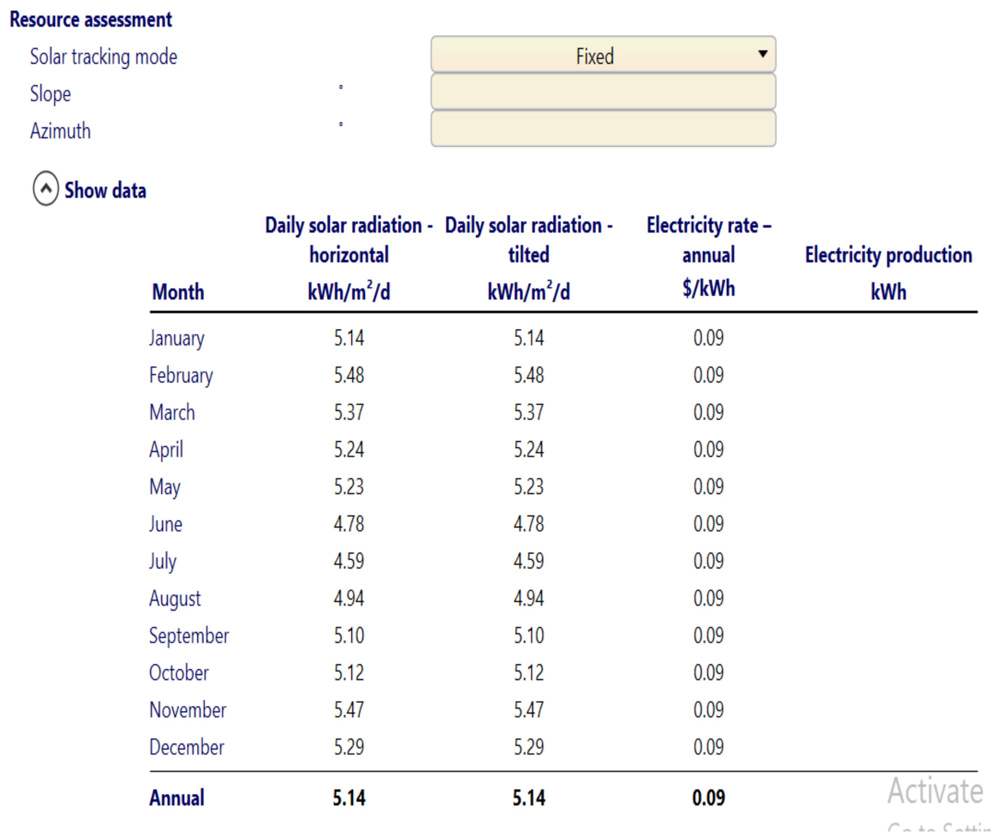
This was carried out using RET screen to identify the best combination of parameters which could generate optimum energy by simulation of tilt and azimuth angles for fixed installation. Uganda in particular Kampala was selected on RET screen page as shown in the figure 3.1, this was because Kyambogo University is located with in Kampala city.

Figure 3.1: RET screen window for site location

The Tilt and Azimuth Angles were input into RET screen software to determine which combination of installation parameters would generate optimum energy as shown in the figure 3.2. The solar tracking mode was maintained fixed while variations were done on tilt and azimuth angles for all simulations. The simulations involved tilt angles of zero, five, ten, fifteen, twenty, twenty-five and thirty on different azimuth angles as shown in the table 3.2.

Table 3.2: Azimuth and tilt angles

Azimuth angles(degrees)	Tilt angles(degrees)						
0	0	5	10	15	20	25	30
90	0	5	10	15	20	25	30
180	0	5	10	15	20	25	30
270	0	5	10	15	20	25	30



Resource assessment
Solar tracking mode: Fixed
Slope °
Azimuth °
Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity rate – annual $/kWh	Electricity production kWh
January	5.14	5.14	0.09	
February	5.48	5.48	0.09	
March	5.37	5.37	0.09	
April	5.24	5.24	0.09	
May	5.23	5.23	0.09	
June	4.78	4.78	0.09	
July	4.59	4.59	0.09	
August	4.94	4.94	0.09	
September	5.10	5.10	0.09	
October	5.12	5.12	0.09	
November	5.47	5.47	0.09	
December	5.29	5.29	0.09	
Annual	**5.14**	**5.14**	**0.09**	

Figure 3.2: RET screen window for energy simulation

3.5.2 Collection of environmental data parameters of the PV Modules.

The performance of the suggested solar power system for the Kyambogo University parking lot was precisely modeled and examined using datasets gathered from trustworthy source. The main goal was to gather temperature and solar irradiance data in order to model the energy generation of the system. In order to ensure high accuracy and dependability, historical irradiance data for this project was taken from NASA's satellite databases. UNMA data was not utilized due to study site and time period constraints. Because NASA data provides long-term, standardized, and validated solar records that are regularly available and publicly accessible, it is more reliable for system design and optimization.

3.5.3 Data Preprocessing for Analysis and Simulation

After data was downloaded from NASA data source databases, it was analyzed using MATLAB code for any values that were inaccurate for the simulations due to wrong data collections as shown in the figure 3.14 under listed categories below.

i. **Omission.** Data preprocessing included omission of solar irradiance data that was not yet recorded (from 31st July 2024 to 31st December 2024) that had -999 values.

ii. **Extraction.** The solar irradiance data was then used to create a vector of values for solar irradiance for further analysis.

iii. **Creation of time series. The collected data was grouped into time** series using MATLAB programming to express data based on time. It represents data against time as a continuous count necessary for simulation purposes.

iv. **Sorting.** Data preprocessing also included sorting the solar irradiance data into periods of years and monthly basis that was necessary for further data analysis.

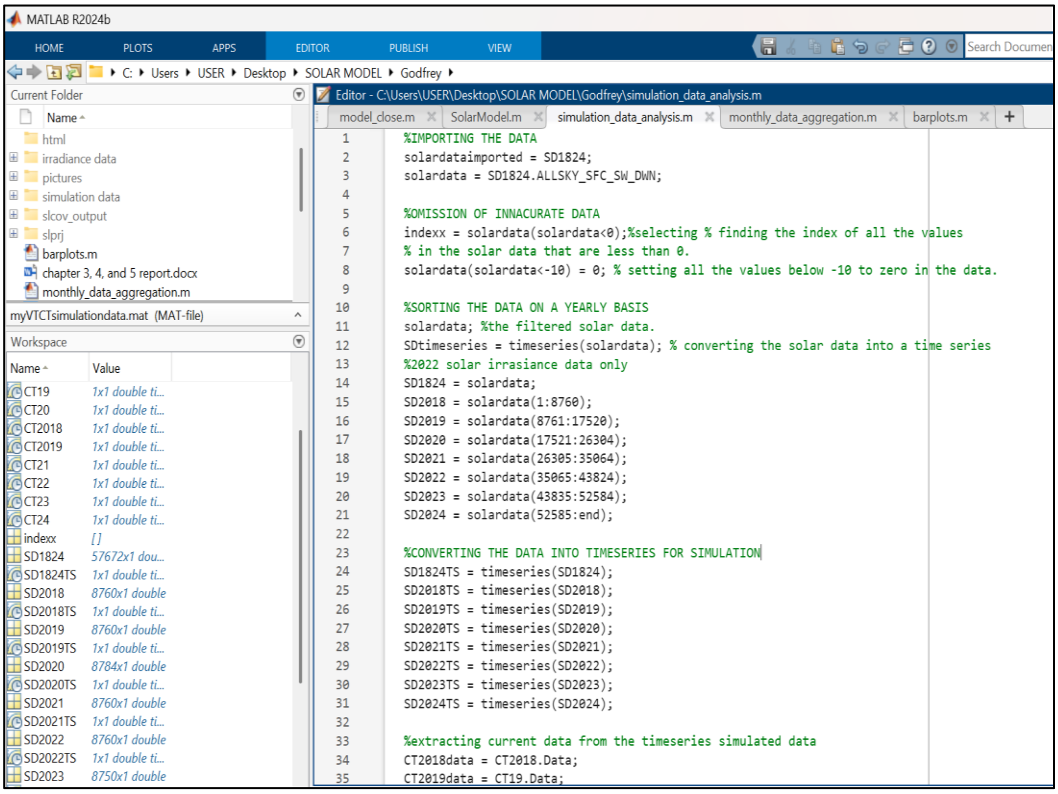


Figure 3.3: Screenshot of the code showing data preprocessing activities in MATLAB

3.5.4 PV module arrangement on the available area

a) Double slope roof with a crest

Mathematical calculations were performed to identify how many solar PV modules can be fitted on a double slope roof inclined at 15^0 on an area of $240m^2$ using figure 3.4.

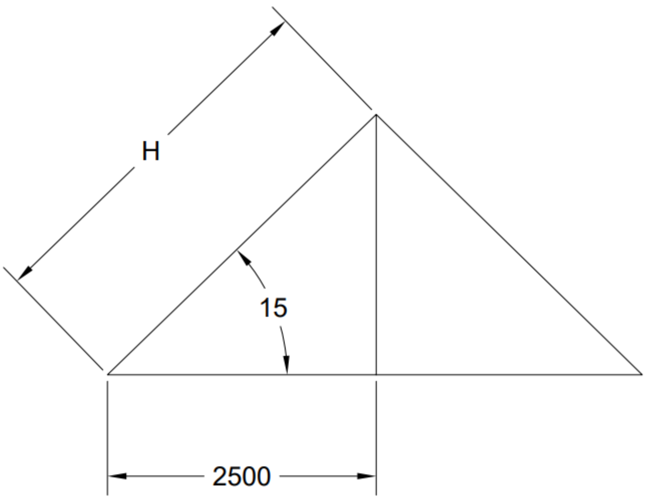


Figure 3.4:Double slope roof with a crest

Using Pythagoras theorem

$$\text{Cos}15^0 = \frac{Adjacent}{Hypotenuse} \text{..} 3.1$$

Where;

15^0 is the selected tilt angle of the PV modules

Adjacent is the half of the width of the parking inclined at 0^0

Hypotenuse is the width of one side of the roof inclined at 15^0

a) Single slope arrangement

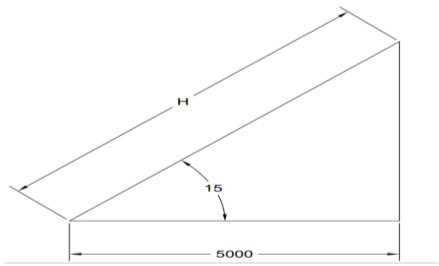


Figure 3.5: Side view of the single canopy top (facing south)

Applying Pythagoras theorem on the figure 3.11

$$\text{Cos}15^0 = \frac{Adjacent}{Hypotenuse} \text{..} 3.2$$

Where; 15^0 is the selected tilt angle of the PV modules, Adjacent is the width of the parking inclined at 0^0 and Hypotenuse is the width of the roof inclined at 15^0

3.5.5 Model Development for Simulation in Simulink

After the solar data, the size and power ratings of the panels were obtained, a Simulink model representing this data set up was designed in Simulink simulation environment to study the performance of the system as shown in the table figure 3.6.

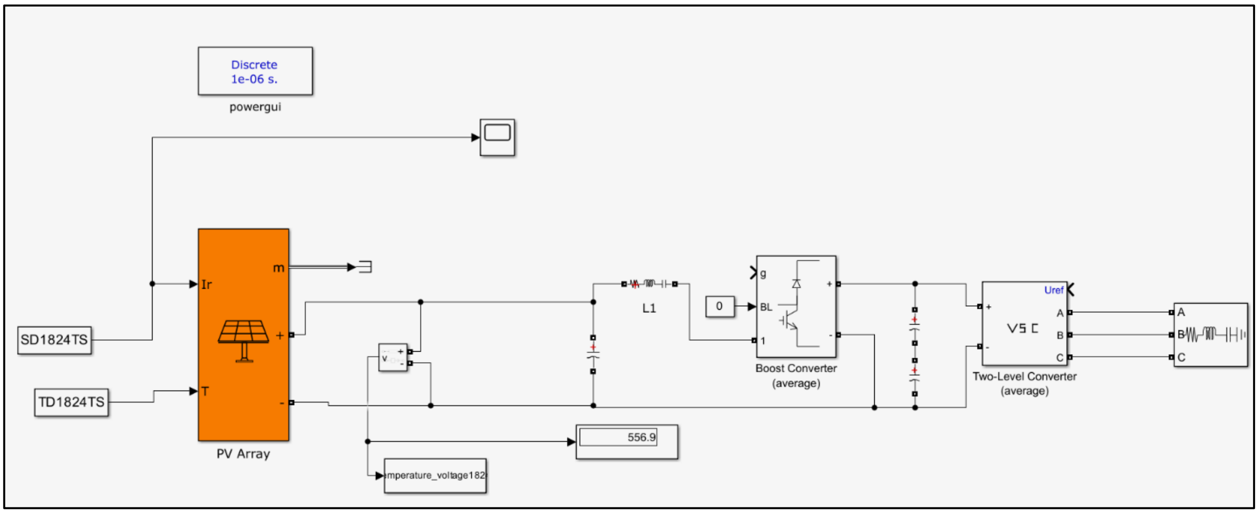


Figure 3.6: Setup of the system for simulation of the solar system performance

i) SD1824TS and TD1824TS block.

Figure 3.6 was used to import the analyzed solar data and temperature data time series variables from MATLAB to Simulink for simulations.

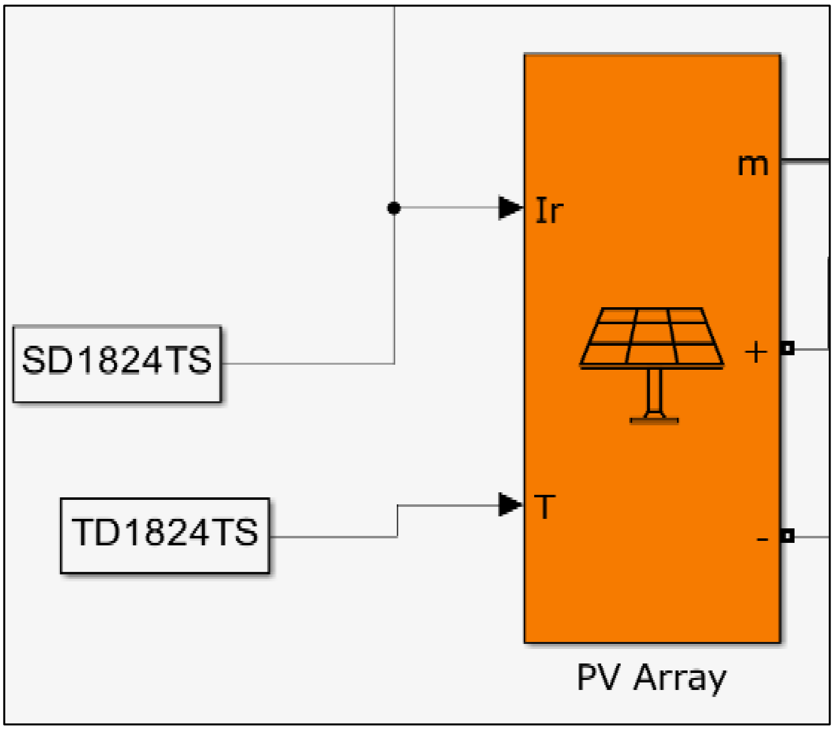


Figure 3.7: Solar irradiance, Temperature and PV array blocks

PV array block. This was used to implement the layout and connection of the different solar panels and simulate their performance under different conditions such as different solar irradiances under different temperatures. This block allowed for inputs of irradiance and temperature and could be adjusted to allow inputs of irradiance and set temperature to a constant value of 25^{0}C.

The electrical parameters of the solar panels were input into this PV array block to simulate their actual performances as shown in the figure 3.7.

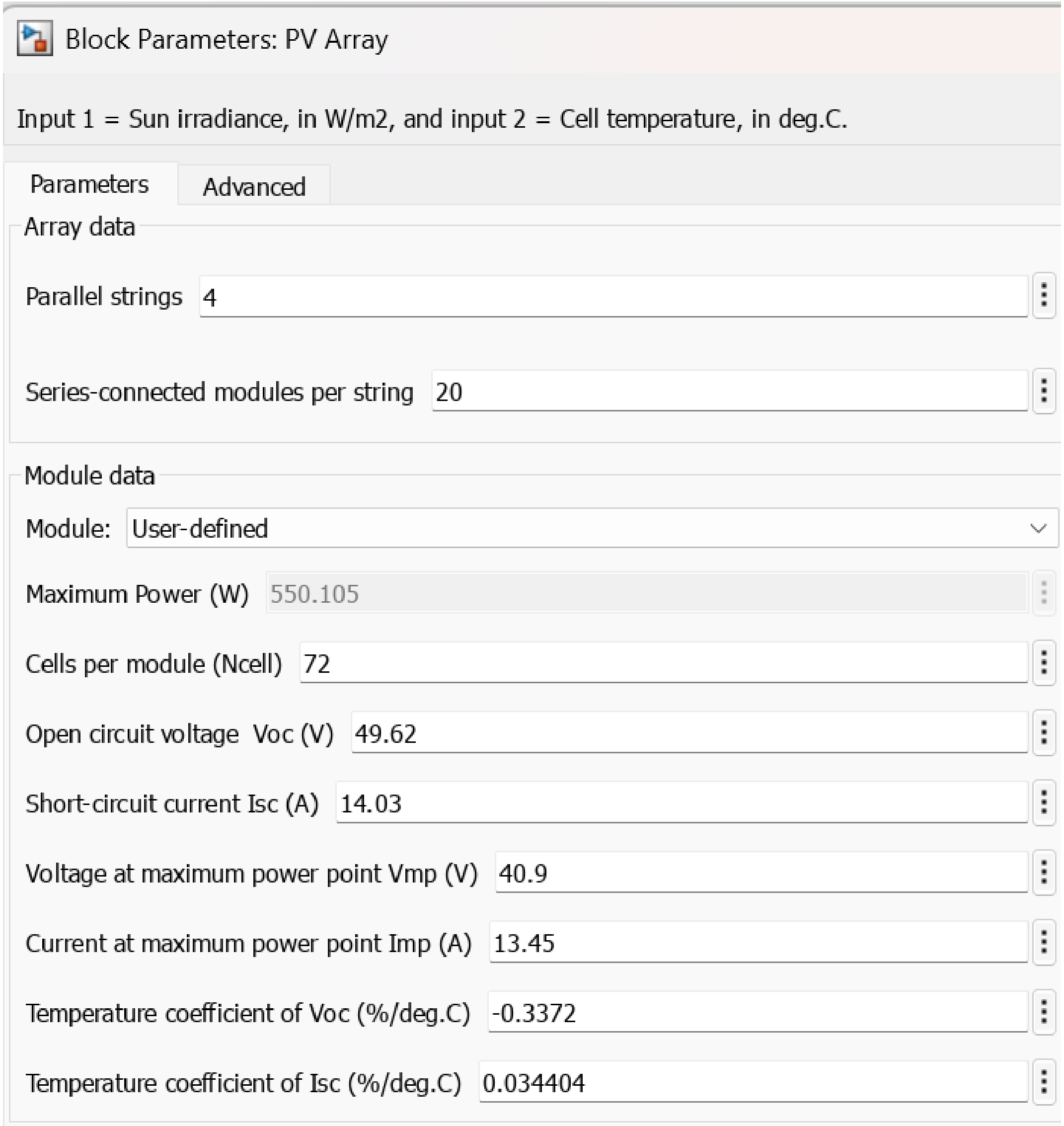


Figure 3.8: Solar panel and array parameters input into the PV array block

ii) Power GUI block

Figure 3.8 was a block in Simulink that allowed all electrical models to run in Simulink. It set the sample time for the simulation to run, set the type of solver to run the simulation and did all the necessary computations necessary in the model that was designed. Without this block, the simulation of the block would bring errors.

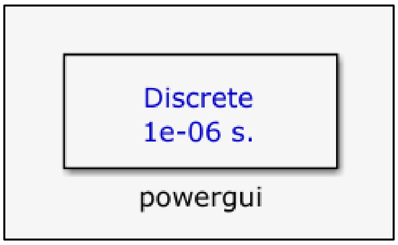


Figure 3.9: Power GUI block

iii) Switching, converter and load blocks.

These are the other blocks that were connected to the solar PV array to represent other components of the system as shown in the figure 3.9.

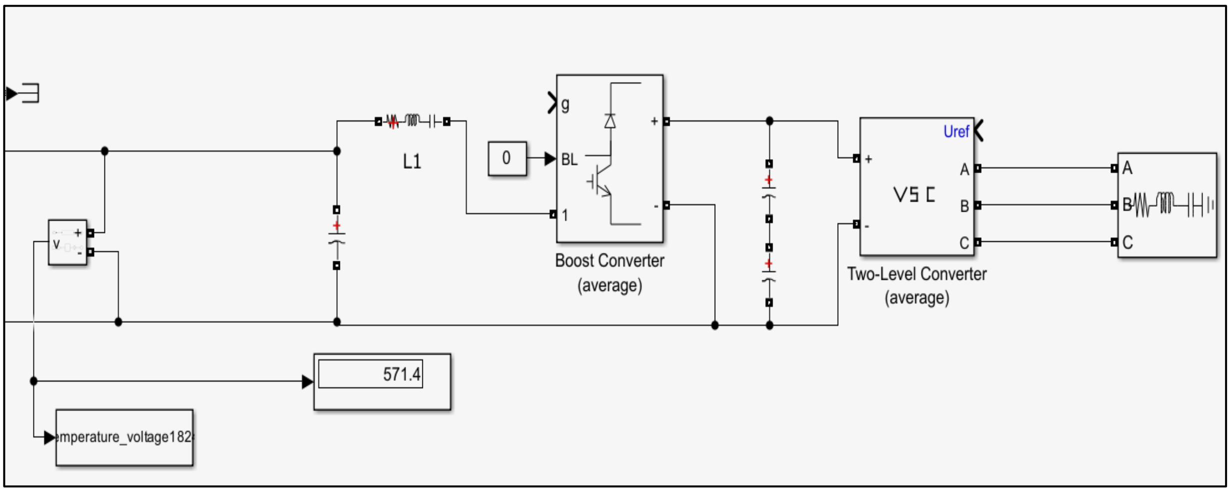


Figure 3.10: Other blocks connected in the solar PV system model

3.5.6 Simulation of the Performance of the developed PV System

After the model was developed, the simulation and analysis of the system performance was done under different operating conditions. The simulations included currents and voltages obtained under different solar irradiances, energy outputs at a fixed temperature of 25^0C and at different temperatures as fed in from the TD1824TS block.

The simulations were done for the currents and voltages from 2018 to 30^{th} July 2024 and their respective values exported back to MATLAB for further analysis. The analysis included calculating the energy generated, obtaining the maximum values of the energy generated per year, summing monthly, yearly energy generated, and the total energy generated by the system for the seven years.

3.6 Economic Analysis

An economic analysis of a solar project entails assessing the project's long-term financial sustainability. To ascertain whether the project is a wise investment, this analysis takes into account a number of variables.

3.6.1 Capacity factor

The capacity factor (CF) measures how much energy a solar system generates compared to its maximum possible generation in a given period of year (sro, 2016).The capacity factor range from 11% to 32% according to different researchers who have computed capacity factors of different PV solar systems in different location (Boretti et al., 2020),(Febrian et al., 2023),(Ayompe, 2007).

$$CF = \left(\frac{Actual\ energy\ generated(kWh)}{Installed\ capacity\ (kW)*Total\ hours}\right) \times 100 \qquad 3.3$$

3.6.2 Average Annual Energy Generation (E_t)

To obtain this value, the average annual energy generated from the installed capacity was obtained from the simulations for the past six years (2018-2023)

Using equation 3.4 the average energy generated per year(E_t) was calculated

$$\boldsymbol{E_t} = \frac{Annual\ energy\ of\,(2018+2019+2020+2021+2022+2023)}{6} \qquad 3.4$$

3.6.3 Mean, Median and Standard Variation

By using energy simulated for the six years from 2018 to 2023 mean, median and standard variation were also calculated.

$$\text{Mean} = \frac{\text{Total energy generated(2018 to 2023)}}{\text{Total number of years}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

Median= The annual energy in the middle (2018 to 2023) when arrange in ascending order……………………………………………………………………………...3.6

$$\textit{standard deviation} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

Where X_i is the total energy generated in a given year, $\overline{X}$ is the mean and N is the total number of years.

3.6.4 Inputs of the Economic Analysis Metrics to the Project

By using these inputs to the solar project, an economic analysis frame work was obtained in order to guide in decision making. The inputs for the computation of the economic analysis included.

i. **Initial investment cost (C_0).** This included the cost of solar panels used, inverters, installation, and all other equipment used.

ii. **Annual energy generation (E_t).** This is the annual electrical energy generated from solar panels obtained from Simulink simulation results.

iii. **Operational costs (O_t).** These included maintenance cost, cleaning and repairs.

iv. Revenue or savings (C_t). This represents how much the university will save by using solar instead of grid power.

v. **Discount rate (r).** This represents inflation, interest rates, or cost of capital.

vi. **Project lifetime.** This is usually 25 years for solar projects.

3.6.5 Revenue or Savings (C_t), Operational costs(O_t)

a) Revenue or Savings (C_t)

This is the amount of money saved from using alternative sources of electricity; hence the total cost of electricity saved in one year is given by.

$$Total\ cost\ saved = electrical\ energy\ generated \times cost\ of\ energy \ldots\ldots\ldots.3.8$$

b) Operational Costs(O_t)

Operations and maintenance, usually found as O&M, costs which include all the expenditure categories from the beginning of PV plant operations. Examples of them are PV module cleaning, monitoring or on-site inspections, security costs minor repairs and other administrative costs. Due to the absence of moving parts, the operational costs of solar systems are estimated at 5% of the system components cost. Hence,

$$\text{Operational costs, } \mathrm{O_t} = \frac{5\times(\text{Total cost of the system})}{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.9$$

3.6.6 Levelized Cost of Energy (LCOE)

LCOE is the cost of generating one unit (kWh or MWh) of electricity over the lifetime of a power system. It is widely used to compare the cost-effectiveness of different power generation technologies.

$$LCOE = \frac{\sum I_t + O_t + F_t}{\sum E_t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.10$$

Where I_t is the investment cost in year t, O_t is the operation and maintenance costs in year t, F_t, is the fuel cost (zero for solar), E_t is the energy generated in year t and t is the year index which ranges from one to the project lifetime. LCOE tells how much each unit of electricity costs to generate over the system's lifetime. A lower LCOE means a more cost-effective project while a higher LCOE implicates a higher cost making the option less effective. This method allows comparison with grid electricity costs and other power generation options (Aldersey-Williams, 2019).

3.6.7 Net Present Value (NPV)

This method assesses the present value of all future cash flows generated by the solar project, subtracting the initial investment. It accounts for the time value of money, meaning future revenues are worth less than money today

$$NPV = \sum \frac{C_t}{(1+r)^t} - C_0 \quad \text{...} 3.11$$

Where C_t is the net cash flow in year t that is the revenue minus expenses C_0 is the initial investment cost, r is the discount rate (the interest rate or required return on investment) and t is the year index. If NPV is greater than zero, the project is profitable and worth investing in while if it is less than zero, the project loses money and requires reconsideration (Gaspars-Wieloch, 2019).

3.6.8 Internal Rate of Return (IRR)

If IRR is greater than r (discount rate), the project is profitable and if IRR is less than the discount rate, the project is not profitable and may not be worth investing in. Its formula is derived from the net present value formula by making the NPV zero as shown in the equation 2.3. (Mellichamp, 2017).

$$0 = \sum \frac{C_t}{(1+IRR)^t} - C_0 \quad \text{...} 3.12$$

3.6.9 Payback Period (PBP)

Payback period is the minimum time taken to recover investment costs. It is used to determine the minimum time a system must last in order to recover the investment costs. The payback method is often used as a rough guide to cost-effectiveness (Al-Ani, 2015). Due to its ease of use and liquidity, the payback technique is recommended when evaluating capital budget decisions.

(Stamalevi, 2015).The payback period for an energy system is calculated as the total investment cost divided by the first year's revenues from energy saved, displaced, or produced. The unit of measurement is the number of years to "pay back" the investment cost and if it is significantly less than the expected system life, the project is considered cost effective.

$$PBP = \frac{Initial\ Investment\ Cost}{Annual\ Cash\ Flow} \qquad 3.13$$

Table 3.3: Summary table for tools used per specific objective

Objective	**Tools**	**Expected output**
To identify and evaluate a potential site for photovoltaic system installation	Literature review Site visits	A suitable site for optimal solar energy was identified
To develop the 3D models of photovoltaic systems	Literature review Auto card software	3D PV system models
To optimize the performance of the developed photovoltaic systems	Literature review RET screen and MAT Lab software	An optimized PV system
To determine the economic viability of the optimized system	Standard financial evaluation methods	An economic feasibility of PV system Technical recommendations

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents and discusses the results obtained from the study of design and optimization of power generation system using solar photovoltaic modules at Kyambogo University. The study aimed to evaluate the energy generation potential of the proposed solar installation and assess its economic feasibility. The simulations were conducted in RET Screen and MATLAB/Simulink, incorporating real-world meteorological data of solar irradiance and temperature which was obtained from NASA. The results provided insights into the performance of the system under varying environmental conditions and its impact on the overall efficiency and financial viability of the project.

The results discussed in this chapter include solar resource assessment, system design and configuration, simulation results for system performance, temperature impact analysis, annual energy estimation and economic analysis. The findings from these analyses helped understand the feasibility and practicality of installing the solar system at Kyambogo University.

4.2 Case Study: Kyambogo University solar parking lot project

Kyambogo University is one of Uganda's leading higher education institutions located in the capital city of Kampala. Having encountered a challenge of high costs of electricity power outages due to power reliability issues, a proposal for a mini solar power plant was developed that led to this project which focused on using parking slots for solar generation while providing shelter to the vehicles from harsh weather conditions like sunshine and heavy rains. This case study focused on designing and optimizing a photovoltaic system tailored to this location, ensuring optimal energy generation while making efficient use of available space. The objective of this case study was to implement a practical and sustainable solar energy solution that meets part of the university's electricity demand while reducing reliance on grid electricity.

4.3 Potential site for PV system installation for optimum energy output at Kyambogo University.

Multipurpose science laboratory building and technical teacher education buildings had the highest number of parking slots in the same portion. These two sites were further studied to identify the best for solar PV installation. Multi-purpose science laboratory is located in the west end and the technical teacher education is located towards the administration offices of the university as shown in figure 4.1. The parking slots at Multi-purpose science laboratory building are portioned in the ratio of 4:6:20.The portion of twenty slots was considered because of the biggest area.

Figure 4. 1: Geographical location of two proposed sites at Kyambogo University

Figure 4. 2: Multipurpose science laboratory building

Using Google earth software satellite images of the sites were extracted to have a clear view of the sites as shown in figures 4.3 and 4.4.The trees near the Technical Teaching building causes shading of the site for long periods compared to multipurpose science laboratory.

Figure 4. 3: Multi-purpose science laboratory site developed from satellite

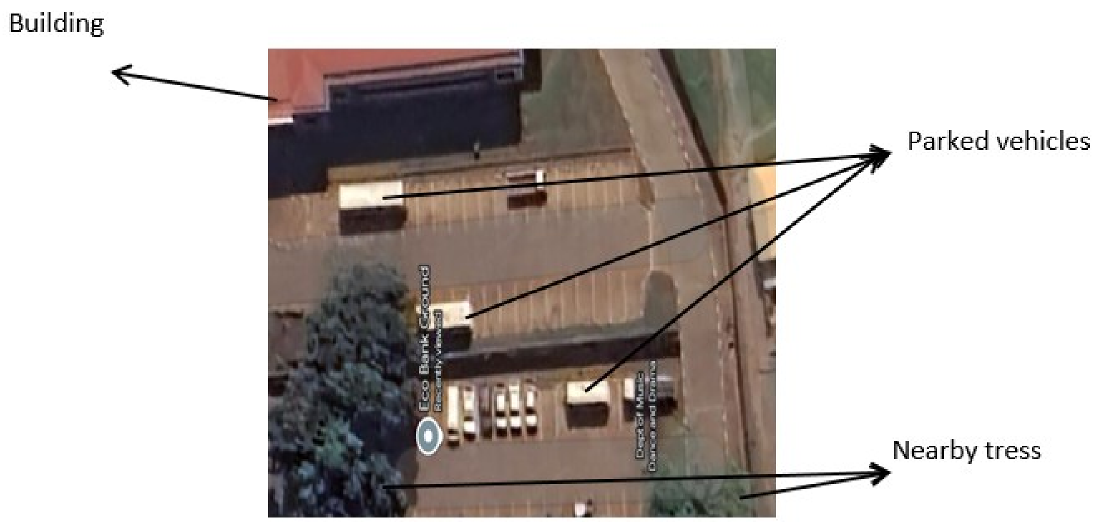


Figure 4.4: Teacher Technical Parking Developed From Satellite

There are two tall trees at far distance in East direction of the site which shades the 60 square meters at 7:00am and the area keeps on reducing up to zero by 9:00am.At the west direction of the site there is also a tall tree which shades the site at 18:00pm on 10 square meters and this area keeps on increasing until the sun sets. The multipurpose science laboratory building does not cast shade on to the site because it is seventy meters away from the site. Using auto card Figure 4.5 and 4.6 were developed which shows the shading structures at the site.

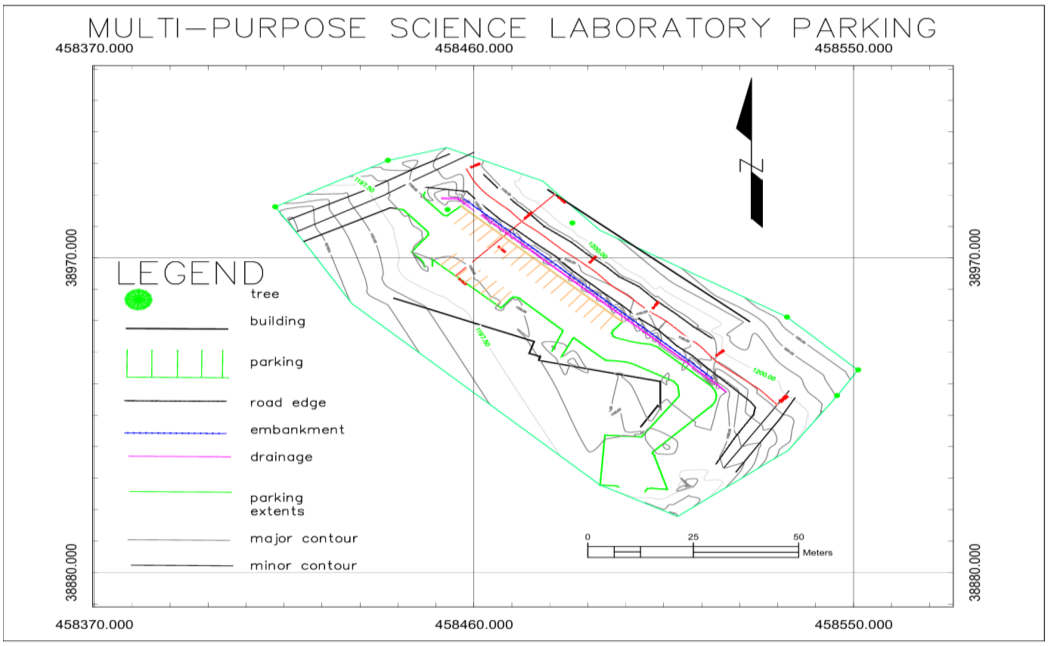


Figure 4.5: Multipurpose Science Laboratory Parking Developed using AutoCAD

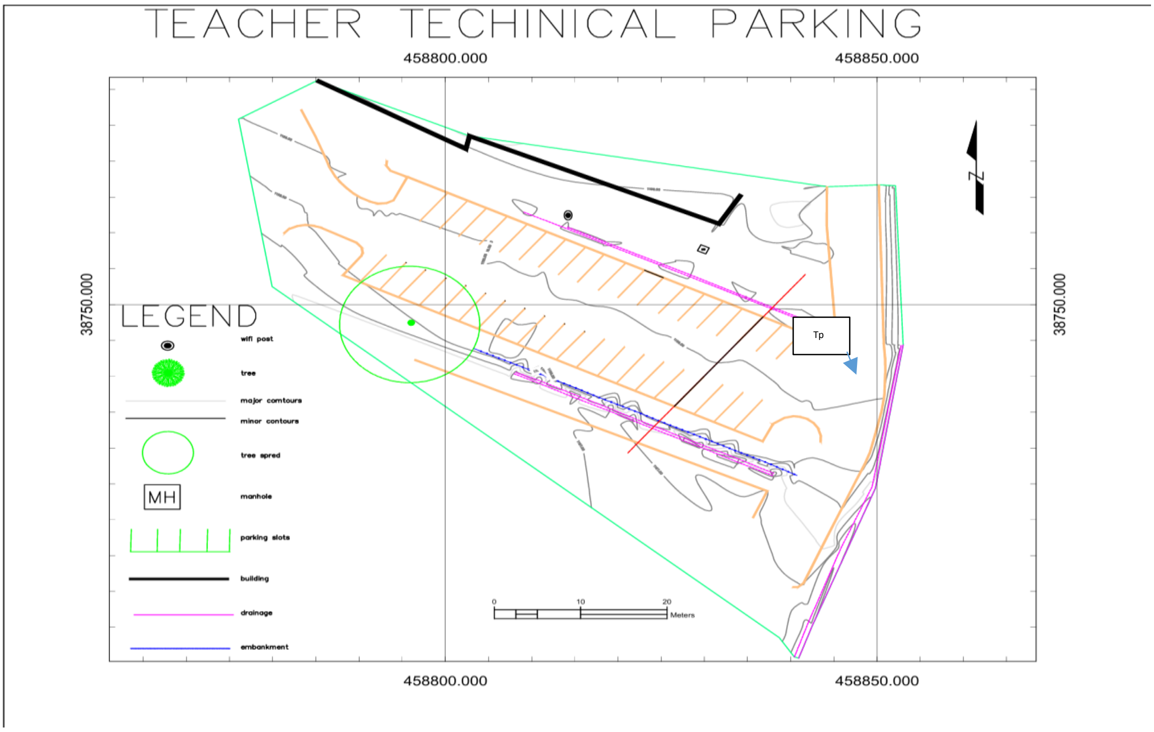


Figure 4.6: Technical Teacher Education Parking Developed using Auto Cad

Even though Kyambogo University has a number of parking lots, following a methodical site selection procedure, this study focused on the Multipurpose Science Laboratory parking lot. This specific lot was chosen as the best option because it offers the most contiguous space, has less shade than other locations, like the Technical Teacher Education lot, is conveniently located for installation and maintenance, and has a favorable orientation for solar capture. The study had to be restricted to a single lot in order to allow for thorough technical and financial optimization within the project's parameters and to guarantee that the results would be scalable and applicable to additional university parking lots in the future.

4.4 Proposed designs

4.4.1 A mono pitch design (single slope)

Mono pitch design is shown in figure 4.7; this had one side of inclination angle. Because of it merits like simplicity to construct, fewer materials for construction and its efficient water drainage, this design was further considered for analysis.

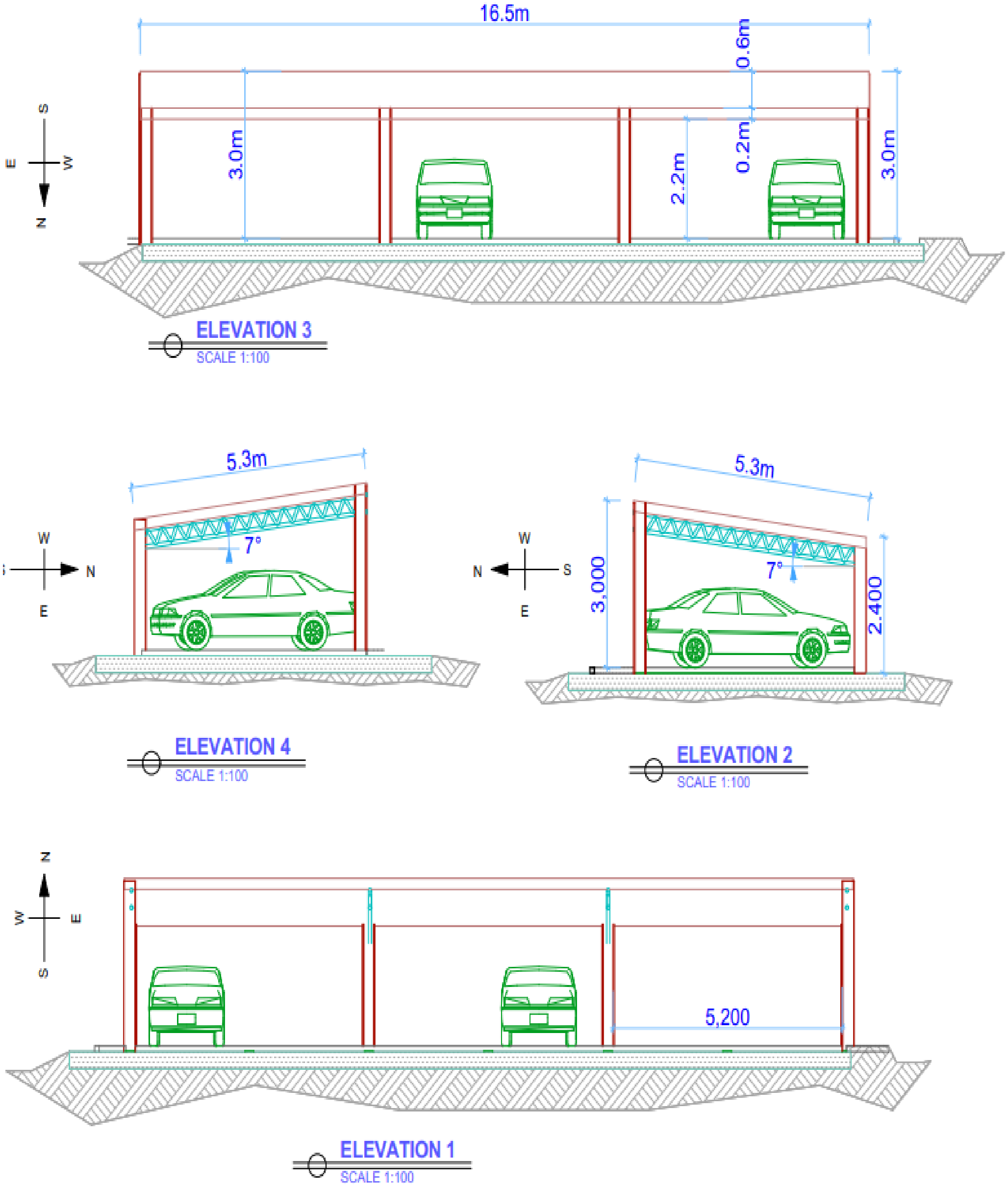


Figure 4.7:Mono pitch design

4.4.2 A duo pitch design with a peak (double slope with a crest)

Figure 4.8 shows a duo pitch design; this had two symmetrical slopes meeting at a central ridge to produce a characteristic crest at the highest roof top. Because of its consistent orientation where by each slope faces a different direction, this makes it easier to optimize solar radiations, this design was further considered for analysis.

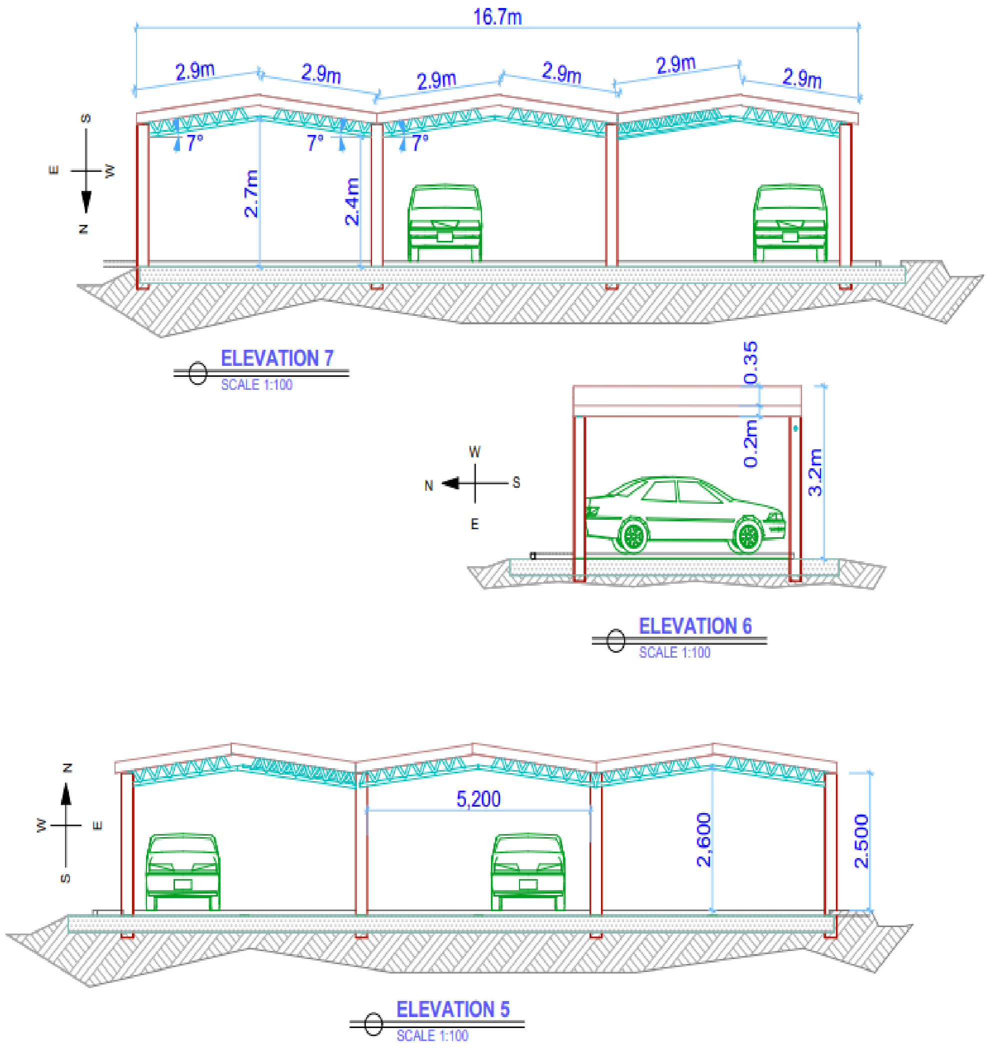


Figure 4. 8: Double slope roof with a peak

4.4.3 A duo pitch design with a valley

Figure 4.9 shows a duo pitch design with a valley; this is two symmetrical slopes that met at a central ridge to produce a characteristic inverted V-shape, sometimes referred to as double-pitch roofs. Because valleys create areas where water and debris can accumulate, which calls for more frequent cleaning and also Valleys are natural places for shading to occur, this design was not considered for further analysis.

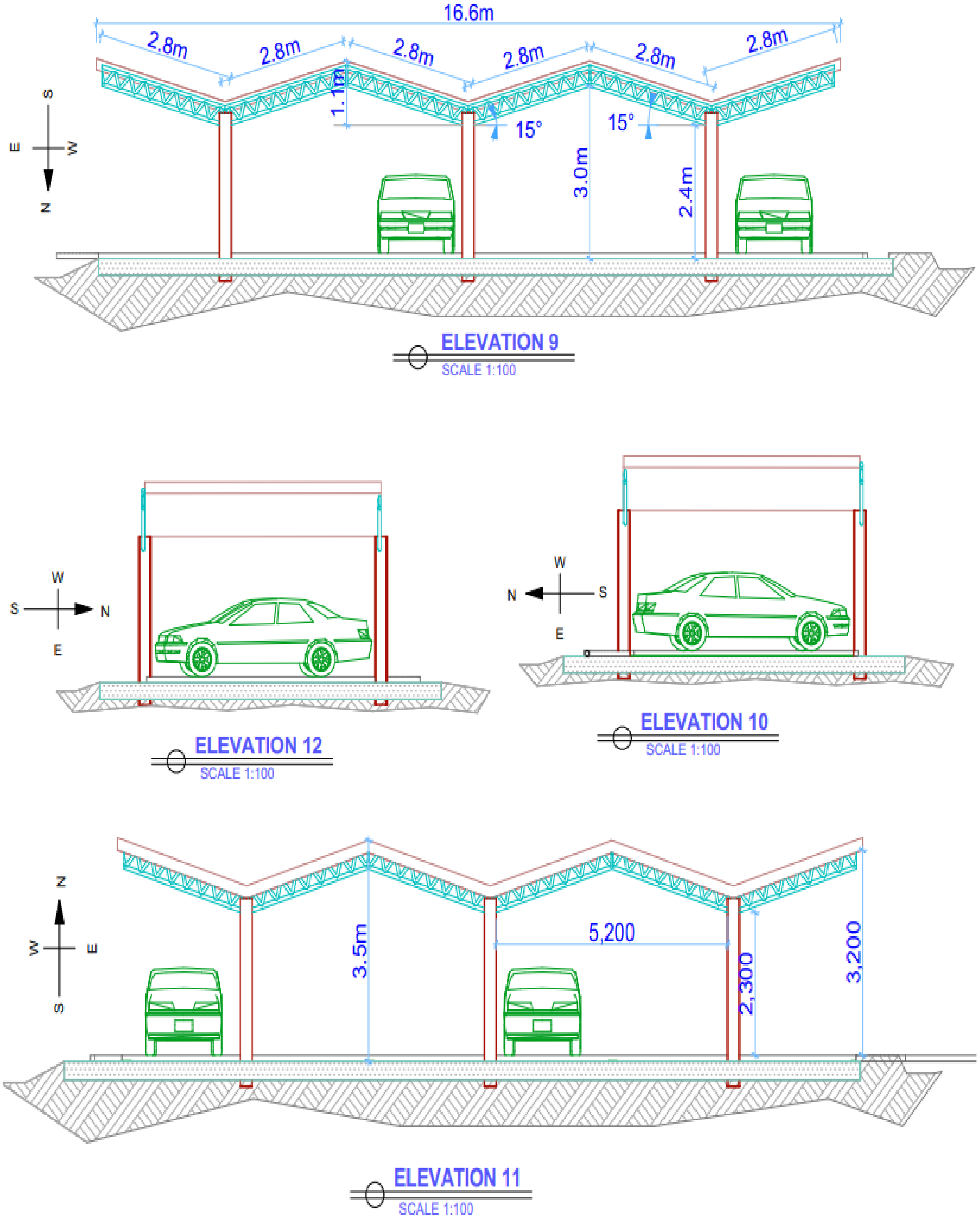


Figure 4.9: A duo pitch design with a valley

4.5 Optimisation of the developed photovoltaic systems

This involved analysis of parameters, designs and technical specification to make a combination of what combination of what can be used to generate maximum energy using a PV module system at Kyambogo University.

4.5.1 Optimization of installation parameters

This involved the simulation of tilt and azimuth angles to select the best combination which can give optimum energy at Kyambogo University using solar PV system.

i. Simulation on 0^0 Azimuth Angle with Different Tilt Angles

The simulation of zero, five, ten, fifteen, twenty, twenty-five and thirty degrees of the tilt angles of PV modules showed that as the tilt angle increase, the annual power generated reduces however the increase in tilt angle of solar module has different impact on monthly solar power generated. The power produced in the months of October to February increases as the tilt angle increases and vice versa to the months of March to September as shown in table B1.1

ii. Simulation on 90^0 azimuth with different tilt angles

The simulation process of zero, five, ten, fifteen, twenty, twenty five and thirty degrees of the tilt angle of PV modules showed that as the tilt angle increase, the energy generated reduce both on monthly and annually basis as shown in table B.2

iii. Simulation on 180^0 degrees azimuth with different tilt angles

The simulation process of zero, five, ten, fifteen, twenty, twenty five and thirty degrees showed that as the tilt angle increase, the energy generated annually reduces. The monthly energy generated reduce for the months of September to April as the tilt angle of PV modules increase and vice versa to the months of May to August as shown in table B.3

iv. Simulation on 270^0 degrees azimuth with different tilt angles

The simulation process of zero, five, ten, fifteen, twenty, twenty-five and thirty degrees showed that as the tilt angle increase, the power generated reduced on both monthly and annually as shown in table B.4

From all simulations performed the results showed that tilt angle has big impact on power generated unlike to the azimuth angle. At Kyambogo University the optimum power is generated when the tilt angle is zero in all azimuth angles and power generated reduces as the tilt angle increased. This is because when sunlight strikes solar modules perpendicularly, they produce maximum energy. Season and site latitude affect the sun's apparent trajectory in the sky. The average angle of incidence between the sun's rays and the module surface is reduced throughout the year by tilting the modules at an angle corresponding to the site latitude. This maximizes the annual energy yield by capturing the highest amount of irradiance. The tilt angle of 15-degree was selected to maximize solar exposure and self-cleaning aspect of the panels to ease maintenance overtime making a 2% kWh loss compared when zero degree tilt angle was used. On the other hand using a 15-degree tilt angle instead of zero increased the area by 3.4%.

4.5.2 PV module arrangement on the available area

The chosen location in the multipurpose building for the module covered 240 square meters in total. Multiplying width (5 m) by length (48 m) yielded the area. The number of solar modules that could fit in the designated space for both single slope and double slope with crest modes was assessed.

a) Double slope roof with a crest

From equation 3.1, hypotenuse (H) was 2.588m therefore, a half of the inclined width of the available space could accommodate one PV module (2.279×1.134×0.035m).Since the length of the selected site was 48 meters, for double slope roof arrangement, the space was to accommodate eighty PV modules forty on each slope.

b) Single slope arrangement

From equation 3.2, hypotenuse (H) was 5.176m therefore, the inclined width of the available space could accommodate two PV modules (2.279×1.134×0.035m).since the length of the selected site for solar PV installation was 48 meters ,for single slope roof arrangement, the space was to accommodate eighty PV modules stacked in a pair as shown in figure 4.10.

The results indicated that both single and double slope could accommodate eighty PV modules, therefore a single slope was selected because it is easy to construct and takes less Materials compared to double roof.

The arrangement of the panels was such that 80 panels were stacked in a single canopy of display, with 20 solar panels in series and four parallel strings (20S4P). This design ensured that the system's voltage did not exceed 1000V DC and that the combination's maximum current did not exceed 35A.

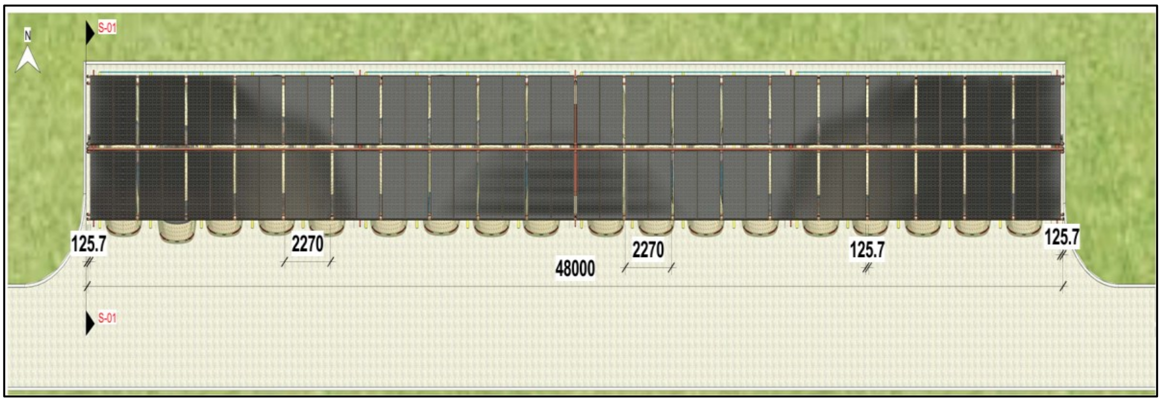


Figure 4. 10: Arrangements of solar panels in the parking lot on single slope arrangement

4.5.3 Average solar irradiance received per day for the period of 2018 to 2024

Using equation 4.1, average solar irradiance received per day for the period of 2018 to 2024 was calculated.

$$Average\ \boldsymbol{I_r} = 5.2042\ kW$$

Kyambogo University (case study area) per day for the seven years of data collected. By analyzing the average solar irradiance received in the area for a day and it was found to be greater than 5.1kw, the area receives enough solar energy and supports solar generation throughout the year hence a feasible and economical investment.

4.5.4 Simulation of solar irradiance on the Performance of the System

Data was in put to get Simulation results on solar energy generated on an hourly, daily, monthly and yearly basis.

Hourly basis

On an hourly basis, since the solar irradiance data was recorded on an hourly basis (average solar irradiance per hour), the energy was obtained by simulating currents and voltages generated by the solar array system as a result of being exposed to that irradiance as shown in table 4.1

Table 4.1: Solar irradiances, voltage, current and energy generated for the first twenty-four hours of 1st January 2018.

Time	Average Irradiance (W/m^2) per hour	Current (A)	Voltage (V)	Energy (KWh)
00	0	0	0	0.000
01	0	0	0	0.000
02	0	0	0	0.000
03	0	0	0	0.000
04	0	0	0	0.000
05	0	0	0	0.000
06	49.3000	2.3086	719.3367	1.627
07	165.0500	7.7286	758.8919	5.748
08	350.8000	16.4257	783.5977	12.614
09	477.7500	22.3691	793.7613	17.401
10	596.8800	27.9460	801.0430	11.938
11	555.5800	26.0127	798.6727	20.360
12	580.1500	27.1629	800.0828	21.298
13	462.3800	21.6496	792.6691	16.818
14	410.2000	19.2067	788.7527	14.846
15	279.8300	13.1029	776.2105	9.967
16	148.0700	6.9335	755.3430	5.132
17	23.5200	1.1014	695.1032	0.750
18	0	0	0	0.000
19	0	0	0	0.000
20	0	0	0	0.000
21	0	0	0	0.000
22	0	0	0	0.000
23	0	0	0	0.000

The results indicated that maximum energy is generated at mid-day; this is because Kyambogo University is located near equator and at that time the sun is directly overhead.

Daily basis

For the solar energy generated on a daily basis, the total energy generated for each hour was added together as shown in table 4.2 for some few selected day.

Table 4.2: Total energy generated for the first seven days.

Day	Daily energy (kWh)
1^{st} Jan. 2018	148.4998
2^{nd} Jan. 2018	161.7799
3^{rd} Jan. 2018	204.8875
4^{th} Jan. 2018	181.4434
5^{th} Jan. 2018	217.1906
6^{th} Jan. 2018	210.1749
7^{th} Jan. 2018	204.5628

Monthly basis

The monthly results were obtained by adding the daily totals for each month of each year. This resulted in the total monthly power generated for each month of each year, as indicated in table 4.3 below.

Table 4.3: Simulated monthly energy generations for the years from 2018 to 2024.

Month Energy (MWh)							
	2018	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Jan	6.2627	6.8093	6.2090	5.5056	6.2474	6.8381	5.4184
Feb	5.9781	6.4366	6.2191	5.5967	4.9878	6.1963	5.6562
Mar	5.3821	7.3069	5.9472	6.4881	6.7591	5.7429	6.9648
April	5.0580	6.3338	5.8395	5.9285	5.8784	5.7668	5.8098
May	5.1798	6.0126	5.8592	5.6391	5.8463	6.2815	6.0529
Jun	5.1736	4.7540	5.3705	5.5034	5.6052	5.0629	5.7033
Jul	5.7464	5.2781	4.9015	5.5224	5.2445	5.8646	4.7985
Aug	5.7170	5.5408	5.6194	6.1351	5.5649	5.8866	
Sep	6.0037	6.0344	6.0278	5.8767	5.7271	5.6735	
Oct	5.9806	5.7414	5.6185	6.1034	6.1785	6.3510	
Nov	6.2960	5.5134	5.5318	5.7984	4.7468	5.0632	
Dec	5.8428	5.6366	6.1376	5.8203	5.4097	5.3581	

Yearly basis

The total electric energy generated on a yearly basis was obtained by adding the monthly total for each month for each year as shown in the table 4.4

Table 4. 4: Summation of annual solar energy generated.

Year	Total energy (MWh))
2018	68.621
2019	71.398
2020	69.281
2021	69.918
2022	68.196
2023	70.086
2024(for seven months)	40.404

4.5.5 Simulation Impact of temperature changes on solar energy generation

Based on the acquired data, it would take too long to replicate the energy generation under changing temperatures in order to simulate the effect of temperature on energy generation. Therefore, as indicated in table B6, the effect of temperature was only simulated for values of maximum sun irradiation of 1080W/m2.

By comparing the changes in voltage and current with temperature as simulated and tabulated in table B6, it can be seen that temperature has a negative relationship with voltage, meaning that a rise in temperature causes a fall in voltage, and a positive relationship with current, albeit one of very small magnitude. As the graphic illustrated, the total effect of temperature on current and voltage affects the amount of energy produced. For a solar intensity of 1080 W/m2, the fluctuating temperature illustrated the energy generated once the temperature was fixed to 25^0C.

Table 4.5: Analysis of impact of temperature on energy generated.

Irradiance (W/m²)	Temperature (⁰C)	Current (A)	Voltage (V)	Energy (KWh)
1080	25	50.3	816.5	41.069

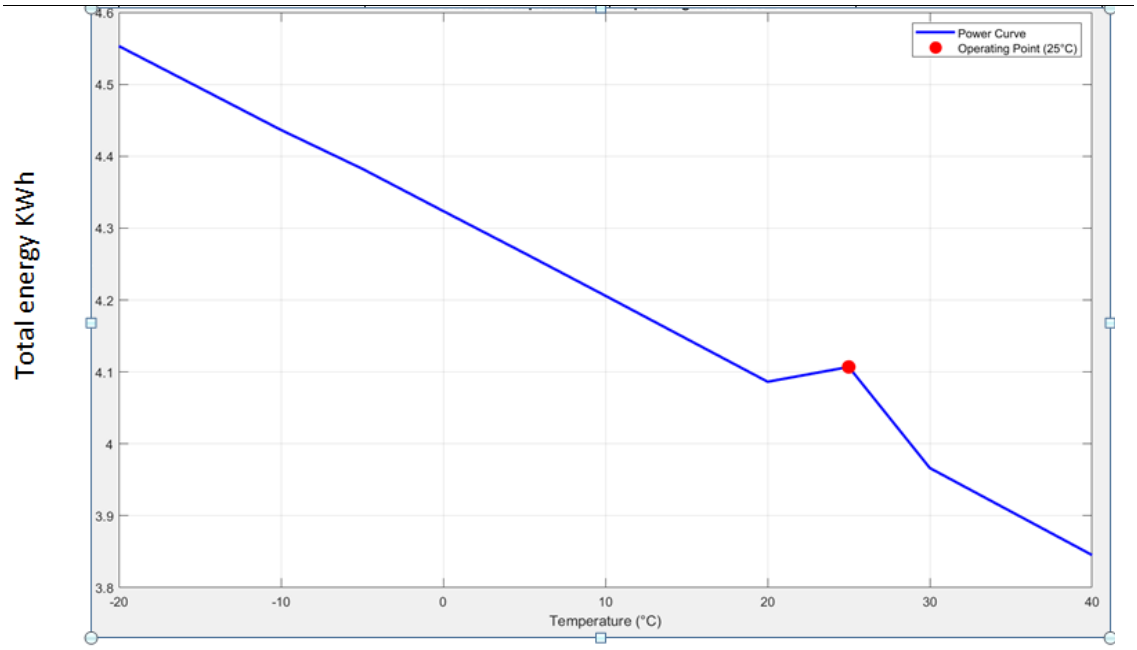


Figure 4. 11: Energy Vs Temperature with the operating point at temperature of 25 degrees

Under ideal conditions, solar panels are supposed to work at very low temperatures for maximum energy output. This is because they generate a significantly high voltage at low temperatures hence making the power generated high too. However, their current generated increases as the temperatures increase. As a result, there is an optimal operating point where there is a balance between current and voltage generated due to environmental conditions.

The energy generated is affected by the temperatures at which the panels are exposed, making it hard and costly to keep the panels at low temperatures to generated maximum energy. Figure 4.11 showed that the optimal temperature which can be achieved easily, at no cost and with high energy produced was 25^0.Therefore on installation of solar PV modules consideration to maintain operation temperature at 25^0 for efficiency of the designed system.

4.5.6 Minimum and maximum monthly energy generation from 2018 to 2024

The maximum and minimum values from the table 4.6, the month with maximum solar energy generated was March of 2019 while the month with the lowest energy generated was November of 2023. This was due to change in shifts of seasons across the year hence affecting the solar irradiance and the area receiving maximum energy randomly as observed in the table 4.6.

Table 4.6: Minimum and maximum monthly energy generation from 2018 to 2024

Year	Month with lowest power		Month with highest power	
	Month	**Solar energy (MW)**	**Month**	**Solar energy (MW)**
2018	April	5.0580	November	6.2960
2019	June	4.7540	March	7.3069
2020	July	4.9015	February	6.2191
2021	June	5.5034	March	6.4881
2022	November	4.7468	March	6.7591
2023	June	5.0629	January	6.8381
2024	July	4.7985	March	6.9648

4.5.7 Capacity factor

From equation (3.7), considering total energy produced per year, the table 4.7 shows the capacity factor for the suggested system based on the simulated solar energy generated.

Table 4.7: Capacity factor for the suggested system based on the simulated solar power generated.

Year	Total (MWh)	Installed capacity (MWh)	Capacity factor (%)
2018	68.621	385.44	17.8033
2019	71.398	385.44	18.5238
2020	69.281	386.496	17.9254
2021	69.918	385.44	18.1398
2022	68.196	385.44	17.6930
2023	70.086	385.44	18.1834
2024(for7 months)	40.404	223.872	18.0478

From the table 4.7 above, the capacity factor of the system is within the limit of 15 to 25% for the commercial/grid tied systems. This capacity factor was affected by several factors like weather conditions, solar irradiance in the area and system efficiency.

4.5.8 Monthly energy generated for the years 2018 to July 2024

The optimal energy was generated in January and March for all the years. This is the time when Kyambogo University receives the most sunshine hence highest energy generation. The months when Kyambogo University receives less power is during the periods of June and July. This is because the sun is low in the sky for areas near the equator and only high in areas in the northern hemisphere. In figure 4.12, It is observed that March 2019 the maximum energy was generated which implies that high solar irradiance. It is also observed that the lowest power was generated in November of 2022, meaning this month received the least solar irradiance.

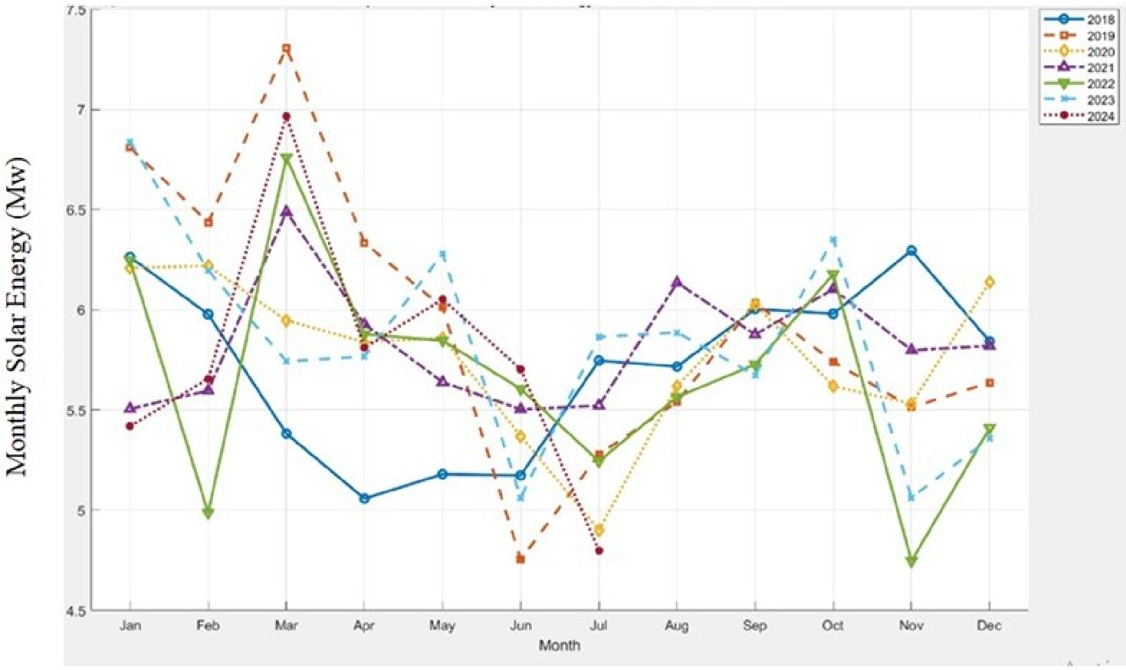


Figure 4. 12: Comparison of monthly solar power across the years 2018 to 2024

4.5.9 Sizing of the PV module system

a) Cable Size Estimation:

Based on the current carrying capacity

Each series string (20 panels) operates at high voltage (Vmax) (~20 × 40.9V = 818V).

Each parallel string carries $I = \frac{550 \times 20}{818} = 13.44A$......................................4.1

$$Total\ current\ at\ the\ combiner\ box = 13.44 \times 4 = 53.76A$$

Hence cable sizes should be 6mm² DC cables for each string (safe for ~15A) and 10mm² DC cable from combiner box to inverter (safe for 60A over distance)

Estimated Length: Panel to combiner box: ~2m per panel × 20 panels × 4 strings = 160m

Combiner box to inverter: Since the powerhouse is at one end of the 48m space, assume ~50m run for safety → 50m of 10mm² cable

b) AC Cables (Inverter to Distribution Board)

Type: XLPE insulated copper cable.

Size estimation: Total output power = 2×30KW= $60kW$

Voltage: 415V (3-phase system)

Current: $\frac{60000}{\sqrt{3}\times 415} = 83.5A$

Cable size recommendation: 35mm² XLPE cable per inverter output

Estimated Length: ~10m per inverter hence 40m total

c) MC4 Connectors. These are for connecting panels in series and parallel

Quantity: Series connections (20 panels per string → 19 connectors × 4 strings) = 76 MC4 pairs

Parallel connections: 4 strings → need 4 additional pairs at combiner box

Total: ~80 MC4 connector pairs

d) String protection fuses

Fuse type: DC fuses for overcurrent protection

Rating: 15A (since each string carries ~13.44A)

Quantity: 4 (one per series string)

e) Combiner box. The combiner box is used to combine DC output from all 4 strings and provides surge protection.

Specifications: 4 input terminals (one per string), DC disconnect switch, surge protection device (SPD), DC fuse holders.

f) AC protection

Circuit breakers. 125A breaker for the total system at the main distribution board and 63A breaker per inverter output

g) Earthing system.

Copper earth rod (2.5m)

Earthing cables (16mm² copper)

h) Monitoring & control system

Energy meter (for tracking power output)

Remote monitoring device (WiFi/GSM-based)

i) Miscellaneous. These include cable ties, conduits, and junction boxes, mounting bolts, and grounding lugs.

j) Solar Panel Data

After the solar data was collected, and preprocessed for data analysis, solar panel sizes and their outputs were also collected to confirm the type and size of the solar panels that would suite the space and application for the selected area. These solar panels were selected such that all the space was fully used without any free space left. The solar panels considered in this project have dimensions of 2279×1134×35mm. The electrical specifications of the panels are shown in the table 4.8.

Table 4.8: Electrical specifications of the solar panels selected for use.

Parameter	Value
Maximum power (W)	550.105
Number of cells per module	72
Open circuit voltage (V)	49.62
Short-circuit current(A)	14.03
Voltage at maximum power point (V)	40.9
Current at maximum power point (A)	13.45
Temperature coefficient of Voc (%/degC)	-0.3372
Temperature coefficient of Isc (%/degC)	0.034404

4.5.10 Mean, Median and Standard Variation

By simulating, calculating, and plotting the total energy of the solar energy generated per year, figure 4.12 shows a bar graph plot of the total energy generated for each year from 2018 to July 2024. The year with the highest energy generated is 2019 while the year with the lowest energy generation is 2022. By calculating the mean, median and standard variation, it is also observed that the area receives relatively and averagely high solar irradiance hence is not affected by seasonal variations. Only six years were considered during calculations (2018-2023), because 2024 was not fully simulated due to missing data of months August to December.

Mean

From equation (3.5)

$Mean = 69.583MW$

Median

From equation (3.6)

Median = 69.599MW

Standard deviation

From equation (3.7)

$standard\ deviation = \ 1.1489\ MW$

4.5.11 Interpretation of mean, median and standard deviation on the energy generated

i. Average energy generation. The system generated 69.583 MWh per year over the six fully available years. This suggests that the system has a potential of producing energy consistently over time. This is the potential energy the proposed system can generate per year.

ii. Median (69.599 MW) ≈ Mean (69.583 MW). Since the mean and median are very close, the energy generation data is symmetrically distributed with no extreme peaks or drops indicating steady performance of the solar system over the years. This makes reliability on solar for Kyambogo University.

iii. Standard deviation (1.149 MW). A small standard deviation suggests that the total energy generated across the years is fairly stable with little variation. This is because there were no extreme fluctuations in solar energy generation.

4.6 Economic analysis

4.6.1 Average Annual Energy Generation (E_t), Revenue or Savings (C_t), Operational Costs(O_t)

Average Annual Energy Generation (E_t)

From equation (3.4)

$\boldsymbol{E_t} = \ 69.583\ MWh$

Revenue Or Savings (C_t)

From equation 3.8

$Revenue = \ 6{,}768\ USD$

Operational Costs(O_t)

From equation 3.9

$operation$al costs, $\mathrm{O_t} = 1{,}209$ USD

4.6.2 Calculating the LCOE, NPV, IRR, AND PBP

Levelized cost of energy (LCOE)

From equation (3.10)

$\mathrm{LCOE} = 113.4337\ \mathrm{UGX/kWh}$

Net Present Value (NPV)

From equation (3.11)

At a discount rate, r = 8%,

$$\mathbf{NPV = 34,020\ USD}$$

At a discount rate, r = 10%

$$\mathbf{NPV = 24,890\ USD}$$

As a result, a higher discount rate leads to a smaller net present value making the project less profitable. As long as the net present value is positive, the project is always viable for investment.

Internal rate of return (IRR)

From equation (3.12)

By setting the net present value to 0, the IRR is calculated as shown in the equations below.

$$0 = \sum \frac{C_t}{(1+IRR)^t} - C_0$$

$$\mathbf{IRR = 21\%}$$

Payback period (PBP)

From equation (3.13)

$$\mathbf{Pay\ back\ period\ = 4.8536\ years}$$

4.7 Contextualization of Results with Previous Studies

Kyambogo University's ideal tilt angle, according to the study's findings, was 0°, with an azimuth orientation toward the south. A 15° tilt was used for design considerations, nevertheless, in order to improve structural stability and self-cleaning, with just a slight 2% decrease in energy yield. Such results are consistent with those of Lehloka et al.

(2020), who found that near-horizontal tilt angles optimize solar collection in equatorial locations, where seasonal fluctuations in solar altitude are negligible. Confirming the suitability of the selected parameters, Ibrahim and Aljanabi (2024) also noted that ideal tilt angles in low-latitude regions typically differ from latitude-based estimates.

The simulation further revealed that temperature has a significant negative impact on PV output, with higher module temperatures reducing conversion efficiency. This observation is consistent with Kumar et al. (2018), who highlighted thermal losses as a critical factor influencing PV performance in tropical environments. Comparable findings were also reported by Shaik et al. (2025), who emphasized that elevated module temperatures accelerate performance degradation over time. Thus, the results from this study confirm that temperature is an intervening parameter that must be incorporated in PV optimization for Uganda's climatic conditions.

With regard to canopy designs, the mono-pitch and duo-pitch crest structures demonstrated higher feasibility compared to the duo-pitch valley design, which presented shading and debris accumulation challenges. These results support Umer et al. (2019), who recommended mono-pitch and dual-slope configurations for parking lot applications due to their structural simplicity and reduced maintenance requirements. In contrast, Khoso et al. (2022) examined barrel-arch designs and reported potential for higher energy yield but also noted increased structural complexity and higher costs. The current study therefore prioritizes designs that are not only energy efficient but also cost-effective and contextually suitable for institutional deployment.

Economically, the results indicated that the system is viable when evaluated using Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and Payback Period (PBP). These outcomes are consistent with Aboagye et al. (2020)

and Asnawi et al. (2024), who demonstrated that institutional PV projects present long-term cost savings despite relatively high initial capital investment. However, unlike many previous studies that relied only on generalized tariff structures, this research incorporated site-specific Ugandan electricity tariffs (ERA, 2025), providing more realistic financial projections.

Overall, the study not only confirms established theories on tilt angle, azimuth, and temperature dependence of PV performance but also extends the literature by contextualizing these parameters within the specific micro-environment of Kyambogo University. The real climatic datasets (2018–2024), and economic evaluation provides a holistic framework that addresses a knowledge gap identified in earlier studies, particularly those in sub-Saharan Africa.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study looked at Kyambogo University's solar photovoltaic (PV) power generation system's design and optimization with the goal of enhancing cost-effectiveness, sustainability, and energy dependability. System orientation, site compatibility, PV canopy design, environmental effects, and financial viability were all thoroughly assessed in this study.

The multipurpose science laboratory parking lot was identified as the optimal site for installation due to its relatively large area, minimal shading, and proximity to key university infrastructure. Among the proposed structural designs, the single-slope canopy with a south-facing orientation at a tilt of 15° emerged as the most suitable, balancing efficiency, structural practicality, and ease of maintenance.Simulation results using RETScreen and MATLAB/Simulink demonstrated that:

i. Energy generation remained stable across the 2018–2024 dataset, with mean and median annual outputs closely aligned and a low standard deviation.

ii. Seasonal variations were minor, with peak generation in January, March, and November, and reduced output in April, June, and July.

iii. Temperature had a measurable inverse effect on PV efficiency; however, the system maintained a favorable capacity factor, underscoring operational reliability under local climatic conditions.

The economic analysis confirmed project viability. Net Present Value (NPV) was positive, the Internal Rate of Return (IRR) exceeded typical discount rates, the Levelized Cost of Energy (LCOE) was competitive with current grid tariffs, and the Payback Period (PBP) was within a reasonable timeframe. Collectively, these findings demonstrate that the proposed PV system is both technically and economically feasible, providing a pathway for Kyambogo University to reduce energy costs, enhance sustainability, and model best practices in renewable energy adoption.

In conclusion, the study validates that solar PV canopy integration is a viable dual-purpose infrastructure solution, contributing to institutional energy resilience while advancing Uganda's broader renewable energy and climate objectives.

5.2 Recommendations

Based on the findings presented in Chapter Four, the following recommendations are proposed to enhance the technical, economic, and operational viability of solar PV deployment at Kyambogo University:

i. **Implementation of the Proposed PV Canopy System:** Kyambogo University should proceed with the installation of the optimized PV canopy at the multipurpose science laboratory parking site to improve energy reliability and offset electricity expenses.

ii. **Maintenance and operational efficiency**: since the simulations showed that the PV system maintained a stable capacity factor with minimal variation across the years; performance reliability can be preserved through structured maintenance. It is therefore recommended that panel cleaning schedules be intensified during the dry season (January–March and November), when dust accumulation is highest, to minimize performance ratio decline. Preventive maintenance should also be aligned with inverter lifetime cycles to avoid unexpected downtime.

iii. **Temperature mitigation**: The analysis revealed a negative correlation between temperature and PV output, particularly in warmer months (April–July). To counter these losses, passive cooling measures such as increasing module standoff distance for natural ventilation should be adopted in the carport design. For future large-scale expansion, feasibility of hybrid cooling methods (e.g., water sprinkling systems integrated with rainwater harvesting) should be investigated to enhance summer performance.

iv. **Energy storage and grid-integration optimization**: Simulation results indicated seasonal peaks in energy generation (January, March, November), with lower production in June and July. To balance these fluctuations and evening demand, integration of lithium-ion battery storage sized at approximately 20–30% of average daily load is recommended. Furthermore, synchronizing the PV system with the national grid using smart meters will allow surplus energy during holidays or low-demand periods to be exported, improving project revenue and reducing university expenditure on grid electricity.

v. **System expansion and design optimization**: The economic evaluation (positive NPV and favorable payback period) confirmed long-term financial viability. Expansion of the system to other university parking sites should therefore be prioritized. Future designs should consider dual-axis or single-axis tracking systems, particularly for sites with larger open space, as this would increase annual yield by 15–25% compared to fixed tilt, thus lowering the effective levelized cost of electricity (LCOE).

vi. **Policy and institutional alignment**: In line with Uganda's National Development Plan (NDP III) and UN SDG 7, the University should formalize a renewable energy strategy that incorporates lessons from this study. Establishing Kyambogo as a demonstration site for solar carports can attract funding, foster partnerships, and provide a training platform for engineering students.

5.3 Areas for Further Study

While this research provided a technical and economic feasibility framework, further studies were recommended to build upon the findings:

i. **Hybrid System Integration:** Future work should investigate coupling PV with complementary technologies such as battery storage, wind, or biomass to enhance energy reliability during low irradiance periods.

ii. **Long-Term Degradation Studies:** Extended monitoring is needed to quantify the impact of dust accumulation, humidity, and material degradation on system performance over decades.

iii. **Dynamic Tilt and Tracking Systems:** Research into the cost-benefit trade-offs of single- and dual-axis tracking systems in Uganda's equatorial context could provide insights into further optimization.

iv. **Socioeconomic Impact Assessments:** Broader studies should analyze how institutional adoption of PV systems contributes to local employment, knowledge transfer, and community sustainability.

v. **Scaling and Replication:** Comparative studies across other Ugandan universities and urban institutions could validate explicability and inform national energy policy on institutional renewable energy adoption.

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APPENDICES

Appendix A: Supplementary Data

Table A1: Kyambogo University parking site

S/N	Location	parking slots
1	Kalubya Block	8
2	Pearl Block	15
3	Faculty of Education	20
4	Faculty of special needs and Rehabilitation	20
5	Civil and Building Engineering Department	10
6	Department of Electrical and Electronics Engineering	18
7	Department of Mechanical and Production Engineering	30
8	Department of Agriculture	15
9	Barclays Library	45
10	Administration Block	44
11	Nanziri Hall	10
12	Faculty of Arts and Social Sciences	15
13	Directorate of Planning and Development	3
14	Central Teaching Facility	65
15	AFDB Library with virtual Capabilities	19
16	Engineering Workshop (AFDB) Building	24
17	Technical Teachers Education Building	92
18	Multi-Purpose Science Laboratory Building	40
	Total	493

Source: Estates department as at July 2018

Table A2: Estimated bills of quantities for the solar PV modules, accessories and installation

Equipment	Unit	Quantity	Unit price(USD)	Total cost(USD)
Solar PV modules (550W)	Piece	80	163	13,040
Inverters (40KW)	Piece	1	48,649	48,649
DC cables; Panel to combiner box, ($6mm^2$)	Roll	1.5	100	150
DC cables; combiner box to inverter($10mm^2$)	Roll	0.5	130	65
MC4 connectors	Pair	80	9	389
Combiner box	Piece	1	149	149
Surge protection device	Piece	1	20	20
AC cables; from inverter to PDB($35\ mm^2$)	Meters	20	20	400
AC protection; Inverter breaker (63A)	Piece	2	8	16
AC protection ;Main distribution board (125A)	Piece	1	20	20
Earthing rod (2.5m)	Piece	1	22	22
Earthing cables; copper ($16mm^2$)	Meter	5	2	10
Miscellaneous			811	811
Subtotal				20,149
Labour				4,029
Total				24,178

Table A3: Estimated bills of quantities for the construction of the single slope structure

ITEM	SIZE	Units	Quantity	Rate (USD)	Amount (USD)
Plaster sand		Tones	2	8	16
Lake Sand		Tones	2	11	22
Aggregates		Tones	4	9	36
Cement	50kg	Pieces	12	10	120
Steel Bars	T12	Pieces	12	10	120
Steel Bars	T16	Pieces	14	19	266
Formwork timber	4" X 2"	Pieces	5	2	10
Formwork timber	12" x 1"	Pieces	15	3	45
Nails	3"	Kg	3	2	6
Nails	4"	Kg	2	2	4
Base plates (mild steel plate)	4feet×4feet ×8mm	Pieces	1	122	122
Steel poles (hollow section)	75×125×6	Pieces	10	61	610
Major steel Rafters (hollow section)	50×100×3	Pieces	5	34	170
Minor steel rafters (hollow section)	40×60×3	Pieces	37	24	888
Major steel purlins (hollow section)	50×100×3	Pieces	24	34	816
Panel seat flames angle line	40×40×3	Pieces	47	10	470
Minor steel purlins (hollow section)	40×60×3	Pieces	32	24	768
Welding electrodes	4mm diameter	Packets	5	14	70
Labour					**1365**
Total					**5,914**

Table A4: Electricity tariffs in Uganda for the first quarter of 2025 (JAN - MAR) (Electricity Regulation Authority, 2025)

S/N	category of consumers	October to December 2024(shillings)	January to march 2025(shillings)
1.	Domestic	796.4	775.7
2.	Commercial	599.9	575.2
3.	medium industrial (manufacturing)	448	417.8
4.	medium industrial (services)	—	434.5 (new)
5.	large industrial (manufacturing block 1)	378.6	351.5
6.	large industrial (manufacturing block 2)	362.2	333.9
7.	large industrial (services)	—	367.1 (new)
8.	extra-large industrial (block 1)	320.1	299.1
9.	extra-large industrial (block 2)	296.1	284.2
10.	public amenities	370	360

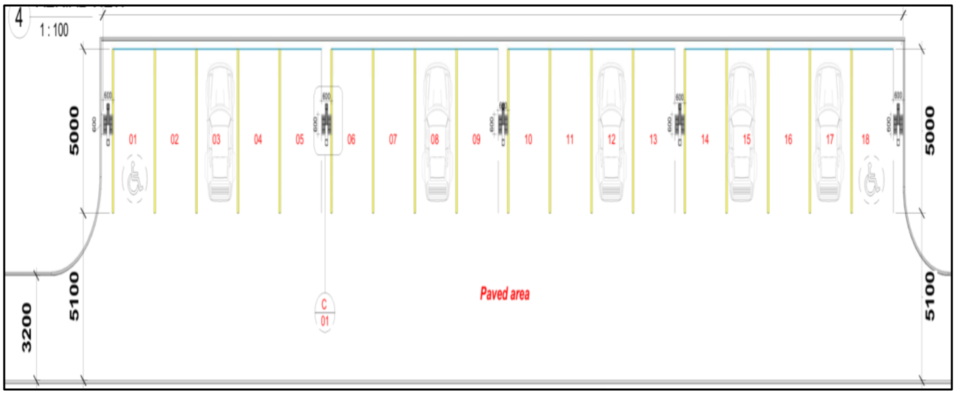
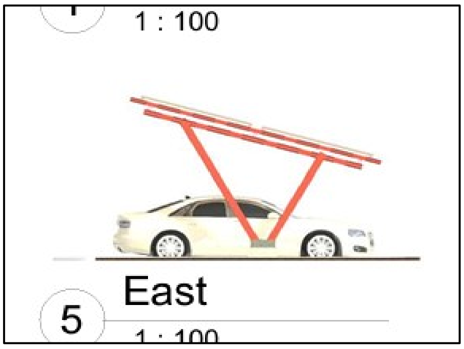


Figure A1: Parking lot before constructing the steel support structure.



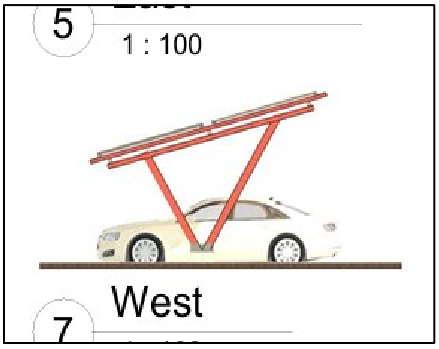


Figure A2: East end.

Figure A3: West end.

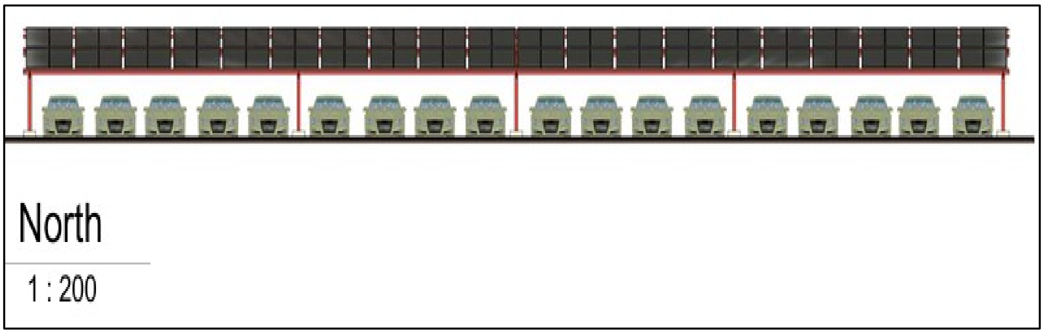


Figure A4: North end.

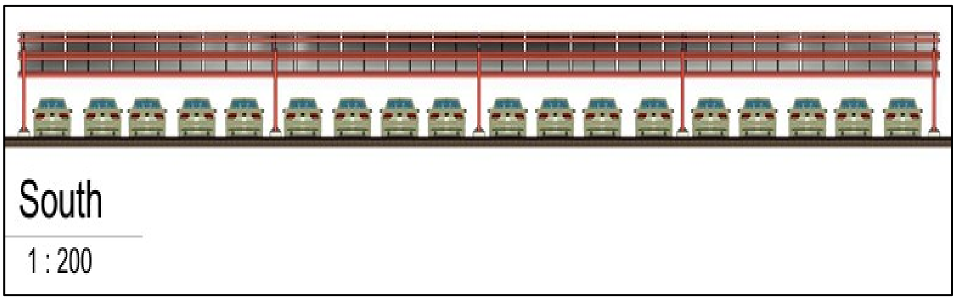


Figure A5: South end.

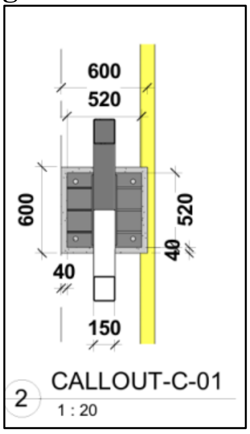


Figure A6: Design of the steel support structure.

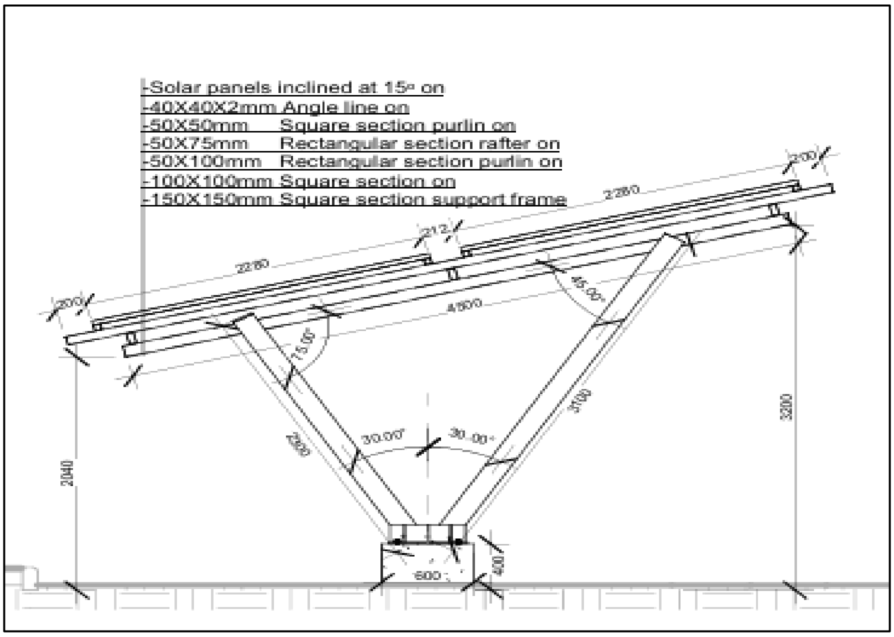


Figure A7: Solar support structure at a tilt angle of 15 degrees.

Appendix B: Supplementary results

Table B.1: Energy production (kWh) by different tilt angles at 0^0 azimuth

	tilt angle	0	5	10	15	20	25	30
Month								
January		5,391.63	5,515.43	5,612.31	5,681.74	5,723.35	5,736.92	5,722.35
February		5,153.29	5,221.96	5,265.31	5,283.12	5,275.19	5,241.83	5,182.90
March		5,599.24	5,602.73	5,579.62	5,530.02	5,454.19	5,352.50	5,225.47
April		5,313.44	5,234.94	5,131.80	5,004.68	4,854.32	4,681.60	4,487.52
may		5,494.63	5,333.49	5,147.39	4,937.51	4,705.19	4,462.74	4,204.63
June		4,887.39	4,718.78	4,528.72	4,318.43	4,154.42	3,865.42	3,617.51
July		4,861	4,714.48	4,546.67	4,358.69	4,648.96	3,942.29	3,713.76
August		5,200.52	5,087.19	4,970.27	4,820.55	4,934.84	4,456.54	4,246.41
September		5,180.51	5,155.04	5,105.41	5,031.87	4,934.84	4,814.83	4,672.50
October		5,383.20	5,429.35	5,449.82	5,444.50	5,413.41	5,356.69	5,274.65
November		5,556.28	5,676.08	5,767.77	5,830.85	5,865.00	5,870.01	5,845.85
December		5,552.60	5,702.57	5,824.11	5,916.58	5,979.50	6,012.22	6,015.44
Annual		63,573.76	63,402.05	62,929.19	62,158.55	61,105.58	59,793.88	58,208.96

Table B.2: Electricity production (kWh) by different tilt angles at ninety azimuth

	tilt angle	0	5	10	15	20	25	30
MONTH								
January		5,391.63	5,367.21	5,327.17	5,270.88	5,189.85	5,097.77	4,994.05
February		5,153.29	5,133.82	5,099.41	5,049.75	4,976.08	4,891.65	4,796.30
March		5,599.24	5,584.40	5,552.77	5,504.43	5,430.04	5,343.16	5,244.18
April		5,313.44	5,295.91	5,262.27	5,213.09	5,139.29	5,053.49	4,956.68
may		5,494.63	5,470.72	5,430.32	5,374.59	5,293.16	5,199.60	5,095.57
June		4,887.39	4,864.59	48,826.74	4,775.00	4,700.88	4,615.63	4,520.91
July		4,861.04	4,839.85	4,803.43	4,752.79	4,680.20	4,596.28	4,502.50
August		5,200.52	5,181.52	5,146.48	5,096.16	5,022.04	4,935.98	4,839.15
September		5,180.51	5,167.37	5,138.37	5,093.75	5,025.27	5,118.58	5,019.74
October		5,383.20	5,365.27	5,331.16	5,280.69	5,205.57	5,257.81	5,152.35
November		5,556.28	5,531.58	5,491.17	5,434.42	5,351.64	5,243.37	5,135.88
December		5,552.60	5,525.67	5,483.08	5,424.02	5,339.15	5,243.37	5,135.88
Annual		63,573.76	63,327.90	62,892.36	62,269.55	61,353.15	60,298.18	59,110.46

Table B.3: Electricity energy (kWh) by different tilt angles at 180^0 azimuth

	tilt angle	0	5	10	15	20	25	30
MONTH								
January		5,391.63	5,218.98	5,022.48	4,803.40	4,567.50	4,322.47	4,059.16
February		5,153.29	5,045.68	4,914.31	4,760.00	4,583.70	4,386.44	4,170.87
March		5,599.24	5,566.06	5,506.53	5,420.97	5,309.86	5,173.80	5,013.52
April		5,313.44	5,356.89	5,374.75	5,366.91	5,333,404	5,274.39	5,190.16
may		5,494.63	5,607.95	5,693.59	5,751.09	5,780.14	5,780.58	5,752.38
June		4,887.39	5,010.40	5,108.84	5,182.19	5,230.05	5,252.17	5,248.41
July		4,861.04	4,965.22	5,045.60	5,101.74	5,133.33	5,140.20	5,122.29
August		5,200.52	5,256.84	5,306.08	5,321.05	5,310.64	5,274.89	5,213.99
September		5,180.51	5,179.70	5,154.55	5,105.20	5,031.64	4,935.00	4,815.03
October		5,383.20	5,301.20	5,194.56	5,063.94	5,910.14	4,734.05	4,536.71
November		5,556.28	5,387.08	5,192.67	4,974.29	4,733.29	4,484.87	4,218.42
December		5,552.60	5,348.77	5,120.37	4,868.87	4,607.78	4,333.07	4,040.07

Table B.4: Electricity production (kWh) by different tilt angles at 270^0 azimuth

	tilt angle	0	5	10	15	20	25	30
MONTH								
January		5,391.63	5,367.21	5,327.17	5,270.88	5,189.85	5,097.77	4,994.05
February		5,153.29	5,133.82	5,099.41	5,049.75	4,976.08	4,891.65	4,796.30
March		5,599.24	5,584.40	5,552.77	5,504.43	5,430.04	5,343.16	5,244.18
April		5,313.44	5,295.91	5,262.27	5,213.09	5,139.29	5,053.49	4,956.68
may		5,494.63	5,470.72	5,430.32	5,374.59	5,293.16	5,199.60	5,095.57
June		4,887.39	4,864.59	4,836.74	4,775.00	4,700.88	4,615.63	4,520.91
July		4,861.04	4,839.85	4,803.43	4,752.79	4,680.20	4,596.28	4,502.50
August		5,200.52	5,181.52	5,146.48	5,096.16	5,022.04	4,935.98	4,839.15
September		5,180.51	5,167.27	5,138.37	5,093.75	5,025.27	4,944.88	4,853.15
October		5,383.20	5,365.27	5,331.16	5,280.69	5,205.57	5,118.58	5,019.74
November		5,556.28	5,531.58	5,491.17	5,434.42	5,351.64	5,257.81	5,152.35
December		5,552.60	5,525.67	5,483.08	5,424.02	5,339.15	5,243.37	5,135.88
Annual		63,573.76	63,327.90	62,892.36	62,269.55	61,353.15	60,298.18	59,110.46

Table B.5: Peak energy generated at a given day for each year.

Year	Date and time	Maximum current (A)	Maximum voltage (V)	Maximum energy (KWh)
2018	04-Feb-2018 11:00:00	48.337	819.14	38.835
2019	03-Feb-2019 12:00:00	49.864	820.25	40.083
2020	10-Feb-2020 12:00:00	49.591	820.05	39.854
2021	11-Mar-2021 11:00:00	49.986	820.34	41.085
2022	05-Mar-2022 11:00:00	49.554	820.02	39.823
2023	13-Feb-2023 12:00:00	50.579	820.78	40.684
2024	17-Mar-2024 11:00:00	49.984	820.34	40.184

Table B.6: Simulation impact of temperature changes on solar energy generation.

Temperature (^0C)	Current (A)	Voltage (V)	energy (KWh)
-20	49.8103	914.1092	45.532
-15	49.8927	900.9210	44.949
-10	49.9752	887.7328	44.365
-5	50.0658	875.3688	43.826
0	50.1482	862.1806	43.237
5	50.2389	848.9923	42.652
10	50.3213	835.8041	42.059
15	50.4120	822.4510	41.461
20	50.4944	809.2628	40.863
25	50.3	816.5	41.069
30	50.6675	782.8039	39.663
35	50.7500	769.6157	39.058
40	50.8406	756.3450	38.453