



School of Electrical & Mechanical Engineering
Department of Mechanical, Energy and Industrial Engineering

DESIGN, CONTROL AND COST ANALYSIS OF AN MPPT BASED DUAL-AXIS SOLAR TRACKING SYSTEM

by

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Abstract

This study investigates the simulation, optimization and development of a solar tracking system aimed at enhancing photovoltaic solar energy capture. The optimization process is analysed from two perspectives: the control system and the mechanical system. For the control system, a methodology is proposed to identify the optimal control strategy for a two-axis solar tracking system, specifically applied to a stand-alone low power photovoltaic application. Initially, four control strategies (adaptive neuro-fuzzy inference system, artificial neural network, perturb & observe, and fuzzy logic controller) are selected based on the most commonly used strategies, and are subsequently simulated within the MATLAB environment. A comparative analysis is conducted to determine the best suited control strategy for the designed solar tracking system. The optimization of the mechanical system involves a thorough review of existing knowledge to uncover trends and challenges, which subsequently informs the analysis of motion range and load variations. This process establishes critical specifications, such as stroke length and load capacity, for commercially available electric actuators. Additionally, a structural analysis of the mechanical structure is conducted to guarantee resilience against wind forces, which aids in identifying optimal design parameters for enhanced system performance. Moreover, a cost analysis is undertaken to assess the financial feasibility of the proposed tracking system, addressing the need for economic justification and competitiveness within the energy market. This study presents the application of perturb and observe control algorithm, recognized as the most suitable technique, for a low-cost stand-alone dual axis solar tracking system. To validate the design, the elevation and azimuth angles obtained from the solar tracker are compared with those calculated using Joseph Michalsky's solar position algorithm. The findings affirm the effectiveness of the proposed methodology and system design, revealing a levelized cost of electricity of 1.48 \$/kWh, annual energy losses of about 15% of the generated energy, and tracking accuracies of 84.77% for elevation and 62.41% for azimuth angles. Although the tracking accuracy and LCOE can be enhanced further by addressing the research limitations, it is anticipated that this research will serve as a valuable reference and provide important insights into photovoltaic solar tracking systems and maximum power point tracking.

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Abbreviations

PV – Photovoltaic

MPPT – Maximum power point tracking

MPP - Maximum power point

FLC – Fuzzy logic controller

ANN – Artificial neural network

P&O – Perturb & Observe

ANFIS – Adaptive neuro fuzzy inference system

DC/DC – Direct current to direct current

PSC – Partial shading conditions

STC – Standard testing conditions

LDR – Light dependent resistor

CFD - Computational fluid dynamics

FEA - Finite element analysis

LCOE - Levelized cost of electricity

NPV – Net present value

Chapter 1 Introduction

This chapter explores three fundamental approaches for improving the energy yield of photovoltaic systems, each focusing on different aspects of the conversion process from solar energy to usable electrical power. Particular attention is given to the dual-axis tracking systems, and maximum power point tracking (MPPT) algorithms, with the intent to enhance reliability, economic viability, and simplify the decision-making process regarding the selection of MPPT techniques. Section 1.1 covers the optimization strategies for enhancing the efficiency of photovoltaic systems, Section 1.2 discusses motivation of research, Section 1.3 states the problem statement, Section 1.4 specifies the research aim and objectives, Section 1.5 summarizes the thesis structure, while Section 1.6 mentions work that has contributed to this study.

1.1 Background

Energy has been a fundamental driver of socioeconomic advancement, with fossil fuels serving as the primary energy source since the inception of the First Industrial Revolution. However, the utilization of fossil fuels, being limited on our planet, has resulted in significant alterations to the atmosphere and the global ecological landscape. Consequently, there is a growing recognition of the imperative for environmental preservation, spurring the quest for alternative energy sources with lesser environmental impact. Solar photovoltaic systems have emerged as a promising clean and renewable energy option, particularly in electricity generation, owing to concerns over the depletion and pollution associated with fossil fuels [1]. Various strategies have been devised to enhance the energy output of photovoltaic systems. One approach involves improving solar cell efficiency, while another entail employing energy conversion systems equipped with maximum power point tracking algorithms. Additionally, solar tracking structures have been deployed to optimize solar energy capture from the sun [2].

1.1.1 Solar cell efficiency

There exists a diverse array of PV (photovoltaic) solar cell materials and categories that scientists and researchers have developed with the aim of enhancing solar cell efficiency while reducing costs. According to [3] and [4], PV cells are categorized into three primary generations: first generation: crystalline silicon, second generation: thin films, and third generation: advanced thin films. According to references [5] and [6], it has been noted that first-generation cells, although more expensive than second generation cells, continue to dominate the market because they offer the highest efficiency currently available. Third-

generation cells offer relatively high efficiency and low cost but are still in the pre-commercialization stage. Second-generation cells are attractive because of their low cost, yet they exhibit lower efficiency levels and possess a limited market share.

Previous literature indicates that most second and first-generation cells have undergone minimal changes in recent years, while a significant portion of third-generation cells remain in the early stages of laboratory prototypes, demonstrating promising outcomes but have not yet been widely implemented. Despite the ongoing development of new solar cell technologies, the current market leader (first-generation cells) remains challenging to surpass and further reinforces its position [6].

1.1.2 Maximum power point tracking techniques

A PV system directly converts solar energy into electricity. The amount of energy generated depends on factors such as solar radiation, voltage produced by the PV module and temperature. However, photovoltaic systems suffer from two main drawbacks: low conversion efficiency in electric power generation and variability in power generation due to weather conditions. Consequently, maximum power point tracking (MPPT) techniques are necessary to ensure that the photovoltaic array operates at its maximum power point [7]. With the multitude of MPPT algorithms available and the diverse applications of photovoltaic systems, it can be challenging for users to select the most suitable algorithm for their specific needs. This complexity arises from the varying requirements of photovoltaic systems for different applications. For instance, solar space satellites prioritize performance and reliability over cost and complexity, while residential solar systems aim to reduce payback time and optimize performance under partial shading. On the other hand, street lighting systems focus on charging batteries efficiently, emphasizing low-cost and simple implementation [8].

1.1.3 Solar tracking framework

A solar tracker is a mechanical device crafted for solar photovoltaic panels, aimed at following the sun's path across the sky and adjusting the panels accordingly to optimize sunlight exposure throughout the day. When a photovoltaic panel is aligned perpendicular to the sun's rays, it receives the highest amount of solar radiation. A tracking system is integrated into the solar panel to ensure the incidence of solar rays strikes the panel perpendicularly. Solar incidence on a panel is determined by three angles: azimuth, elevation, and incidence [9]. Fixed solar systems have been utilized for many years. However, with technological

advancements, the efficiency of solar systems has increased through the use of automatic single-axis and dual-axis solar tracking systems, capable of adjusting to the position of the sun according to the season and time of day. Research conducted by [10], [11], and [12] demonstrated that dual-axis tracking systems can achieve a maximum energy output of approximately 30-45% higher than fixed photovoltaic systems, while [13], [14], and [15] showed that single-axis tracking systems can increase electrical yields by 15-30% compared to fixed photovoltaic systems.

Generally, dual-axis solar tracking systems outperform single-axis and fixed photovoltaic systems. However, due to the presence of rotating components or moving joints, these systems require maintenance and have more complex mechanical designs and control mechanisms. This issue was highlighted by [16], whose study aimed to develop a functional model of a dual-axis solar tracker with reduced energy consumption. However, the fragile bar linkage mechanism made it challenging to implement a driving mechanism for maximum solar power extraction. Hence, the crucial need for solar power generation technologies to adopt standardized designs adaptable to various environments.

1.2 Motivation of the research

Three approaches have been utilized to enhance the efficiency and performance of PV systems: maximizing power production through maximum power point tracking techniques, improving the conversion efficiency of PV cells by using high quality manufacturing materials to capture more radiation, and employing mechanical structures to automatically adjust the orientation of the PV modules towards the sun. The primary issue addressed in the proposed study is the challenges faced in implementing solar tracking systems for photovoltaic energy generation, due to high installation costs, high drive power consumption, complex mechanical designs and low system efficiency. As a basis for this study, two key issues emerge:

The first prevailing issue identified is that existing literature on MPPT algorithms primarily focuses on comparing the dynamic performance of MPPT techniques based on generalized criteria such as operating principles, advantages, drawbacks, and their efficiencies. While these reviews provide valuable insights into the strengths and weaknesses of different algorithms, they often fail to address the core research question: *"Which MPPT technique should a user implement from the various existing ones?"*. This inadequacy arises because the comparison methodologies used are typically too broad and lack specificity for real-world applications. Photovoltaic (PV) systems are used in diverse applications, each with unique requirements such as cost, environmental conditions, load variability, and system complexity. Current approaches do not adequately consider these application-specific factors, leaving users without a clear

framework for selecting the most suitable MPPT technique for their needs. Consequently, the decision-making process becomes subjective and less effective, potentially leading to reduced system performance or higher implementation costs.

Second, the advancement of renewable energy technologies has highlighted critical limitations in existing solar tracking structures. Present day solar tracking structures are increasingly characterized by complex mechanical designs, high drive power consumption, and intricate rotational components that compromise overall system performance. These structural challenges create a significant performance-cost dilemma, resulting in high implementation expenses, reduced market penetration, and diminished return on investment. Current solar tracking systems lack a unified approach that effectively combines aerodynamic efficiency, structural strength, mechanical simplicity, and thorough load distribution analysis. The existing design methods are often disjointed, focusing on separate optimization strategies and performance factors without a complete system view. This approach leads to complex and inefficient systems, that demand extensive maintenance, exhibit high failure rates, and struggle to adapt to the changing needs of renewable energy applications.

For this purpose, this research, aims to contribute to literature by presenting the adaptation and refinement of an established methodology, incorporating user-specific and application-specific requirements as part of the selection process for MPPT techniques and address the critical challenges discussed above by developing an innovative dual axis tracking system that prioritizes reduced manufacturing complexity, utilizes lightweight yet durable materials, minimizes moving parts, and advances system design through an integrated approach of aerodynamic, structural, and motion analysis.

1.3 Problem statement

The renewable energy sector faces two critical challenges in solar power system optimization. First, Maximum Power Point Tracking (MPPT) algorithm selection suffers from a generalized approach that fails to consider application-specific requirements. Current selection methods lack a structured decision framework, leaving system designers unable to determine which MPPT algorithm would maximize efficiency for their specific operational constraints, environmental conditions, and performance requirements. Second, solar tracking systems exhibit significant limitations including high drive power consumption, unnecessarily complex mechanical designs, and inadequate structural engineering for wind resistance. These issues contribute to elevated Levelized Cost of Energy (LCOE) and high maintenance requirements, reducing the economic viability of solar tracking technology. Without addressing these

challenges, solar energy systems will continue to operate with reduced efficiency, face reliability issues, and maintain higher-than-necessary costs, which will ultimately slow down the adoption of renewable energy technologies.

1.4 Research aim and objectives

The aim of this research is to adapt an existing framework to the specific context of selecting MPPT algorithms, customizing it to address application-specific factors and user requirements, and design a two-axis solar tracking system that implements an MPPT control technique, thereby enhancing the functionality while addressing the challenges of system complexity and installation costs.

The objectives of this research are to:

- Design and model a photovoltaic system.
- Design and analyse four commonly MPPT control strategies.
- Develop a decision matrix MPPT selection model.
- Design and analyze a dual axis tracking system.
- Build a miniaturized prototype of a dual axis tracking system.
- Conduct performance and economic analysis of a PV dual axis solar tracking system.

1.5 Thesis structure

1. This thesis is organized into five distinct chapters. The first chapter introduces and discusses three methods for enhancing photovoltaic power generation, while also outlining the research problem, motivation and objectives.
2. The second chapter provides a literature review that covers the characteristics of the solar cell, an overview of maximum power tracking algorithms, the distinctive features of existing dual axis trackers, and the challenges they encounter.
3. In the third chapter, the methodology employed to achieve the research objectives is detailed, including a comprehensive description of the simulation procedures and methods utilized to

evaluate the effectiveness of the developed MPPT techniques, as well as an in-depth analysis of the proposed solar tracking system's stability in relation to environmental influences.

4. The fourth chapter presents the key findings of the research, including results and validation.
5. The fifth chapter provides the conclusions and summary of the work conducted, discusses the limitations of the current study, and offers recommendations for future research endeavours.

1.6 Contributions of this research

The work leading to this thesis has been published in two scientific journals, the list of contributions is as follows:

1. Kamela, G., Matsebe, O., Tjiparuro, Z., 2024. Optimizing Photovoltaic Systems: A Decision Matrix Approach for Selecting the Optimal Maximum Power Point Tracking Technique. JERA. <https://doi.org/10.4028/p-mh8clf>
2. Kamela, G., Tjiparuro, Z., Matsebe, O., 2024. Wind load analysis and cost assessment of a dual-axis stand-alone. Engineering Research Express. <https://dx.doi.org/10.1088/2631-8695/ad2b25>

Chapter 2 Literature review

2.1 Introduction

This chapter explores the significant impact of solar panel orientation on energy production, which has led to the creation of solar tracking systems. Additionally, it discusses the complex challenges affecting the performance of dual axis trackers, such as mechanical limitations, environmental factors, the energy consumption of the tracking mechanism, maintenance requirements, and the economic considerations that affect the cost-effectiveness of these systems. Section 2.2 discusses what is and the need for maximum power point tracking and the various techniques, while Section 2.3 discusses the sun path diagrams and how they are used in solar tracking systems, unique features of existing solar trackers, design considerations and optimization challenges in solar tracking systems.

2.2 Characteristics of a solar cell and maximum power point

Solar cells, also known as photovoltaic cells, are used to develop photovoltaic modules, which can produce clean, renewable energy for a range of applications. Photovoltaic cells are electronic components that use solar energy to generate electrical energy. According to [17] and [18] the efficiency of solar photovoltaic cells is influenced by the type of the materials used to manufacture the solar cells. Figure 2-1 depicts the generations of various solar cells along with their average efficiencies.

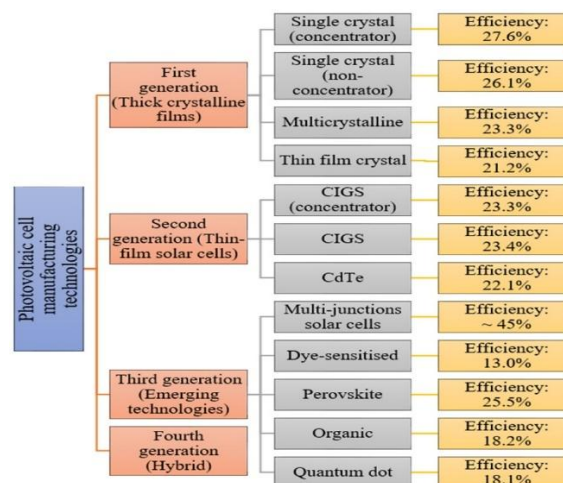


Figure 2-1. Solar cell efficiencies [19], [20].

The solar cell's maximum power point (MPP) is the peak at which it generates the most amount of power. This point, which is dependent on variables like solar irradiance, temperature, and shading, is determined by the maximum current and voltage output of the cell. Past and recent literature has demonstrated and discussed the qualities of a typical solar cell. According to [21], temperature has an impact on the open-circuit voltage of the cell, as well as the efficiency of the power conversion process. The efficiency of the solar cell typically declines as temperature rises.

Additionally, a rise in temperature can cause a decrease in the open-circuit voltage of the solar cell, which can lead to a reduction in the power output of the cell. Whereas the power output increases with the level of solar irradiance. However, there is a limit to the amount of sunlight that a solar cell can transform into electrical energy, and this limit is known as the saturation current. When the irradiance level is too high, the current generated by the solar cell will saturate, and the power output of the cell will no longer increase.

2.2.1 Maximum power point tracking

It is evident that a solar cell must operate at its maximum current and voltage to prevent power loss. Additionally, the maximum power point (MPP) is not a fixed point and will change throughout the day because temperature and insulation are influenced by weather, geographical aspect, and altitude. The introduction of a Maximum Power Point Tracking (MPPT), which continuously monitors the output of the solar cell and adjusts the load on the cell to maintain the MPP, is the solution to this issue. By ensuring that the solar cell is operating at its MPP, the MPPT will increase the efficiency of the PV panel and increase the amount of power that it can produce [22], [23].

A PV module comprises of several parallel and series connected cells. The current-voltage relation of a PV module is represented in equation (1), [24]. Where q is the electron charge 1.602×10^{-19} , T is the temperature of the PV module, k is the Boltzmann constant $1.3806503 \times 10^{-23}$, I_o is the saturation current of the diode, N_s is the number of PV cells connected in series, I_{pv} and V_{pv} represent the output current and voltage of the PV module, R_p and R_s represent the shunt and series resistance and α represents the diode ideality factor.

$$I_{pv} = I_p - I_o \left(e^{\frac{q(V_{pv} + I_{pv} \times R_s)}{N_s \times \alpha \times k \times T}} - 1 \right) - \left(\frac{V_{pv} + I_{pv} \times R_s}{N_s \times R_p} \right) \quad (1)$$

Numerous MPPT control techniques have been developed, with various classifications proposed in literature. The most common classification separates MPPT methods into conventional and soft computing methods. Conventional methods, which have been available for some time, are popular due to their simplicity and ease of implementation. Common conventional MPPT methods include incremental conductance (INC) [25], perturb and observe (P&O) [26], etc. These methods are insufficient for partial shading conditions and require robust algorithms to extract the optimal global maximum power point (GMPP).

On the other hand, soft computing methods are relatively complex but are robust, flexible, and reliable. These methods are highly suitable for partial shading conditions. Soft computing methods include ant colony optimization (ACO) [27], artificial neural network (ANN) [28], [29], grey wolf optimization (GWO) [30], fuzzy logic controller (FLC) [31], [32], differential evolution algorithm (DE) [33], particle swarm optimization (PSO) [34], [35], artificial bee colony (ABC) [36], genetic algorithm (GA) [37], [38], etc. These algorithms excel at solving non-linear tasks, providing optimal or multi-peaks GMPPs with high efficiency, and exhibiting superior tracking performance compared to conventional methods.

Different MPPT techniques have been employed to optimize the performance of photovoltaic (PV) systems. However, the challenge arises when determining the most suitable MPPT technique for a specific PV system configuration and conditions. Each algorithm has its own drawbacks and benefits, as discussed by [39]. To facilitate the decision-making process for researchers and field engineers, numerous reviews have been published on this topic, as highlighted by [39], [40].

Choosing the appropriate MPPT technique for a specific photovoltaic (PV) system can be challenging, as there are different limitations that need to be considered. These limitations have been identified in research as areas to be explored to evaluate the effectiveness of MPPT algorithms. It is difficult to find standardized evaluation criteria in the literature since some of these criteria cannot be precisely measured and require approximations. However, the most considered factors include algorithm complexity, hardware implementation, tracking speed, accuracy in steady-state and global maximum detection. Additionally, factors such as ease of implementation, number of sensors, and cost are also considered desirable [39], [41].

2.3 Solar panel orientation

Solar panel orientation refers to the positioning of solar panels relative to the sun's trajectory in the sky. This aspect is crucial because solar technology operates most effectively when directly facing the sun at a 90° angle. However, achieving this optimal positioning can be challenging due to the sun's movement

throughout the day, shifting from east to west, and over the course of the year, transitioning between the winter and summer solstice [42]. Solar tracking becomes necessary to follow the sun's trajectory across the sky, thereby maximizing sunlight capture, resulting in enhanced system output and efficiency compared to fixed solar systems. Sun path diagrams, depicting the sun's trajectory at different times and from specific locations, serve as valuable tools for optimizing the efficiency and output of solar tracking systems. By providing insights into the sun's ideal position, these diagrams assist in determining the proper orientation of solar photovoltaic modules [43].

2.3.1 Existing solar trackers and their unique features

Studies such as [44], [45] and [46] designed and constructed dual-axis tracking systems. One challenge highlighted in these studies is the uneven weight distribution within the structure after mounting the solar panels around their pivot points. To address this issue, these studies employed counterweights. Although counterweights help balance the load and reduce mechanical stress on the motors and moving parts, they add complexity to the design and installation process, and their effectiveness depend on precise engineering and calibration.

Studies [47], [48] and [49] presented dual axis tracking systems driven by two linear actuators. However, these systems typically have a limited tilt range, usually within $\pm 45^\circ$. This range may prove insufficient to track the sun's position during certain times of the year or in specific geographical locations. Using linear actuators with longer strokes becomes necessary for accommodating large angular movements, albeit at the expense of significantly increasing the cost of the tracking system and adjusting the mechanical design.

Different studies have explored effective mechanisms for moving the payload. Some studies have opted for bar linkage mechanisms actuated by linear actuators, as discussed in [46] and [50]. However, depending on the actuator stroke length, such systems can be prone to self-locking during solar tracking.

From the review [51], it is observed that solar trackers are location sensitive, as their design and efficiency depend on the latitude and sunshine hours of the specific location. Solar trackers are more effective at lower latitudes where the sun follows a higher and more consistent path across the sky. At higher latitudes, the sun's path is lower and changes more drastically with the seasons, making it harder for trackers to optimize their orientation effectively throughout the year. Therefore, this mandates solar tracking systems that can adapt to different geographical environments [52].

2.3.2 Key considerations of dual axis solar trackers

Design considerations for dual-axis solar trackers are essential for achieving maximum efficiency and performance. The following outlines several important factors to consider in the design process:

1. **Material selection:** The selection of materials for the structure and components of a dual-axis solar tracker must be strong, durable, and resistant to environmental factors. Common materials used for trackers include steel, aluminium, and composite materials. Material selection affects the size and weight of a dual-axis solar tracker, which must be optimized to provide stability and structural integrity while minimizing the overall weight. The size of the tracker should be designed to fit the solar panel and maximize the surface area exposed to sunlight [53].
2. **Actuator type:** When designing a dual-axis solar tracker, the choice of the actuator type is crucial. Electric motors, hydraulic actuators, and linear actuators are examples of common actuator types. Accuracy, load on the actuator, speed, and efficiency should all be taken into consideration when selecting an actuator. Most of the time, the actuator uses between 5-10% of the energy generated by the photovoltaic modules. In some cases, this energy consumption can even render tracking methods impractical, as such the consumption should be minimum as possible in order to maximize the efficiency of the tracking systems and most importantly the selected actuator should be able to accommodate the load from the tracking system [54], [55].
3. **Control system:** Real-time monitoring and positioning adjustments of the solar panels are handled by the control system. The control system must be dependable, responsive, and capable of adjusting the position of the panel, while taking changing weather and environmental conditions into account. Existing solar tracking systems employ either the closed-loop or open-loop control strategy. Open-loop control strategies use latitude and longitude location data to determine the sun's position, and unlike closed-loop strategies they have no feedback loop to resolve steady-state errors or adjust the system for any disturbances. Closed-loop control strategies use feedback sensors to determine the sun's position; their only drawback is that they cannot effectively track the sun's position on a cloudy/overcast day [49], [54], [56].
4. **Tracking algorithm:** The tracking algorithm is responsible for calculating the optimal position of the solar panels based on the position of the sun in the sky. The tracking algorithm should be accurate and able to account for changes in the position of the sun throughout the day and throughout the year. There are three tracking strategies: sensor, chronological or hybrid, as discussed by [54].

2.3.3 Challenges and limiting factors that impact performance of dual axis trackers

- Reliability and energy consumption

Tracking systems comprise complex mechanical and auxiliary components, including motors, gears, bearings, power electronic devices and batteries. Ensuring the long-term reliability and durability of these components, particularly in harsh environmental conditions, poses a challenge [57]. Electrical energy is necessary to operate the motors and control system, and this energy consumption can offset some of the gains in energy production, especially if the system is not optimized for reducing the driving forces from the actuators and adopting battery management systems [48].

- Structural Stability

Tracking structures have to support internal and external loads, and fatigue failure due to wind load is the most prominent. Tracking systems require robust support structures to withstand wind loads, snow loads, and other environmental stresses. Ensuring the structural stability of these systems, especially in regions prone to high winds or seismic activity, is critical for long-term performance and safety [58].

- Costs and complexity of the tracking system

The mechanical complexity and energy generation costs associated with a solar tracking system surpass those of a fixed system. This is primarily due to the ongoing operational and initial expenses incurred by the tracking system, casting doubt on its economic viability. Moreover, solar tracking systems demand regular maintenance to uphold the functionality of both mechanical and electronic components [52]. The inclusion of sensors, electronic devices, motors and moving fixtures inevitably leads to higher expenses in solar tracking systems [57]. However, it is feasible to mitigate capital expenditures by optimizing design principles for cost-effective solar tracking while upholding tracking efficiency.

- Climatic conditions and location

The diverse geographical locations across the earth lead to considerable differences in climate. Factors such as cloud cover, wind speed and temperature significantly influence the performance of solar tracking systems in terms power output. Therefore to enhance the efficiency of tracking systems, they need to be designed to accommodate various geographical environments [52]. This

entails incorporating features like cooling [59] and cleaning mechanisms, especially in hot and dusty climates, as well as wind resistance designs and strategies to mitigate the impact of cloud cover.

2.4 Conclusion

This study addresses significant challenges in implementing solar tracking systems for photovoltaic (PV) energy generation. These challenges include high installation costs, high drive power consumption, complex designs, and low system efficiency. The research identifies two primary issues: the need for effective selection procedures for maximum power point tracking (MPPT) techniques to enhance PV module productivity and the necessity for advanced, cost-effective tracking mechanisms/systems that ensure stability and reliability.

To solve these problems, this research aims to tailor the decision matrix model to the unique demands of MPPT algorithm selection, incorporating criteria such as environmental conditions and user preferences. Additionally, this study aims to develop an innovative solar tracking system that balances mechanical complexity, performance, and cost while ensuring structural integrity. This study also focuses on several factors influencing efficiency and reliability. This includes the development of a flexible tracking system that can accommodate the diverse environments of Southern Africa, minimizing actuator driving forces, and positioning the structure's centre of mass as close as possible to the correlating rotation axis without relying on counterweights. Furthermore, this analysis encompasses all the moving components to identify potential collision risks during operation, the implementation of an affordable transmission mechanism to achieve full range tracking and the optimal selection of actuators by analysing the range of motion, load variation and actuator stroke length.

Chapter 3 Research methodology

3.1 Introduction

This chapter outlines the steps involved in selecting the most appropriate MPPT technique for a standalone PV (photovoltaic) system, as well as the design and development of a robust PV mechanical framework. It provides a comprehensive explanation of the simulation procedures and methods utilized to assess the effectiveness of the simulated MPPT techniques, along with a thorough examination of the structure's stability in response to wind effects and its economical assessment.

3.2 Software design

3.2.1 Design and description of the MPPT based PV system

A conventional system utilizing Maximum Power Point Tracking (MPPT) comprises a solar panel, a DC/DC (direct current to direct current) converter, and a load. To assess four chosen MPPT techniques, the initial phase involves the design of the photovoltaic module, the DC converter, and the corresponding control strategies.

3.2.1.1 Preselection of control strategies

Although there are multiple MPPT techniques that are mentioned in literature, the four most popular controllers are selected [60], i.e. fuzzy logic, artificial neural network, perturb & observe, and a hybrid technique, adaptive neuro-fuzzy inference system based MPPT technique. These techniques are selected with the intent to identify the most suitable MPPT algorithm for an efficient and low-cost stand-alone photovoltaic system with an electrical energy storage (battery) for DC (direct current) load power.

3.2.1.2 Mathematical modelling of the PV module

First generation photovoltaic cells are comprised of mono-crystalline and poly-crystalline silicon technologies, which can achieve high efficiency rates ranging from 20-25 % while maintaining a relatively low cost [4]. Consequently, this research employs a poly-crystalline photovoltaic module (GDLITE 035WP) to assess the performance of the photovoltaic system. The simulation of the GD-035WP PV panel is conducted using parameters from the manufacturer datasheet to implement the single diode PV model,

as depicted in Figure 3-1. The choice of this model for the current investigation is informed by the advantages discussed by [61].

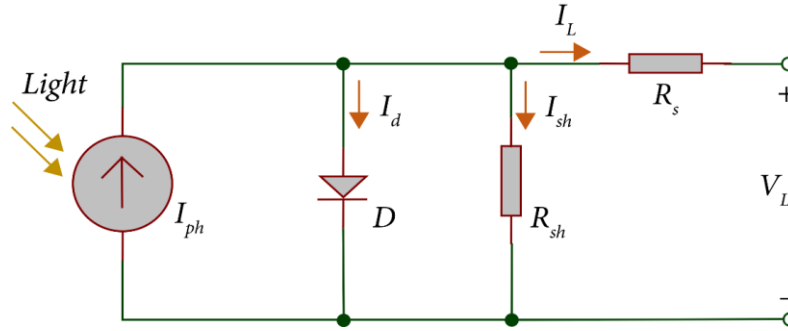


Figure 3-1. Single-diode equivalent circuit of a PV module [62].

Table 3-1. Manufacturer electrical parameters of the GD-035WP PV module.

Maximum power voltage V_{mp}	6V
Short circuit current I_{sc}	0.58A
Open circuit voltage V_{oc}	7.2V
Total number of cells in parallel N_p	1
Maximum power rating P_{max}	3W
Series-resistance R_s	0.53958Ω
Shunt resistance R_{sh}	105.253Ω
Total number of cells in series N_s	15
Maximum power current I_{mp}	0.49A

The mathematical representation of the PV module is formulated based on the fundamental physical principles, utilizing Kirchhoff's current law applied to the single diode equivalent circuit depicted in Figure 3-1, leading to the formulation of equation (2). Equation (2), is subsequently deconstructed into equations (3)-(7), to capture the actual behavior of the PV module [61], [62], [63]. For the purpose of simulating the PV model, these equations, along with the parameters listed in Table 3-1 and Table 3-2, are implemented within the Matlab/Simulink environment, as depicted in Figure 3-2.

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (2)$$

$$I_{ph} = \frac{G}{1000} (I_{sc} + K_i(T - 298)) \quad (3)$$

$$I_d = I_o \left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{nKT N_s}\right) - 1 \right] \quad (4)$$

$$I_o = I_{rs} \left(\frac{T}{T_n}\right)^3 \exp\left[\frac{qE_{g0}\left(\frac{1}{T_n} - \frac{1}{T}\right)}{nK}\right] \quad (5)$$

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{nN_sKT}\right) - 1} \quad (6)$$

$$I_{sh} = \frac{V_{sh}}{R_{sh}} = \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (7)$$

Table 3-2. Electrical input parameters for PV modelling [64].

Parameters (units)	Symbol	Value
Nominal temperature (K)	T_n	298
Solar irradiation (W/m ²)	G	-
Short circuit current of cell at 25°C & 1000W/m ² (%/°C)	K_i	0.102
Operating temperature (K)	T	-
Electron charge (C)	q	$1.6 \cdot 10^{-19}$
Ideality factor of the diode	n	0.78104
Boltzmann's constant (J/K)	K	$1.38 \cdot 10^{-23}$
Band gap energy of semiconductor (eV)	E_{g0}	1.1

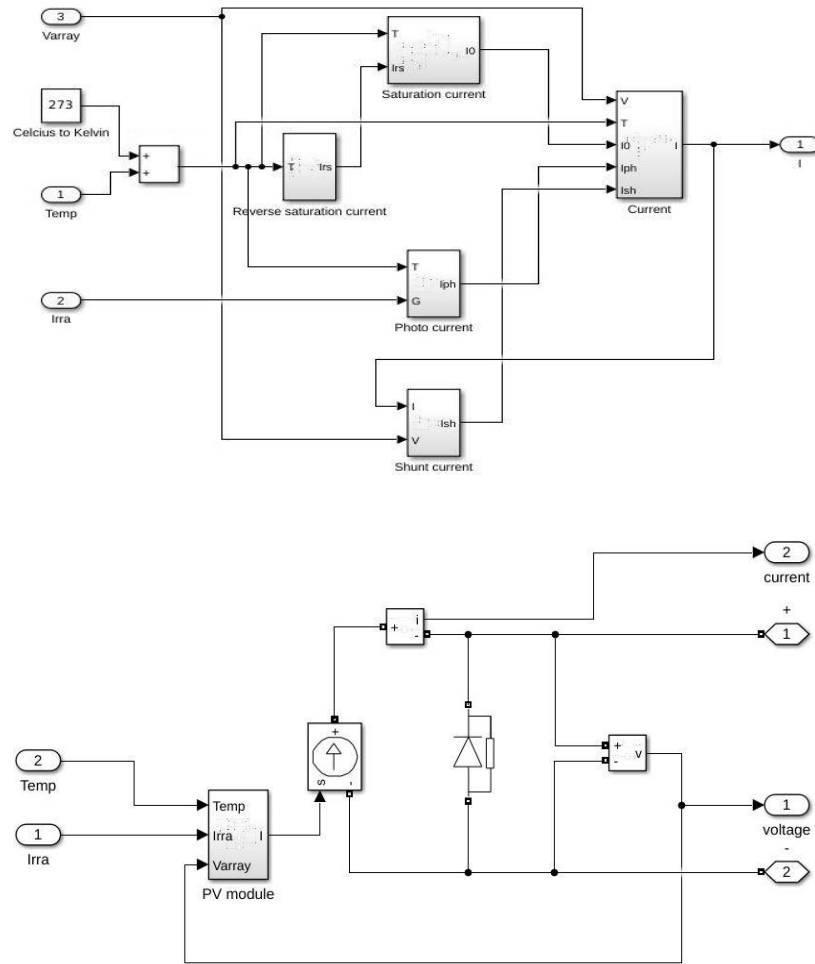


Figure 3-2. Subsystem of the saturation, shunt, photo, reverse and output current (top); subsystem of the PV Simulink model (bottom).

3.2.1.3 Design of the DC-to-DC converter

The procedure for establishing the parameters of the DC-to-DC converter involves adopting the methodology suggested by [65] for the design of a boost converter specifically tailored for MPPT applications. The first step in this process is to determine the maximum power point resistance of the PV module. This determination is achieved by evaluating the extreme irradiance levels of 1000 W/m^2 and 200 W/m^2 . The maximum and minimum power point resistances are derived from the power-voltage (P-V) characteristic curves depicted in Figure 3-3, using equation (8).

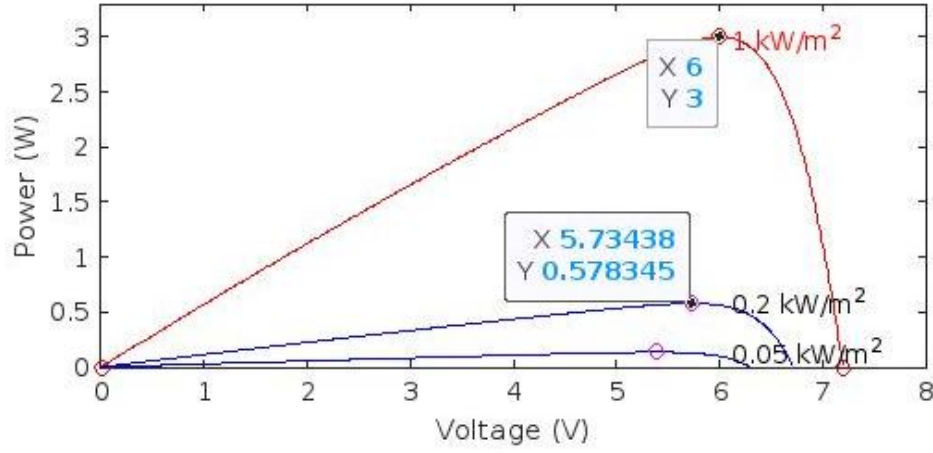


Figure 3-3. Power and voltage characteristic curves of the PV module.

$$R_{mp} = \frac{V_{mp}^2}{P_{max}} \quad (8)$$

Where V_{mp} , P_{max} and R_{mp} represent the maximum power point voltage, power and resistance from the PV panel.

The next step involves applying the recommended and calculated parameters necessary for the boost converter's design into the designated Matlab graphical user interface calculator [66], as outlined in Table 3-3. The duty cycle and ripple factor ranges are established in accordance with the guidelines provided by [65]. This guidance indicates that the duty cycle should be maintained between 10% and 60%, with a recommended output voltage and maximum power point voltage ripple factor of 1%. Additionally, it is advised that the inductor current ripple factor should not be set to excessively low values, as this can adversely impact the inductance and input capacitance of the boost converter.

In their research, the inductor current ripple factor, switching frequency, and duty cycle range were set at 15%, 20 kHz, and 10-60%, respectively. However, for the current study, these parameters are adjusted to 25%, 10 kHz, and 10-75%. Consequently, the user interface is utilized to compute the minimum inductance, as well as the output and input capacitance required for the boost converter, as illustrated in Figure 3-4. The results of these calculations are recorded in Table 3-4, while Figure 3-5 showcases the simulated model of the boost converter.

Table 3-3. Parameters required to calculate the components of the boost converter.

Parameters	Value
Minimum power resistance at 1000W/m ² , $R_{mp(min)}$ (Ω)	12
Maximum power resistance at 200W/m ² , $R_{mp(max)}$ (Ω)	57
Inductor current ripple factor, γ_{IL} (%)	25
Maximum power voltage ripple factor, γ_{Vmp} (%)	1
Output voltage ripple factor, γ_{Vo} (%)	1
Max. duty cycle, D_{max} (%)	75
Min. duty cycle, D_{min} (%)	10
Switching frequency, f (kHz)	10

Boost Converter Design for MPPT Application

Input Parameters

MPP Resistance

Minimum MPP Resistance (Ohm)

Maximum MPP Resistance (Ohm)

Pulse Width Modulation (PWM)

Minimum Duty Cycle (%)

Maximum Duty Cycle (%)

Switching Frequency (kHz)

Ripple Factor

Input Capacitor Ripple Factor (%)

Output Capacitor Ripple Factor (%)

Inductor Ripple Factor (%)

Safety Factor

Input Capacitor Safety Factor

Output Capacitor Safety Factor

Inductor Safety Factor

Load

Chosen Load

☐ Fixed ☒ Limited ☐ Unlimited

1. Check Load Range

Ro Range

Min Ro Max Ro

Min G Max G

$\leq$ Ro(max) $<$

Fixed/Max Output Resistance (Ohm)

Inductance-Capacitance (LC) Parameters

2. Calculate LC Parameters

Input Capacitance (F)

Output Capacitance (F)

Inductance (H)

Figure 3-4. Matlab graphical user interface calculator.

Table 3-4. Components required for the design of the boost converter.

Parameter	Value
Load resistance	120 Ω
Inductance	0.009 H
Input capacitance	1.85e ⁻⁵ F
Output capacitance	1.85e ⁻⁴ F

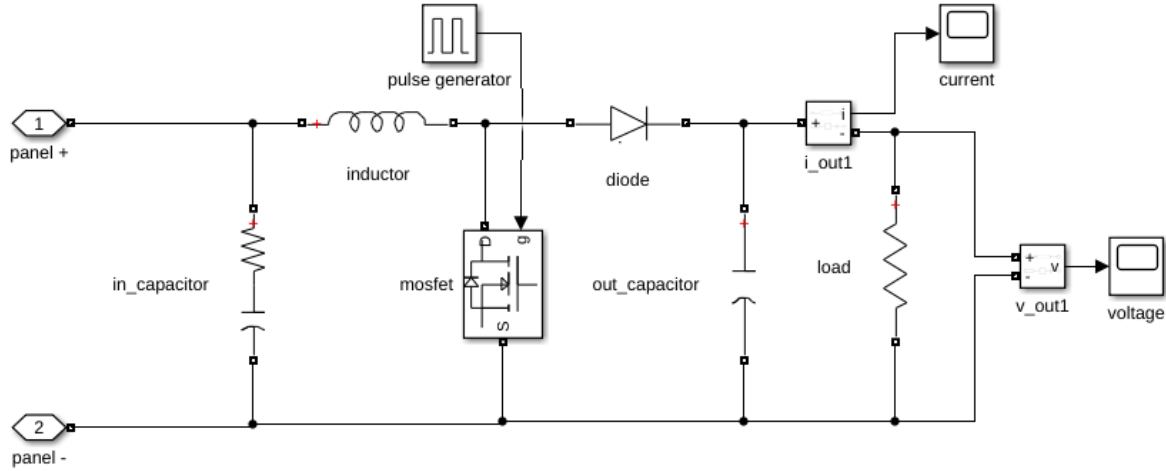


Figure 3-5. Simulink model of the boost converter.

3.2.2 Design of the maximum power point tracking techniques

As discussed in section 3.2.1.1, four algorithms are identified for assessment with the intend of determining the most appropriate algorithm, capable of reliably providing energy without depleting resources for a standalone PV system. These algorithms encompass two artificial intelligence-based techniques, a hybrid, and one conventional technique, specifically the artificial neural network, fuzzy logic controller, adaptive neuro-fuzzy inference system, and perturb and observe technique.

3.2.2.1 Fuzzy logic controller (FLC)

The initial step in the design of a fuzzy logic controller commenced with identifying the factors influencing the performance of the PV module. These factors include the voltage and current of the PV module, and the output variable to be optimized by the fuzzy logic controller, which is the duty ratio. The total power generated by the PV module is determined by monitoring the voltage and current. Furthermore, the input variables to the fuzzy inference system, error (E_{rr}) and change in error (ΔE_{rr}), are calculated as follows [67]:

$$E_{rr} = \frac{P_{out}(\sigma) - P_{out}(\sigma - 1)}{V_{out}(\sigma) - V_{out}(\sigma - 1)} \quad (9)$$

$$\Delta E_{rr} = E_{rr}(\sigma) - E_{rr}(\sigma - 1) \quad (10)$$

Here, $P_{out}(\sigma)$ represents the photovoltaic power output at the σ th instant, while $P_{out}(\sigma - 1)$ corresponds to the photovoltaic power output at the $\sigma - 1$ th instant. Similarly, $E_{rr}(\sigma)$ and $E_{rr}(\sigma - 1)$ represent the error at the σ and $\sigma - 1$ instants, respectively. As illustrated in Figure 3-6, the controller's design is based on the slope of the power-voltage (P-V) curve (E_{rr}) of the PV module and the rate of change of this slope (ΔE_{rr}).

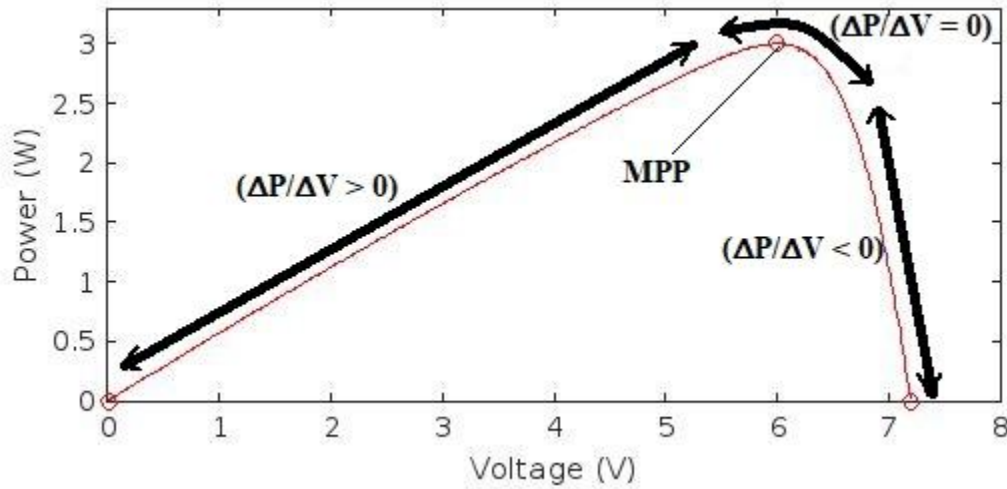


Figure 3-6. Power and voltage characteristic curve of the GD-035WP module.

Table 3-5 summarizes the implemented fuzzy rules, the fuzzy set for both input and output variables is composed of five triangular membership functions, which are illustrated in Figure 3-7. The selection of the triangular shape is influenced by research conducted by [68], which demonstrated that this shape yields the best controller response when compared to other shapes.

Table 3-5. Fuzzy rule base.

$\Delta E \backslash E$	NB	NS	ZE	PS	PB
NB	PS	PB	NB	NB	NS
NS	PS	PS	NS	NS	NS
ZE	ZE	ZE	ZE	ZE	ZE
PS	NS	NS	PS	PS	PS
PB	NS	NB	PB	PB	PS

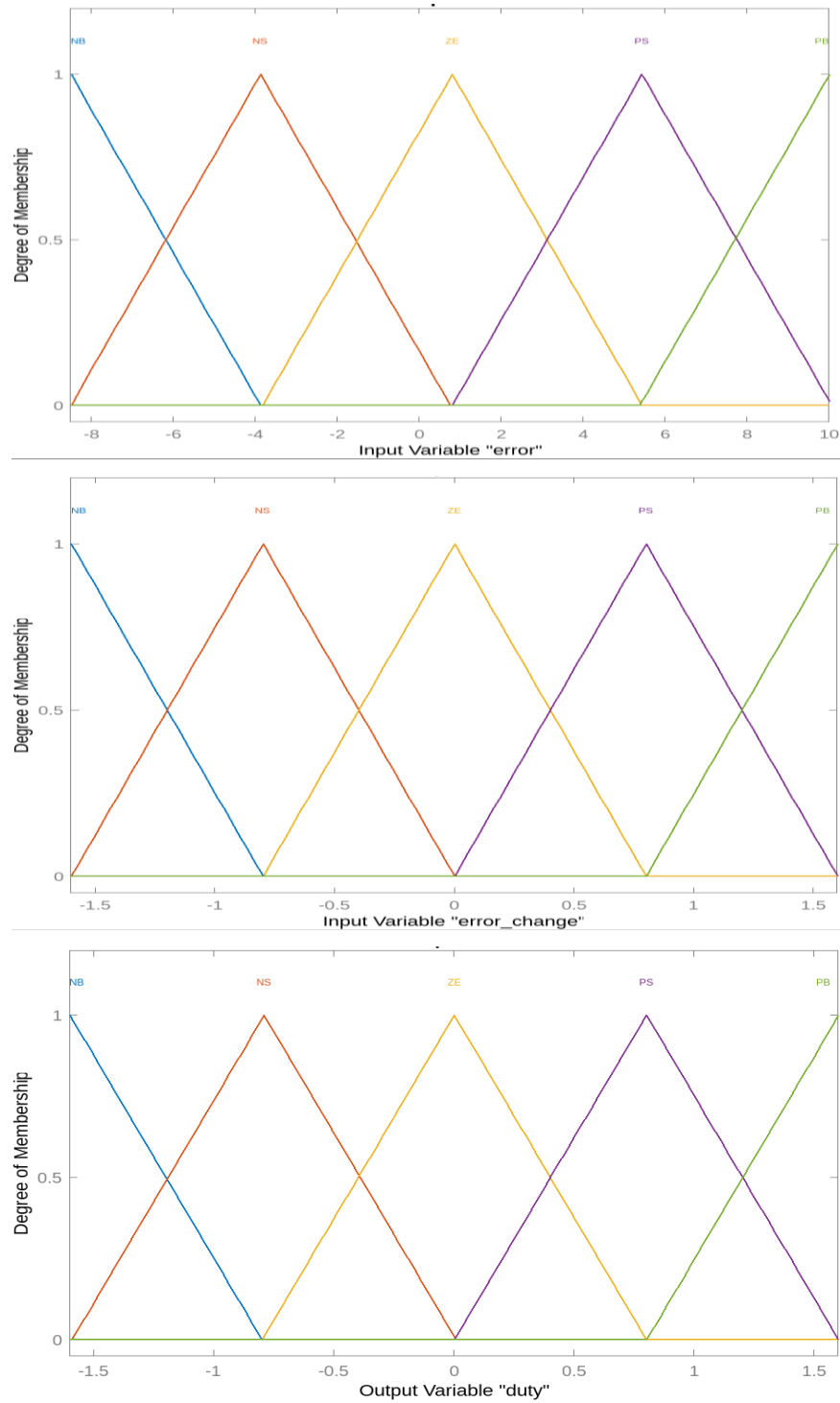


Figure 3-7. Membership functions of the fuzzy inference system.

The rule base depicted in Table 3-5 incorporated linguistic terms related to both input and output variables, specifically Zero (ZE), Negative Big (NB), Positive Small (PS), Negative Small (NS), and Positive Big

(PB). The error range is defined as $[-8.5, 10]$, while the change in error and duty ratio fell within $[-1.6, 1.6]$. To develop the controller, the Matlab fuzzy logic designer application is employed. Type 1 Mamdani template, the MAXMIN method for the inference engine and centroid method for the defuzzification are used. Figure 3-8 provides a three-dimensional visualization of the control surface generated by these five membership functions.

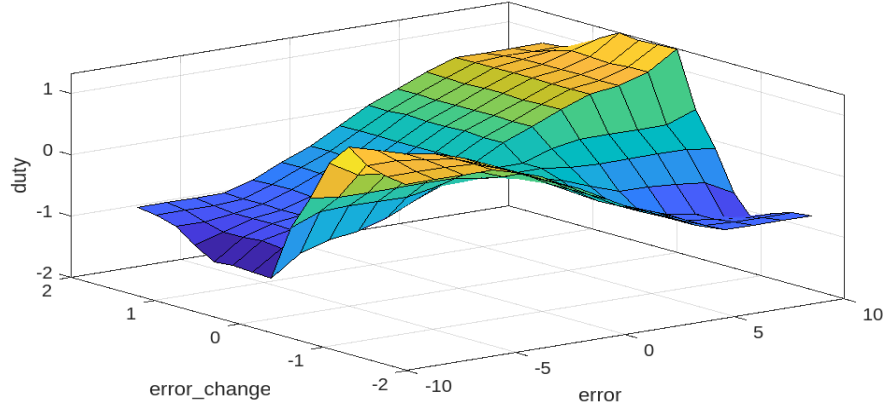


Figure 3-8. Surface view of the rule base.

3.2.2.2 Perturb & observe (P&O)

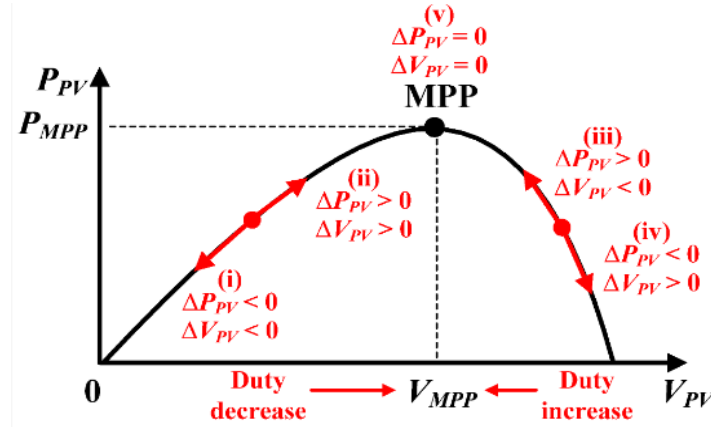


Figure 3-9. Perturb & observe operational principle.

The perturb and observe algorithm is based on the aim to bring the variation in PV power and voltage to zero when at MPP. Figure 3-9 illustrates this operational principle, which is subsequently utilized to create the flow chart shown in Figure 3-10. In this method, the system continuously monitors both the PV current and voltage to calculate the total PV power.

The input parameters are defined as changes in voltage and power, with the duty ratio serving as the control variable. Utilizing Figure 3-9 and Figure 3-10 as references, the perturbation technique, involving incremental and decremental adjustments, is employed. To implement this approach, a Simulink function block is utilized to hard code the algorithm, guided by the representations in Figure 3-10.

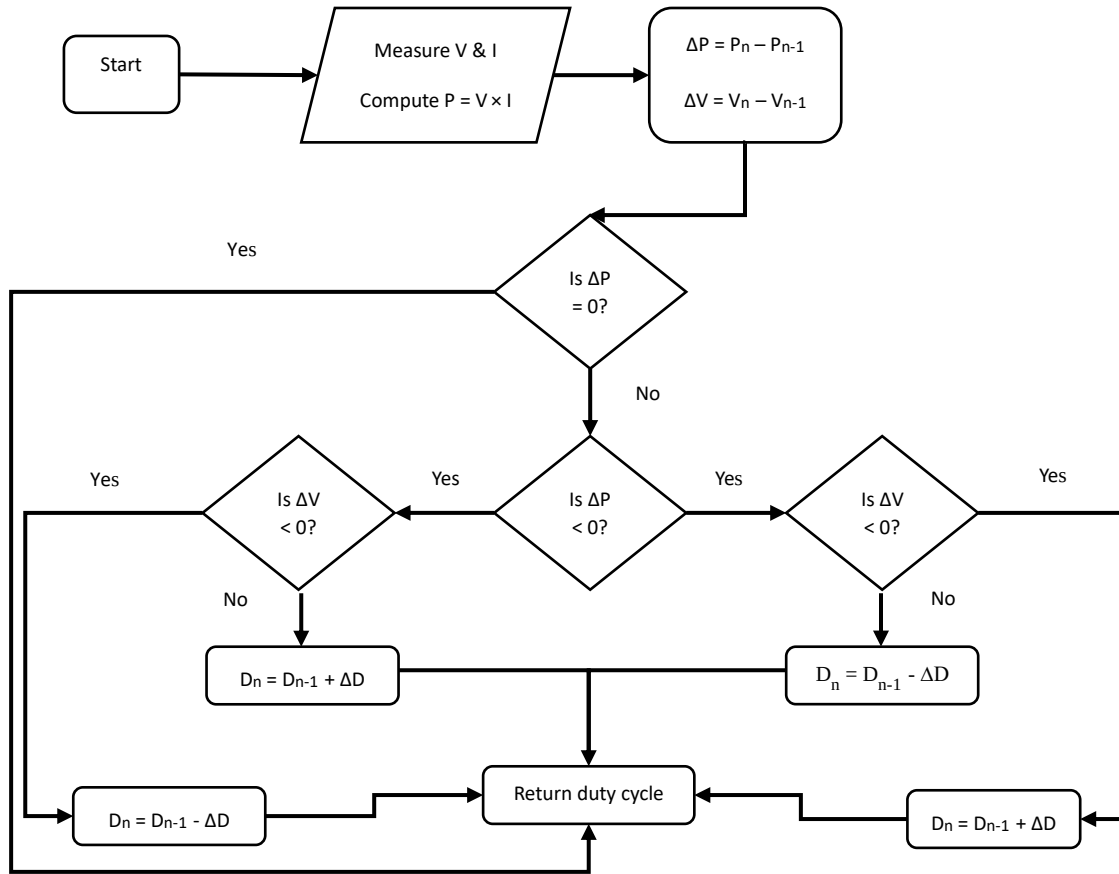


Figure 3-10. Perturb & observe flow chart.

3.2.2.3 Artificial neural network (ANN)

To develop the artificial neural network controller for predicting MPP of the PV module, a three-step process is undertaken, which is summarized as follows:

1. Selection of ANN architecture: a feedforward multi-layer perceptron network is implemented for the ANN structure. This network consists of three layers namely input, hidden and output as illustrated in Figure 3-11. The input layer receives raw data and passes it on to the next layers for

processing, in this case, the raw data includes the irradiance and temperature data set. The hidden layer performs computations on the input data using weighted connections between neurons, while the output layer provides the network's response based on the processed information. For this study the output layer provides voltage at maximum power point.

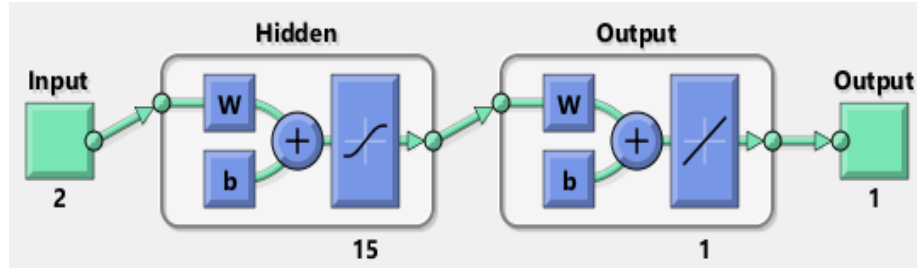


Figure 3-11. ANN model structure.

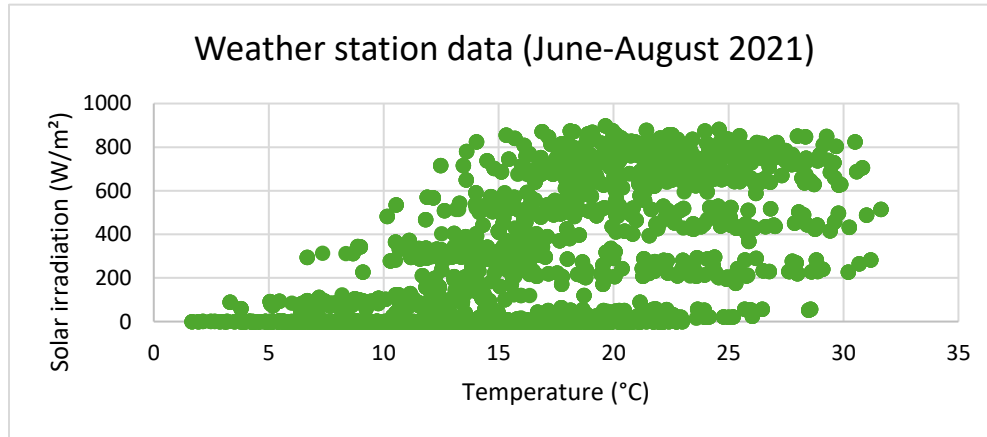


Figure 3-12. Training dataset from BIUST.

2. Data collection: Figure 3-12 showcases the dataset obtained from the Botswana International University of Science and Technology (BIUST) weather station, serving as the training dataset. This dataset comprises seven thousand patterns of irradiance and temperature levels. Using this temperature and irradiance dataset, the maximum power point voltage is computed as follows [67]:

$$V_{mp}(i) = V_{mps} + (\beta(T - T_s)) \quad (11)$$

Where V_{mps} , β , T_s and T represent the maximum voltage from the panel, voltage temperature coefficient, standard testing condition temperature and the temperature dataset matrix, respectively.

3. Training and testing the ANN: In this final phase, the Matlab neural network fitting application is employed to design, train, and validate the neural network. The data set is divided into three parts: 15% for validation, 15% for testing, and 70% for training. To determine the optimal number of neurons in the hidden layer, their quantity is varied from 5 to 20 in intervals of 5. This variation helps identify the quantity that will yield the least estimation errors. As indicated in Table 3-6, 15 neurons are found to be the optimal quantity, because they have the least estimation errors. To evaluate the performance and accuracy of the network, a regression plot is generated to measure the correlation between target and output. Figure 3-13 represents the correlation of the model predictions with the actual data points.

Table 3-6. The effect of neuron quantity on the mean squared errors.

Learning data error	Testing data error	Validation data error	Quantity of neurons
1.47×10^{-9}	1.68×10^{-9}	1.73×10^{-9}	5
4.37×10^{-10}	5.00×10^{-10}	4.64×10^{-10}	10
2.81×10^{-10}	2.66×10^{-10}	3.30×10^{-10}	15
2.90×10^{-10}	4.01×10^{-10}	3.73×10^{-10}	20

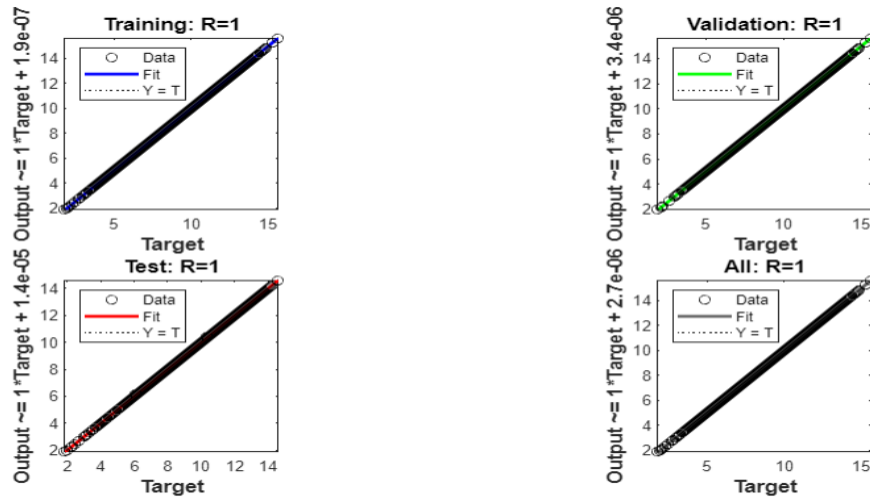


Figure 3-13. ANN regression output.

3.2.2.4 Adaptive neuro fuzzy inference system (ANFIS)

ANFIS is a hybrid technique that combines two powerful techniques namely, artificial neural network and fuzzy logic controller. The first step in designing the ANFIS controller consists of data collection and preprocessing. Input variables are identified as temperature and irradiance, while the output variable is the voltage at maximum power point. Similar to ANN the dataset depicted in Figure 3-12 serves as the training data for the model, and the output variable is computed using equation (11). Each input and output have three triangular-shaped-type membership functions, as demonstrated in Figure 3-14. This choice is in line with the recommendations made by [69].

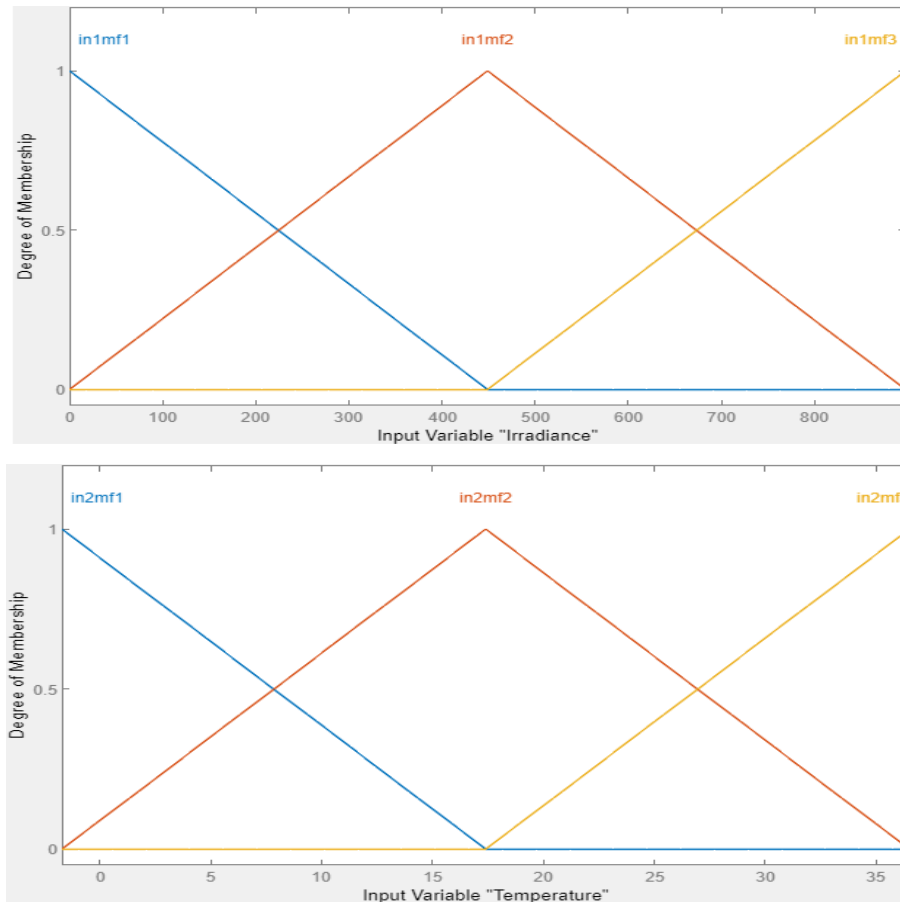


Figure 3-14. Membership functions of the input variables.

To train the ANFIS model, Matlab/Simulink Neuro fuzzy designer application is employed, utilizing a Sugeno type fuzzy model as the basis of the design. The data set is divided into three parts: 15% for validation, 15% for testing, and 70% for training. Throughout the training process, the aim is to minimize

the root mean squared error between the collected data and trained data, and a value of 2.79813×10^{-7} is achieved, as shown in Figure 3-15. Figure 3-16 offers a visual representation of the fuzzy rules created by ANFIS controller. To generate the appropriate gate pulses for the boost converter, the last step involves computing the difference between the PV module current (I_{pv}) and current at maximum power point (I_{mpp}), which is then fed into the duty generator.

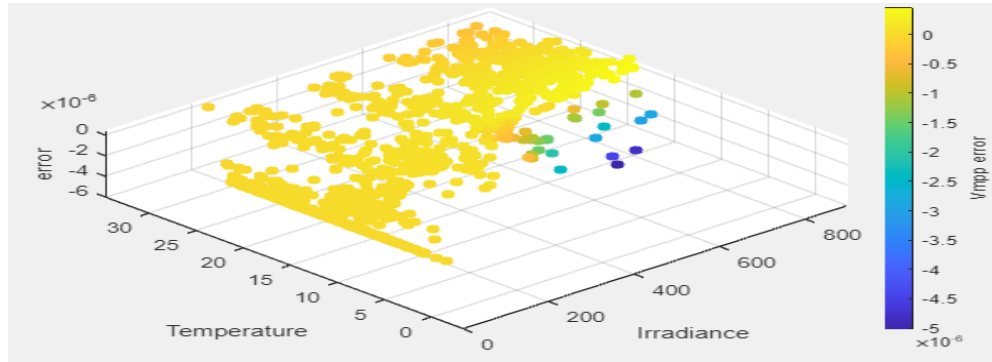


Figure 3-15. Root mean squared error distribution.

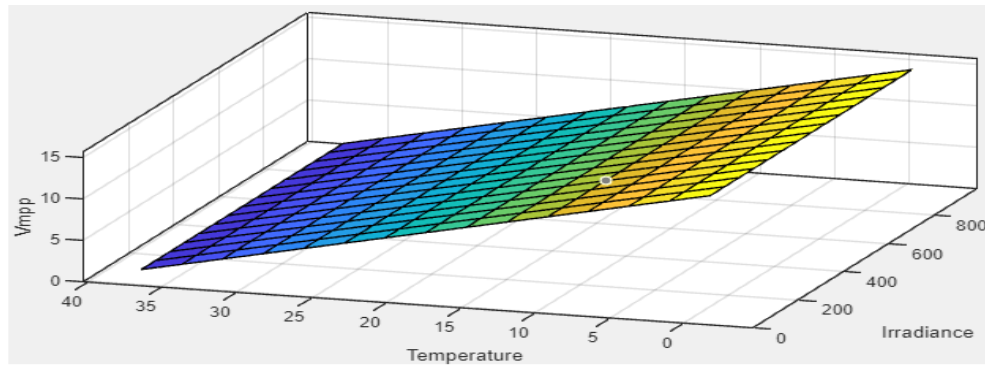


Figure 3-16. Control surface of the ANFIS model.

3.2.3 Decision matrix model and selection criteria

A decision matrix tool is used to determine the most suitable MPPT algorithm based on specific user requirements and preferences for a cost-effective dual axis tracking system. The results derived from this analysis do not conform to the conventional comparison format of “algorithm 1 is x-times faster than algorithm 2”. Instead, they articulate that “given user requirements A, algorithm 1 is favoured over algorithm 2”. This research employs this particular tool due to its user-friendly nature, which facilitates the

decomposition of a complex issue into a quantifiable and simplified array of solutions. Notably, it enables the selection of an algorithm prior to its implementation. To the authors' knowledge, this represents the first application of the decision matrix tool in addressing the optimization of MPPT algorithm selection. The methodology for constructing the decision matrix is illustrated in Figure 3-17.

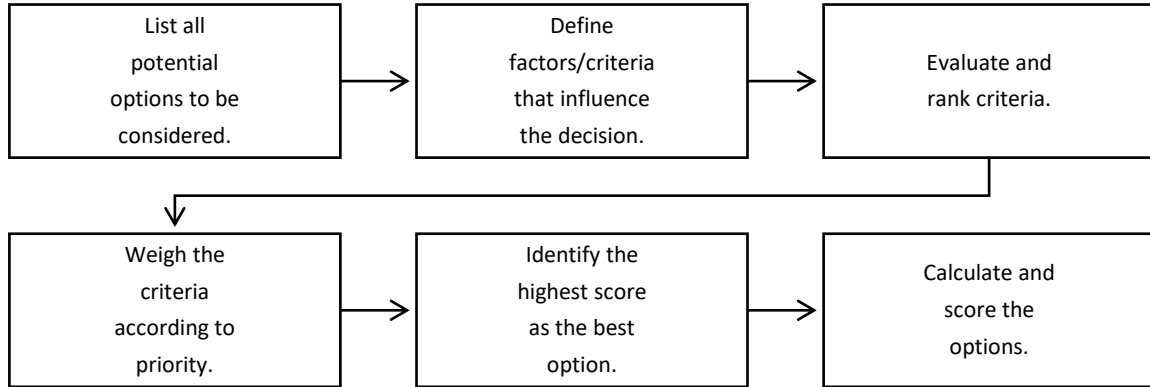


Figure 3-17. Decision matrix analysis model

Below is a list of the criteria that are most important for the PV standalone application, they reflect the key factors influencing the choice of the best suited MPPT technique for such an application.

3.2.3.1 Definition of decision criteria

- Low implementation costs: this evaluates the cost of implementing the MPPT system, including hardware and software expenses.
- Partial shading detection capability (PSC): this criterion indicates the MPPT system's ability to detect and mitigate the effects of partial shading, which can significantly impact the PV system performance.
- Sensitivity (rise time): this assesses how sensitive the MPPT system is to changes in environmental conditions. A faster rise time indicates quicker response to changes.
- Tracking efficiency (η): measures how effectively the MPPT system captures and maintains the PV system at MPP. It considers energy losses during tracking by computing the ratio between actual

maximum power (P_{mpp}) and the extracted power (P_{pv}) at a specific time test profile denoted as (t), and is computed through the formula, [70]:

$$\eta = \frac{\int_0^t P_{pv}(t)dt}{\int_0^t P_{mpp}(t)dt} \times 100\% \quad (12)$$

- Variance (V_m): this criterion evaluates the level of voltage or current fluctuations that occur around the MPP as the MPPT system operates. Smaller oscillations indicate a stable MPP operation [70].

$$V_m = \frac{\int_0^t (P_{mpp}(t) - P_{pv}(t))^2}{(t)} \quad (13)$$

- Tracking speed (settling time): this criterion assesses how quickly the MPPT system can detect and adapt to changes in environmental conditions. A lower settling time indicates a fast response to changes.

3.2.3.2 Assignment of weights

A grading scale is established to assign values for each criterion, reflecting their importance or demand according to user requirements. This scale ranges from 1 to 5, where 1 denotes minimal importance and 5 signifies the maximal importance. In this study, high tracking efficiency and low implementation costs are rated at 5, indicating their crucial importance. The ability to detect partial shading conditions (PSC) is assigned a rating of 4, while low power oscillations and high sensitivity are given a score of 3, representing their moderate importance. Conversely, fast-tracking is rated at 2, indicating it has lesser priority within the context of this study.

3.2.3.3 Evaluation of alternatives

Each MPPT technique is assessed on how well it fulfills each criterion. A rating scale from 1 to 3 is used to rank each algorithm, where 1 signifies that the MPPT algorithm fails to meet the criterion, and 3 indicates full compliance. For instance, both P&O and FLC receive a rating of 3 for the criterion of low implementation costs, as they primarily require the use of current and voltage sensors, which are more economical compared to the irradiation and temperature sensors required for ANN and ANFIS. The weighted score for each algorithm is calculated by multiplying the rank of each criterion by the corresponding rating of the MPPT technique. For example, ANFIS receives a rating of 3 for high tracking

efficiency, which is ranked at 5, resulting in a weighted score is 15. The total cumulative weighted scores for each MPPT technique are then computed; for instance, FLC yields weighted scores of 10, 15, 6, 4, 8 and 6, culminating in a total of 49, as presented in Table 3-7.

Table 3-7. MPPT evaluation and selection analysis.

		Alternatives			
		Perturb & observe	Fuzzy logic controller	Artificial neural network	Adaptive neuro fuzzy inference system
Criteria	Weight	Rating	Rating	Rating	Rating
		Weighted score	Weighted score	Weighted score	Weighted score
High tracking efficiency	5	2	2	3	3
		10	10	15	15
Low implementation costs	5	3	3	1	1
		15	15	5	5
Low variance	3	2	2	3	3
		6	6	9	9
Fast tracking speed	2	3	2	3	3
		6	4	6	6
PSC detection capability	4	3	2	3	3
		12	8	12	12
High sensitivity	3	2	1	2	2
		6	6	6	6
Total		55	49	53	53

3.3 System modelling and simulation

3.3.1 Functional analysis

The initial stage in the design of an effective solar tracking control system involves determining the needs and requirements of the customers. The process of analyzing these requirements is detailed below:

1. Accumulation of information: a comprehensive search of existing databases (i.e. science-direct, google scholar and elicite) is executed to gather foundational knowledge regarding solar tracking systems. This entails extracting relevant data to pinpoint the customer requirements. Keywords such as 'solar photovoltaic tracking systems', 'efficiency of PV systems', and 'design and implementation of tracking systems' are used.
2. Identification of user requirements: examination and assessment of current solar tracking systems and mechanisms is carried out by doing full text review of the selected studies, to gain insights into how present systems align with customer demands and to identify potential usability concerns.
3. Formulation of design specifications and requirements: design specifications and requirements are established to guarantee that the proposed design functions fall within the predefined user-specific parameters.

3.3.1.1 Identification of user requirements

Following a list of recommended features, this study realized that customers demand a cost effective, precise, and automated tracking system. This system should ensure optimal energy capture without the need for manual intervention. It should also incorporate advanced control systems to accurately determine the sun's position and adjust the angles of the PV panels accordingly. The identified usability issues included the following factors:

- The complexity of transmission mechanisms and mechanical structure can lead to system failures if not well calibrated or when operated by unskilled individuals.
- Installation and maintenance costs have the potential to impact on the overall return on investment.

This study's findings highlight the need for a cost effective, precise, and automated tracking system equipped with advanced control capabilities. Additionally, it emphasizes the importance of regular maintenance, proper calibration, and skilled operators to ensure system reliability and maximize returns on investment. As such, the primary objective involves designing, developing, and implementing a two-axis solar tracking system, as literature indicates that they yield greater energy capture compared to single axis and fixed solar systems. The intended system requires precise solar tracking, including autonomous positioning for both the azimuth and elevation axes. Furthermore, this study aims to contribute to the advancement of technologies that make solar tracking systems more affordable and less complex.

Four key functions essential for achieving effective solar tracking are identified as follows [71]:

- To generate the self-positioning tracking motion
- To accurately determine the sun's position
- To regulate the azimuth-elevation drive mechanism
- To monitor the effectiveness of tracking

3.3.1.2 Design and system specifications

Once the design objectives are established, the system's design specifications, performance, and system requirements, along with their design constraints are defined as shown in Table 3-8 and Table 3-9. Following the methodology proposed by [72], the initial step involves breaking down the four objective functions derived from the design goal into lower-level functions. This process aims to identify the fundamental functions that the dual axis tracker system must perform. The outcome of this analysis is a functional tree, which is developed by inquiring how the higher-level functions could be realized to ascertain the corresponding lower-level functions.

Table 3-8. Stand-alone PV system design specifications.

Design descriptions	Specification dimensions	Design implications
Azimuth tracking	$-65^{\circ} < \gamma < 65^{\circ}$	Azimuth range of freedom
Elevation tracking	$0^{\circ} < \alpha < 90^{\circ}$	Elevation range of freedom

Table 3-9. Stand-alone PV system design requirements.

System requirements	Performance requirements	Design constraints
• Should have a reliable backup power supply • Should facilitate ease of maintenance & repair • Should account for space constraints • Should be completely automated • Should be manufactured with locally available material and components • Should have an optimum return on investment	• Should have low tracking error tolerances • Should be capable to react quickly to changes in solar position • Should be energy efficient and minimize energy losses • Should ensure no risk of self-shading between panels • Should accurately determine the sun's position • Should account for weather conditions (e.g. cloud cover) when sunlight is limited • Should ensure the system can withstand wind loads in the installation area • Should be capable of real time tracking with smooth and accurate adjustments when sunlight is limited • Should record tracking data for analysis and optimization • Should be aesthetically appealing to customers	• Power supply • Land availability • Structural stability and material selection • Environmental conditions (e.g. rainfall) • Budget and cost • Operator technical skills and knowledge

3.3.1.3 Function decomposition

Through the decomposition procedure, various branches are generated until the basic functions can no longer be subdivided. For instance, the top-level function ‘To regulate the azimuth-elevation drive mechanism’, from Figure 3-18 is decomposed by questioning ‘how can the solar tracker regulate the azimuth & elevation drive mechanism’. The answers to this question include ‘To calculate the optimal position of the PV panels’ (i.e. to obtain and process information), ‘To mechanically adjust position of PV panels’ (i.e. to provide guidance based on information), ‘To maintain alignment with the sun's position’ (i.e. to minimize errors), and ‘To implement safety protocols during non-operational periods’ (i.e. to prevent damage to the positioning mechanism).

Once the basic functions are identified in the lower branches of the function tree as depicted in Figure 3-18, the next step involves associating these functions with their corresponding physical components. This mapping procedure is established by asking, ‘which components possesses the capability to execute this

basic function'. Ultimately, all basic components are determined, and Figure 3-19 represents the resultant solution to the function tree. For instance, the basic function, 'to translate sun position data into drive control commands' is analyzed by asking which component can be able to perform this function, and the solution emerges as a control unit.

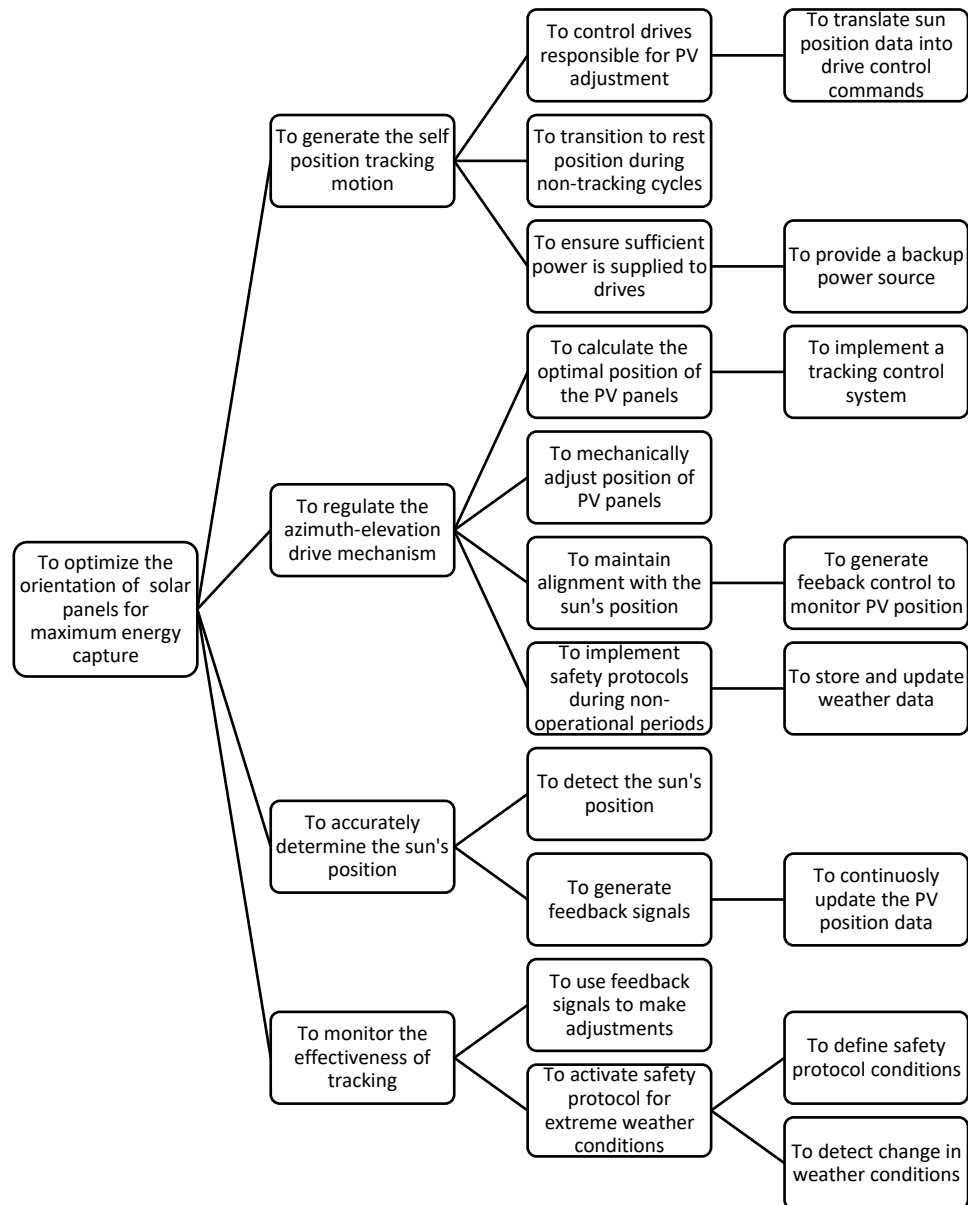


Figure 3-18. Function decomposition tree.

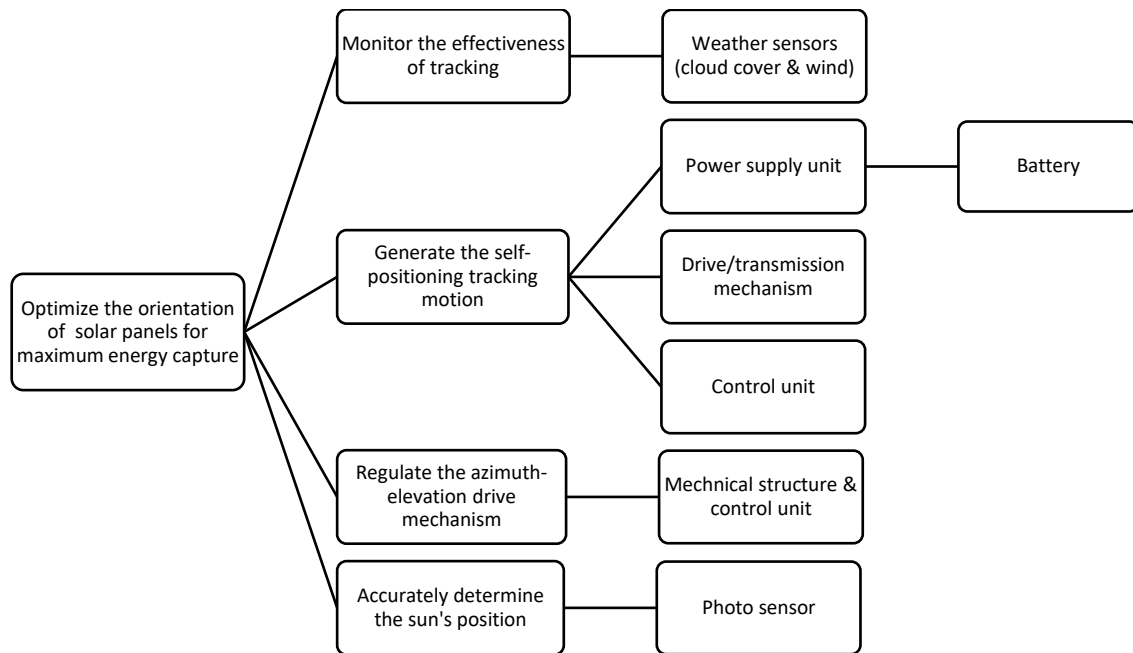


Figure 3-19. Product tree relating basic functions to their components.

Several components or devices are initially identified, and some of these answers are quite broad, for instance, there are various options for control units. Therefore, the next step focuses on identifying the potential and practical component alternatives for the solutions outlined in the product tree. Table 3-10 illustrates these alternative components.

Table 3-10. Practical component alternatives for the solar tracking system.

Function	Alternatives
Control unit	Programmable logic controller, Raspberry Pi, Arduino and Field programmable gate array
Drive/transmission mechanism	Integrated slew mechanism, Motor & chain mechanism and Integrated actuator and rack & pinion
Photo sensor	Camera image processing, Pyranometer and Light dependent resistor
Cloud-cover sensor	Ceilometer and Sky camera
Wind sensor	Ultrasonic wind sensor and Electronic anemometer

3.3.1.4 Embodiment of concept

The last step involves an evaluation process to determine the most suitable component options for the proposed solar tracking system. To facilitate this selection, specific evaluation criteria are established, as defined below.

3.3.1.4.1 Definition of decision criteria

- Availability: refers to the ease with which components can be obtained in the local market.
- Interfacing: involves how well the selected components can integrate with each other and the broader control system.
- Robust & reliable: it is critical for a solar tracking system to withstand environmental factors and ensure consistent performance over its operational life
- Inexpensive: cost effectiveness is a significant factor; it is important to balance performance with cost to achieve the desired return on investment.
- Maintenance & serviceability refers to components that are easily accessible and require minimal downtime for maintenance.
- Adaptable to control: the components should include the ability to accommodate different control algorithms or strategies.

3.3.1.4.2 Assignment of weights and evaluation of alternatives

An assessment of the component alternatives is conducted using a decision matrix model, the same rating and ranking scale described in sections 3.2.3.2 and 3.2.3.3 is used to determine the weighted score and cumulative total of each alternative. The outcome of this process is illustrated in Table 3-11.

Table 3-11. Evaluation of generated design alternatives.

		Alternatives			
		Programmable logic controller	Arduino	Raspberry Pi	Field programmable gate array
Criteria	Weight	Rating	Rating	Rating	Rating
		Weighted score	Weighted score	Weighted score	Weighted score
Fast response	2	3	2	3	3
		6	4	6	6
Interfacing	4	2	3	2	2
		8	12	8	8
Inexpensive	3	1	3	2	3
		3	9	6	9
Adaptable to control	5	3	2	2	1
		15	10	10	5
Availability	2	1	3	2	2
		2	6	4	4
Total		34	41	34	32
		Motor & chain mechanism	Integrated actuator and rack & pinion	Integrated slew mechanism	
Maintenance & serviceability	2	2	3	2	
		4	6	4	
Interfacing	4	2	3	3	
		8	12	12	
Compatible with support structure	5	1	3	1	
		5	15	5	
Robust & reliable	3	1	2	3	
		3	6	9	
Inexpensive	2	3	2	1	
		6	4	2	
Total		26	43	32	
		Ultrasonic wind sensor	Electronic anemometer		
Interfacing	3	2	3		
		6	9		
Availability	5	2	2		

		10	10	
Inexpensive	3	1	3	
		3	9	
Robust & reliable	4	3	3	
		12	12	
Total		31	40	
		Light dependent resistor	Pyranometer	Camera image processing
Availability	3	3	1	1
		9	3	3
Robust & reliable	4	2	3	1
		8	12	4
Interfacing	4	3	2	1
		12	8	4
Maintenance & serviceability	5	3	2	1
		15	10	5
Inexpensive	2	3	1	1
		6	2	2
Total		50	35	18
		Ceilometer	Sky camera	
Inexpensive	3	2	1	
		6	3	
Maintenance & serviceability	4	2	1	
		8	4	
Availability	4	1	1	
		4	4	
Interfacing	5	2	1	
		10	5	
Total		28	16	

Table 3-12 presents the comprehensive design embodiment of the proposed dual-axis solar tracking concept. From the possibilities presented in Table 3-11, alternatives with the highest total indicating the best option in satisfying the criteria, are selected as shown below.

Table 3-12. Comprehensive design embodiment of the proposed dual-axis solar tracking concept.

Function	Selected alternative
Control unit	Arduino
Drive mechanism	Integrated actuator and rack & pinion
Photo sensor	Light dependent resistor
Cloud-cover sensor	Ceilometer
Wind sensor	Electronic anemometer

3.3.2 Concept design

3.3.2.1 Research & benchmarking

Three existing designs for dual axis solar trackers are examined to assess their features, strengths and weaknesses as depicted in Figure 3-20 and Table 3-13. Based on the actuation mechanisms and mechanical design aspects of these trackers, a potential design solution is conceived. An innovative and effective dual axis mechanical structure is developed by integrating various elements from the three designs.

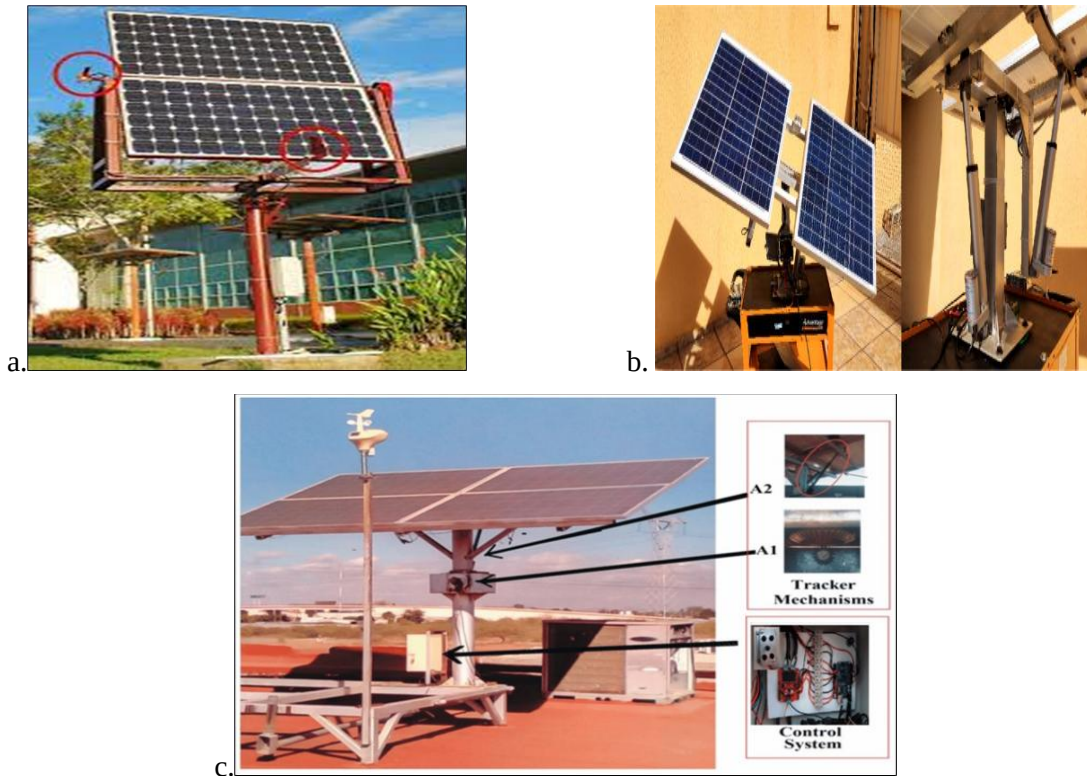


Figure 3-20. Dual axis solar tracker prototypes (a.)[44]; (b.)[74]; (c.)[75].

Table 3-13. Analysis of existing solar tracking systems.

Prototype	Design aspect	Strengths & Weaknesses	Key success factors
a.	• structure complexity: medium • wind load rating: 21.7m/s • material selection: mild steel • drive mechanism: DC motor and chain & sprocket	• regular maintenance required for the lubrication of chain and sprockets • need for balancing elements • land requirement	• structural optimization needed for weight reduction and lower maintenance requirements
b.	• structure complexity: low • wind load rating: N/A • material selection: aluminum • drive mechanism: linear actuators	• limited tracking range due to the actuator stroke length • unsecured base frame promotes compromised stability in high winds • lower maintenance needs	• needs improved weather resilience and proper transmission mechanism
c.	• structure complexity: high • wind load rating: 33.3m/s • material selection: mild steel • drive mechanism: linear actuator & bevel gear	• high torque • land requirement • better wind resistance	• robust design for diverse conditions; high reliability but high cost; simpler design could reduce cost

In design (a.), the approach of utilizing balancing elements to position the structure's center of mass as close as possible to the rotation axis is discouraged due to the potential increase in weight and power consumption by the actuators. Additionally, the chain and drive mechanism require regular maintenance for lubrication and has lower durability. Nevertheless, this design provides good tracking capabilities and enhances wind stability through the implementation of a cement foundation. Design (b.) emphasizes simplicity and cost-effective by incorporating a linear actuator drive mechanism, which is favored despite the need for a more robust base to ensure wind stability and an effective transmission mechanism to address

the limitations of actuator stroke length. In design (c.), there is preference for the gear drive mechanism due to its compatibility with heavy loads and its provision of stable and reliable tracking. However, further investigation is needed to identify a more budget-friendly option. This design has a robust design and excellent wind resistance.

This study proposes a modified design that combines some of the elements from all three designs. It aims for low complexity akin to design (b.) while enhancing wind stability similar to design (c.). The proposed design will use aluminum for its lightweight properties, as seen in design (b.), and will incorporate strategic steel reinforcement at the base of the structure like design (c.). Furthermore, it will integrate a linear actuator with a rack & pinion gear mechanism, merging the affordability of linear actuators with the performance benefits of a gear-based solution [73].

In light of the preceding discussion, a design solution integrating a linear actuator, alongside a rack & pinion drive mechanism is formulated. The operational aspects of this design are explained below. The proposed solution consists of two PV mounting frames, each designed to accommodate four small or two medium sized PV modules, a robust base frame capable of providing stability of the structure, and a support frame that connects the PV mounting frames to the base frame. The inclusion of both a PV frame and a support frame indicates that the system will feature dual axes of rotation, enabling precise tracking of the sun's trajectory.

Consequently, the primary axis will incorporate two linear actuators for the two PV mounting frames, while the secondary axis will use a single linear actuator. These actuators will work in conjunction with the rack and pinion drive mechanism to translate motion from the actuators to the support and PV mounting frames through metal shafts that traverse the centres of the frames and connect to three bearings and bushings. The primary axis will be constructed with aluminum cross members to reduce the load on the actuators, with additional reinforcement provided by a steel base structure for enhanced stability, as depicted in Figure 3-21. Figure 3-22 and Figure 3-23 provide a detailed description of the proposed system through a block diagram and flow chart detailing the solar tracking system.

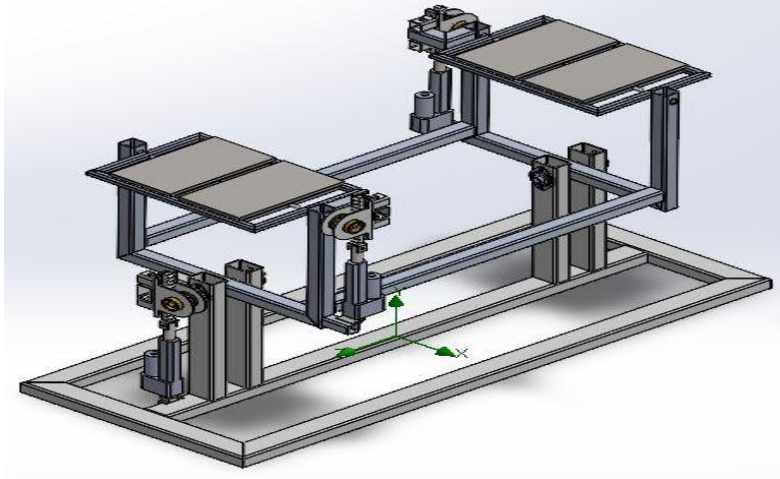


Figure 3-21. Illustration of the proposed design.

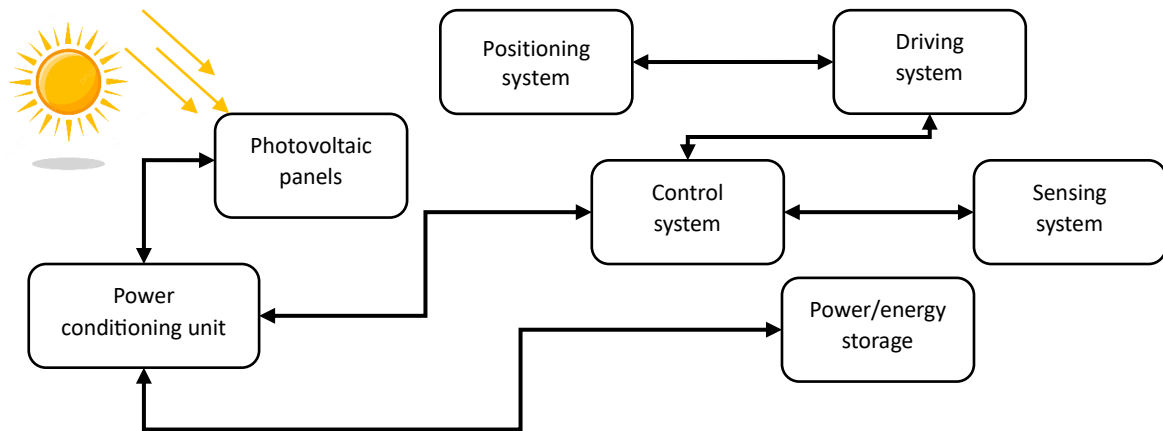


Figure 3-22. Block diagram of the proposed concept.

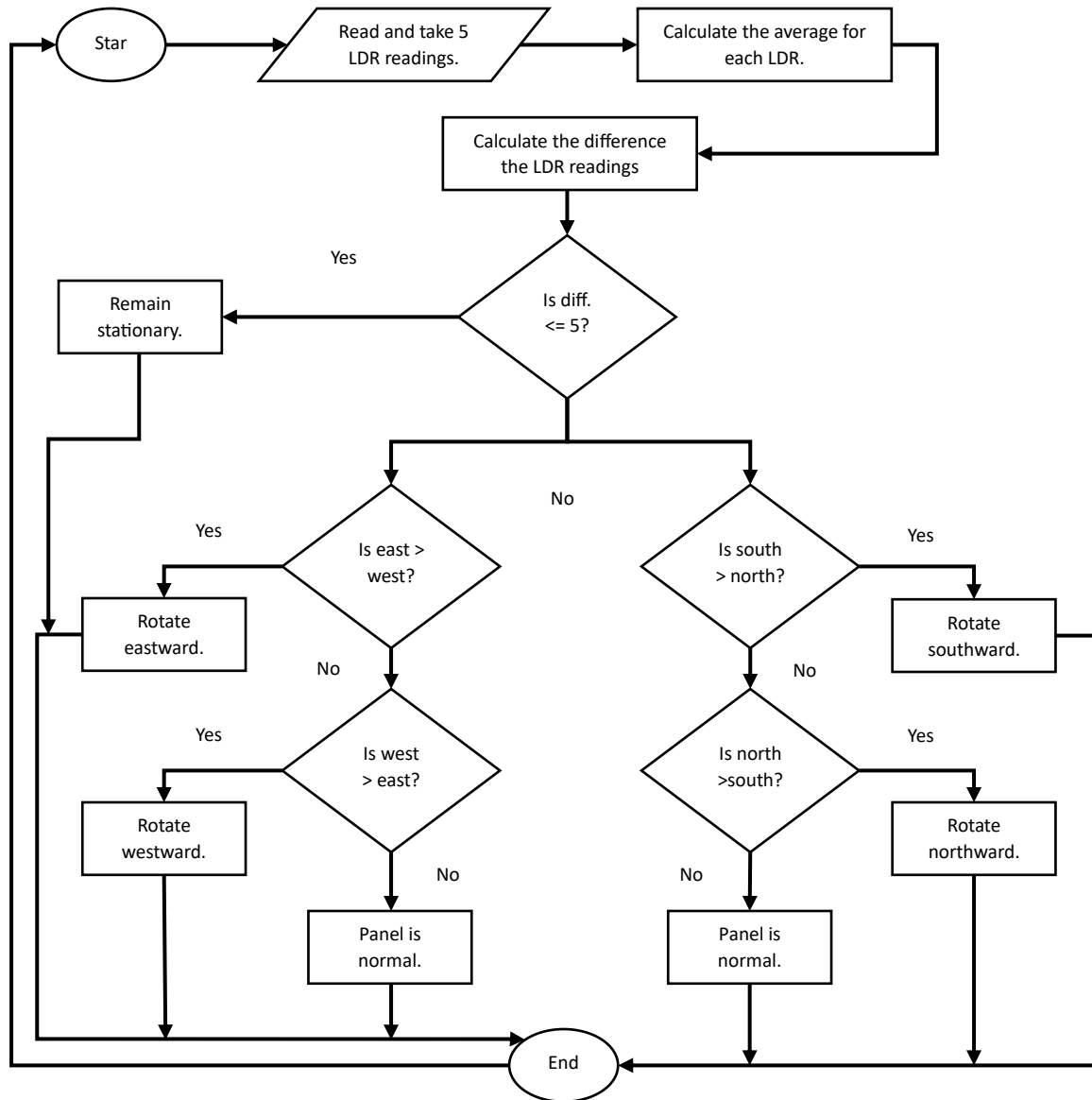


Figure 3-23. Flow chart of the sensor array positioning system.

3.3.2.2 Determination of the module inter-row spacing

A photovoltaic system is highly sensitivity to partial shading occurrences. Various factors contribute to partial shading, including objects in close proximity like trees or poles, as well as self-shading resulting from the adjacent photovoltaic panel rows. Therefore, it is crucial to thoroughly optimize the tilt and spacing between rows of modules [76], [77]. Following the methodology outlined in [77], the calculation for the inter row spacing between the PV modules is determined as follows:

$$\text{min. module row spacing} = \frac{\sin \beta \times L \times \cos \delta}{\tan \alpha} \quad (14)$$

Where β is the optimal tilt angle of 37.55° , L is the PV module width of 145mm, δ represents a solar azimuth angle of 46° and α represents a solar elevation angle of 27° . The solar path chart illustrated in Figure 3-24, is used to determine the solar elevation and azimuth angles for the worst-case scenario (winter solstice) during the time period from 09:00 to 15:00.

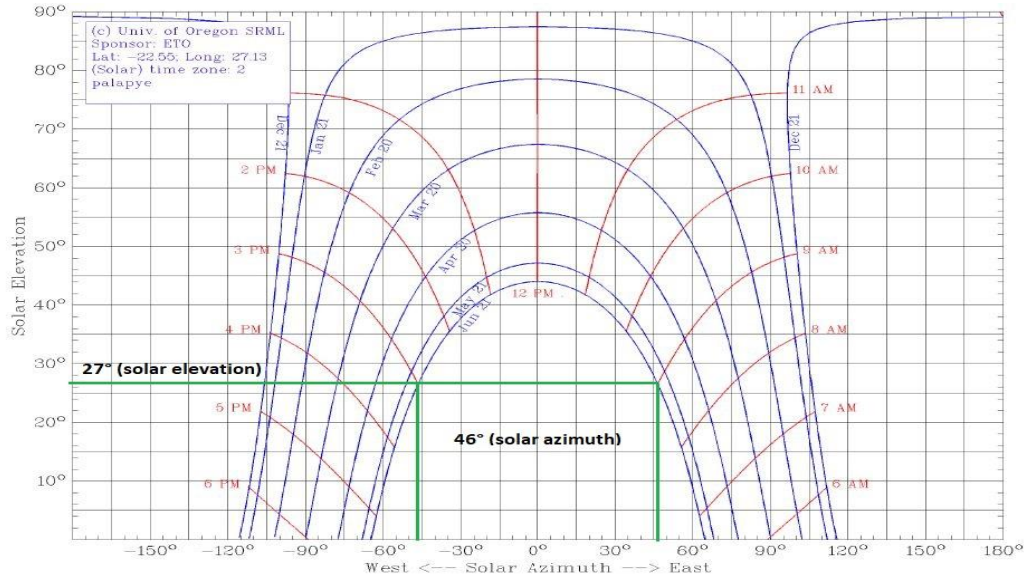


Figure 3-24. Solar path chart for Palapye, Botswana.

3.3.3 Wind load and structural analysis

The process of material selection for the solar structure is further informed by an analysis detailed in [78], which evaluated four materials suitable for the fabrication of wind turbine blades: glass fiber, aluminum alloy, mild steel, and stainless steel. The investigation concentrated on four key criteria: lightweight characteristics, resistance to corrosion, cost-effectiveness, and durability. In this context, aluminum alloy and mild steel are identified as the most appropriate materials for the construction of the photovoltaic (PV) frame and base frame of the solar structure, respectively. Aluminum is favored due to its excellent corrosion resistance, durability, and lightweight nature, which is intended to minimize the load on the actuators. Conversely, mild steel is selected for its cost efficiency and high density, providing a robust base capable of enduring wind forces.

Recognizing the importance of analyzing the kinematics of a solar structure prior to developing it into a PV solar tracking system, a thorough investigation of external factors such as wind load, motion dynamics and interrelations among its components is conducted. The analysis focuses on utilizing SolidWorks Motion Analysis add-in to identify suitable actuators capable of providing the required force/torque and precision for effective solar tracking. Additionally, structural analysis techniques, including computational fluid dynamics and finite element analysis, are utilized to evaluate wind flow around the structure, assess the structural integrity and optimize the design for enhanced strength and stability.

3.3.3.1 Simulating the effects of motion

Table 3-14. Material properties of the PV structure.

Material	Component	Yield strength N/m ²	Mass density kg/m ³	Tensile strength N/m ²
Aluminium alloy	PV module and intermediate support frame	2.75742e+07	2700	6.89356e+07
Mild steel	Base support frame	2.20594e+08	7800	3.99826e+08

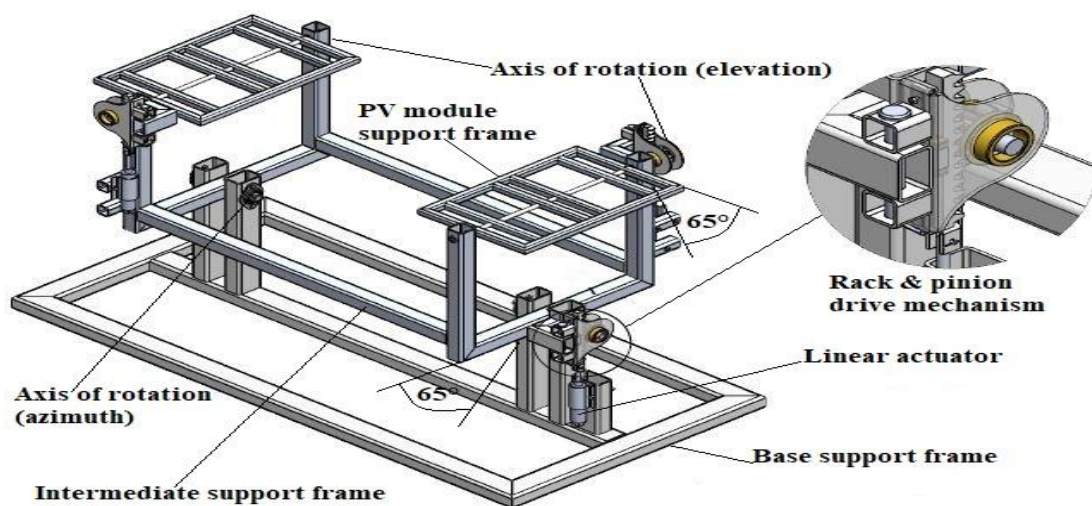


Figure 3-25. Dual axis solar tracking structure.

- The analysis of motion effects is conducted using the SolidWorks motion add-in tool, which facilitated the examination of the forces and loads acting on the drive mechanism. The primary objective of this motion study is to assess the forces exerted on the linear motors during the adjustment of the PV structure, ensuring that the PV modules are accurately oriented towards the sun's optimal position.
- The initial phase involves the creation of a comprehensive 3D model of the dual-axis solar structure utilizing SolidWorks 3D sketches. This modelling process encompasses the individual components, including the rack and pinion mechanism, the support structure, and other relevant features. Each component of the dual-axis structure is assigned specific material properties and mass, with mild steel and aluminium selected as the materials, as detailed in Table 3-14. As demonstrated in Figure 3-25, a limit angle mate ranging from 0° to 65° is implemented to define the motion range for both the azimuth and elevation axes.
- To determine the force required for the tracking application, simulations are executed, resulting in a plot that illustrates the dynamic motor force over time. This data is instrumental in facilitating the sizing of the actuators based on the simulation outcomes.

3.3.3.2 Numerical simulation and analysis of wind flow effects on the PV structure

- To validate the design of the proposed dual axis tracker, a performance evaluation is conducted using the SolidWorks Flow simulation add-in tool. This assessment aims to assess the structural stability and robustness under potential environmental conditions. Literature indicates that the most primary load affecting photovoltaic (PV) systems is attributed to wind [79], [80]. Consequently, the next step involves performing numerical wind studies, which are crucial for the design's success.
- To accurately simulate the wind flow around the design, the structure is enclosed within a specially designed virtual wind tunnel that replicates the environmental conditions present at the physical site. The dimensions of the computational domain are determined in accordance with the guidelines provided by COST (European Cooperation in the field of Scientific and Technical Research), with measurements taken relative to the height of the structure (H) [81]. The height of the computational domain is set to $6H$, with a lateral extension of $5H$ on either side of the structure. Additionally, a distance of $5H$ is maintained from the inlet wall to the front of the structure, while a distance of

15H is measured from the outlet wall to the rear. Consequently, the overall dimensions of the domain are 11H*6H*21H, as illustrated in Figure 3-26.

Table 3-15. Inflow data for the computational domain.

Unit system	International system of units (SI)
Analysis type	External flow
Physical features	Gravity: -9.81m/s ² , direction: y component
Fluid type	Air (gases)
Flow type	Laminar & turbulent
Wall conditions	Adiabatic, 0- roughness
Thermodynamic parameters	Pressure 101325 Pa, Temperature 30 °C
Velocity parameters	8m/s, direction: z component
Turbulence parameters	Intensity 0.1%, length 0.0122m

- Boundary conditions are established to replicate real-world scenarios and to assess the impact of wind loads on the PV structure. These conditions are detailed in Table 3-15.

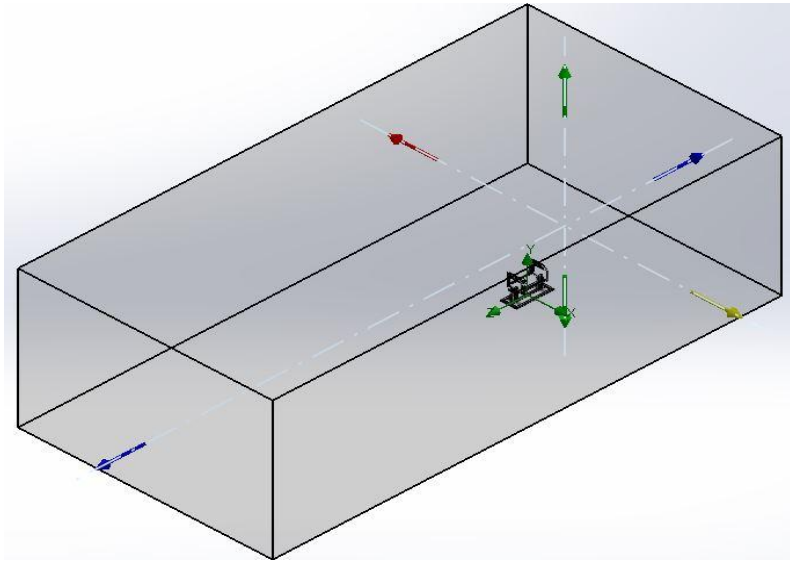


Figure 3-26. Computational domain of the dual axis tracker.

- The primary design objectives of the simulation are established through the identification of specific outcomes to be monitored. These outcomes encompass average velocity, average total

pressure, as well as drag and lift forces. The drag and lift forces, as discussed by [82] are represented by equation (15):

$$F_i = 0.5\rho V^2 AC_{Fi} \quad (15)$$

- Where ρ denotes the air density; V is the wind velocity; A is the frontal area of the PV modules; F is the wind force; C_F is the wind coefficients, while i represents the direction of wind force. In the context of this study, F_y and F_z correspond to the lift and drag force respectively. To assess the influence of variations in flow or model parameters on the structure, air flow is adjusted to speeds of 8m/s (29km/h), and 28m/s (101km/h). Additionally, the rotation angles of both the elevation & azimuth axes are configured at 25°, 90°, and 155°, using an angle mate assigned to the structure, with the wind direction maintained at 0°.
- A wind velocity parameter of 8m/s is selected based on the maximum wind speed recorded for Palapye, Botswana, as illustrated in Figure 3-27. For the worst-case scenario, a maximum wind speed of 28m/s is considered.

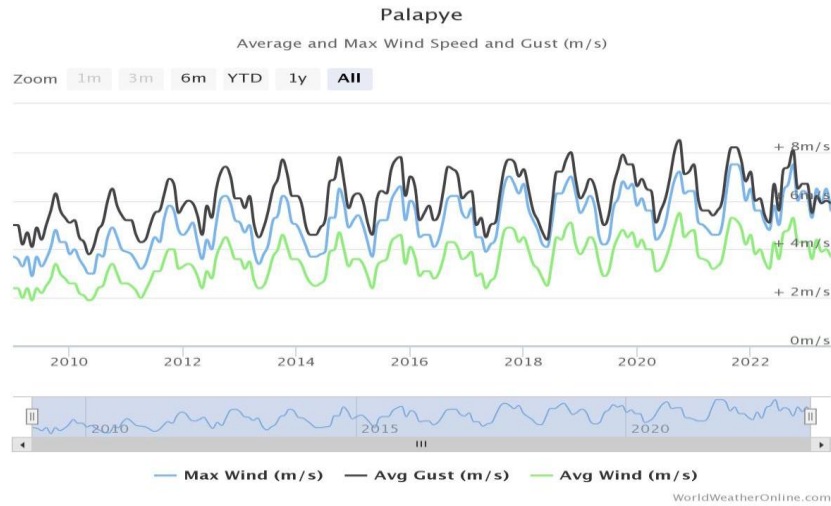


Figure 3-27. Botswana, Palapye (22.5515° S, 27.1147° E) annual wind speed data [83].

3.3.3.3 Finite element analysis (FEA)

- In order to analyse the structural behaviour under various loads (force, pressure, and temperature), results obtained from the flow simulation in section 3.3.3.2 are utilized in the FEA study.

- A mesh independence study is conducted across four grid sizes. The size of the mesh elements varies from 40mm, 25mm, 15mm and 10mm, to ensure that the simulation results are adequately independent of the grid. As depicted in Figure 3-28, when the element size is 10mm, the maximum axial and bending stress at the reference point stabilizes and remains nearly unchanged. Consequently, a mesh element size of 15mm is used for further simulations.
- Appropriate fixtures, and connectors are defined for the model. Fixtures restrict the degrees of freedom and stabilise each component of the model, while connectors describe a mechanism that defines how the faces and edges of the components are connected to one another. The structure is fixed to the ground by applying a fixed geometry at the base, while virtual bearings and pins are applied to the model. These simulated connectors (bearings and pins) replicate the behaviour of their real counterparts within the overall design. Following the completion of the static analysis, a safety check is conducted specifically for the pins, which includes defining parameters such as setting tensile stress area, bolt/pin strength and desired safety factor.

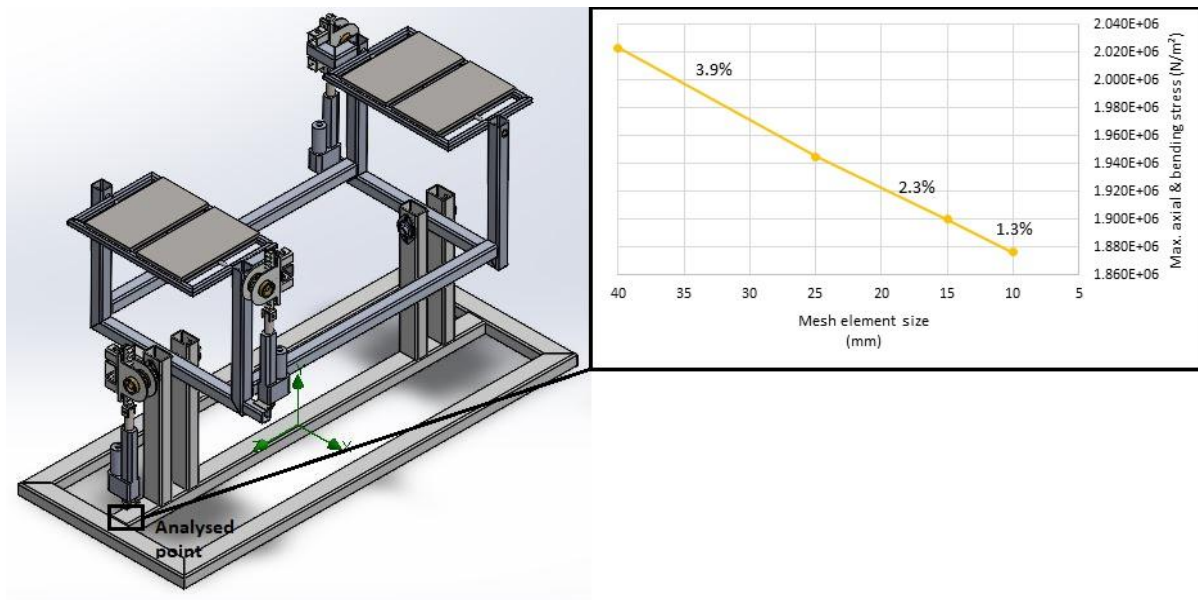


Figure 3-28. The effect of different mesh element size on the PV structure.

- After determining the appropriate mesh size, the FEA simulation is executed to analyse stress distribution, deflection, and deformation of the components of the solar tracker. Critical areas with high stress are assessed, and potential failure points are identified in order to optimise and refine the design for improved strength and durability.

3.4 Fabrication, assembly and system integration

3.4.1 Mechanical structure

An investigation was undertaken to identify reliable local suppliers of aluminium and mild steel, which led to the successful procurement of these materials. Subsequently, the solar tracking structure is fabricated using the acquired materials, as demonstrated in Figure 3-29. The cutting, welding and assembly of the structure were executed with meticulous attention to detail, guided by technical drawings.



Figure 3-29. Fabricated dual axis solar tracking framework.

3.4.2 Sensor array holder

The sensor system uses four photo-resistors (LDRs), two for the east-west axis and another two for the north-south axis, which are separated by a divider to locate the correct position of direct sunlight. The divider is produced through 3D printing, as illustrated in Figure 3-30. This design aims to read and compare the difference in resistance values of the LDRs which will help in the alignment of the tracking system in the direction in which the intensity of the sun rays is maximum.



Figure 3-30. Sensor array housing and circuit board.

3.4.3 Control circuit

The control circuit schematic is designed using EasyEDA software and serves as a foundation for creating the printed circuit board (PCB) as illustrated in Figure 3-31 and Figure 3-32. For the software component of the system, the perturb and observe technique, along with sensor array tracking algorithm, is uploaded to the control unit (Arduino), with the crucial role of processing the sensor data and regulating the linear motors to enhance the orientation of the photovoltaic modules, ensure optimal exposure to sunlight, and that the PV system always operates at MPP.

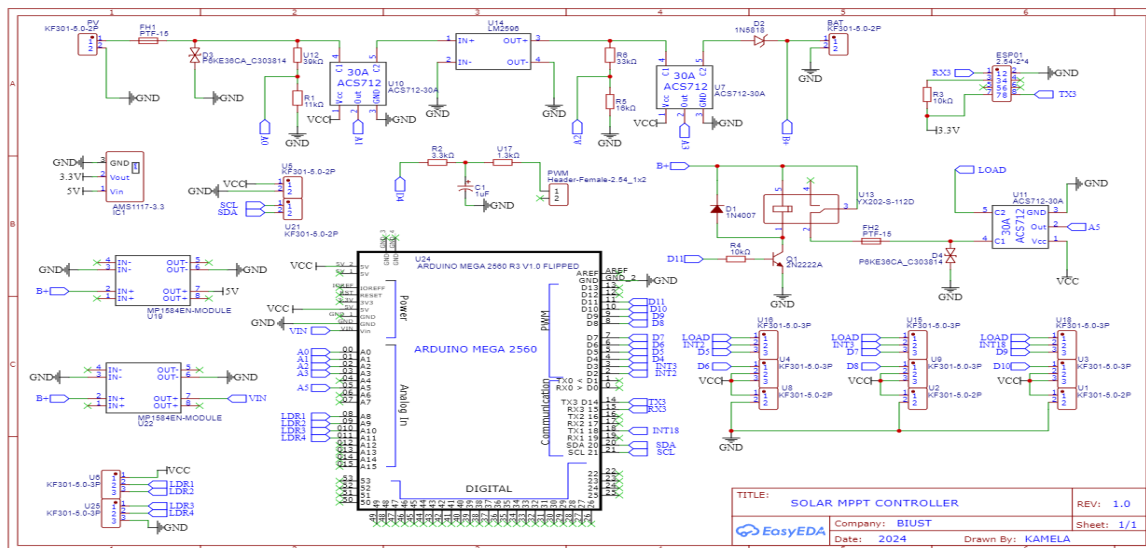


Figure 3-31. Control system circuit diagram.



Figure 3-32. Printed circuit board layout.

3.5 Cost analysis of the PV system

One of the most crucial factors in an investment lies in assessing the economic viability of the specific project at hand. The aim of the economic feasibility study is to gauge the financial worthiness of the proposed project in order to determine whether it is justifiable to implement. To assess the economic performance of the proposed PV solar tracker, the levelized cost of the electricity it produces is calculated. Estimating the levelized cost of electricity (LCOE) involves considering both the costs associated with the energy-generating system and the energy it generates over its useful lifespan. The LCOE, as presented in equation (16), is computed following the methodology outlined by [84] and is given as:

$$LCOE = \frac{C_{capital} + \sum_{i=0}^n \left[\frac{C_{O\&M}}{(1+r)^i} \right]}{\sum_{i=0}^n \left[\frac{E_i(1-d)^i}{(1+r)^i} \right]} \quad (USD/kWh) \quad (16)$$

Where $C_{O\&M}$ is the operation and maintenance costs, $C_{capital}$ is the initial investment of the project for i , E_i is the total electrical energy output for i (kWh), d is the PV degradation factor, n is the lifetime of the project in years (15 years for the purpose of this study), r is the discount rate for i , and i is the year. In order to assess the economic viability of the PV system, a cost analysis by comparing the cost of purchasing electricity from BPC (Botswana Power Corporation) over the system's operational life with the costs of generating electricity using the PV system is conducted. To facilitate this cost analysis, it is imperative to obtain electricity tariffs, which are to be contrasted with the LCOE.

Unlike the LCOE, electricity prices are not fixed, as depicted in Figure 3-33. Consequently, it becomes necessary to establish an annual escalation rate for the electricity prices, which is linked to the unpredictable fluctuations in the electricity market. Given the expectation that electricity prices will continue to increase in the foreseeable future, an annual escalation rate equivalent to the inflation in Botswana is assumed. Using equation (17), the present cost/kWh of procuring electricity from BPC over the PV system's operational lifespan is calculated. Where C_c is the current cost of electricity per kWh and g is the average annual inflation rate of Botswana (5.2% in 2023) [85].

$$\sum_{i=0}^n \frac{C_c((1+g)^i)}{(1+r)^i} \quad (17)$$

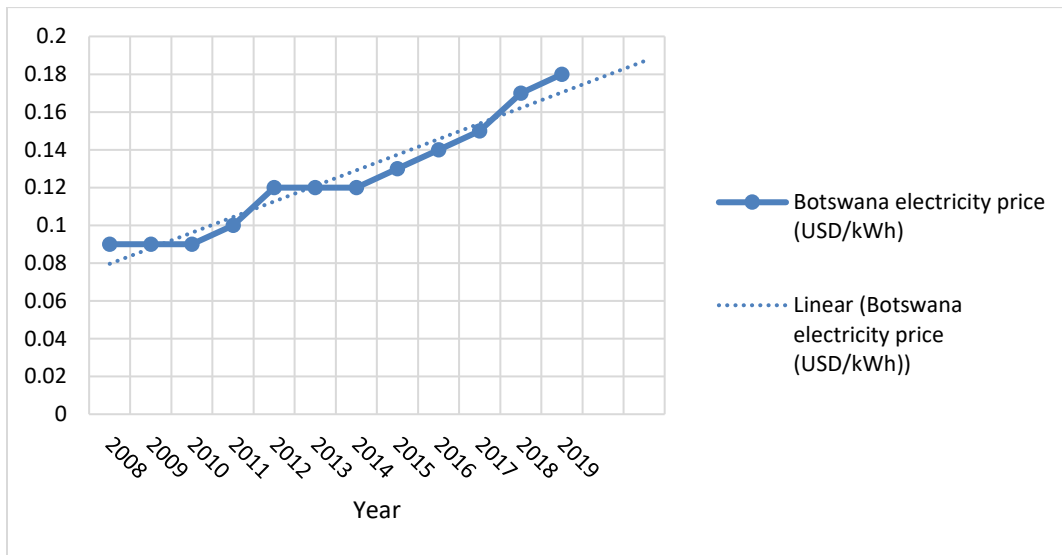


Figure 3-33. Botswana Electricity Price from 2008 to 2019.

Chapter 4 Results and discussions

4.1 Introduction

This chapter showcases the simulation results achieved by employing ANN, ANFIS, P&O and FUZZY LOGIC as maximum power point tracking algorithms for the proposed stand-alone PV system. A Matlab/Simulink model for a stand-alone PV system has been simulated, which consists of a PV module/array, DC-DC converter with an MPPT controller and resistive load. The simulation results offer a comparative analysis of the implemented MPPT techniques, serving to validate the performance of the selected controller. The second section of this chapter presents results obtained from the wind-load, structural analysis, along with the cost assessment of the proposed PV system and experimental results.

4.2 Software design

4.2.1 Design and simulation of the PV module

The characteristic curves and the optimal operational points of voltage, current and power at maximum power point change when weather conditions such as irradiance (G), temperature (T) and shadow vary. In the presence of non-linear variations, the inherent composition of the solar cell experiences multiple occurrences that have a detrimental impact on the conductivity of the silicon material. Consequently, this leads to a decline in the power output produced, as illustrated in Figure 4-1 and Figure 4-2. The simulation results are divided into three scenarios: fixed solar irradiance/temperature (standard testing conditions), varied solar irradiance/temperature and partial shading conditions.

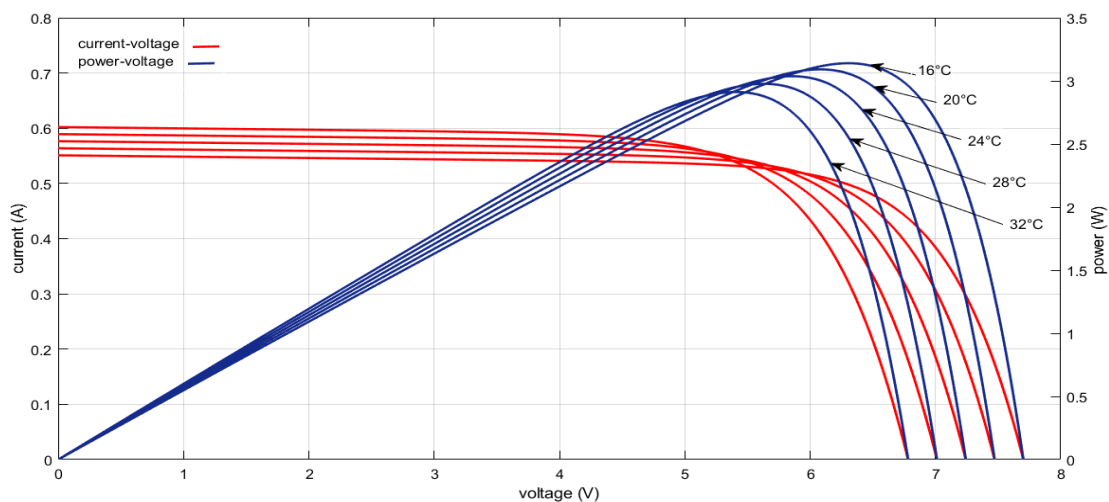


Figure 4-1. Characteristic curves showing the effect of temperature change on the PV module.

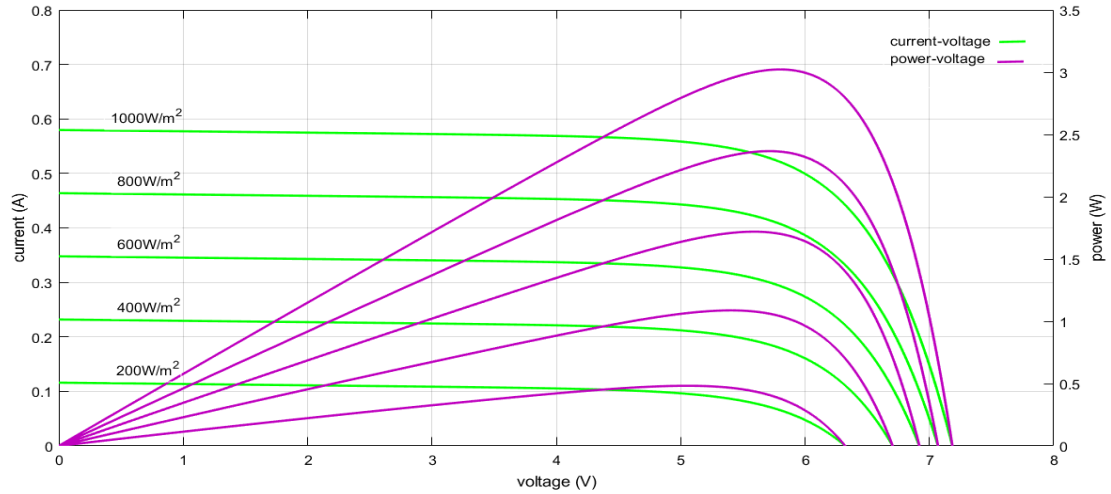


Figure 4-2. Characteristic curves showing the effect of irradiance change on the PV module.

4.2.1.1 Response of MPPT techniques under standard testing conditions (STC)

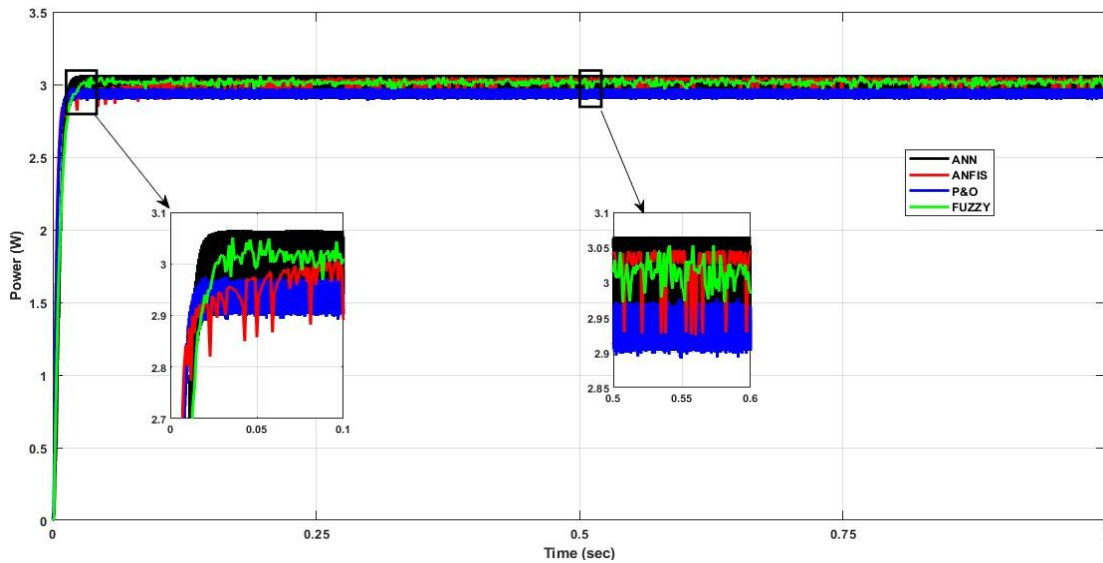


Figure 4-3. Power output of the MPPT techniques under STC.

Under fixed conditions, the input temperature and irradiance are maintained at 25°C and 1000W/m², respectively. The detailed analysis presented in the enlarged section of Figure 4-3 indicates that all algorithms exhibit fluctuations around the MPP. However, variance calculations reveal that FUZZY and ANN show greater stability in comparison to P&O and ANFIS. Table 4-1 demonstrates both the transient and steady state response of these algorithms. Notably, ANN exhibits a quicker response time, while

FUZZY is the slowest. Furthermore, Table 4-1 indicates that the FUZZY and P&O controllers are more cost effective than the ANFIS and ANN controllers, as they require voltage and current sensors, whereas the latter require temperature and solar irradiation sensors. This finding is supported by the research conducted in studies [70], [86].

Table 4-1. Tracking performance of the MPPT techniques under STC.

Evaluated parameters	P&O	FUZZY	ANN	ANFIS
Power production (W)	2.940	2.996	2.983	2.959
Settling time (ms)	10.088	17.672	5.689	14.128
Variance (W)	0.00188	5.33×10^{-6}	9.63×10^{-5}	0.00056
Rise time (ms)	5.592	10.959	6.972	11.858
Efficiency (%)	98	99.9	99.4	98.6
Sensor parameters	Current, voltage	Current, voltage	Temperature, irradiation	Temperature, irradiation

4.2.1.2 Response of MPPT techniques under slow and fast varying irradiance and temperature

To comprehensively evaluate the performance of the implemented MPPT algorithms, the PV model is subjected to gradual variations in solar irradiance and temperature. Initially, the PV system is exposed to slow and fast changes in irradiance, ranging from 200W/m^2 to 835W/m^2 , while maintaining an operation temperature of 22°C . Subsequently, it undergoes gradual and sudden temperature variations from 12°C to 29°C , with the irradiance held constant at 600W/m^2 , as depicted in Figure 4-4.

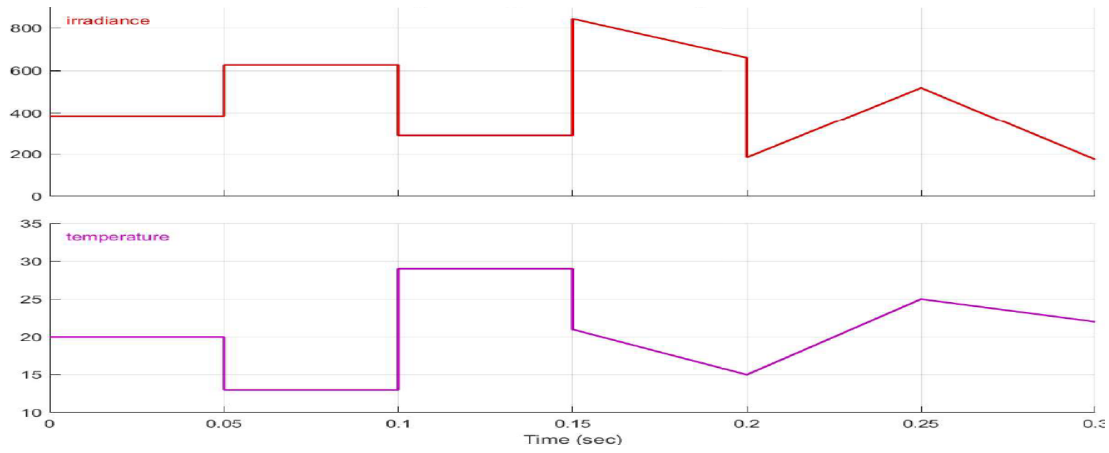


Figure 4-4. Input solar irradiance and temperature profile under slow and fast changes.

The output power characteristics corresponding to these gradual and sudden changes in irradiance are presented in Figure 4-5. The findings indicate that the P&O method has the highest overall efficiency (99% on average) across all time intervals, followed by ANN (98%), then FUZZY (94%), and finally ANFIS (90%) as shown in Table 4-2. Although all techniques can track the maximum power point effectively, the simulation results reveal that the performance of the soft computing controllers (ANFIS and ANN) is lower than that of P&O, which is not in-line with expectations. This limitation may be linked to inadequate data representation in the training dataset of the neural network, as highlighted in prior research studies [70], [87].

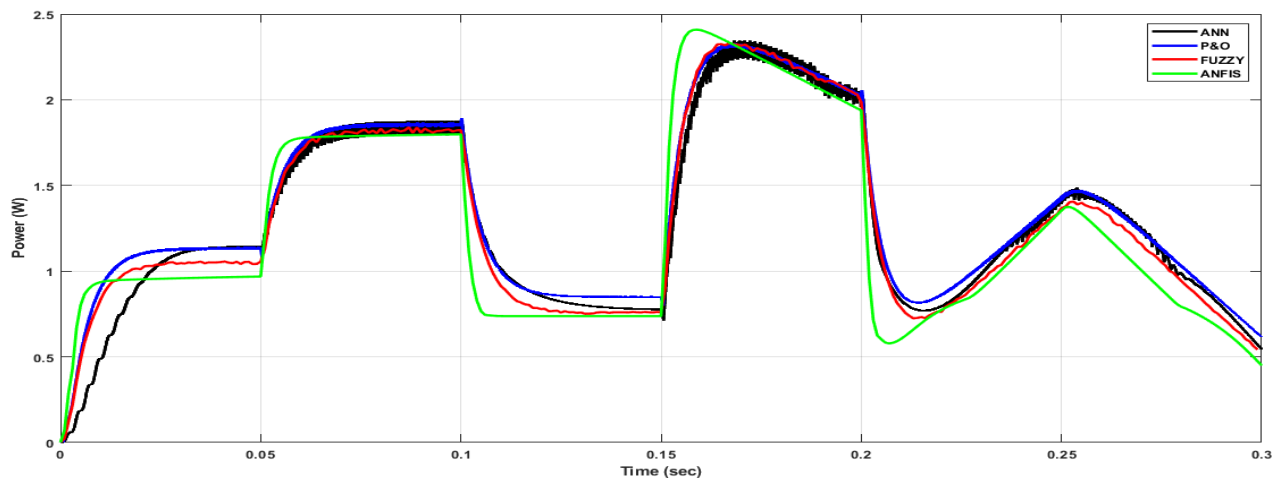


Figure 4-5. Power output of the MPPT techniques for slow and fast irradiation changes.

Table 4-2. Tracking performance of the MPPT techniques under slow and fast irradiation changes.

Time (sec)		0-0.05	0.05-0.1	0.1-0.15	0.15-0.2	0.2-0.25	0.25-0.3	Average
Theoretical max. power		1.150W	1.855W	0.865W	2.230W	1.139W	1.080W	
ANN	Extracted power (W)	1.148	1.837	0.821	2.192	1.119	1.039	
	Efficiency %	99.8	99	95	98.3	98.2	96.2	98
FUZZY	Extracted power (W)	1.080	1.809	0.760	2.160	1.071	0.980	
	Efficiency %	94	98	88	97	94	91	94
P&O	Extracted power (W)	1.137	1.844	0.858	2.158	1.137	1.052	
	Efficiency %	99	99.4	99.2	97	99.8	97.4	99
ANFIS	Extracted power (W)	0.952	1.775	0.745	2.180	1.008	0.947	
	Efficiency %	83	96	86	98	88.5	88	90

Table 4-3 shows that both ANN and P&O achieve the highest average efficiency (99%) across all time intervals, followed by FUZZY with a 97% average efficiency, and finally ANFIS with the lowest overall performance at 94% average efficiency. Figure 4-6 visually confirms these findings, with ANFIS performing particularly poorly in the 0.1-0.15 second interval (dropping to 82.3% efficiency). All techniques respond well to the temperature variations, but ANFIS is likely limited by the quantity of training data, as discussed previously. This study acknowledges the need for retraining with extensive real-life data, most likely data covering all the four seasons, but is limited by the computational intensity of these techniques, as they require large amounts of processing memory and computing power.

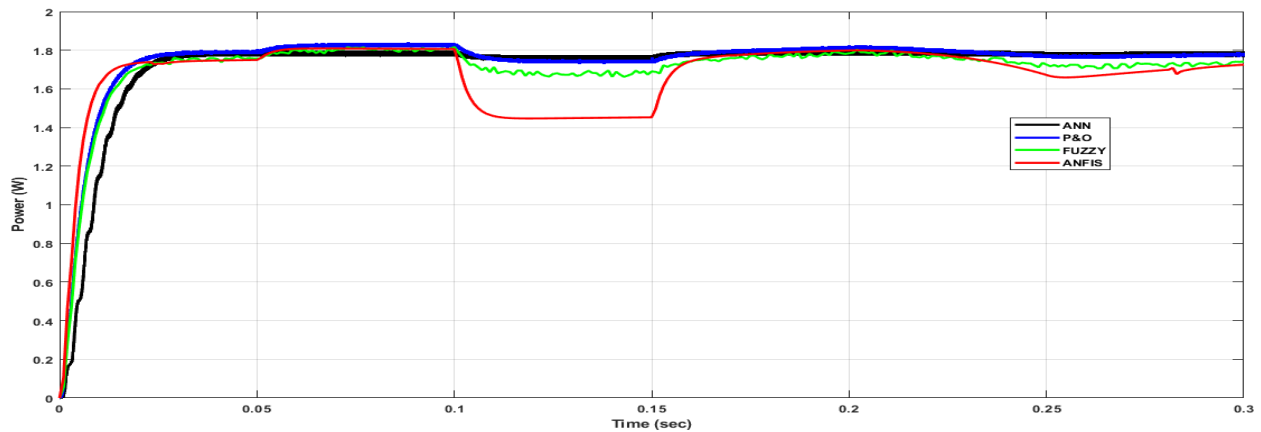


Figure 4-6. Power output of the MPPT techniques for slow and fast temperature changes.

Table 4-3. Tracking performance of the MPPT techniques under slow and fast temperature changes.

Time (sec)		0-0.05	0.05-0.1	0.1-0.15	0.15-0.2	0.2-0.25	0.25-0.3	Average
Theoretical max. power		1.800W	1.845W	1.750W	1.820W	1.790W	1.788	
ANN	Extracted power (W)	1.773	1.770	1.750	1.775	1.772	1.787	
	Efficiency %	99	96	100	98	99	99.9	99
FUZZY	Extracted power (W)	1.753	1.802	1.656	1.729	1.746	1.746	
	Efficiency %	97.4	98	95	95	98	98	97
P&O	Extracted power (W)	1.779	1.825	1.732	1.767	1.778	1.778	
	Efficiency %	99	99	99	97	99.3	99.4	99
ANFIS	Extracted power (W)	1.735	1.795	1.440	1.774	1.713	1.678	
	Efficiency %	96.4	97.3	82.3	97.5	96	94	94

4.2.1.3 Response of MPPT techniques under partial shading conditions (PSC)

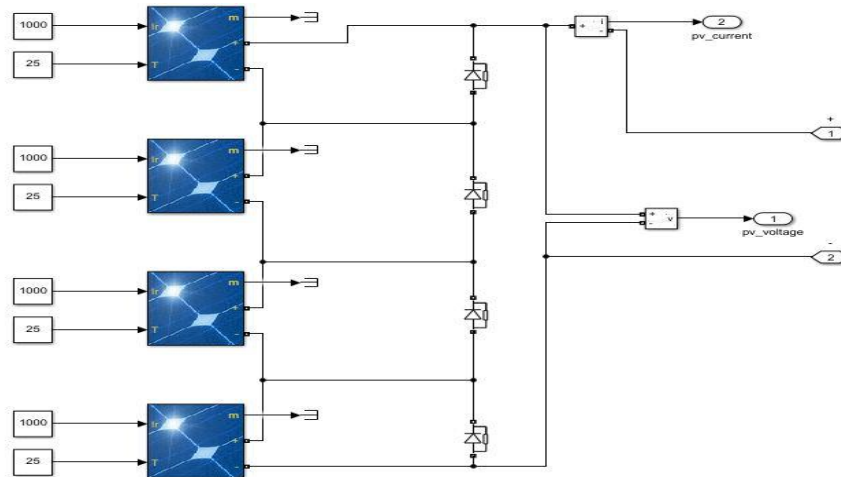


Figure 4-7. Series based configuration circuit of the PV array with bypass diodes.

In addressing the hot-spot effect identified by [23] and [88], the third scenario involves the configuration of four PV modules (GD 035WP) arranged in series, each paired with a bypass diodes connected in parallel, as illustrated in Figure 4-7. The PV array is exposed to non-uniform irradiation intensity, resulting in the

formation of multiple peaks that include both local and global maximum power points within the PV characteristic curves, as demonstrated in Figure 4-8. The arrangement of the PV modules is detailed in Table 4-4. Initially, the first, second, third and fourth panel operate under irradiance levels of 823W/m², 630W/m², 423W/m², and 850W/m², respectively.

To further evaluate the robustness of these techniques, the shading pattern is modified to 300W/m², 300W/m², 639W/m², and 722W/m². Figure 4-9 and Figure 4-10 depict the output power of the PV system across all four MPPT algorithms, highlighting their ability to differentiate between global and local maximum power points. The tracking performance and the global maximum power achieved by each algorithm are summarized in Table 4-5.

In both cases, it is noted that the ANN and ANFIS demonstrate the quickest tracking times and highest efficiency in case 1. However, they do not maintain the same level of efficiency in case 2. This variation may be due to the requirement of extensive training data that covers the full range of possible environmental conditions, as noted by [89]. Although the FUZZY controller produces slightly higher power output in Case 2, it experiences longer settling and rise times in both scenarios. This may also be linked to the necessity for well-designed fuzzy rules and membership functions, as discussed by [89]. The P&O method demonstrates competitive power tracking but lower efficiency in Case 1, with moderate response times.

Table 4-4. Partial shading patterns and their corresponding global peaks.

Case	Irradiance on each PV module (W/m ²)				GMPP (W)
	PV 1	PV 2	PV 3	PV 4	
1	823	630	423	850	5.775
2	318	300	639	722	3.504

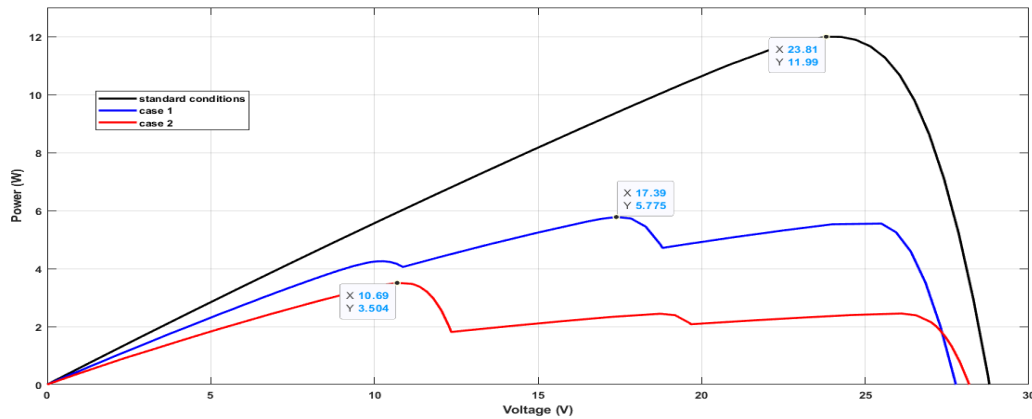


Figure 4-8. Characteristic curves of the PV array for uniform and partial shading conditions.

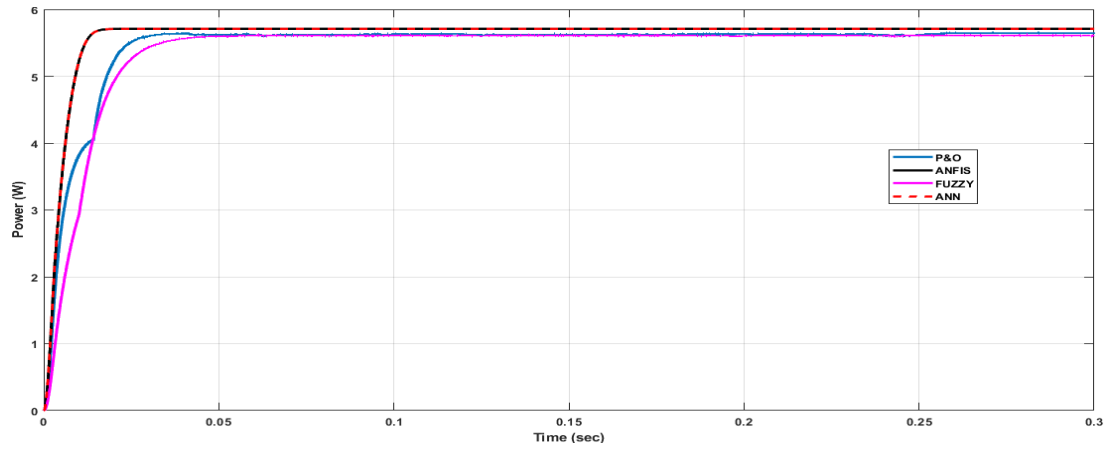


Figure 4-9. Power output for the partial shading conditions in case 1.

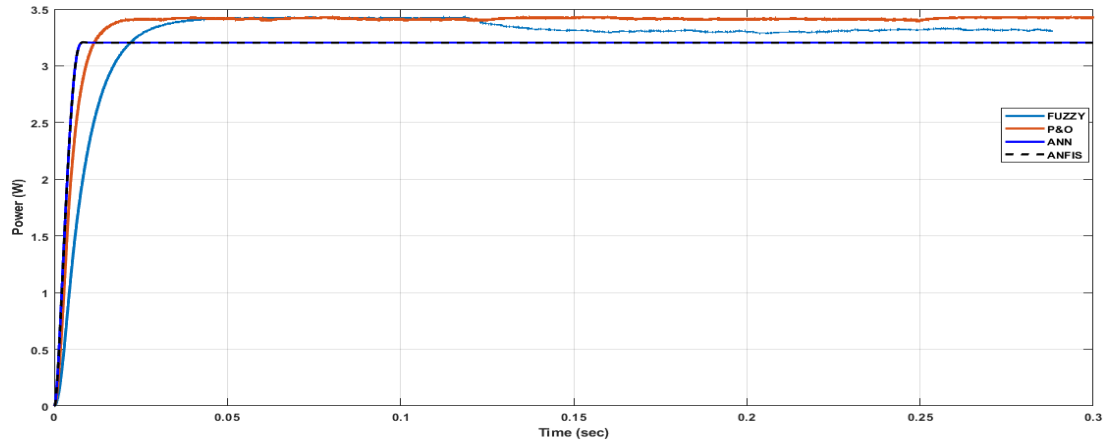


Figure 4-10. Power output for the partial shading conditions in case 2.

Table 4-5. Tracking performance of the MPPT algorithms under PSC.

	ANN	ANFIS	FUZZY	P&O
CASE 1				
Tracked power	5.709W	5.709W	5.620W	5.657W
Settling time	6.969ms	6.969ms	16.938ms	16.188ms
Rise time	8.146ms	8.146ms	18.959ms	16.924ms
Efficiency, variance	99%, 0.00013W	99%, 0.00013W	97%, 0.00073W	98%, 0.0004W
CASE 2				
Tracked power	3.208W	3.208W	3.356W	3.434W
Settling time	3.127ms	3.127ms	13.711ms	8.458ms
Rise time	4.565ms	4.565ms	14.479ms	8.327ms
Efficiency, variance	92%, 0.00263W	92%, 0.00263W	96%, 0.00066W	98%, 0.00015W

4.3 System modelling and simulation

4.3.1 Actuator sizing and motion analysis

The proposed solar tracker is designed as a dual axis structure with continuous actuation to always maintain the solar angle perpendicular to the orientation of the PV panels. The movement of the structure involves two rotations, namely azimuth and elevation, both motions are enabled by linear actuators, which, in turn, transfer their linear translation to the corresponding axes through a rack and pinion mechanism. To ensure precise sun, the appropriate actuator size capable of providing the necessary force, needs to be identified. To achieve this, graphical data is generated based on the simulated motion of the structure using SolidWorks Motion add-in tool.

Figure 4-11 and Figure 4-12 depict the required actuator forces for the actual movements of the intermediate support frame and PV module support frame when subjected to the tracking mechanism. For east-west tracking, a combined force of 4N is needed, while for the north-south tracking, a force of 850N is necessary. The different positioning requirements in the elevation and azimuth tracking lead to distinct loads on the actuators. The elevation tracking results in a continuous load that is somewhat influenced by the weight of the panels, while the azimuth tracking involves less frequent adjustments but requires more force influenced by the weight of the panels, panel support frame and the intermediate mounting structure.

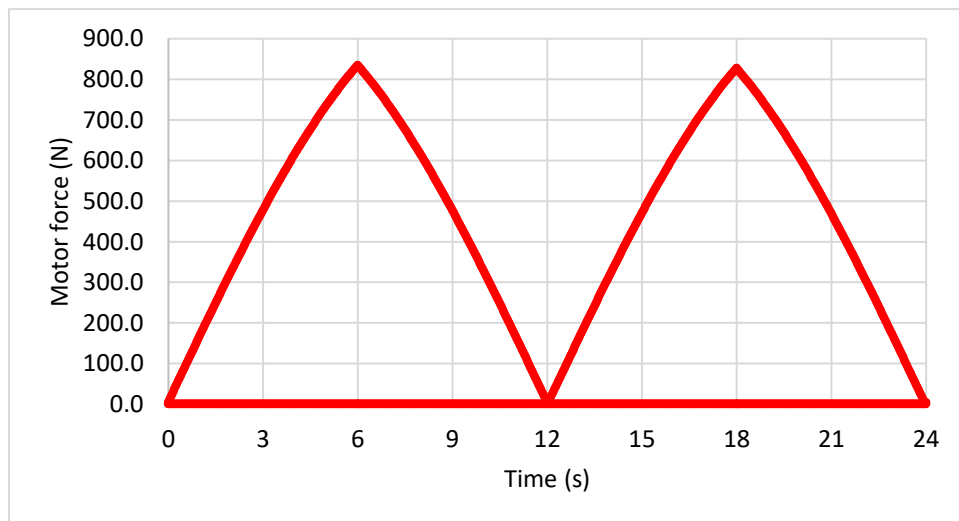


Figure 4-11. Motor force for the intermediate support frame of the PV system.

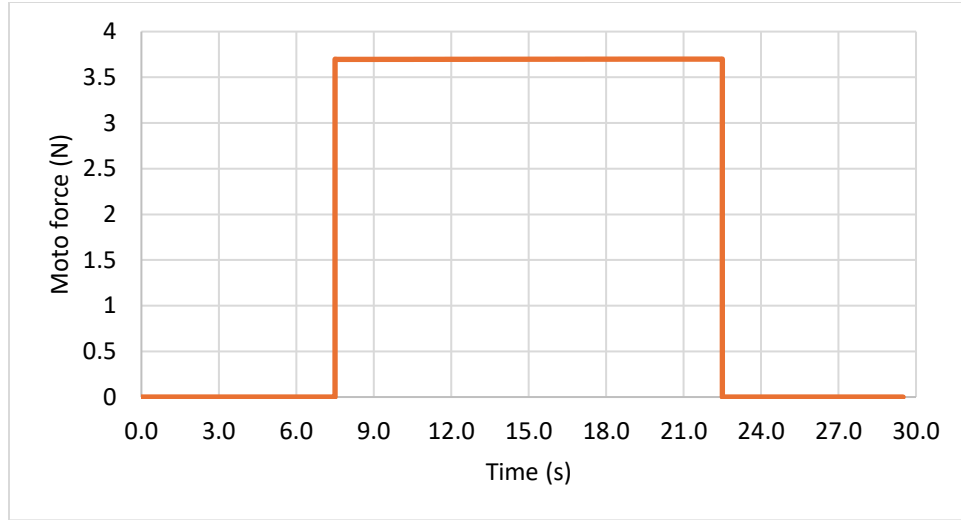


Figure 4-12. Motor force for the support frame of the PV modules.

4.3.2 Computational fluid dynamic analysis (CFD)

4.3.2.1 Validation of simulation data

In order to validate the findings of this study, the lift and drag coefficients of the PV model, inclined at angles of 25° , 90° , and 155° (equivalent to -25° , 0° , and 25°), as illustrated in Figure 4-14, are compared with the corresponding coefficients obtained from the computational fluid dynamics analysis of a flat plate wing conducted by [90], shown in Figure 4-13. This comparison is made at nearly similar pitch angles of -20° , 0° , and 25° degrees, where the wind flows directly against the models at 0° in both experimental setups.

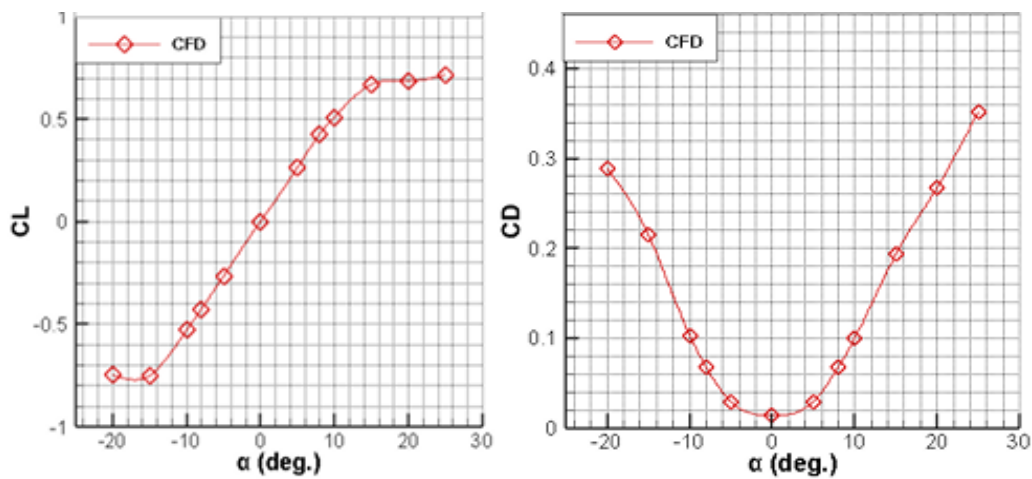


Figure 4-13. Lift and drag curves of a flat plate wing for varied pitch angles [90].

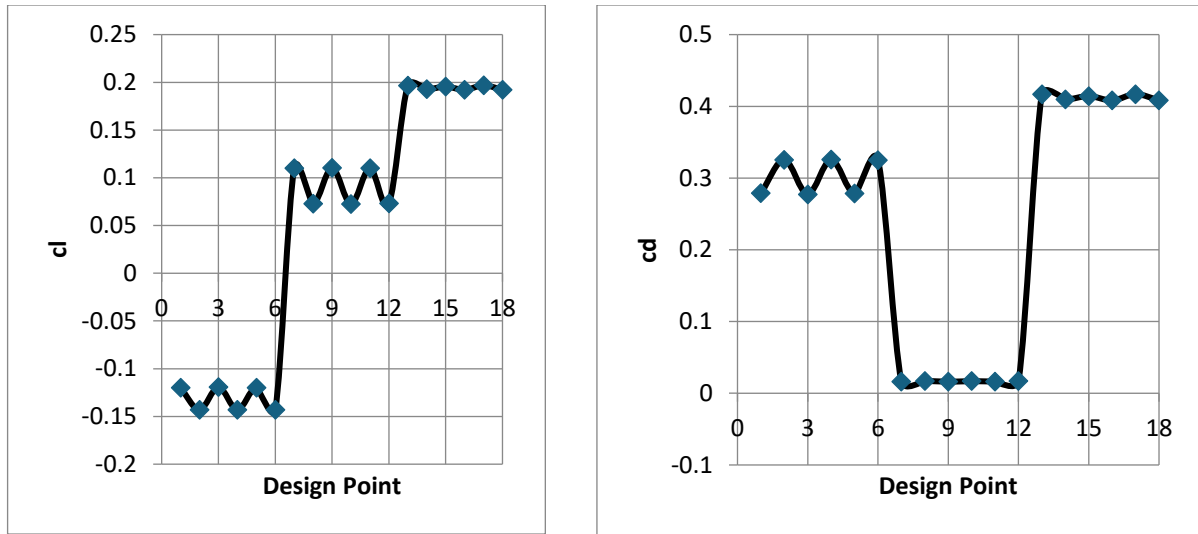


Figure 4-14. Lift and drag curves for different wind speeds, azimuth, and elevation angles.

The results summarized in Table 4-6 indicate that the drag and lift coefficients of the PV model are in close agreement with those derived from the flat plate analysis. However, notable discrepancies in the lift coefficients are observed, which may be attributed to the presence of a support structure in the current study, a factor that was absent in Malik's [90] numerical analysis of the flat plate model, or to variations in the mesh design as proposed by [90], [91].

Table 4-6. Comparison between present study and Malik [90].

Angle of attack (pitch/tilt)	Present	Malik
-25	$C_l = -0.13$ and $C_d = 0.31$ (design point 1-6)	$C_l = -0.75$ and $C_d = 0.29$
0	$C_l = 0.09$ and $C_d = 0.01$ (design point 7-12)	$C_l = 0$ and $C_d = 0$
25	$C_l = 0.19$ and $C_d = 0.41$ (design point 13-18)	$C_l = 0.7$ and $C_d = 0.35$

4.3.2.2 Lift and drag force characteristics

Figure 4-15 and Figure 4-16 depict the lift and drag forces under different wind speeds, elevation angles, and azimuth angles. These figures clearly demonstrate significant variations in forces according to angle of attack and velocity. Specifically, when the elevation angle is set to 90° (design point 7–12), aligning the surface of the photovoltaic panels parallel to the ground, the drag and lift forces reach their lowest values.

This can be attributed to the fact that, at 90° , the wind load only affects the PV modules' smallest windward surface area, reducing the air resistance. At low elevation angles, 25° (design point 1–6) negative lift forces are observed in Figure 4-15 due to the downward directed force and less airflow to generate lift. However, the drag force is relatively high because the airflow encounters a larger surface area of the PV modules, leading to increased air resistance. Notably, for angles 25° and 155° (design point 13–18), the drag and lift forces exhibit slightly different values, a phenomenon also observed by [91]. Moreover, it is evident that the load forces increase with rising wind speed. Design points 1, 3, 5, 7, 9, 11, 13, 15, and 17 at 8 m/s display lower load values compared to design points 2, 4, 6, 8, 10, 12, 14, 16, and 18 at 28 m/s.

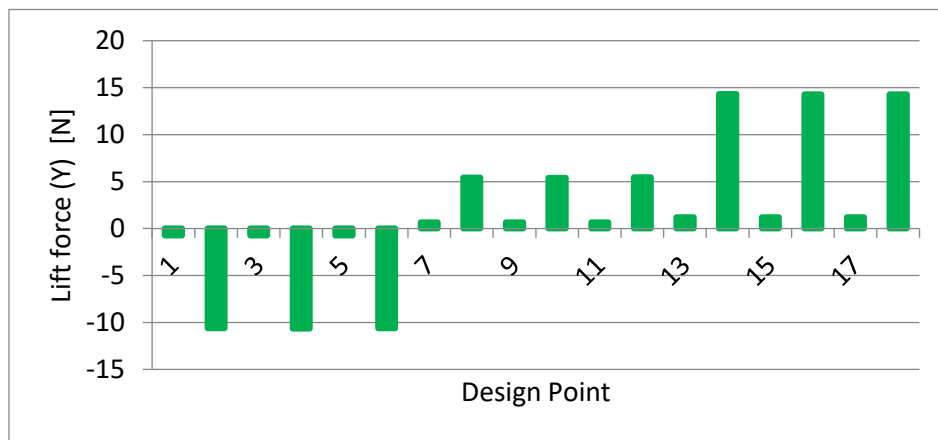


Figure 4-15. Variation of lift force with wind speed, elevation angle, and azimuth angle.

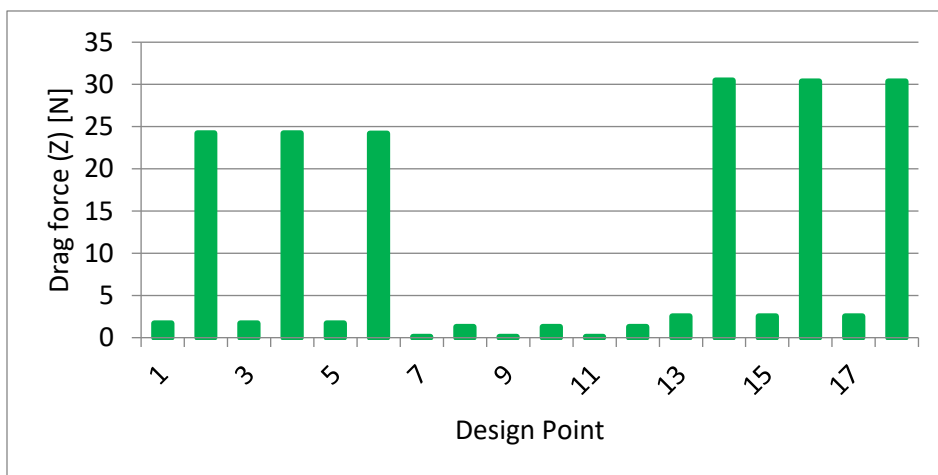


Figure 4-16. Variation of drag force with wind speed, elevation angle, and azimuth angle.

4.3.2.3 Velocity and pressure distribution

Figure 4-17 depicts the contour diagrams that represent the pressure distribution and streamlines related to flow velocity around the PV structure, specifically for wind speeds of 8m/s and 28m/s at various elevation angles. It is evident that the foremost row of the PV array experiences the highest wind load, thereby providing shelter for the subsequent row, as supported by the findings of [80], [92], [93].

At elevation 25° and -25° , a recirculation flow is observed on the leeward side of the PV modules, which is attributed to flow separation occurring at the edges and the gaps between the modules. When orientated at 25° , the PV modules obstruct the air flow, leading to high pressures on the windward side and lower pressures in the leeward side, which in turn generates a downward directed lift (negative lift force). As the elevation angle approaches 90° (parallel to the ground), the pressure difference between the front and rear surfaces of the PV modules decreases due to the reduced projected area exposed to the wind flow, leading to minimal drag and lift forces.

Conversely, when the elevation angle is adjusted to -25° , allowing air flow to come from the backside of the PV modules, the windward projected area increases, blocking the air flow once again. This situation creates high pressures on the leeward side of the PV modules and lower pressures above them, producing an upward directed lift (positive lift force).

In conclusion, the wind pressure and velocity acting on the PV panels in the stowed position (90° – 90°) are lower due to reduced exposure area. This configuration can effectively safeguard the panels and overall PV structure from potential damage during adverse weather conditions while optimizing energy capture during normal operating conditions. Analyzing the characteristics of pressure and velocity distribution, along with the structural capacity to withstand such wind loads, supports the conclusion that this model is particularly suitable for regions like South Africa, Namibia, and Zimbabwe, which experience average wind speeds between 4.5 and 6 m/s [94].

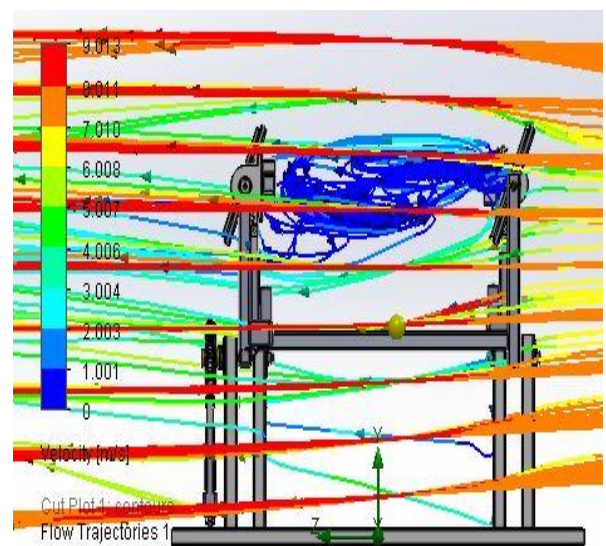
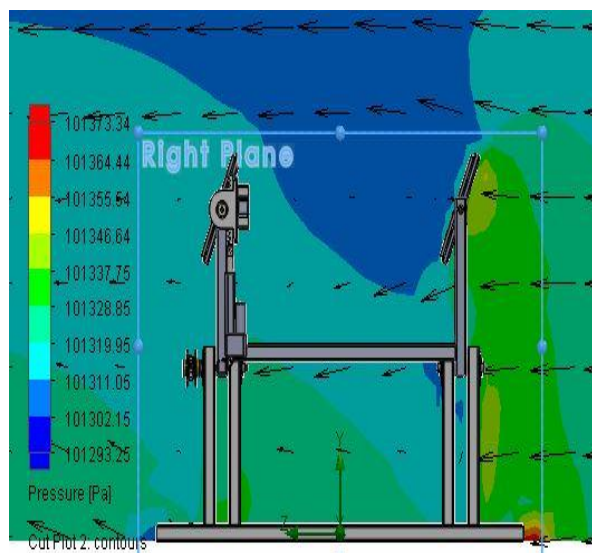
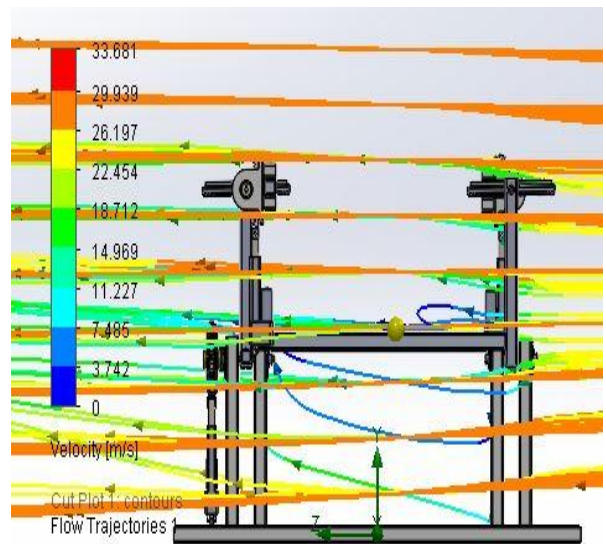
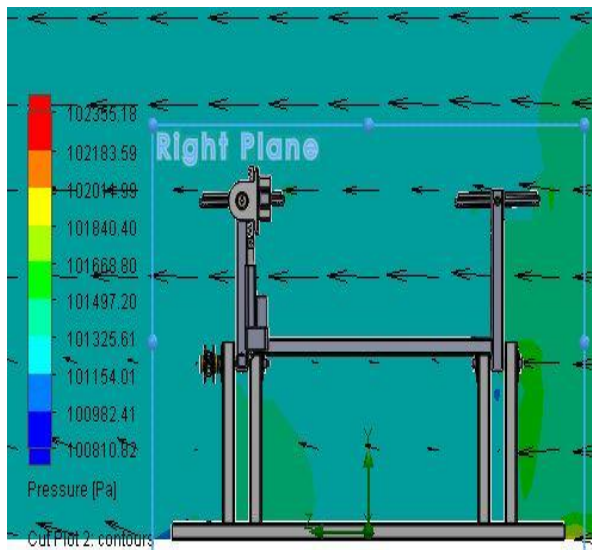
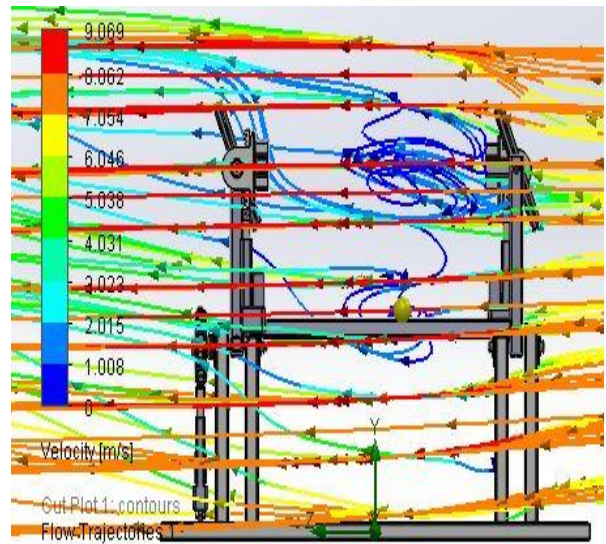
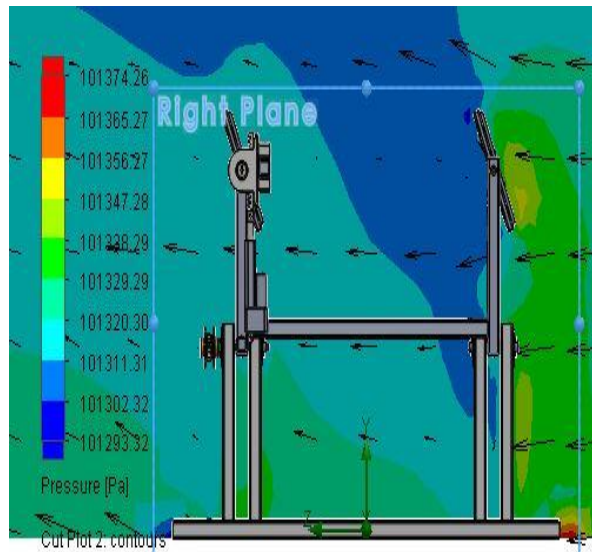


Figure 4-17. Pressure contours and velocity streamlines at varied speeds, elevation 25 (top), 90 (middle), and 25(bottom).

4.3.3 Structural analysis

Investigating the behavior and stability of the dual axis structure under wind load necessitates an analysis of the maximum stress and deformation associated with the design. Figure 4-18 displays the maximum axial and bending stress experienced by the solar tracking structure as a function of varying wind velocities, elevation, and azimuth angles. The peak stress value recorded is $7.271 \times 10^6 \text{ N/m}^2$, occurring at an elevation of 90° and azimuth of 155° , under wind speeds of 8 m/s and 28 m/s , as depicted Figure 4-19. These maximum stress values are identified at the joint connections within the base frame and its supporting arms, which aligns with the observations made by [58], that joints represent the weakest and most critical areas. Notably, these stress values remained well below the yield strengths of mild steel ($2.20594 \times 10^8 \text{ N/m}^2$) and aluminum ($2.75742 \times 10^7 \text{ N/m}^2$), suggesting that the model is capable of enduring the applied wind loads.

Additionally, Figure 4-20 and Figure 4-21 present the variations and maximum deformation recorded across the solar tracking structure, with a recorded high of 3.345 mm . This deformation corresponds with the highest stress levels observed in the structure. Nevertheless, the overall structural deformation remains minimal and can be disregarded. Consequently, it is reasonable to conclude that the structure can withstand wind speeds of up to 28 m/s .

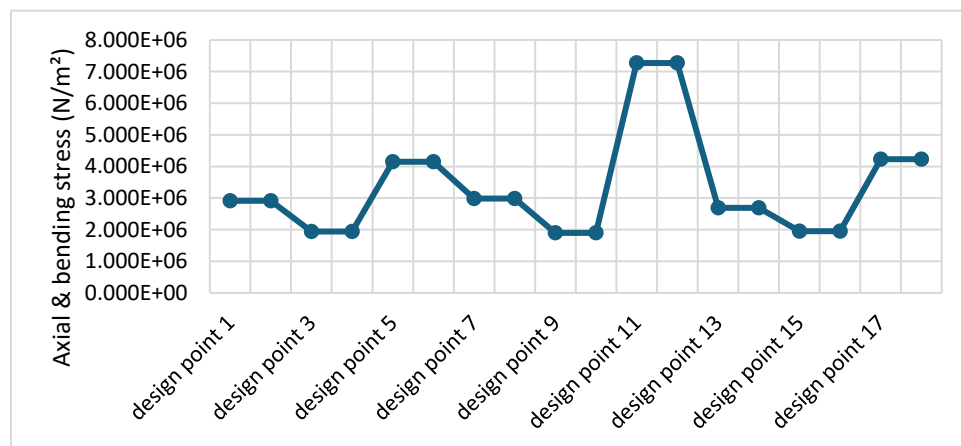


Figure 4-18. Variation of Axial & bending stress of the solar structure.

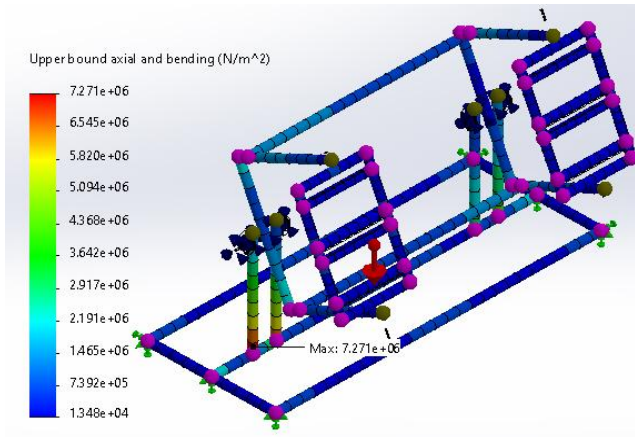


Figure 4-19. Axial and bending stress at 28m/s, and orientation 90-155 (elevation-azimuth).

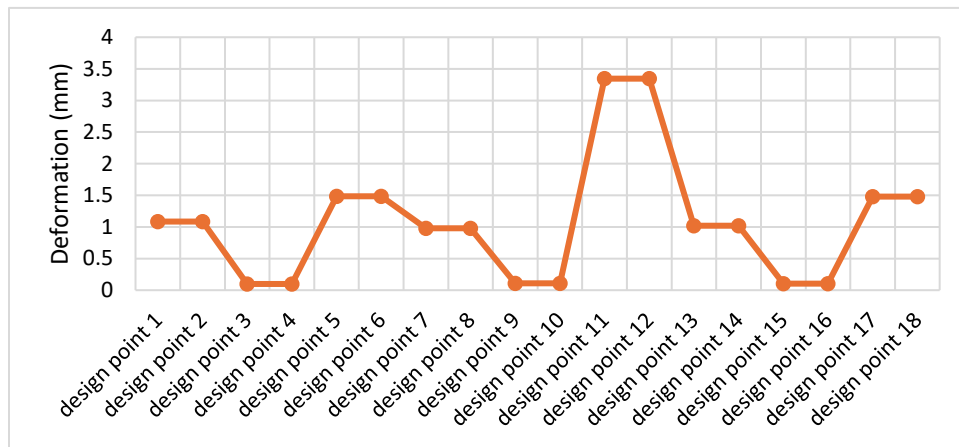


Figure 4-20. Variation of deformation of the solar structure.

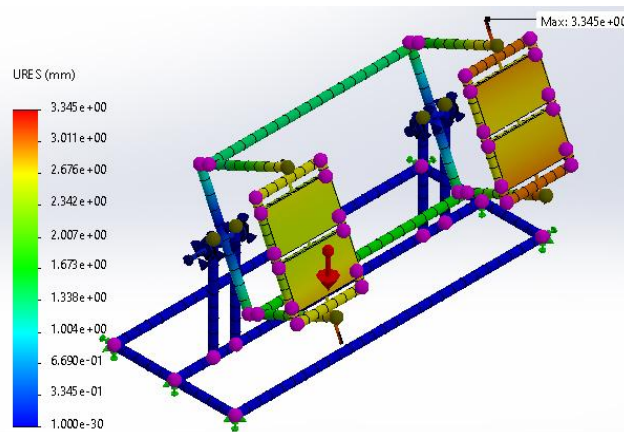


Figure 4-21. Deformation at 8m/s, and orientation 25-90 (elevation-azimuth).

The primary objective of performing a factor of safety assessment is to evaluate the ability of the photovoltaic structure to endure both anticipated and unanticipated loads, thereby mitigating the risk of unexpected failures within the assembly. A factor of safety of 1 indicates that the structure will fail exactly at the designated load limit, rendering it incapable of supporting any additional weight. It is generally deemed inappropriate for structures to possess a safety factor lower than one, as this is considered the absolute minimum [95]. Figure 4-22 illustrates the variations in safety factors for the photovoltaic model influenced by elevation angles, azimuth angles, and wind speed. The most concerning safety factor is illustrated in Figure 4-23, where both the elevation and azimuth angles are positioned at 90–90°, resulting in a value of 1. Unfortunately, this falls below the recommended standard and fails to meet safety regulations. This highlights the need for significant design alterations in the PV module support frame, as the current design proved inadequate even under a wind load of 8 m/s.

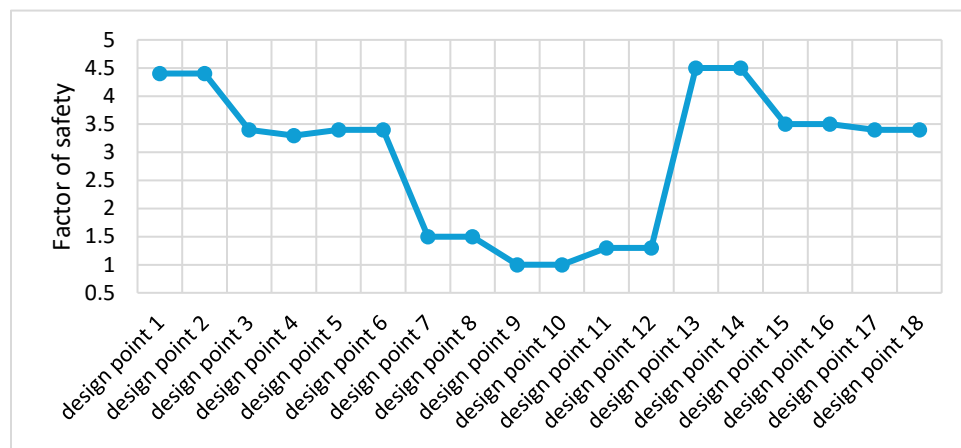


Figure 4-22. Variation of safety factors of the solar structure.

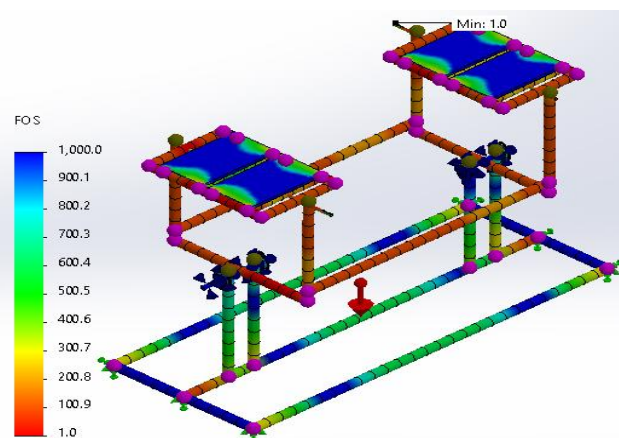


Figure 4-23. Factor of safety at 28m/s, and orientation 90-90 (elevation-azimuth).

Pretensioned bolts are commonly found in solar systems, but they may become loose over time due to improper installation or vibrations caused by wind. Loose bolts can cause unexpected movements, which can negatively impact the stability of the structure and overall performance [96]. Therefore, it is crucial to determine whether the bolt or pin connectors used in the assembly of photovoltaic structures assembly can withstand the applied loads without failing. The bolt/pin check pop-up window provides information about two categories of bolt/pin connectors. The first category identifies connectors that are likely to fail or require reinforcement, while the second category includes connectors that have passed the loading check. Figure 4-24 illustrates that all three pins in the assembly have successfully passed the loading check.

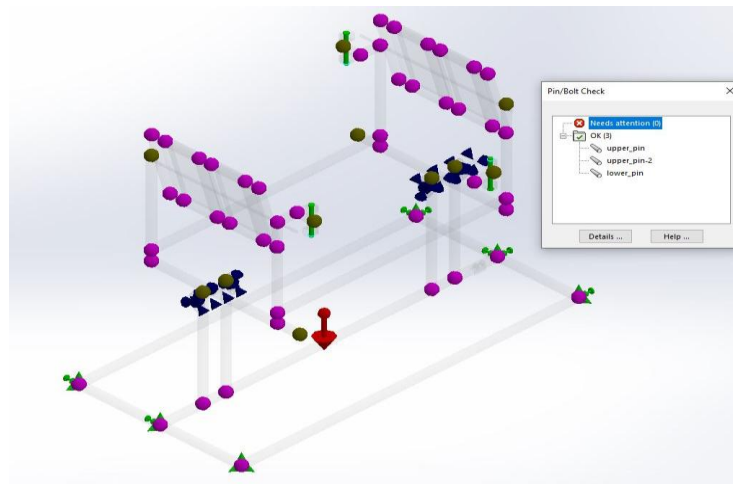


Figure 4-24. Bolt/pin safety check.

4.3.4 Design validation and analysis of the tracking system

This study involves the measurement of the elevation and azimuth angles of the two-axis solar tracker, utilizing an MPU6050 module, and an ESP01 Wi-Fi module for data collection and monitoring. These measured angles are subsequently compared to those computed using Michalsky's solar position algorithm, which is accessed through the website sunearthtools [97], [98]. Through this comparative analysis, the tracking error and accuracy of the solar tracker are assessed. Figure 4-25 represents the proposed PV tracking system.



Figure 4-25. Prototype of a two-axis solar tracker.

4.3.4.1 Representation of tracking angles and error

Figure 4-26 and Figure 4-27 illustrate a graphical depiction of the solar tracker and solar position angles during a sunny day. This representation is intended to demonstrate the variations in both the elevation and azimuth angles of the proposed solar tracker over the course of the day. The solar elevation and azimuth angles are reproduced from the Sun Earth Tools website [97], which utilizes calculations derived from Joseph Michalsky's solar position algorithm [98]. The data spans from 08:00 to 16:00 on October 08, 2024, for the geographical coordinates of -22.55° latitude and 27.13° longitude.

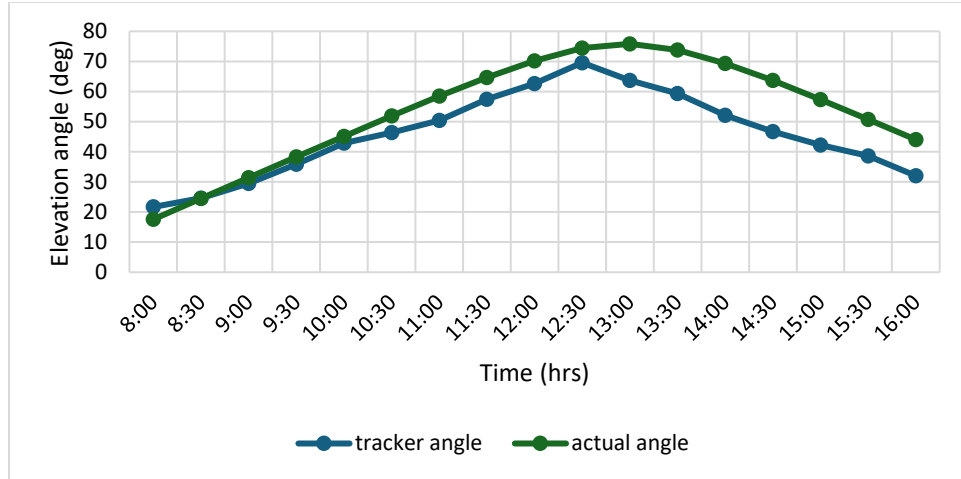


Figure 4-26. Behavior of the solar tracker and solar elevation angle.

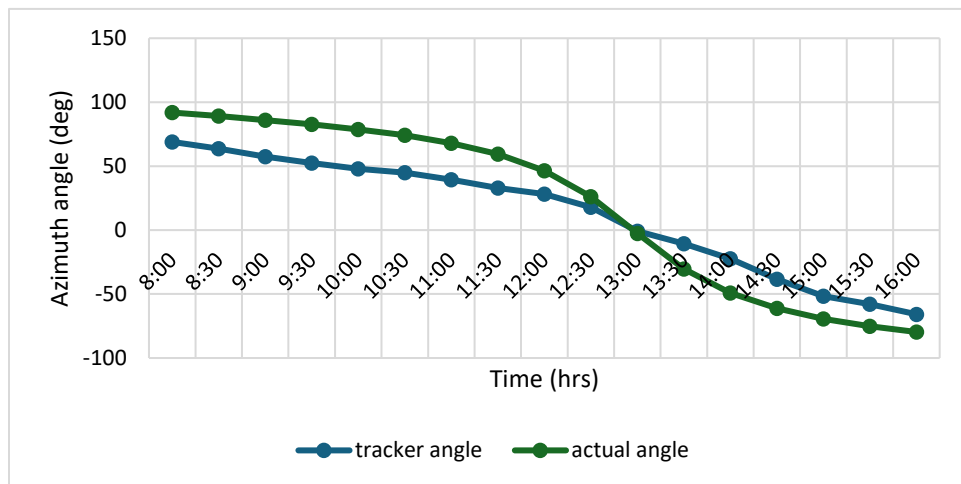


Figure 4-27. Behavior of the solar tracker and solar azimuth angle.

The calculations for tracking error (T.E) and accuracy (T.A) are performed as detailed in equations (18) and (19). Figure 4-26 reveals notable differences between the solar elevation angles and those recorded by the tracker, particularly during the afternoon, with an average error of 15.23%. In contrast, Figure 4-27 depicts the significant differences between the solar azimuth angle and those of the tracker, during both morning and afternoon periods, with an average error of 37.59%. A tracking error of zero would indicate that the tracker is perfectly aligned with the sun. Table 4-7 illustrates a comparison of tracking errors of previous studies on dual axis tracking systems, alongside the findings of the current research. One potential explanation for this significant error observed may be attributed to the mechanical backlash inherent in the

transmission drive system, which resulted in lost motion and reduced accuracy of the overall design. Additionally, the tracker's limit angles of -65 and 65 degrees, especially for the azimuth axis, may also contribute to this issue. Nevertheless, the movement of the tracker appears to be consistent with the solar position, achieving tracking accuracies of 84.77% for elevation and 62.41% for azimuth angles.

$$T.E(\%) = \frac{(|angle_{meas.} - angle_{act.}|) \times 100}{angle_{act.}} \quad (18)$$

$$T.A(\%) = 100 - |T.E(\%)| \quad (19)$$

Table 4-7. Comparison of tracking error with existing studies.

Tracking type	Solar tracking error	Location	Reference
Dual axis	Altitude maximum error: 6° Azimuth maximum error: 15°	18.8375° N, 95.3324° E	[99]
Dual axis	Altitude maximum error: 15° Azimuth maximum error: 10°	16.8409° N, 96.1735° E	[100]
Dual axis	Altitude maximum error: 17° Azimuth maximum error: 29°	22.5515° S, 27.1147° E	Current study

Based on the backlash issues identified, and without redesigning the current structure, using an angled rack & pinion gear (helical teeth) would help achieve smoother engagement, or modifying the control algorithm to account for the estimated/known backlash when changing direction, would greatly improve the tracking accuracy. Alternatively implementing a magnetic rack and pinion coupling, or using a closed loop feedback system that measures the actual panel angular position, allowing the controller to adjust for the error, would also greatly improve this system.

4.4 Cost analysis

An estimation of the electricity generated by the stand-alone PV system is accomplished using PVGIS online software (photovoltaic geographical information system). Essential input parameters, including location data, PV technology, installed peak PV power and tracking mounting options, are entered into the software, as outlined in Table 4-8. Figure 4-28 demonstrates the PVGIS simulation output.

Table 4-8. PVGIS input data for the PV tracking system.

Inputs	
Location	-22.540, 27.086
PV installed [kWp]	0.02
Tracking mounting options	Two axes
Outputs	
Yearly PV energy production [kWh]	55.03
Yearly in-plane irradiation [kWh/m]	3111.68

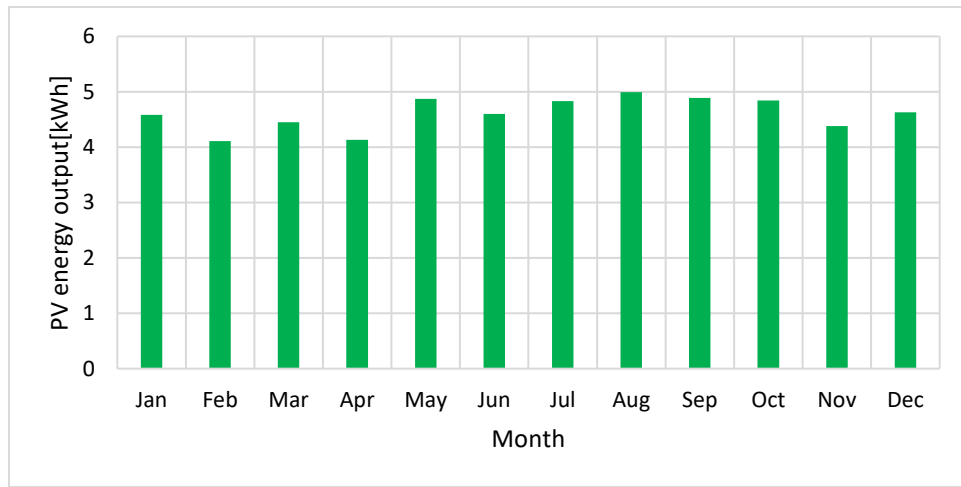


Figure 4-28. Monthly energy output from the tracking system.

A fundamental aspect of the implementation of a PV tracking system is the evaluation of energy consumption of all electrical devices linked to the system, as well as the energy losses attributed to the installed motors. To determine the actual electricity generated by the PV system, the difference between the simulated annual PV electricity output and the energy consumed by both the azimuth and elevation motors is computed. The power consumption of these actuators is analysed, and the energy losses are computed using equation (20), as referenced in [101].

$$\sum P_{motor} (Wh) = \frac{\sum \sum \beta(N) \times P_{\beta}}{\frac{\omega_{rpm}}{GR} \times 360^{\circ} \times 60} + \frac{\sum \sum \alpha(N) \times P_{\alpha}}{\frac{\omega_{rpm}}{GR} \times 360^{\circ} \times 60} \quad (20)$$

In this equation, $\sum \sum \alpha(N)$ ($135\ 214^\circ$) and $\sum \sum \beta(N)$ ($400\ 140^\circ$) represent the annual cumulative range of motion for the elevation and azimuth actuators, respectively. The power consumption values P_α (10Watts) and P_β (60Watts), correspond to the elevation and azimuth actuators, derived from the actuator forces detailed in section 4.3.1. GR is the gear ratio (20:1), while ω_{rpm} (3.63 revolutions/min) is the angular speed of the actuators. Table 4-9 presents the estimated annual energy losses, which amounted to 6.9887 kWh. A comparison with previous research reveals that the current system exhibits the lowest energy consumption, thereby positioning it as a favourable option for implementation.

Table 4-9. Comparison of yearly cumulative power loss against existing studies.

Yearly cumulative power loss (kWh)	Country	Reference
20	South Africa	[101]
22	Zimbabwe	
6.9887	Botswana	Current study

The proposed solar tracking system is composed of the solar tracking structure, the monitoring and control system. Table 4-10 provides the costs required for the design of the solar tracking system, excluding import taxes and charges. The total expense of the developed solar tracking system amounted to USD \$522.

Table 4-10. Approximate cost of the solar tracker and control system.

Quantity	Element	Amount (USD)
2	Aluminium square tubes	\$41
3	Optical Feedback Linear Actuator	\$105
2	Mild steel square and rectangular tubes	\$95
3	Spur gears and rack	\$85
3	Miniature linear rail	\$21
4	Bushings	\$10
4	Bearing units	\$55
Total cost		\$412
3	IBT 2 motor driver	\$15
1	Arduino mega 2560	\$20
1	Battery 12V 17Ah	\$30
1	Basic electronic components	\$15
4	PV module	\$30
Total cost		\$110

Table 4-11 demonstrates the breakdown in the estimation of the maintenance and operations costs, with the assumption that the battery needs to be replaced every five years, the solar panels and rack and pinion yearly maintenance costs are \$5 and \$7 respectively. The life time operation and maintenance costs of PV system are computed based on a methodology in [102]. Table 4-12 outlines the parameters employed in computing the levelized cost of energy and the net present value of the PV system.

Table 4-11. Life-time maintenance and operation costs estimation.

Component	Cost of component (\$)	Future worth (\$)
PV modules maintenance for 15 years	5/year	71
Battery replacement at year 5	30	29
Battery replacement at year 10	30	28
Rack and pinion maintenance for 15 years	7/year	99
Total estimate of maintenance and operation costs (\$)		227

Table 4-12. Financial specifications of the PV system.

Parameter	Units	Values
Discount rate	%	6
Life time operation & maintenance costs	\$	227
Lifetime of the project	Years	15
PV degradation rate	%	0.5
Initial investment	\$	522
Average annual inflation rate	%	5.2
Amount of electricity generated	kWh	48.0413
Actuator energy losses	kWh	6.9887

According to the parameters and specifications outlined in Table 4-12, the levelized cost of electricity (LCOE) of the proposed system, as determined by equation (16), is calculated to be 1.48\$/kWh. Table 4-13 illustrates the cost per kWh for electricity purchased from Botswana Power Corporation (BPC) in 2021, noting the absence of updated tariff information for 2024 [103], and the calculated electricity costs over the life span of the PV system. The findings indicate that the LCOE of the PV system is economically viable when compared to electricity prices for both small businesses and domestic consumption. As discussed by [104] and [105], a PV project's viability depends on comparing the market electricity prices with the LCOE to determine grid parity.

Table 4-13. Cost competitiveness evaluation.

Consumption	2021 cost [USD \$/kWh]	Life span cost [USD \$/kWh]	LCOE of PV system [USD \$/kWh]
Domestic	0.089	1.58	1.48
Small business	0.107	1.90	

The calculated LCOE exceeds typical market ranges because of the relatively small installed energy generation capacity. However, a significant cost optimization opportunity exists since the current mounting structure can accommodate two larger PV modules without requiring additional structural investments. The initial capital, operational and maintenance costs would be distributed across a greater energy production.

Chapter 5 Conclusion

The primary objective of this research was to identify the most appropriate MPPT algorithm for a standalone PV system and develop a robust mechanical framework for the PV panels. These aspects were critical for enhancing the system's performance, longevity, and safety. To fulfill these aims, a decision matrix model was utilized for the selection of the most favorable MPPT technique, alongside analyses of wind load and motion study for the mechanical structure. This conclusion summarizes the comprehensive approach taken in the decision-making process, which included identifying user requirements, conducting functional analysis, performing research & benchmarking, designing and testing the PV tracking system.

5.1 System outline

The initial phase of this work involved a detailed assessment of user requirements. Gaining insight into the specific needs and limitations of the end users was pivotal in establishing the groundwork for the subsequent decision-making stages. A functional analysis was conducted to decompose the PV system into its essential functions and components. This systematic deconstruction enhanced the understanding of the system's operational aspects, enabling for the identification of critical components such as the MPPT algorithm, mechanical structure, and actuators necessary for optimal system performance.

5.2 Control system

To systematically assess and prioritize the available MPPT algorithms, a decision matrix model was employed. The model provided a straightforward, effective and organized approach for evaluating and selecting the most suitable MPPT algorithm. By considering a range of factors such as cost, accuracy and sensitivity to environmental changes, a well-informed decision was reached. The P&O algorithm was found to effectively balance the maximum power point tracking with manageable computational complexity and costs to the user. It successfully tracked the maximum power point (MPP), achieving efficiencies ranging from 98-99% under conditions of partial shading, as well as rapid and gradual changes in irradiance and temperature.

5.3 Dual axis solar tracking framework

A mechanical structure was developed to ensure structural integrity, safeguard against environmental influences, and facilitate optimal orientation of solar panels. The design of this framework underwent extensive wind load and structural analysis. To evaluate the stability and resilience under diverse wind conditions, finite element analysis and virtual wind tunnel simulations were employed. This thorough examination was instrumental in validating the structure's dependability and safety. The sizing process for actuators in the solar tracking system was conducted with strict attention to force requirements and stroke length. This led to the choice of two actuators for the elevation axis, each capable of delivering a dynamic force greater than 4N, alongside one actuator for the azimuth axis, which provides a dynamic force greater than 850N. Notably, the alignment and placement of the actuators required all actuators to have a stroke length of 3 inches.

5.4 Economic analysis

In addition to the structural analysis, a detailed cost analysis was performed using the levelized cost of electricity (LCOE) methodology, which provided valuable insights into the economic viability of the PV system. The LCOE assessment demonstrated that the system is economically competitive in comparison to both electricity prices for small businesses and domestic consumption.

5.5 Performance assessment

An experimental evaluation of the physical structure was conducted, focusing on tracking angles and the efficiency of the MPPT controller. The tracking error was determined by comparing the actual solar position with that of the solar tracker. Findings from the study revealed that the tracking system followed the sun with an accuracy of approximately 84.77% for elevation and 62.41% for azimuth angles. This accuracy could be further enhanced by addressing the mechanical backlash present in the transmission drive mechanism.

5.6 Summary

In summary, the implementation of a methodology for selecting the best suited MPPT technique for a stand-alone PV system was successfully accomplished, despite encountering some limitations associated with the soft computing methods. Nevertheless, the development of this methodology equips designers with a

comprehensive framework for informed decision making. The decision matrix model allows for identifying the most important criteria, and while each system and user has unique requirements, the proposed model can be tailored to accommodate various systems. Moreover, the design of a dual axis tracking system was realized by using simple structural components to reduce costs and benchmarking against existing designs. The structure's efficiency was confirmed through an analysis of the actuator power consumption, which demonstrated lower levels than those reported in previous studies. An assessment of the tracking accuracy was also performed, although the accuracy fell short of expectations, this limitation can be addressed by resolving the backlash in the drive transmission. Furthermore, the economic viability of the system proved to achieve grid parity, with potential for further reduction of the LCOE to enhance competitiveness with alternative systems by increasing the energy generation capacity.

5.7 Research limitations

Like many studies, the current research has its limitations. The first limitation is the use of a limited training dataset for the simulation of the soft computing-based MPPT techniques. These methods rely heavily on a broad range of input-output data to achieve accurate and generalized performance across varying environmental conditions. This increases training time and computing memory, particularly for ANN and ANFIS, which are sensitive to both dataset size and quality. The lack of sufficient and diverse training data lead to poor performance, especially when the PV system encountered conditions not represented in the training dataset. Future work should incorporate metaheuristic optimization algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Ant Colony Optimization (ACO), or Grey Wolf Optimizer (GWO) to reduce dependency on large datasets.

The second limitation concerns that this study did not account for potential problems that can appear during implementation, which is why mechanical backlash was observed in the drive system of the PV tracking mechanism. This backlash negatively affected the overall tracking accuracy of the PV system, especially during periods of rapid directional adjustment. To address this limitation, future implementations should consider modification of the control algorithm to account for the estimated/known backlash when changing direction, or consider the use of magnetic gear couplings, which may provide advantages such as reduced maintenance requirements and enhanced reliability.

5.8 Future work

Future work will focus on addressing the limitations identified in the current study, which will include:

- Exploring meta-heuristic MPPT algorithms to identify the best suited algorithm for a low-cost stand-alone PV tracking system, given their reduced requirement for large datasets for model training, thus enhancing computational efficiency compared to soft computing methods.
- Expanding the study to address mechanical backlash in the drive and transmission mechanism, as this could significantly enhance the tracking accuracy of the PV system.
- Adopting standardized 90-degree corner connectors for the aluminum tubes (upper tracking axis), which would simplify assembly and maintenance. The implementation should also include finite element analysis to optimize connector selection based on anticipated loads and environmental conditions specific to the deployment area.

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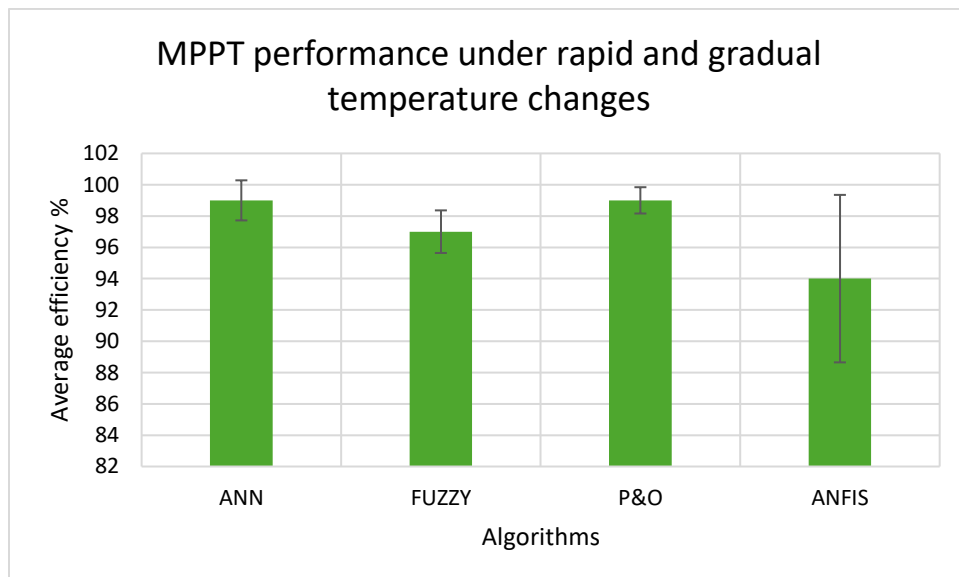
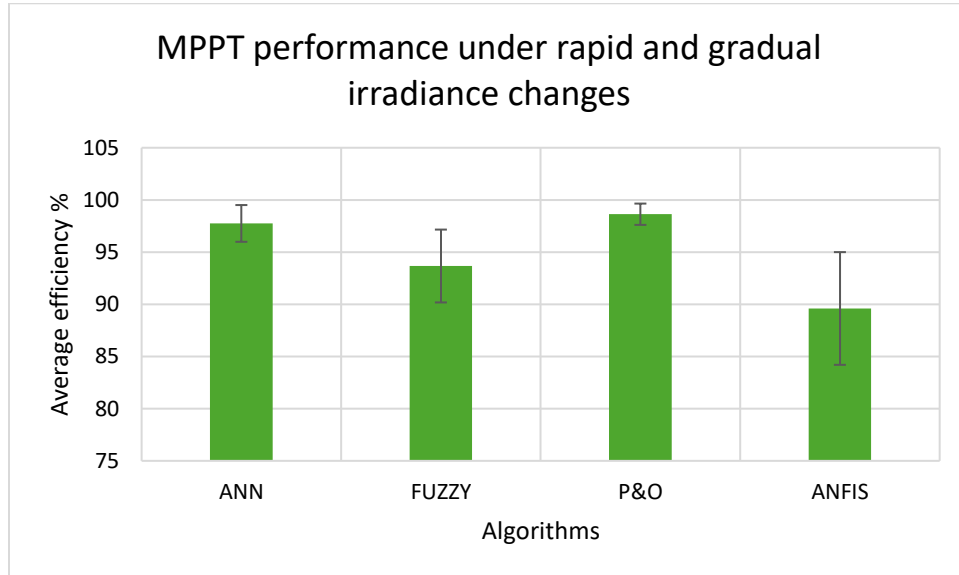
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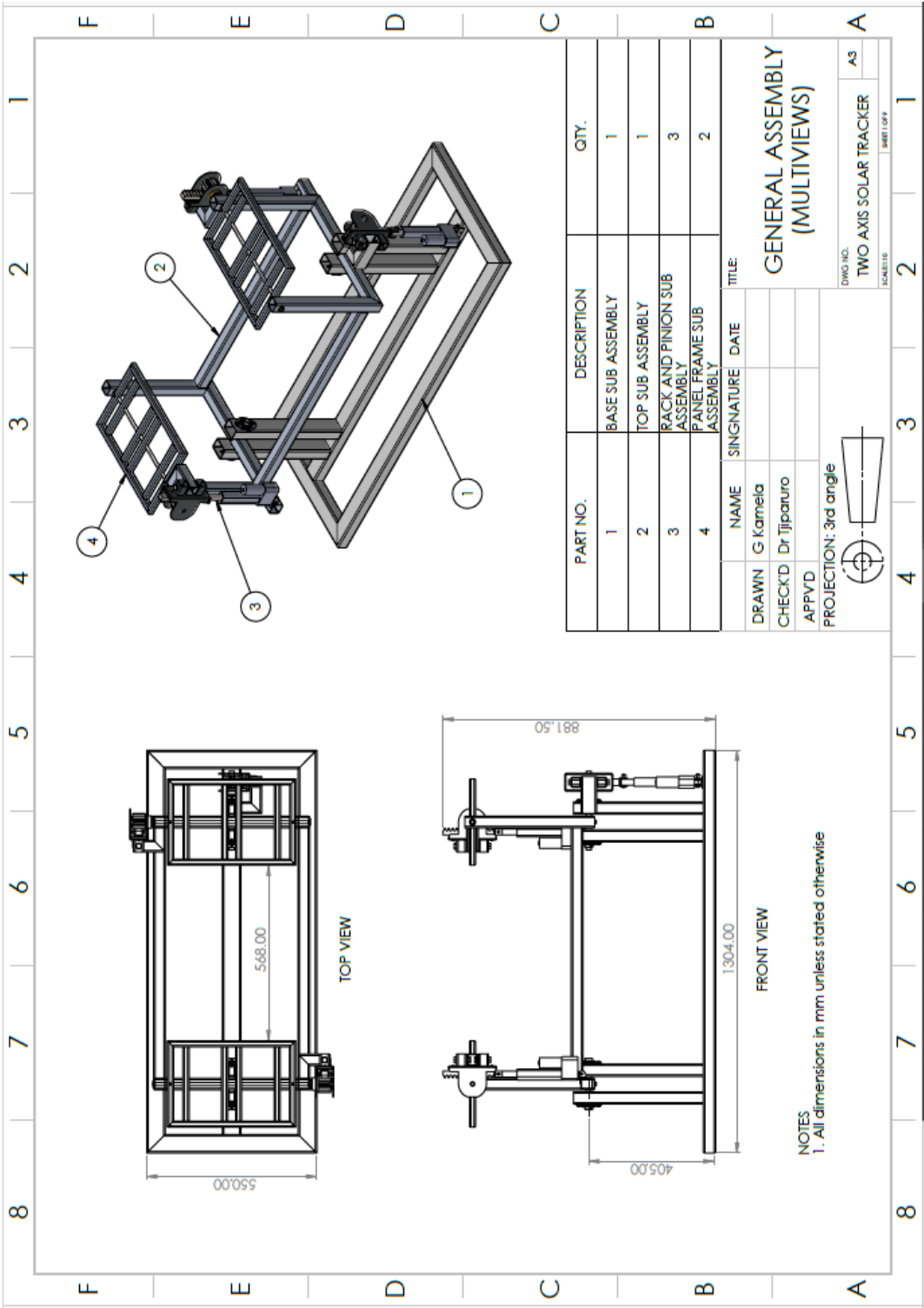
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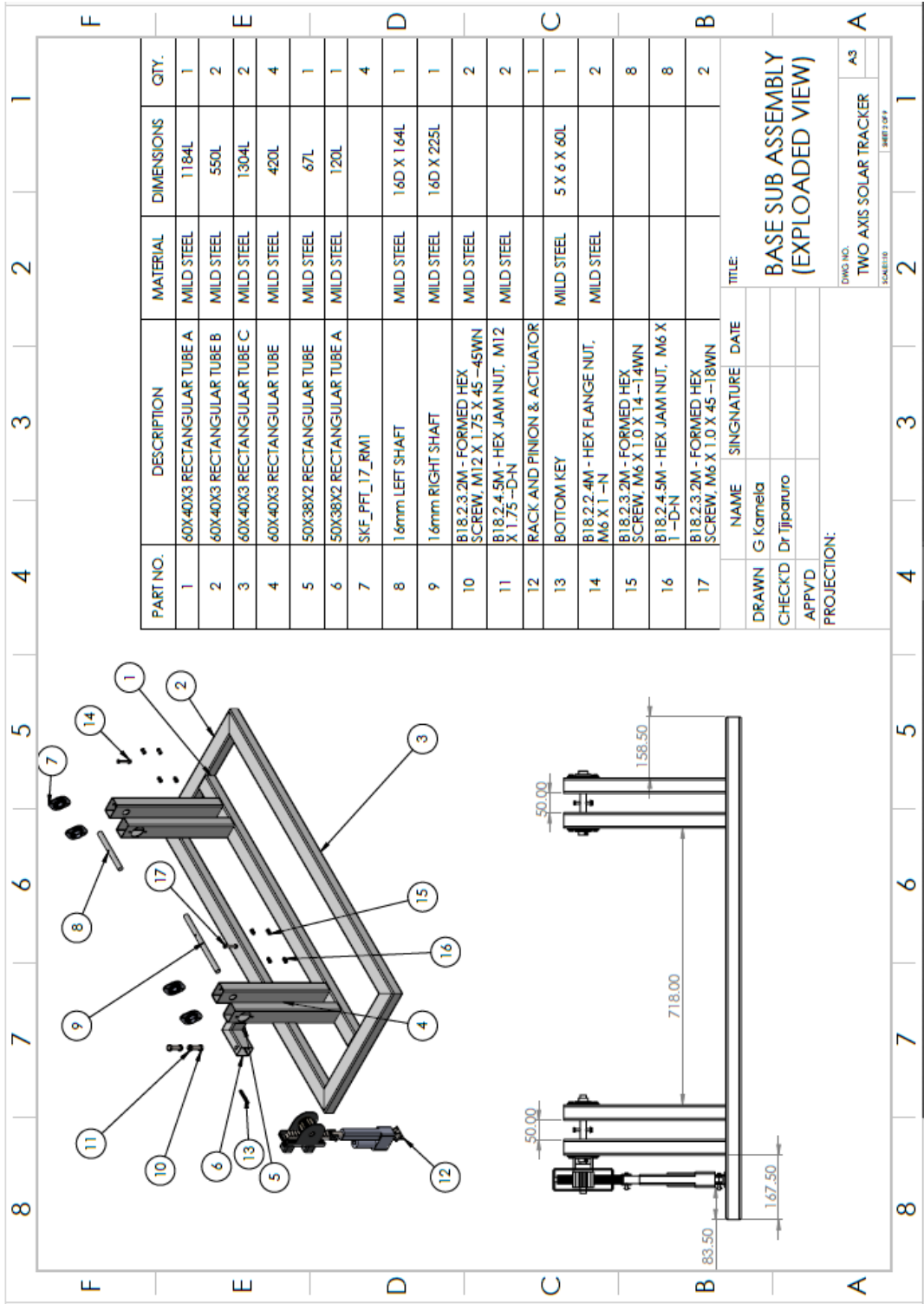
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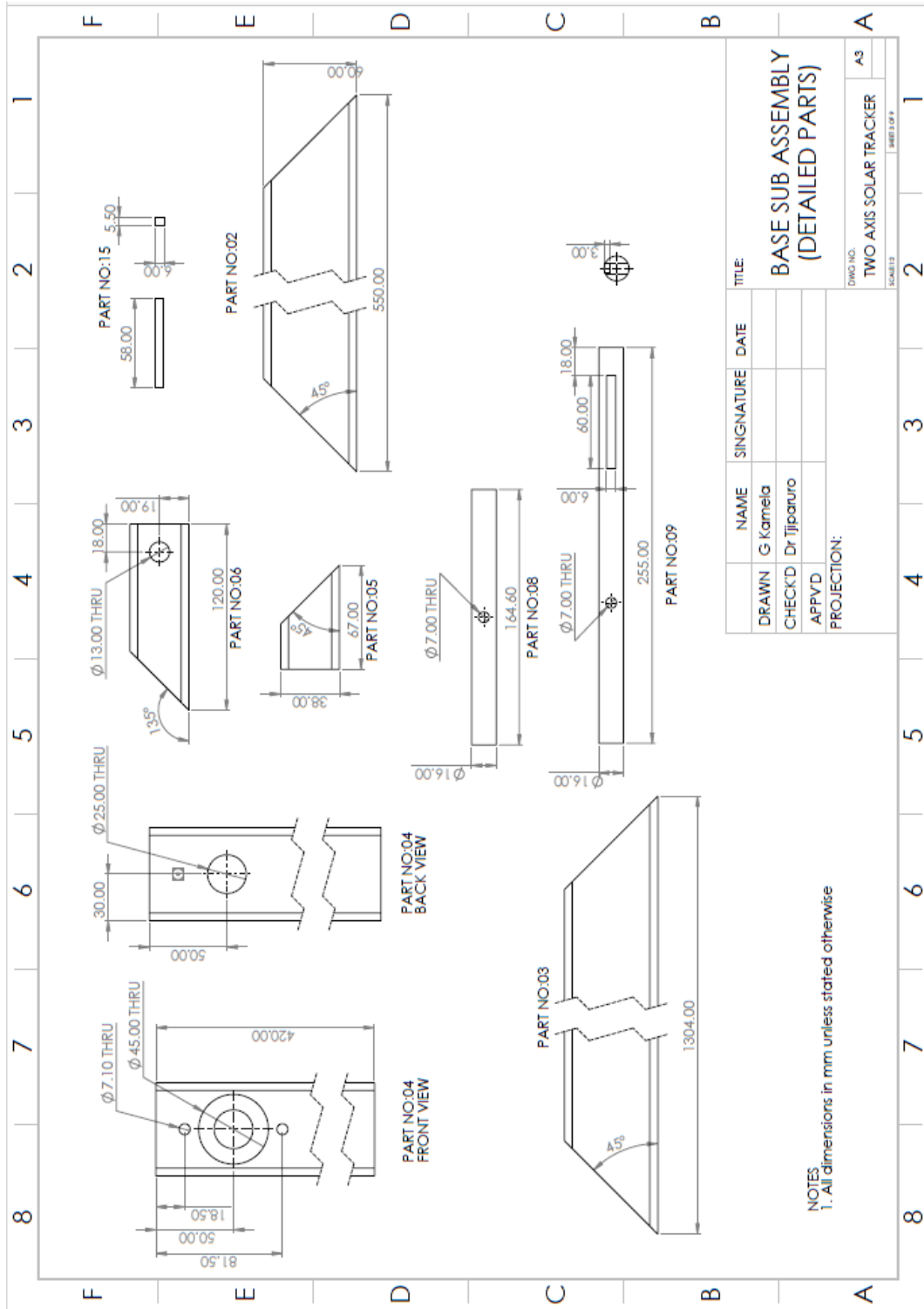
APPENDIX A

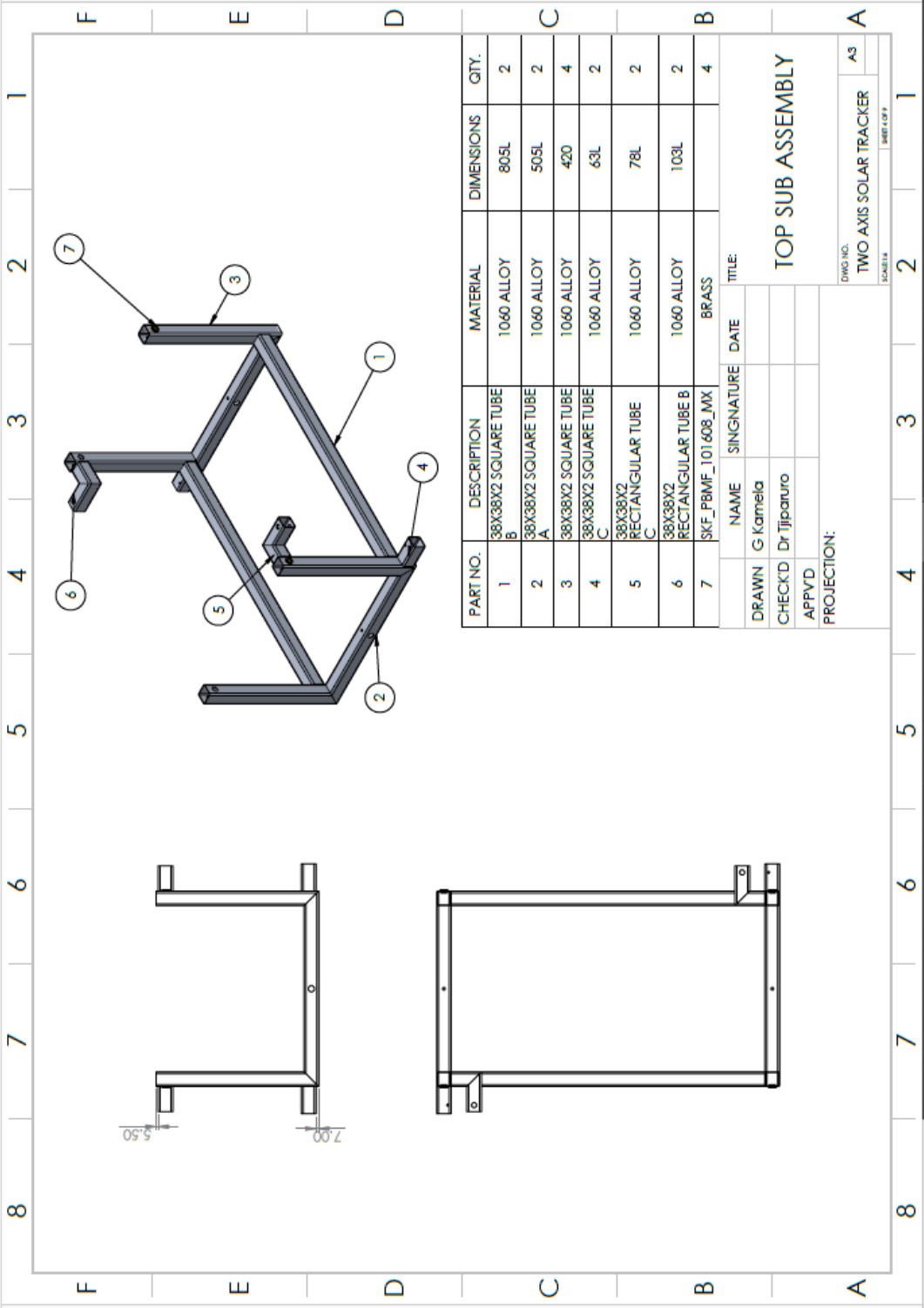


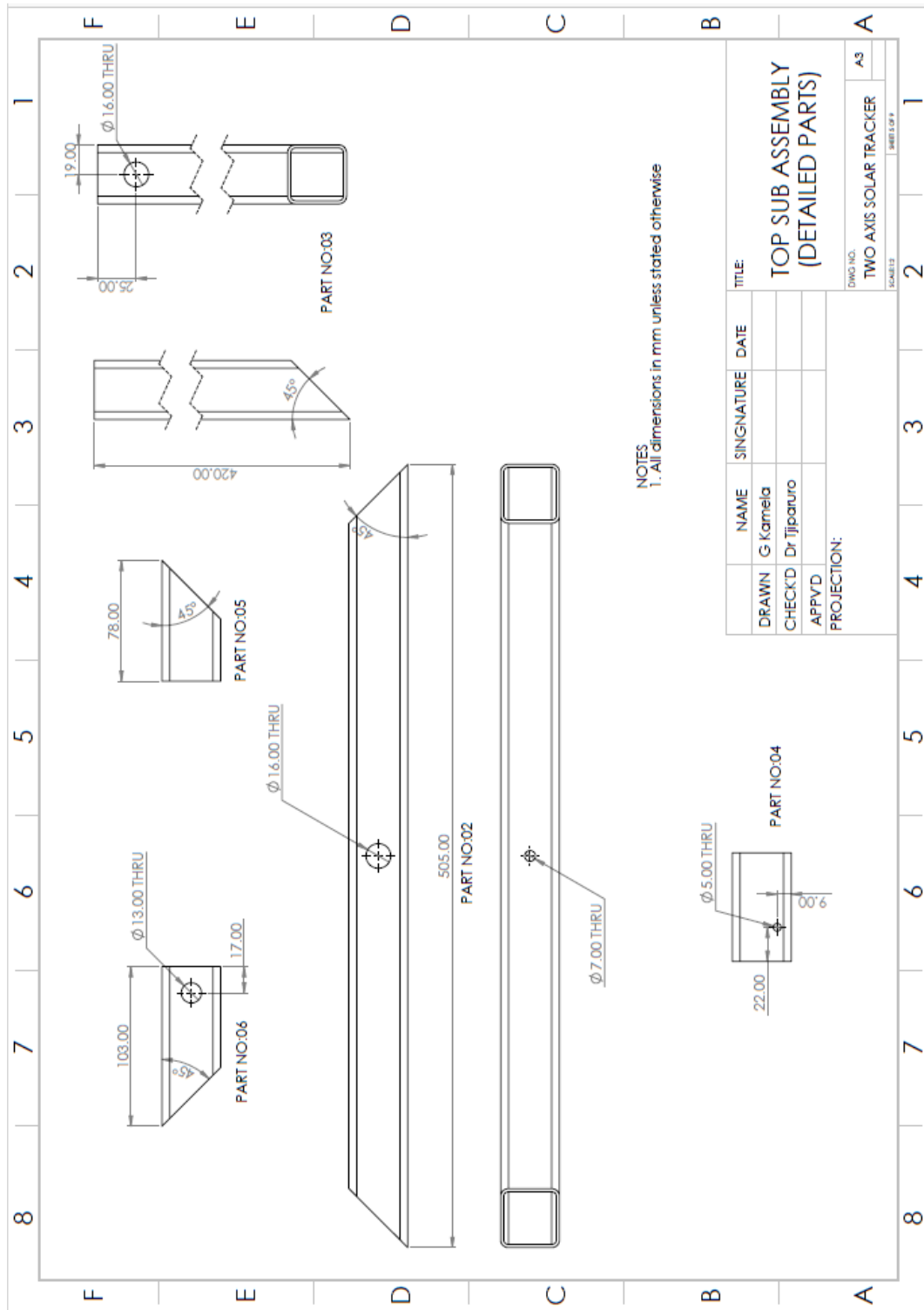
APPENDIX B

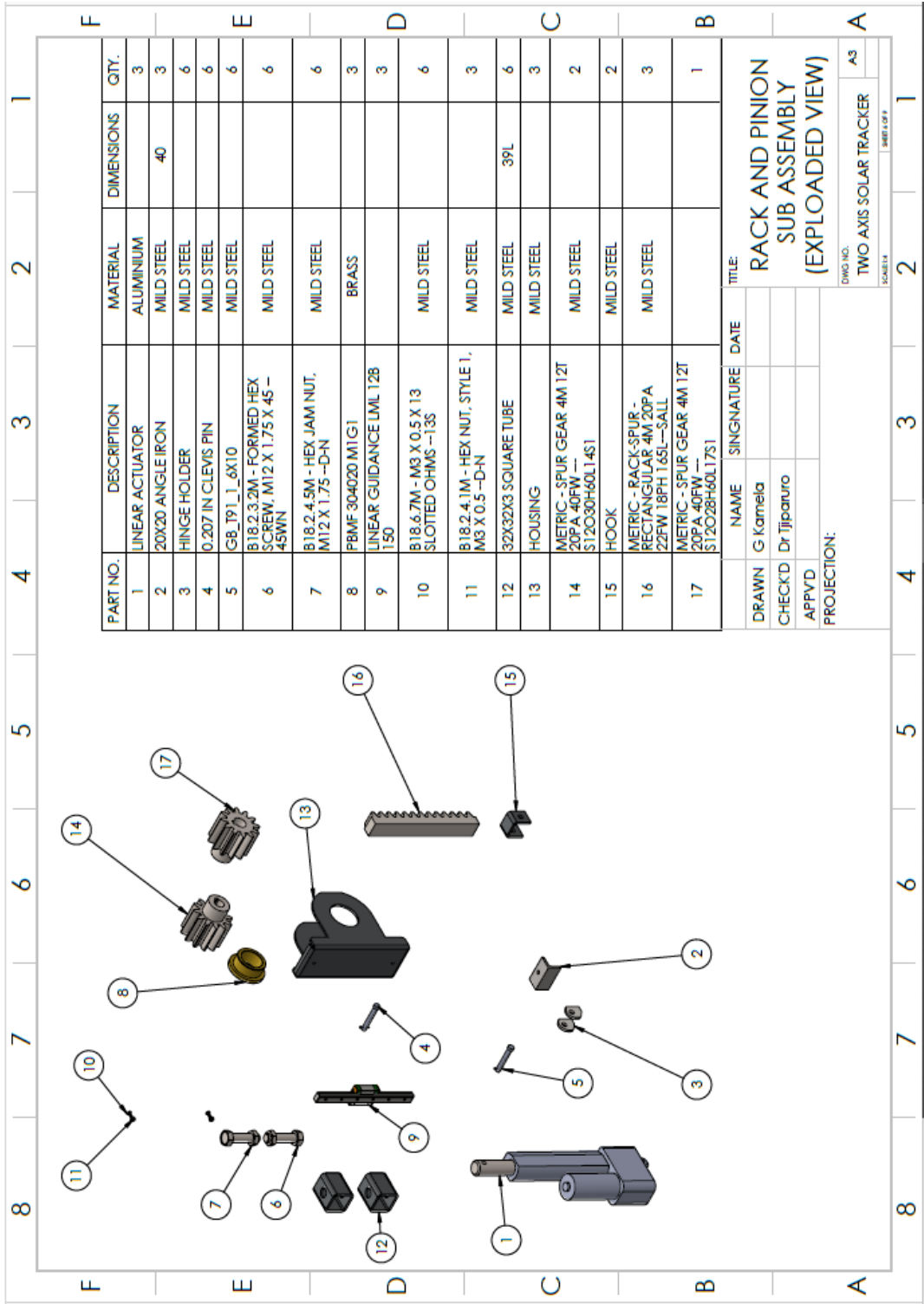






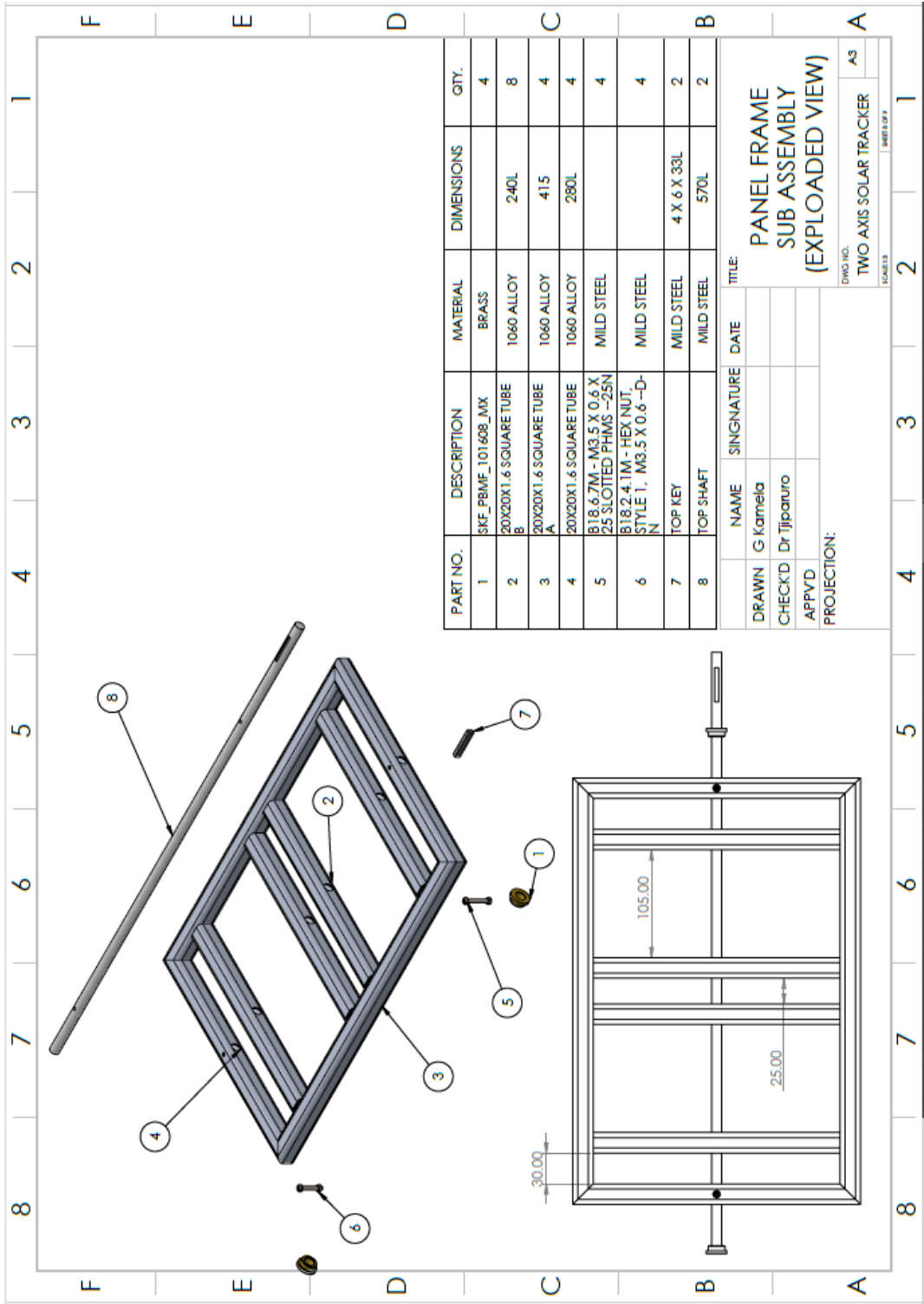


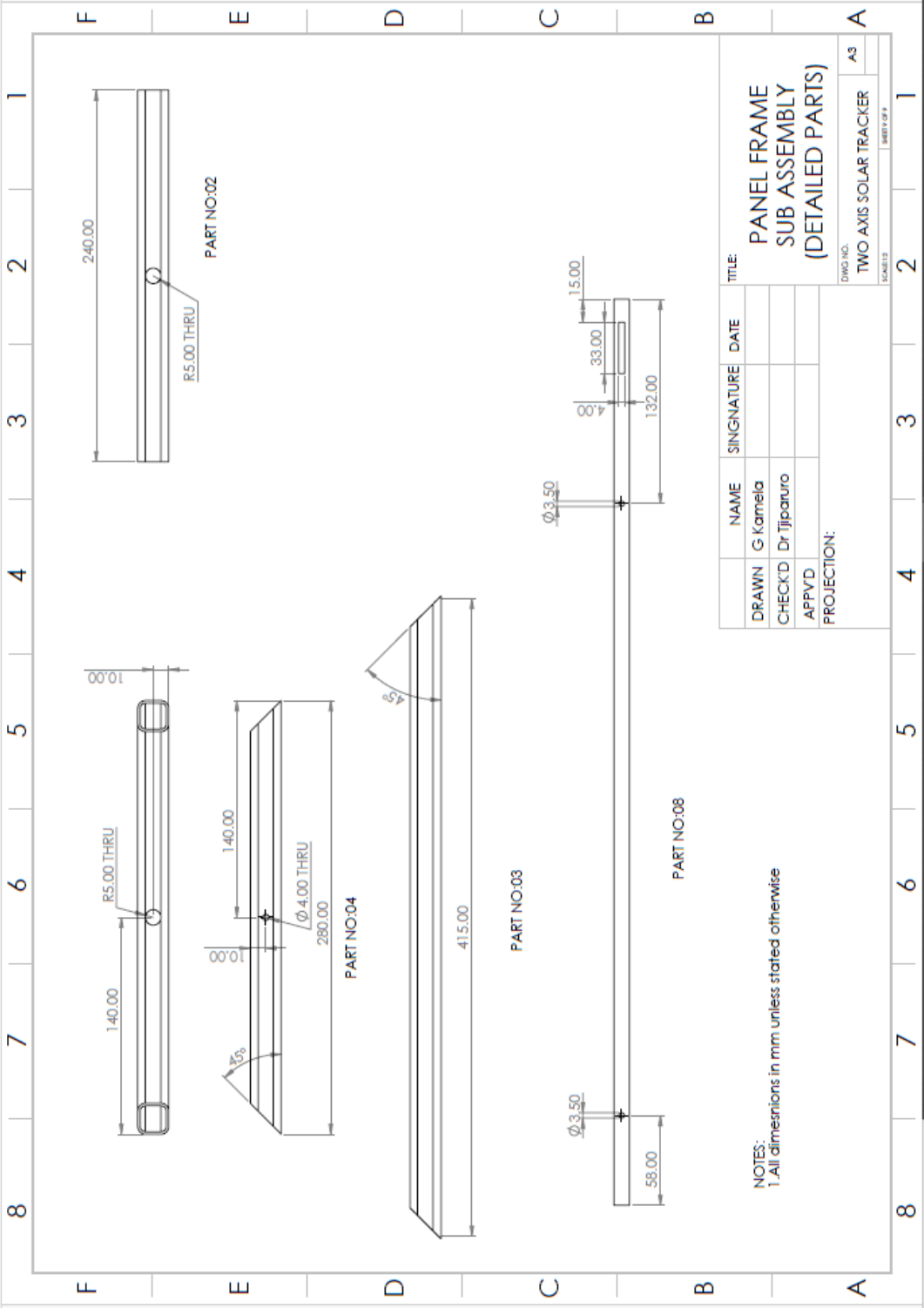




PART NO.	DESCRIPTION	MATERIAL	DIMENSIONS	QTY.
1	LINEAR ACTUATOR	ALUMINIUM		3
2	20X20 ANGLE IRON	MILD STEEL	40	3
3	HINGE HOLDER	MILD STEEL		6
4	0.207 IN CLEVIS PIN	MILD STEEL		6
5	GB_T91_L_6X10	MILD STEEL		6
6	B18.2.3.2M - FORMED HEX SCREW, M12 X 1.75 X 45 - 45WN	MILD STEEL		6
7	B18.2.4.5M - HEX JAM NUT, M12 X 1.75 -D-N	MILD STEEL		6
8	PBMF 304020 M1 G1	BRASS		3
9	LINEAR GUIDANCE LML 128 150			3
10	B18.6.7M - M3 X 0.5 X 13 SLOTTED OHMS -13S	MILD STEEL		6
11	B18.2.4.1M - HEX NUT, STYLE 1, M3 X 0.5 -D-N	MILD STEEL		3
12	32X32X3 SQUARE TUBE	MILD STEEL	39L	6
13	HOUSING	MILD STEEL		3
14	METRIC - SPUR GEAR 4M 12T 20PA 40FW - S12030H60L14S1	MILD STEEL		2
15	HOOK	MILD STEEL		2
16	METRIC - RACK-3PUR - RECTANGULAR 4M 20PA 22FW 18PH 165L-SALL	MILD STEEL		3
17	METRIC - SPUR GEAR 4M 12T 20PA 40FW - S12028H60L17S1			1

DRAWN: G Kamela		TITLE: RACK AND PINION SUB ASSEMBLY (EXPLODED VIEW)	
CHECK'D: Dr Tijanuro	DATE:	DWG NO. TWO AXIS SOLAR TRACKER	
APP'D:		SCALE: A3	
PROJECTION:		SHEET 019	





APPENDIX C

