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Augmentation de l'efficacité énergétique d'un système photovoltaïque sans capteurs spécifiques

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PHD THESIS

Speciality: Automatic and Systems

Enhancing the Efficiency of Solar PV Power Systems without Specific Sensors

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Abstract

Over the past few years, solar trackers have evolved from modern power technology to a significant source of electricity production, dominating the solar power and renewable energy market. While traditional solar trackers utilize sensors for accurate sun positioning, their complexity, inaccuracy, high response time, and additional costs pose challenges. This work aims to enhance solar power efficiency without relying on specific sensors, introducing a novel strategy based on country ZIP codes to determine the sun's position. The project involves designing, simulating, and implementing a low-cost, simple, and accurate sensor-free solar tracking system using geographical coordinates and astronomical equations. Results indicate a substantial 36.9% increase in energy production compared to fixed PV panels, with a minimal energy consumption of 1.16% of produced solar power. Additionally, we proposed a novel approach to sandstorm resilience by incorporating wind data into solar tracking tools. This project offers valuable insights into solar power generation, offering a more efficient and resilient solution for both large and small-scale applications.

Keywords:

Astronomical equations, Geographic coordinates,PV systems, Sandstorm resilience, Sensor-free, Solar power efficiency, Solar tracker, ZIP codes.

Résumé

Au cours des dernières années, les suiveurs solaires ont évolué d'une technologie moderne de production d'énergie à une source majeure de production d'électricité, dominant le marché de l'énergie solaire et des énergies renouvelables. Alors que les suiveurs solaires traditionnels utilisent des capteurs pour une position précise du soleil, leur complexité, imprécision, temps de réponse élevé et coûts élevés posent des défis. Ce travail vise à augmenter l'efficacité énergétique des systèmes photovoltaïques sans recourir à des capteurs spécifiques, en introduisant une nouvelle stratégie basée sur les codes postaux des pays pour déterminer la position du soleil. Le projet implique la conception, la simulation et la mise en œuvre d'un système de suivi solaire sans capteur, à faible coût, simple et précis, utilisant les coordonnées géographiques et des équations astronomiques. Les résultats indiquent une augmentation substantielle de 36,9% de la production d'énergie par rapport aux panneaux PV fixes, avec une consommation d'énergie minimale de 1,16% de l'énergie solaire produite. De plus, nous avons proposé une approche novatrice pour renforcer la résilience aux tempêtes de sable en incorporant des données éoliennes dans les outils de suivi solaire. Ce projet offre des perspectives précieuses sur la génération d'énergie solaire, fournissant une solution plus efficace et résiliente tant pour les applications à grande échelle que pour les petites.

Mots clées :

Équations astronomiques,Coordonnées géographiques, ,Systèmes PV ,Résilience aux tempêtes de sable,Sans capteur, Efficacité énergétique, Suiveur solaire, Code postaux.

ملخص

على مدى السنوات القليلة الماضية، تطورت متتبعات الطاقة الشمسية من تكنولوجيا حديثة لتصبح مصدرا هاما لإنتاج الكهرباء، حيث أصبحت تهيمن على سوق الطاقة الشمسية والطاقة المتجددة. وبينما تستخدم متتبعات الشمس التقليدية أجهزة استشعار لتحديد موقع الشمس بدقة، إلا أن تعقيد هذه التقنيات ونقص الدقة وارتفاع زمن الاستجابة، إلى جانب تكلفة إضافية تشكل تحديات. يهدف هذا العمل إلى تعزيز كفاءة الطاقة الشمسية دون الاعتماد على أجهزة استشعار محددة، حيث يقدم استراتيجية جديدة تعتمد على الرموز البريدية للدول لتحديد موقع الشمس. يتضمن المشروع تصميم ومحاكاة وتنفيذ نظام تتبع الشمس بتكلفة منخفضة وبسيطة ودقيقة دون استخدام أجهزة استشعار، باستخدام الاحداثيات الجغرافية والمعادلات الفلكية. تشير النتائج إلى زيادة كبيرة قدرها 36,9%في إنتاج الطاقة مقارنة بلوحات الطاقة الشمسية الثابتة، مع استهلاك طاقة أدنى يبلغ 1,16% من إجمالي الطاقة الشمسية المنتجة. بالإضافة إلى ذلك، قدمنا نهجا جديدا لتعزيز مقاومة العواصف الرملية من خلال دمج بيانات الرياح في أدوات تتبع الشمس. يقدم هذا المشروع رؤى قيمة في إنتاج الطاقة الشمسية، ويقدم حلاً فعّالا ومتينا لكل من التطبيقات الكبيرة والصغيرة.

كلمات مفتاحية:

المعادلات الفلكية، الإحداثيات الجغرافية، أنظمة الطاقة الشمسية، قاومة العواصف الرملية، بدون مستشعرات، كفاءة الطاقة الشمسية، متتبع الشمس، رمز التتبع

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I wholeheartedly dedicate my thesis and the entirety of my work to my beloved family. This journey has been a profound experience, and it is with immense gratitude that I acknowledge the unwavering support and encouragement provided by my loving parents, Mostefa and Selam Rebiha. Your constant presence by my side, coupled with your relentless push for my betterment, has been the driving force behind my academic endeavors. I am profoundly grateful for your guidance and unwavering belief in my abilities.

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Abbreviation

AST	Active Solar Tracker
CSP	Concentrated Solar Power
CPV	Concentrated Photovoltaic
EEPROM	Erasable Electronic Programmable Read Only Memory
FL	Fuzzy Logic
FRBS	Fuzzy Rule-Based Systems
GPS	Global Positioning System
HCPV	High-Concentration Photovoltaic
IEC	International Electrotechnical Commission
IMUs	Inertial Measurement Units
IoT	Internet of Things
LDR	Light Dependent Resistor
MPC	Model Predictive Control
PI	Proportional Integral
PID	Proportional Integral Derivative
PLA	Programmable Logic Arrays
PLC	Programmable Logic Controller
PST	Passive Solar Tracker
PV	Photovoltaic
RSM	Reluctance Stepper Motors
STS	Solar Tracking Systems
ZIP code	Zone Improvement Plan code

Nomenclature

A_{ref}	Solar panel reference area
α	Right ascension of the Sun
β	Tilt angle of the solar panel
C	Equation of center
CD	Drag force coefficient
CFN	Normal force coefficient
CL	Lift force coefficient
d	day
D	Characteristic length scale
$Decl$	Declination of the Sun
e	Eccentricity of Earth's orbit
ee	Eccentricity correction factor
$elev$	Elevation angle of the Sun
FD	Drag force
$flow$	Flow correction for wind direction
FN	Normal force
fw	Wind velocity probability distribution function
Fx	Force in the horizontal direction
Fy	Lift force
$GrHrAngle$	Greenwich hour angle
$HrAngle$	Hour angle of the Sun
JD	Julian Date
$JDfrac$	Fractional Julian Date
$JDwhole$	Julian Date (whole)
k	Shape parameter of the wind velocity distribution
$L0$	Mean longitude of the Sun
Lat	Latitude of the location
$Ltrue$	True longitude of the Sun
M	Mean anomaly of the Sun
Obl	Obliquity of the Earth's orbit
q	Sand transport rate
R	Earth-Sun distance
RA	Right ascension of the Sun
T	Time in Julian centuries since J2000.0
$\vec{u}$	Horizontal wind component in the eastward direction
$u*t$	Threshold wind velocity
ui	Magnitude of wind speed
URV	Magnitude of wind velocity vector
v	Wind speed
$\vec{v}$	Horizontal wind component in the northward direction
VH	Horizontal wind speed
β	Angle of attack
y	year

INTRODUCTION

The pursuit of solar energy represents a pivotal endeavor in our quest for energy independence and a cleaner, more sustainable future. Solar power, tapping into the sun's nearly limitless energy potential, offers a renewable alternative to fossil fuels. However, despite the sun's substantial energy output of 1370 w/m^2[1] , only a fraction effectively reaches Earth's surface due to reflections by clouds, the atmosphere, and the Earth's surface itself. Consequently, approximately 342 w/m^2 [2] is the only amount of incoming solar radiation at the top of Earth's atmosphere , limiting its contribution to our global energy needs. Nevertheless, solar power remains an attractive option if harnessed effectively due to its cleanliness, sustainability, renewability, inexhaustibility, and numerous advantages. Through the deployment of a substantial number of solar panels designed to efficiently capture and convert the maximum amount of solar radiation, alongside the widespread implementation of advanced solar photovoltaic systems, we have the potential to harness this energy optimally and meet humanity's energy demands exclusively through solar power.

As we delve into this quest to harness solar energy's vast potential, the global photovoltaic (PV) market has undergone a profound evolution in recent times. While Japan and Europe initially led the way, China has now risen as the dominant player, excelling in both PV production and installations.China's annual new solar PV system installations surged significantly between 2012 and 2017[3], driven by larger utility-scale systems and declining PV system prices. This growth resulted in a fourfold increase in global PV power capacity,characterized by an average annual growth rate of 40% within the 2000-2010 period [4] surpassing 400 GW by the end of 2017[5]. Meanwhile, Algeria, with its abundant solar potential, is also making strides in the solar sector. The country aims to achieve a solar power capacity of 22 GW by 2030[6], constituting 60% of its renewable energy generation[7]. Algeria's commitment to solar energy is further exemplified by its exploration of solar tracking systems and plans to construct 15 solar plants across 11 locations in 2023[8], underscoring its dedication to harnessing its solar resources for sustainable energy development. In 2022, the world installed 239 GW of new solar capacity[9], marking a 45% increase compared to the previous year. Furthermore, early 2023 projections suggest an additional 341 GW of new solar capacity by year-end[10], with forecasts indicating the potential to install 1 terawatt (TW) of solar annually by the end of the decade, emphasizing the bright prospects for solar energy on a global scale.

The continuous evolution of the PV market is driven by a global recognition of the pivotal role that PV systems play in harnessing solar energy.They are specifically designed to convert sunlight into electricity. However, when PV panels are fixed in place, they are unable to fully tap into the sun's maximum energy potential due to the Earth's daily and seasonal movements, which affect the intensity of radiation received by solar systems. This is where the significance of solar tracking systems becomes evident, as they can increase energy gain by approximately 30% [11]to 40% [12]compared to fixed systems, significantly enhancing overall efficiency. A solar tracker is a sophisticated device engineered to precisely orient solar panels toward the sun throughout the day. Its primary purpose is to minimize the angle of incidence, defined as the angle between incoming sunlight and the normal surface of the panel. By continuously adjusting the panel's orientation to follow the sun's path, solar trackers optimize the energy output of the system, ensuring that it operates at peak efficiency. This meticulous tracking capability is instrumental in harnessing the full potential of solar energy and significantly enhancing the overall performance of photovoltaic systems.

Solar trackers are classified into several categories based on various aspects, including their tracking axis, drive mechanism, and tracking accuracy. Firstly, based on the tracking axis, solar trackers can be classified into single-axis and dual-axis trackers[13]. Single-axis trackers follow the sun's movement either in the horizontal (east to west) or vertical (north to south) direction[14], while dual-axis trackers follow the sun's movement in both horizontal and vertical axes, maximizing solar energy capture throughout the day. Secondly, solar trackers can be categorized by their drive mechanism as either active or passive[15]. Active trackers use motors or actuators to actively adjust the position of solar panels[16], while passive trackers rely on mechanical or pneumatic systems[17], such as the use of thermal expansion fluids[17], to passively change panel angles. Lastly, solar trackers can vary in tracking accuracy, with some using astronomical algorithms [17]for precise sun tracking, sensor-based systems[18] that rely on sun sensors, and purely mechanical trackers that follow the sun's path through simple mechanical components. These classifications offer a range of options for optimizing solar energy generation in diverse geographical and budgetary contexts.

The literature on solar tracking systems encompasses both sensor-based and sensorless approaches, each with its unique advantages and innovations. Sensor-based systems, exemplified by Morón et al. (2017), who employed Arduino technology, achieved an impressive 18% increase in energy output compared to static panels [19]. Other sensor-based methods include the use of commercial webcams for precise tracking [20], Light Dependent Resistors (LDRs) for monthly energy gains of up to 31.1% [21], and the implementation of Reluctance Stepper Motors (RSM) controlled by Programmable Logic Arrays (PLA) for precise tracking with a 7.5° resolution [22].

In contrast to sensor-based solar tracking systems, the literature on sensorless solar tracking also reveals several noteworthy aspects. Sensorless approaches have emerged as alternatives to address the challenges faced by their sensor-based counterparts. Sidek et al. (2017)

developed a sensorless solar tracker that achieves precise positioning and reduces energy consumption [23]. Seme and Stumberger (2011) introduced an open-loop strategy based on a Differential Evolution algorithm [24], while Nazir et al. (2015) created a sensorless tracker using sunrise and sunset data [25]. Tirmikci and Yavuz (2015) relied on predictable solar movement for their sensorless tracker [26], and Fathabadi (2016) implemented maximum power point tracking (MPPT) in their sensorless system [27]. Additionally, Loon and Daud (2020) utilized current sensors for optimizing panel alignment [28], and Pirayawaraporn et al. (2023) introduced an innovative sensorless system employing a particle filter algorithm [29].

In recent years, the field of solar tracking has seen notable trends encompassing both sensor-based and sensorless systems, reflecting the broader advancements in renewable energy technology. One prevalent trend is the integration of cutting-edge technologies such as the Internet of Things (IoT) [30] and artificial intelligence (AI) [31] into solar tracking systems, enabling real-time monitoring, predictive maintenance, and data-driven decision-making, which enhances the overall efficiency and reliability of both sensor-based and sensorless trackers. Additionally, data analysis approaches [32] and cognitive methods [33] have played pivotal roles in advancing the field by providing valuable insights and intelligent decision-making capabilities. The emergence of unconventional solar tracking applications, like solar-powered trees [34] and floating solar power plants [35], further showcases the versatility of these systems. These unique applications not only maximize energy generation but also demonstrate the adaptability of solar trackers to diverse settings, from urban landscapes to bodies of water. Quantum dots solar cells have also gained attention as a promising technology [36], offering the potential to enhance photovoltaic performance and overall energy efficiency in conjunction with advanced tracking systems.

In light of the comprehensive review of the literature on both sensor-based and sensorless solar tracking systems, it becomes evident that there exist notable gaps and unexplored avenues within this field. While sensor-based systems have demonstrated significant potential in enhancing energy output from photovoltaic panels, the literature lacks comprehensive evaluations encompassing diverse environmental conditions and the development of advanced control algorithms that effectively harness sensor data [19]. Additionally, there is a dearth of real-world field studies [20], [21], which limits our understanding of the practicality and reliability of sensor-based trackers in various operational scenarios. In the realm of sensor-based solar tracking, significant gaps exist, ranging from the need for comprehensive sensor performance evaluations encompassing various environmental conditions to the development of advanced control algorithms that effectively harness sensor data [22]. Additionally, the impact of environmental factors on sensor reliability and the scarcity of real-world field studies [37] further underscore the research void in this domain.

On the other hand, sensorless solar tracking, while presenting a promising alternative, reveals its own set of challenges. As highlighted in previous studies, the gaps in existing sensorless solar tracking research are evident across multiple investigations, highlighting common limitations in the pursuit of cost-effective and simplified tracking solutions [23]. Despite the initial promise of reducing costs and system complexity, a significant number of these investigations turn to the incorporation of various sensors, such as irradiance sensors, inclinometers, and current sensors [26], [27], which can paradoxically escalate overall system intricacy and expenses. The implementation of complex optimization algorithms that necessitate data storage and energy consumption adds another layer of complexity to these sensorless systems [29]. Furthermore, the continuous movement required by sensorless trackers to pinpoint optimal angles for maximum power collection introduces the potential for heightened energy consumption and mechanical strain, compromising long-term reliability [28]. While these studies underscore the potential benefits of sensorless tracking, the recurring reliance on sensor technologies and intricate optimization approaches raises valid questions regarding practical feasibility, scalability, and overall system reliability.These gaps served as a pivotal catalyst inspiring our research endeavors aimed at advancing the field of sensorless solar tracking and unlocking its full potential for achieving cost-effective and highly efficient solar energy generation.

The primary objective of this research is to bridge the existing gaps in solar tracking technology by designing a new, cost-effective, and sensor-free solar tracker that enhances solar power efficiency while prioritizing simplicity and affordability. Many previous studies have concentrated on increasing accuracy through sensor integration or complex algorithms and mechanisms. However, it's worth noting that even with a slight deviation of up to 10 degrees, solar trackers can still yield an impressive 98.5% of full tracking output [38]. In regions with intermittent cloud cover, annual gains can be as high as 20%, while in sunnier locations, these gains typically range from 30% to 40% [38] The daily energy output can vary significantly, from minimal gains to nearly doubling the energy output, depending on the conditions. This is where our design shines, emphasizing simplicity and cost-effectiveness, making it a compelling alternative to fixed solar panels that has the potential to dominate the market and significantly enhance solar power generation efficiency, whether on a small scale or in large-scale installations, such as buildings or PV plants.

To achieve this objective, this study aims to address several pivotal research questions, including: 1. Can a sensor-free solar tracking system, utilizing geographic coordinates and sun position algorithms, effectively enhance solar power efficiency? 2. How does our proposed sensor-free solar tracker stack up against traditional sensor-based systems in terms of accuracy, cost-effectiveness, and simplicity? 3. What is the transformative potential of a sensor-free solar tracker in reshaping solar tracking methodologies and facilitating the widespread adoption of solar energy? By delving into these fundamental inquiries and achieving our predetermined objectives, this research contributes significantly to the realm of solar tracking. It introduces an innovative sensor-free solar tracking solution, eliminating the need for costly and intricate sensor-dependent setups. Our approach harnesses geographic coordinates and sun position algorithms to offer a streamlined and economically viable alternative for optimizing solar power efficiency, aligning with the overarching aim of democratizing solar energy. Furthermore, this research fills a crucial void in current literature by conducting extensive simulations and experimental evaluations, offering an exhaustive appraisal of the sensor-free solar tracker's performance. Comparative analyses against conventional sensor-based trackers provide compelling evidence of our approach's superiority in terms of precision, cost-effectiveness, and simplicity. The outcomes of this study have the potential to redefine solar tracking techniques and play a pivotal role in catalyzing the widespread adoption of solar energy. By presenting a pioneering solution that effectively mitigates the limitations of existing tracking systems, this research advances the cause of sustainable energy technologies. Our sensor-free solar tracker not only paves the way for more efficient solar power generation but also underscores the significance of exploring alternative avenues on our path towards a cleaner and more sustainable future.

Building upon our research aims and questions, our "Research methodology" section details the development and testing of our sensorless solar tracking system, which draws inspiration from Saudi Arabian prayer watches. Our innovative approach utilizes ZIP codes as location indicators and employs sun position algorithms to dynamically track the sun's movement, optimizing solar panel alignment. Rigorous testing was conducted at the University of Ibn Khaldoun in Algeria, where we collected a rich dataset encompassing both quantitative and qualitative measurements to comprehensively evaluate the system's performance. With a focus on practicality and accessibility, we successfully validated our approach and crafted user-friendly mobile and online interfaces for precise system control and real-time monitoring. This research stands as a significant contribution to the advancement of solar energy technology, presenting an attainable and efficient solution for enhancing photovoltaic system efficiency in various applications.

In light of the comprehensive development and testing of our sensorless solar tracking system, it's important to acknowledge certain research limitations. Firstly, the successful deployment of the proposed sensor-free solar tracker may necessitate specific resources and technical expertise, potentially posing challenges related to availability and accessibility, particularly in resource-constrained environments. Additionally, the scope of this research may have inherent limitations as it is contingent on specific geographic regions or particular climatic conditions. The reliance on geographic coordinates and sun position algorithms means that the applicability of our approach may vary across different countries and latitudes. Therefore, while our research offers valuable insights and advancements in solar tracking technology, it is imperative to recognize that further studies and adaptations may be necessary to ensure its suitability and efficacy for a broader range of countries and diverse environmental settings. These limitations provide opportunities for future research and refinement to enhance the versatility and accessibility of our sensorless solar tracking system.

The thesis is thoughtfully structured into four pivotal chapters, each playing a distinct role in shaping the research narrative. In Chapter 1, we embark on an expansive journey through the realm of solar tracking technologies, conducting an in-depth literature review. We establish the groundwork by offering a comprehensive overview that includes research objectives, questions, methodology, results, and limitations. Chapter 2 delves deep into the heart of our research methodology, meticulously detailing the design and implementation of the new solar tracking strategy to upgrade solar power efficiency, using ZIP codes as an alternative to sensors. Chapter 3 presents a novel approach to a storm-resilient solar tracking system for optimum solar power generation. Lastly, chapter 4 is dedicated to showcasing the outcomes of our research, accompanied by an array of tests carefully conducted to validate the accuracy, cost-effectiveness, and simplicity of our innovative solution.

Chapter 1

Introduction and Literature Review

1.1 introduction

In this chapter, the spotlight is cast on the Literature Review, where the foundation of solar tracking systems and energy efficiency augmentation is meticulously examined. As we traverse through this scholarly landscape, we uncover the historical origins, dissect contemporary perspectives, and identify critical gaps that shape the trajectory of this research domain. This comprehensive exploration delves into the works of predecessors, drawing insights and lessons that illuminate the current state of the field and inform our pursuit of innovative solutions. Through an intricate interplay of theories, methodologies, and empirical findings, this chapter sets the context for the subsequent investigations, offering a road map that guides us toward a deeper comprehension of sensor-less solar tracking and its role in sustainable energy enhancement.

1.2 Definition of Solar Tracking

The concept of solar tracking plays a pivotal role in the realm of enhancing energy efficiency within PV systems. Solar tracking refers to the dynamic adjustment of solar panels' orientation to optimize their alignment with the sun's changing position throughout the day, allowing solar panels to capture the maximum amount of solar irradiance and significantly boosting the energy output of PV installations.Figure1.1 represents the definition of a solar tracking system in comparison to conventional PV systems. By actively following the sun's path, solar trackers maximize the utilization of solar energy resources, contributing to a considerable increase in power generation.

This technology represents a continuous journey of innovation and advancement in the field of renewable energy. It encompasses a multitude of crucial components that harmonize seamlessly to drive the widespread adoption of solar energy as a dependable and sustainable power source. Light sensors, including photodiodes and phototransistors, act as the perceptive eyes of solar trackers, meticulously measuring sunlight intensity to ensure precise alignment with the sun's position. Meanwhile, the integration of Global Positioning System (GPS) technology, combined with intricate algorithms, allows for unparalleled accuracy in pinpointing solar trackers' locations and calculating the sun's optimal position for panel orientation.

Sophisticated algorithms, taking into account variables like date, time, geographical coordinates, and even earth's tilt and rotation, compute the perfect azimuth and elevation angles for optimal solar panel positioning. These calculations orchestrate the symphony of movement through advanced control systems, including microcontrollers and Programmable Logic Controllers (PLCs), ensuring that solar panels continuously follow the sun's path with unwavering precision.

The mechanical realm employs various actuators and motors, such as stepper and servo motors, to power the graceful and exacting movements required to capture every ray of sunlight effectively. In the age of connectivity, communication systems like wireless modules and internet interfaces provide remote oversight and control, allowing for real-time monitoring and data logging from afar.

Furthermore, the use of advanced materials, such as lightweight alloys and durable composites, strengthens the structural integrity of STS, reducing weight and extending their operational lifespan. This perpetual commitment to innovation and improvement underscores the quest for ever-enhanced tracking accuracy, durability, and overall performance, ultimately driving the widespread adoption of solar energy as a sustainable and enduring power source for generations to come.

1.3 Historical Background

The history of STS dates back several decades, marked by significant advancements spurred by the pioneering work of researchers. The solar era commenced in 1950[39] when Bell Laboratory scientists created the first silicon solar cell, with low efficiency(only a 4% efficiency[40]). Despite being expensive for mainstream consumers in the 1960s and 1970s, solar panel production began.Figure 1.2 shows the first ever silicon solar cell, this cell was crucial in pioneering solar technology, utilizing a silicon P-N junction to generate an electromotive force when exposed to sunlight, setting the stage for modern PV systems.Concurrently, the evolution of solar tracker systems began with the introduction of the concept by Finster in 1962, who developed an early mechanical system with limited real-world application features [41]. Just a year later, Saavedra improved upon Finster's design by creating an automatically controlled system incorporating a turning pyro-heliometer for sun position determination [42]. Advancements continued in 1975 when McFee studied the effects of mirror surface nonflatness and tracking errors on central receiver solar power systems, providing insights into power collection reduction due to such factors [43]. In 1980, Dorian and Nelson introduced

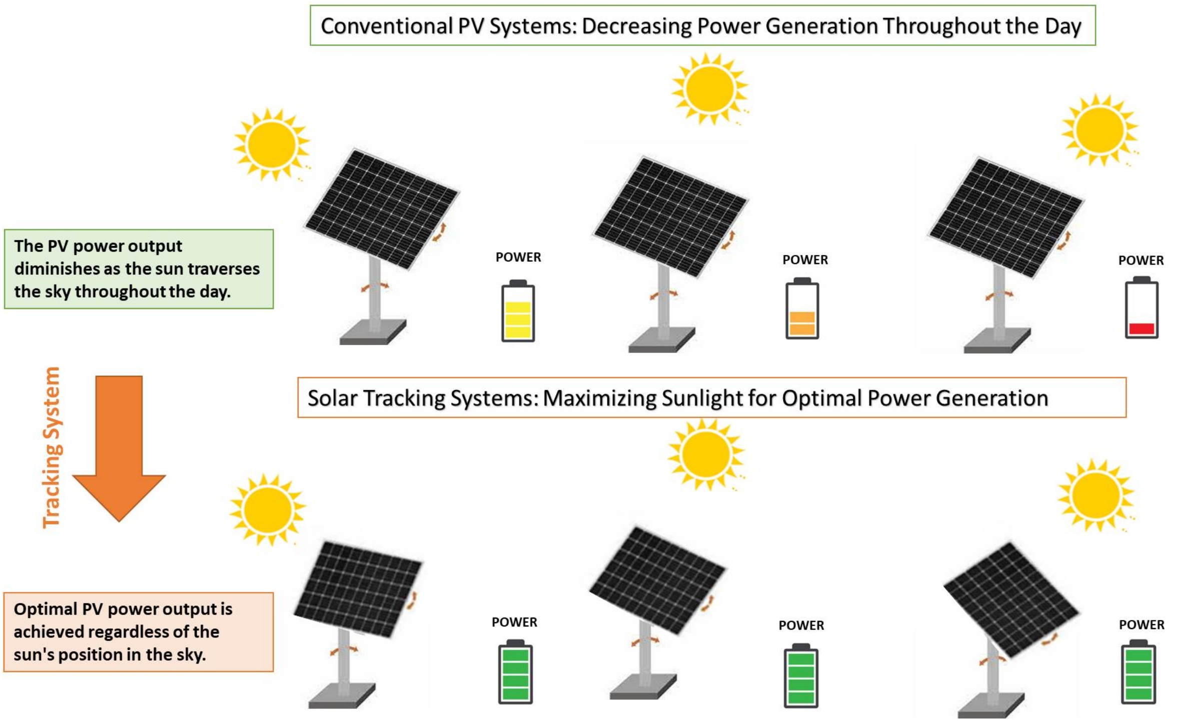


Figure 1.1: An Illustrative Comparison of Solar Tracking Systems vs. Conventional PV Systems

an improved solar tracking arrangement with electrical control mechanisms capable of detecting and correcting misalignments of solar collectors [44]. Building on this foundation, Semma and Imamura in 1981 designed a two-axis sun tracking controller based on an active sun sensing approach, achieving high precision tracking for PV concentrator systems while allowing for stowing, communication, and autonomous operation [45].A plethora of research has been undertaken to develop solar tracking systems since the inception of the first-ever system, leading to recent innovative researches in 2023. Pirayawaraporn et al. [29] introduced an innovative sensorless dual-axis solar tracking system using a particle filter algorithm that eliminates the need for historical meteorological data and complex mathematical models. Similarly, Mariappan et al. [46] leveraged machine learning techniques to maximize power generation from solar panels, showcasing a novel method to optimize energy output. Karabiber and Güneş [47] devised a cost-effective single-motor, dual-axis solar tracking system named Asymmetric Solar Tracker (AST) that utilizes an adjustable asymmetrical stand for improved efficiency and reduced construction costs. Furthermore, Garcia-Fernandez and Omar [48] presented an integrated solar lighting system for optimizing daylight utilization in a public library, demonstrating the potential of nanomaterials and an innovative anidolic lighting system. Moreover, Saldivar-Aguilera and Valentín-Coronado [49] proposed a dual closed-loop control algorithm for parabolic trough solar trackers, using photodiode-based sensors and shadow-based visual devices to enhance accuracy and robustness. Finally, Huang and Huang [50] developed a solar-tracking strategy for sloping terrain using spatial projection analysis, achieving optimized energy production considering terrain effects. These 2023 research endeavors highlight the dedication to enhancing solar tracking systems' efficiency, reliability, and environmental impact through novel techniques and methodologies.Figure 1.3 summarizes the evolution of solar tracking systems, providing a visual representation of key milestones in their development.

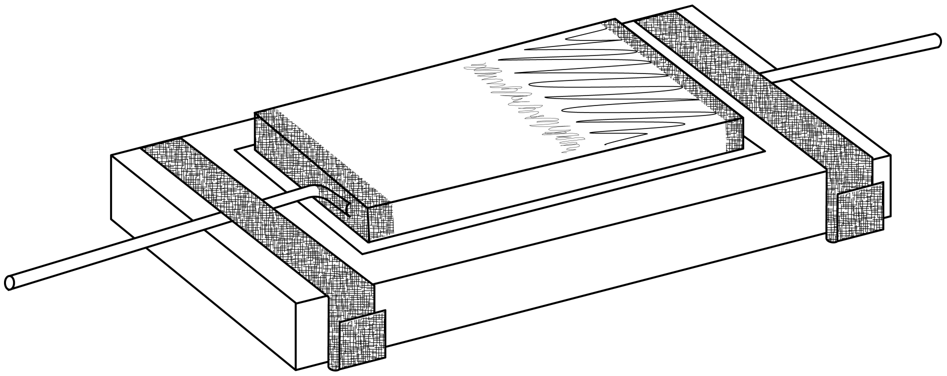
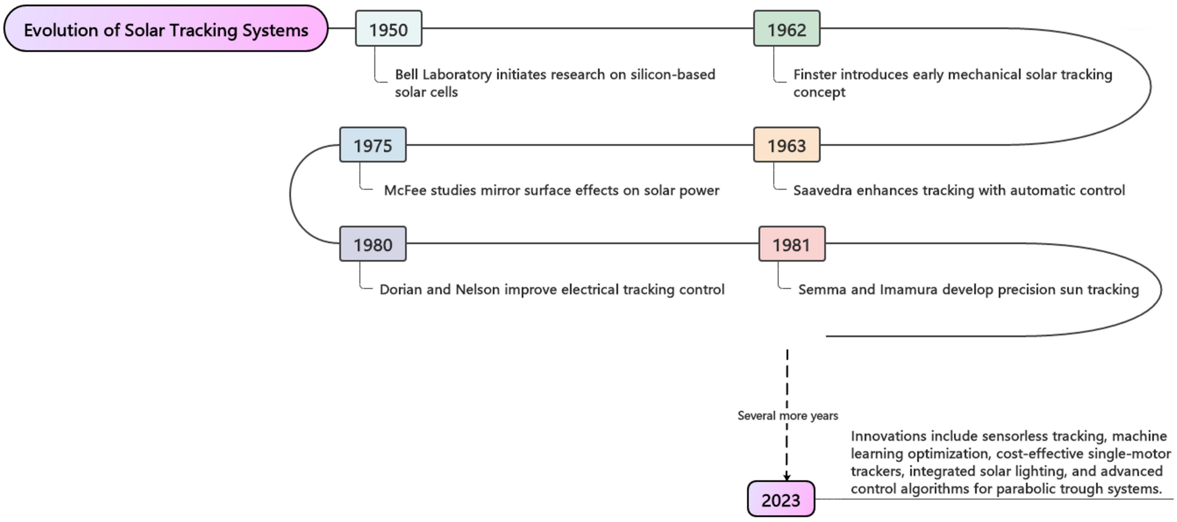


Figure 1.2: The first ever PV panel in the history of solar energy [40]



1950
Bell Laboratory initiates research on silicon-based solar cells

1962
Finster introduces early mechanical solar tracking concept

1963
Saavedra enhances tracking with automatic control

1975
McFee studies mirror surface effects on solar power

1980
Dorian and Nelson improve electrical tracking control

1981
Semma and Imamura develop precision sun tracking

Several more years

2023
Innovations include sensorless tracking, machine learning optimization, cost-effective single-motor trackers, integrated solar lighting, and advanced control algorithms for parabolic trough systems.

Figure 1.3: Timeline of solar tracking system evolution

1.4 Types of Solar Tracking Systems

Solar energy systems have seen the development and utilization of a range of solar tracker types, as depicted in Figure 1.4. These encompass various innovative approaches to optimizing solar panel alignment for enhanced energy capture. These tracker types have been designed to cater to different geographical locations, efficiency requirements, and technological preferences. The diversity includes:

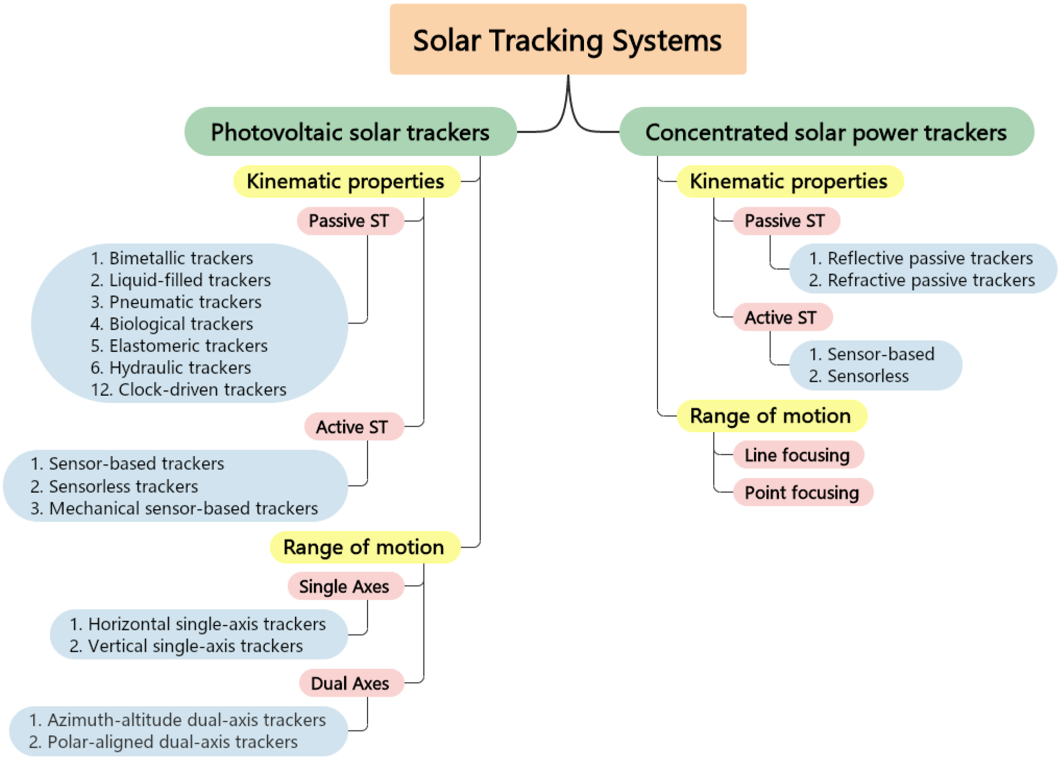


Figure 1.4: Diverse varieties of solar tracking systems

1.4.1 Photovoltaic solar trackers

PV solar trackers (shown in Figure 1.5) are devices or systems designed to enhance the efficiency of photovoltaic (PV) solar panels by continuously adjusting their orientation to follow the sun's path throughout the day [51]. These trackers maximize the capture of sunlight, resulting in increased energy production from PV panels. They can be categorized as follow:

Kinematic Properties

Passive trackers:

Passive trackers use mechanical and gravitational principles to passively align the solar panel with the sun's position. They do not require external power or sensors, making them simpler and more cost-effective.They include:

1. **Bimetallic Trackers:** Passive bimetallic trackers use differential expansion of materials for solar panel adjustments.
2. **Liquid-filled Trackers:** These trackers rely on fluid movement for passive adjustments.
3. **Pneumatic Trackers:** Passive pneumatic trackers operate through changes in air pressure.

Figure 1.5: Photovoltaic solar tracker [51]

4. **Biological Trackers:** Biomimetic trackers mimic natural processes for orientation.
5. **Elastomeric Trackers:** Flexible materials enable passive tracking.
6. **Hydraulic Trackers:** Hydraulic systems achieve passive solar panel movement.
7. **Clock-driven Trackers:** Movement follows a predetermined time-based schedule.

Active trackers:

Active trackers employ sensors and control systems to continuously adjust the solar panel's position for optimal sunlight capture. They rely on real-time data to determine the sun's position and adjust the tracker accordingly.They can be classified into:

1. **Sensor-based Trackers:** Active trackers use sensors to detect the sun's position and actively adjust solar panels.
2. **Sensorless Trackers:** Sensorless trackers determine orientation without external sensors.
3. **Mechanical Sensor-based Trackers:** Active systems combine mechanical components with sensors for tracking.

Range of Motion

Single-axis trackers:

These trackers move the solar panel along a single axis, typically east-west, to follow the sun's daily path. They are relatively simple in design and cost-effective but offer limited tracking accuracy.They can be classified into:

1. **Horizontal Single-Axis Trackers:** These trackers rotate horizontally to follow the sun's path.
2. **Vertical Single-Axis Trackers:** Vertical single-axis trackers adjust around a vertical axis to accommodate seasonal variations.

Dual-axis trackers:

These trackers provide precise tracking by moving the solar panel along both the east-west and north-south axes. They offer superior performance but are generally more complex and expensive than single-axis trackers.They can be classified into:

1. **Azimuth-altitude dual-axis trackers:** These trackers adjust both azimuth (horizontal) and altitude (vertical) angles simultaneously for precise solar tracking.
2. **Polar-aligned dual-axis trackers:** Polar-aligned dual-axis trackers align with the North Star, ensuring precise solar tracking throughout the day.

1.4.2 Concentrated Solar Power (CSP) trackers:

These trackers(shown in Figure 1.6) are specifically designed for concentrated solar power systems [52], where mirrors or lenses concentrate sunlight onto a receiver. The tracker ensures precise alignment of the mirrors or lenses with the sun for maximum concentration and energy generation.CSP solar trackers can be classified into:

Kinematic Properties

Passive Solar Tracking :

Passive solar tracking refers to Concentrated Photovoltaic (CPV) systems that adjust the orientation of solar panels without the use of external energy input. It includes:

1. **Reflective Passive Trackers:** These trackers use reflective materials to passively redirect sunlight towards the solar panels, adjusting their orientation based on changes in sunlight direction.
2. **Refractive Passive Trackers:** Refractive passive trackers employ materials that refract or bend sunlight to achieve passive adjustments in solar panel orientation.

Figure 1.6: Concentrated Solar Power (CSP) trackers [52]

Active Solar Tracking :

Active solar tracking involves the use of external mechanisms or components to actively adjust the orientation of solar panels for optimal sunlight capture. It includes:

1. **Sensor-based Trackers:** Sensor-based trackers use sensors to actively detect the sun's position and provide input for precise adjustments, ensuring that the solar panels are aligned with the sun's rays.

2. **Sensorless Trackers:** Sensorless trackers determine the orientation of solar panels without relying on external sensors. They often use algorithms or calculations to achieve accurate positioning.

Range of Motion

Line Focusing:

Line focusing CPV systems are designed to concentrate sunlight onto a linear receiver or area. They utilize optical components like lenses or mirrors to focus sunlight into a line, maximizing energy capture.

Point Focusing:

Point focusing CPV systems are engineered to concentrate sunlight onto a single point or receiver. These systems use optical elements to focus sunlight to a specific point, increasing energy efficiency.

1.5 Traditional Solar Tracking Methods

Traditional tracking systems can be categorized into three distinct types, each distinguished by its unique tracking mechanism. In Figure 1.7, we illustrate the differences between these tracking approaches. The three types are as follows:

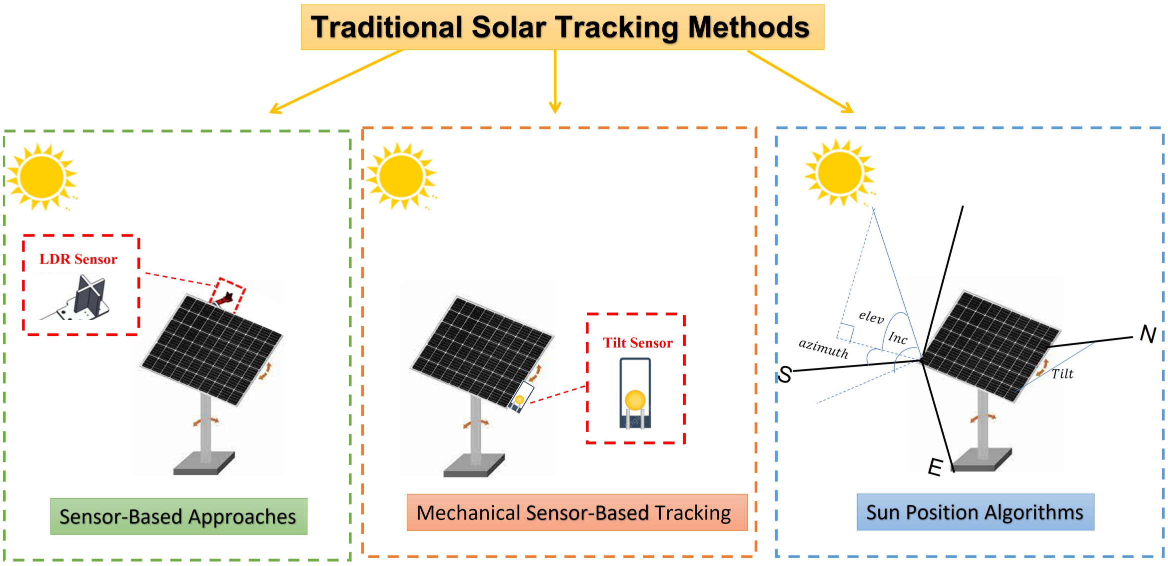


Figure 1.7: Comparison of Traditional Tracking System Types

1.5.1 Sensor-Based Approaches

One common approach in traditional solar tracking involves the use of light sensors or photodiodes to detect the intensity of sunlight. These sensors provide information about the direction from which sunlight is coming, allowing the solar panels to be adjusted accordingly. Light sensor-based tracking systems can accurately determine the sun's position and ensure that the solar panels are optimally aligned. However, these systems may require frequent calibration to maintain accuracy and can be affected by weather conditions such as clouds or shading.

1.5.2 Mechanical Sensor-Based Tracking

Mechanical sensors, such as inclinometers and gyroscopes, are another category of traditional solar tracking methods. Inclinometers measure the angle of tilt or inclination of the solar panels relative to the sun, while gyroscopes detect angular velocity and orientation changes. These sensors provide real-time data that can be used to adjust the position of solar panels. Mechanical sensor-based tracking systems are often robust and reliable but can be complex to implement and require regular maintenance to ensure accurate readings.

1.5.3 Sun Position Algorithms

Some traditional solar tracking methods utilize sun position algorithms that calculate the sun's angles (azimuth and altitude) based on the time of day, date, and geographic location. These algorithms consider the earth's rotation and orbit to determine the sun's apparent motion in the sky. By knowing the sun's angles, solar panels can be oriented to capture maximum sunlight throughout the day. While sun position algorithms eliminate the need for direct sensor measurements, they still rely on accurate time and location data, which may introduce errors if not properly calibrated.

1.6 Factors Affecting Solar Tracking System Performance

Factors affecting solar tracking system performance encompass a range of aspects, including the tracking algorithm, the control system, and the mechanical design. The effectiveness of these factors directly influences the overall performance and energy output of solar tracking systems. These components work in tandem to ensure that solar tracking systems operate optimally, capturing maximum sunlight and converting it into usable energy. The intricacies of the tracking algorithm, the responsiveness of the control system, and the robustness of the mechanical design collectively play a critical role in determining the efficiency and reliability of these systems. As advancements continue in each of these areas, solar tracking systems are becoming increasingly accurate and efficient, contributing to the growth of renewable energy generation worldwide.Figure 1.8 illustrates a comprehensive mind map detailing the factors affecting solar tracking system performance .

1.6.1 The tracking algorithm:

The accuracy of solar tracking in Advanced Solar Tracking Systems (ASTS) is heavily influenced by the intricacies of the tracking algorithm employed. This algorithm plays a pivotal role in determining the sun's position and guiding the optimal orientation of solar panels. Diverse algorithms, including the astronomical algorithm, sun sensor algorithm, and sky imaging algorithm, have been developed to enhance tracking precision [53]. Researchers have tirelessly worked on refining these algorithms by incorporating advanced mathematical models, machine learning techniques, and predictive analytics [54]. These efforts are directed towards not only increasing the accuracy of tracking but also boosting operational

Figure 1.8: Factors Affecting Solar Tracking System Performance

efficiency. Moreover, the selection of tracking strategy, be it open-loop, closed-loop, or hybrid-loop, significantly impacts the overall tracking performance [53]. The choice of control algorithms like On-off, Proportional Integral (PI), and Proportional Integral Derivative (PID) also plays a vital role in shaping the accuracy of solar tracking [54]. The frequency of tracking operations, an aspect highlighted by Mi et al. [55], and the utilization of the Solar Position Algorithm (SPA), a concept explored by Luque-Heredia et al. [56], further contribute to shaping the precision of solar tracking in ASTS. This comprehensive approach underscores the multifaceted nature of research aimed at elevating solar tracking accuracy and underscores the commitment to advancing the capabilities of ASTS.

1.6.2 The control system:

A pivotal component in solar tracking systems is the control system responsible for executing the tracking algorithm and regulating the motion of the solar tracker. The choice of appropriate sensors, actuators, and control strategies plays a fundamental role in determining the overall performance of the system. To achieve precision in solar tracking, recent research has delved into the utilization of advanced sensor technologies, such as Global Positioning System (GPS), Inertial Measurement Units (IMUs), and light sensors, providing real-time data for accurate tracking [56]. These sophisticated sensors contribute to the acquisition of dynamic environmental information, enabling the solar tracker to adjust its orientation optimally. Simultaneously, control strategies have garnered significant attention in enhancing tracking responsiveness and minimizing errors. Techniques such as Proportional-Integral-Derivative (PID) control, fuzzy logic (FL), and Model Predictive Control (MPC) have been extensively investigated [56]. The selection of the control strategy inherently impacts the solar tracker's ability to swiftly adapt to changing solar angles. Factors including unit control type [56], backlash of the actuators [37], characteristics of the solar sensor [56], and the necessity for sensor calibration [37] collectively contribute to the intricate interplay between hardware and control strategies, culminating in the heightened performance of solar tracking systems.

1.6.3 The mechanical design:

The mechanical design of a solar tracking system significantly shapes its stability, longevity, and capacity to endure varying environmental conditions. Factors such as material selection, bearing systems, and structural configuration collectively influence the system's robustness and its ability to withstand operational challenges. Recent research endeavors have been directed towards optimizing the mechanical design through the integration of resilient materials, advanced bearing technologies, and inventive tracking mechanisms, culminating in seamless and dependable tracking performance [57, 37, 56]. Installation deviation [57, 37, 56], lack of maintenance [56, 12], and errors attributed to wind effects [58, 37, 56] are pivotal considerations that underscore the intricate interplay between mechanical design and the operational efficacy of solar tracking systems. Typically encompassing diverse components such as transmission mechanical drive subsystems, electric motors, sun position sensors, solar position algorithms, control units, and limit switches [59], the intricate composition of advanced STS necessitates meticulous evaluation and validation of their mechanical aspects. The assessment of standards such as International Electrotechnical Commission (IEC) 62817, focusing on mechanical testing for tracker validation [60], attests to the industry's commitment to ensuring the reliability and endurance of solar tracking systems.

Existing research has demonstrated the effectiveness of various techniques in optimizing the performance of these factors individually. However, there is still room for further investigation and improvement. Future research could explore the integration of advanced tracking algorithms with intelligent control systems to adaptively respond to changing environmental conditions. Additionally, the development of lightweight and cost-effective mechanical designs, coupled with advanced materials and manufacturing techniques, could enhance the overall performance and cost-effectiveness of solar tracking systems.

By addressing these research gaps, solar tracking systems can be further optimized to maximize energy generation, improve system efficiency, and promote the widespread adoption of solar energy as a sustainable power source.

1.7 Control algorithms

Control algorithms applied to STS refer to sets of computational instructions designed to manage the movement of solar panels or devices in response to the changing position of the sun. These algorithms play a crucial role in maintaining the accuracy of solar tracking, ensuring that solar panels are oriented optimally to capture the maximum amount of sunlight throughout the day. By continuously analyzing the sun's position and adjusting the orientation of the panels, control algorithms enhance tracking accuracy, thereby maximizing energy yield and overall system efficiency in both concentrating solar power and photovoltaic installations.Figure1.9 illustrates a comprehensive mind map showcasing control algorithms utilized in solar tracking systems, along with their respective advantages, disadvantages, and distinctions.

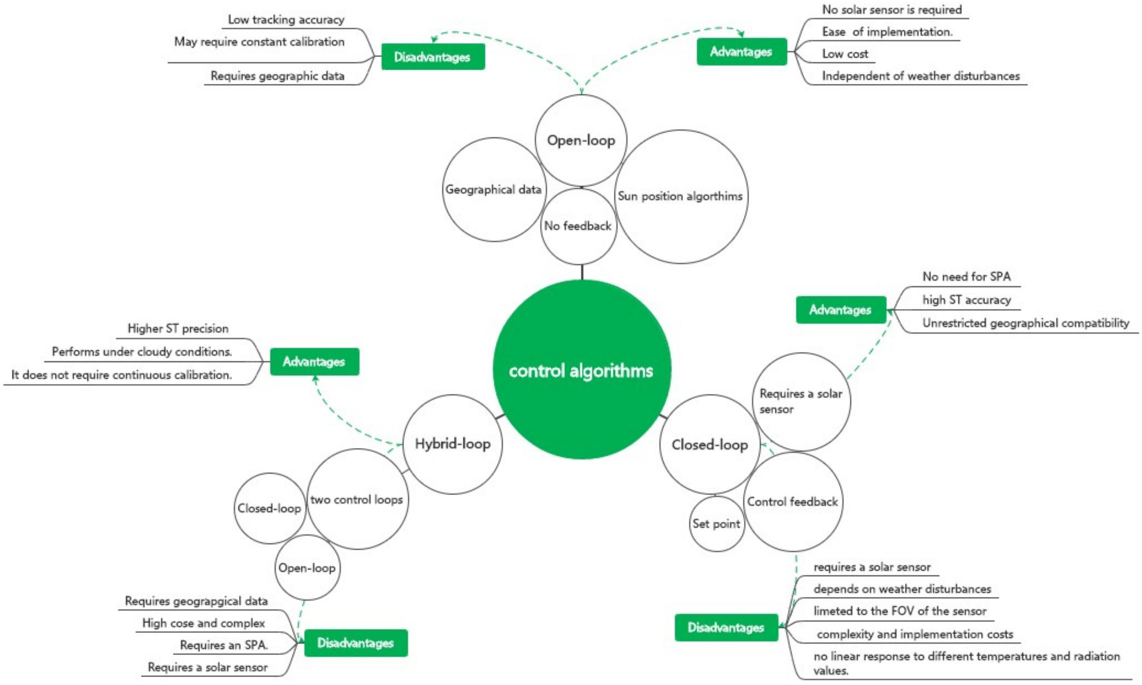


Figure 1.9: Control algorithms applied to solar tracking systems

1.7.1 Open-loop Solar Tracking Strategy

The open-loop solar tracking strategy is a fundamental approach to optimize the alignment of solar panels with the sun's position. Unlike closed-loop systems that incorporate feedback mechanisms, open-loop strategies rely on predetermined algorithms and calculations to adjust the panel's orientation. This approach primarily utilizes astronomical equations, time of day, and geographical coordinates to estimate the sun's position. While open-loop tracking can be simpler and more cost-effective, it might not account for real-time changes in weather or other external factors that could affect solar panel performance.

1.7.2 Closed-loop Solar Tracking Strategy

The closed-loop solar tracking strategy represents a more advanced approach that integrates feedback mechanisms to continually adjust the solar panel's positioning. This method employs sensors and detectors to monitor the actual position of the sun and compares it to the desired orientation. By continuously analyzing this feedback, the system can make real-time adjustments to ensure optimal alignment. Closed-loop strategies offer increased accuracy and adaptability, allowing the system to respond to changing conditions such as clouds or shading. However, their complexity and reliance on sensors can lead to higher implementation and maintenance costs.

1.7.3 Hybrid-loop Solar Tracking Strategy

The hybrid-loop solar tracking strategy aims to combine the advantages of both open-loop and closed-loop approaches. By integrating feedback from sensors while also considering predetermined astronomical data, this strategy seeks to strike a balance between accuracy and simplicity. The system benefits from real-time adjustments based on sensor input while also utilizing the reliability of open-loop calculations. Hybrid-loop strategies could potentially mitigate some of the limitations of pure open-loop systems, offering improved performance without the full complexity of closed-loop mechanisms. However, finding the optimal balance between these two approaches requires careful design and calibration.

1.8 Limitations of Sensor-Based Tracking

1.8.1 Previous Research

Before the emergence of sensorless solar trackers, the field predominantly revolved around sensor-based systems, which have continued to play a pivotal role in the industry. Numerous studies have been dedicated to exploring and advancing these sensor-based solar tracking systems. Notable among these studies is the work by Morón et al. (2017), who devised a PV solar tracker prototype that harnessed Arduino technology. This system, driven by photodiodes, stepper motors, and linear actuators, showcased an impressive 18% increase in energy output when compared to static panels [19].

Similarly, Garcia and Alejandro (2010) made an innovative contribution by utilizing a commercial webcam as a sensor element in their solar tracking system. Their approach offered an unprecedented accuracy of 0.1°, even when subjected to varying weather conditions.

They achieved this through a carefully designed electro-mechanical setup that demonstrated impressive tracking capabilities [20].

Hoffmann et al. (2018) took a different route by developing a dual-axis solar tracking system reliant on LDRs as sun movement sensors. This system's design was backed by a meticulous theoretical framework, and its practical evaluation over 152 days in southern Brazil yielded average monthly gains ranging from 17.2% to 31.1% when compared to fixed panels [21].

Abouzeid (2001) delved into the realm of stepper motor technology, devising a solar tracking system that employed a reluctance stepper motor controlled by a programmable logic array . Through this approach, an angular position resolution of 7.5° was achieved. The mechanism, incorporating an Erasable Electronic Programmable Read Only Memory (EEPROM) and PLA chip, successfully demonstrated accurate tracking [22].

Skouri and Ben Haj Ali (2016) took on the challenge of designing sun tracking systems specifically for solar parabolic concentrators. Their work culminated in the creation of three distinct pilot tracking systems, each capable of dual-axis sun position tracking. Through careful design and construction, they achieved tracking errors below 0.2°, a remarkable feat considering the complexity of the task [61].

In a similar vein, Abdollahpour et al. (2018) explored a machine vision-based approach for dual-axis solar tracking. Their system employed image processing of a bar shadow to accurately determine the sun's position. Their efforts paid off, as the system demonstrated the capacity to track the sun with an accuracy of approximately ±2° [62]. In a distinct avenue of exploration, Canada-Bago and Fernandez-Prieto (2020) embarked on the development of a knowledge-based sensor tailored for controlling high-concentration PV trackers. Their focus lay in augmenting the precision of energy generation in HCPV systems [37]. To achieve this, they harnessed fuzzy rule-based systems in tandem with cutting-edge Internet of Things (IoT) technologies. Two controllers emerged from their study: one rooted in a pointing device, while the other relied on the measurement of generated electrical current.

In a parallel vein of innovation, Carballo et al. (2019) unveiled a novel paradigm for solar tracking systems (STS) by seamlessly amalgamating computer vision, cost-effective hardware, and deep learning methodologies [63]. This forward-looking approach was rigorously tested at the Plataforma solar de Almería (PSA), where its potential as an alternative to conventional systems was boldly underscored.

While these sensor-based solar tracking systems have achieved notable successes, they also share inherent challenges. Calibration, coding intricacies, sensor malfunctions, and maintenance requirements have been persistent issues. This has prompted the exploration of novel, sensorless approaches that strive to overcome these limitations and open new avenues for enhancing solar tracking systems.

1.8.2 Drawbacks and Challenges

Traditional sensor-based solar tracking methods, despite their advantages, come with limitations. The reliance on sensors introduces the risk of sensor failure or inaccuracies due to external factors. Maintenance and calibration of sensors can be labor-intensive and time-consuming. Moreover, the additional components and complexity of these systems can increase installation and operational costs. As a result, there is a need for alternative tracking approaches that address these challenges while maintaining or improving efficiency. Here's a breakdown of the gaps in the existing literature on sensor-based solar trackers:

1. Sensor Performance Evaluation: Existing literature lacks comprehensive studies comparing the performance and accuracy of different sensor types used in solar tracking systems. Research is needed to assess the reliability, sensitivity, and response time of sensors such as LDRs, photodiodes, and pyranometers in various environmental conditions.

2. Sensor-Data Integration and Control Algorithms: Limited research has been conducted on the development and optimization of control strategies that effectively utilize sensor data. Exploring advanced control algorithms, such as predictive control or machine learning-based approaches, can improve the accuracy and responsiveness of sensor-based solar trackers.

3. Environmental Factors: The impact of environmental factors on sensor performance requires further investigation. Dust, humidity, temperature variations, and shading can affect the accuracy and reliability of sensors. Research on sensor housing designs and protective measures is necessary to mitigate these effects and ensure consistent and accurate tracking performance in diverse environmental conditions.

4. Field Studies and Real-World Evaluations: Most existing research on sensor-based solar trackers is conducted in controlled laboratory settings, limiting its applicability to real-world installations. Conducting field studies and evaluations will provide insights into the long-term performance, energy yield, and reliability of sensor-based solar trackers under practical conditions.

Addressing these gaps in the literature through comprehensive sensor performance evaluations, the development of advanced control algorithms, research on environmental factors, and conducting field studies will contribute to the optimization and advancement of sensor-based solar tracking systems.

1.9 Emergence of Sensorless Solar Tracking

1.9.1 Introduction to Sensorless Tracking

A sensorless solar tracking approach reimagines the conventional paradigm of STS by eliminating the reliance on specific sensors for tracking the sun's position. Instead of direct sensor inputs, this innovative approach leverages advanced algorithms, computational models, and intelligent techniques to infer the sun's position based on available data and environmental parameters. By transcending the limitations of sensor-based systems, sensoless ST seeks to streamline system complexity, mitigate maintenance challenges, and enhance cost-effectiveness. This transformative concept holds the promise of simplifying solar tracking implementations, increasing their adaptability across varying geographical locations and solar technologies, and paving the way for more efficient and sustainable solar energy generation.The sensorless ST approach operates through a series of systematic steps, guided by geographic data, solar power generation, algorithms, and control mechanisms, as depicted in Figure 1.10. The workflow unfolds as follows:

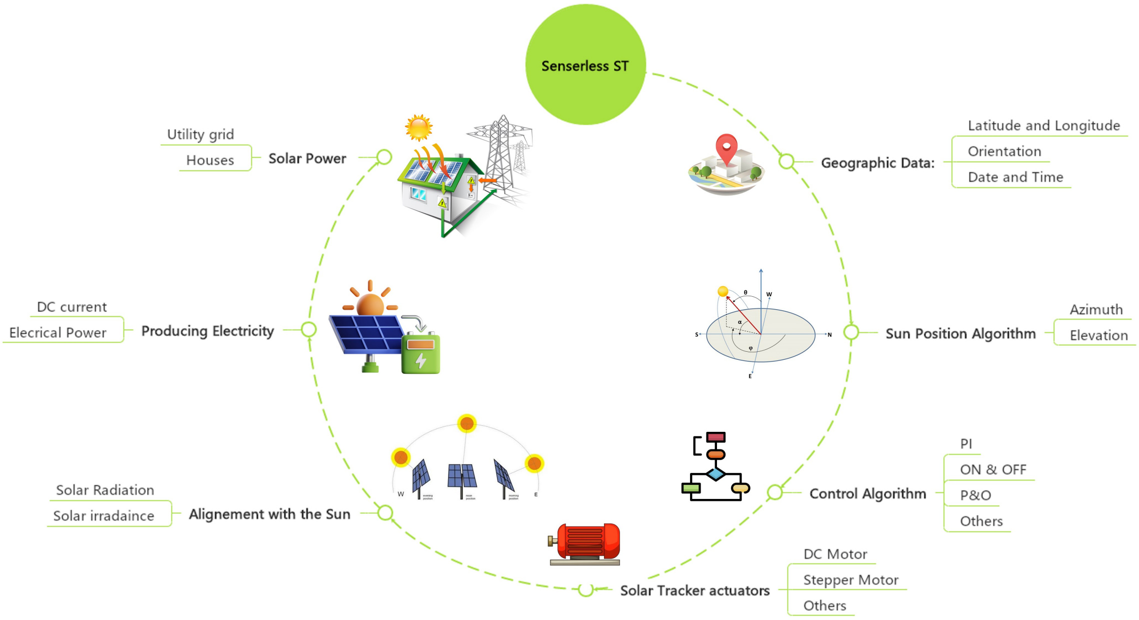


Figure 1.10: Workflow Illustration of the Sensorless Solar Tracking System

1. **Geographic Data:** The process initiates with the collection of crucial geographic data, including latitude, longitude, and orientation of the solar panel installation site, along with the precise date and time. These data points provide the foundation for accurately determining the sun's position relative to the panel.
2. **Solar Power Sources:** The sensoless ST system integrates data from various solar power sources, such as utility grids and residential houses. This data encompasses

details about the amount of electricity generated, including DC current and electrical power outputs.

3. **Producing Electricity:** Based on the collected solar power data, the system calculates and evaluates the electricity being produced by the solar panels at the given location and time.

4. **Sun Position Algorithm:** A sophisticated algorithm calculates the sun's position in the sky using the geographic data and the calculated electricity generation. This algorithm calculates the azimuth and elevation angles of the sun's rays relative to the solar panels.

5. **Alignment with the Sun:** Using the calculated sun angles, the system aligns the solar panels with the optimal orientation towards the sun. This alignment is crucial for maximizing solar radiation and irradiance on the panels.

6. **Solar Tracker Actuators:** The sensoless ST system employs various types of solar tracker actuators, such as DC motors, stepper motors, and others, to physically adjust the orientation of the solar panels. These actuators ensure that the panels remain aligned with the changing position of the sun throughout the day.

7. **Control Algorithm:** The control algorithm dictates the precise movement of the solar tracker actuators to maintain the optimal alignment with the sun. Different control algorithms, such as Proportional-Integral (PI), ON & OFF, Perturb and Observe (P&O), and others, can be used to optimize the solar panel's orientation.

By seamlessly integrating diverse components and advanced algorithms, the sensorless ST approach presents a versatile and flexible solution for achieving optimal solar tracking efficiency across a wide range of locations and applications within the realm of solar power.

1.9.2 Benefits of Sensorless Tracking

Sensorless solar tracking offers a multitude of compelling benefits that set it apart from traditional sensor-based approaches. One of its standout advantages lies in its remarkable cost-effectiveness, achieved through the elimination of dedicated sensors and the associated expenses. This approach also significantly reduces system complexity by relying on mathematical calculations and algorithms for operation. This streamlined hardware configuration not only decreases maintenance requirements but also enhances the overall durability of the system.

Furthermore, sensorless tracking greatly enhances reliability by sidestepping the potential pitfalls of sensor-related failures and calibration discrepancies. The methodology also prioritizes stability, dynamically adjusting solar panel angles to optimize sunlight exposure. Additionally, sensorless tracking algorithms generate soft control signals, leading to smoother motor movements and diminished mechanical wear over extended periods.

The simplicity of implementation further distinguishes sensorless tracking. With fewer components and streamlined setup procedures, the adoption of this technique becomes more accessible. Moreover, sensorless trackers are intricately engineered to uphold energy efficiency. Their energy consumption is meticulously designed to remain within the range of 2% to 3% of the total augmented energy output in a solar power generation system[38], ensuring that energy consumption remains low while simultaneously maximizing energy yield. This amalgamation of advantages positions sensorless solar tracking as an innovative and effective approach to optimizing solar energy generation.Figure1.11 represents an exhaustive exploration of the benefits offered by a sensorless solar tracking system .

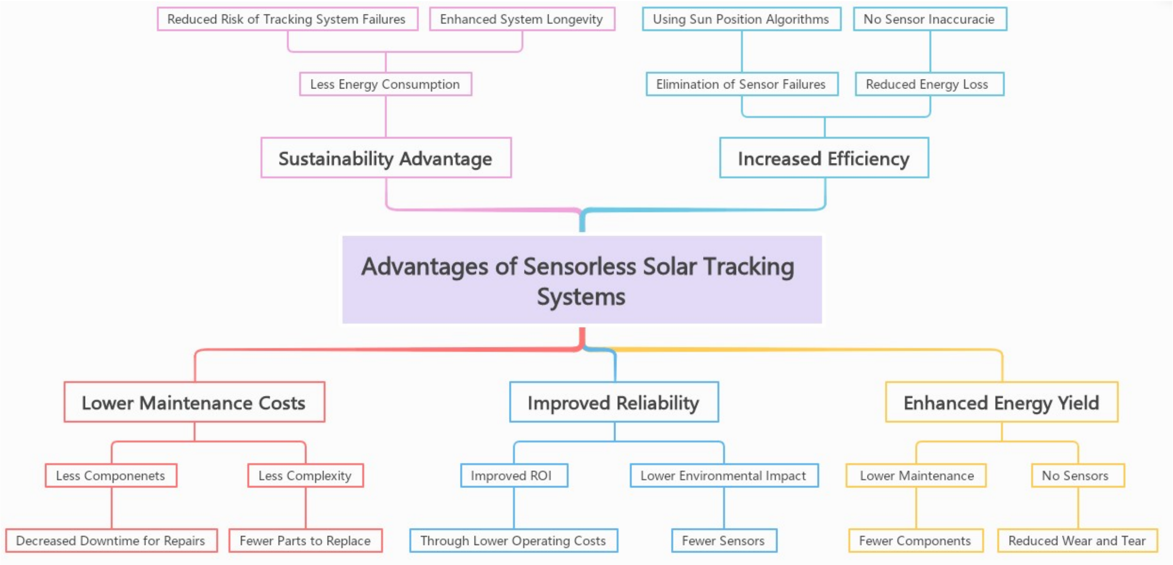


Figure 1.11: the benefits of a sensorless solar tracking system

1.9.3 Innovations in Sensorless Tracking

Recent innovations in sensorless tracking techniques have ushered in significant advancements, revolutionizing the efficiency and adaptability of solar tracking systems. The integration of sophisticated algorithms, precise mathematical models, and optimized control strategies has been instrumental in elevating the overall performance of sensorless tracking mechanisms. These innovations have not only mitigated the drawbacks of traditional sensor-based approaches but have also introduced a new level of precision and responsiveness.

The incorporation of advanced algorithms allows sensorless tracking systems to dynamically adjust solar panel orientations in response to changing environmental conditions. These algorithms take into account various parameters such as solar irradiance, cloud cover, wind speed, and ambient temperature. This data-driven approach enables real-time adjustments, ensuring that the solar panels maintain their optimal alignment with the sun's position for maximum energy capture.

Furthermore, the use of mathematical models has contributed to the accuracy and predictability of sensorless tracking systems. These models take into consideration the complex interactions between solar radiation, panel angles, and environmental factors. By utilizing these models, sensorless trackers can accurately predict the sun's trajectory and optimize the panel orientation accordingly.

Efficient control strategies are another key facet of innovations in sensorless tracking. These strategies not only optimize the solar panel angles but also account for factors such as energy consumption, motor efficiency, and system stability. This holistic approach ensures that the tracking system operates seamlessly and optimally under varying conditions.

One noteworthy innovation is the integration of machine learning techniques, such as neural networks, to enhance the adaptability of sensorless tracking systems. These networks can learn from historical data and patterns, enabling the system to continuously improve its performance over time. This self-learning capability allows the tracking system to adjust to unique environmental conditions and user-specific requirements.

In summary, innovations in sensorless tracking have leveraged cutting-edge technologies to create more efficient, adaptive, and intelligent solar tracking systems. These advancements have not only overcome the limitations of traditional sensor-based approaches but have also opened up new possibilities for enhancing energy capture, system reliability, and overall operational efficiency. As technology continues to evolve, sensorless tracking is poised to play a crucial role in the future of solar energy systems.

1.10 Current State of Research

1.10.1 Review of Literature

- In their 2017 research, M.H.M. Sidek et al[23]. developed a sensorless solar tracker system using a hierarchical control architecture, encompassing master and slave controllers. The master controller, a Microchip's PIC18f4680 microcontroller, oversaw algorithm execution, calculations, and path trajectory database creation, driven by astronomical equations and GPS data for precise solar positioning. Microchip's PIC18f4431 microcontrollers served as slave controllers, interfacing with motor drivers and position feedback sensors. The integration of a Honeywell HMC6352 digital compass sensor module effectively addressed PV offset and misalignment. Notably, an embedded Proportional Integral Derivative (PID) positioning system enhanced angle tracking, minimizing energy consumption. In comparison to fixed PV systems,

- In their 2011 study[24], Sebastijan Seme and Gorazd Stumberger introduced an innovative open-loop solar tracking strategy for optimizing energy production within a photovoltaic (PV) system, distinctively not relying on solar sensors. Their method encompasses a Differential Evolution algorithm, utilizing sunbeam path length and pyranometer data for solar radiation prediction. This predicted radiation is then harnessed to estimate potential energy output. Moreover, they integrate energy consumption and power output data from the tracking system, leveraging the Differential Evolution algorithm to pinpoint optimal azimuth and tilt angles, all while adhering to angular constraints. It's noteworthy that this approach adheres to an open-loop strategy and abstains from employing solar sensors.

- In their 2015 research, Nazir, Refdinal and Hadi, Muhammad and others[25] developed an innovative sensorless dual-axis solar tracking system by leveraging precise sun position data obtained from a sunrise and sunset database. The creation of this database involved meticulous calculations of solar azimuth and elevation, utilizing the Terrestrial Dynamical Time (TDT) system with input parameters such as local date, time, geographical coordinates, altitude, and timezone. By employing linear interpolation techniques, the solar position with respect to two angles, referred to as "a" and "b," could be extrapolated for various times throughout the day. The motion of the solar panel was then orchestrated based on these calculated sun positions along the "a" and "b" angles. The prototype of this solar tracker comprised digital electronic circuits and mechanical components, demonstrating successful functionality, particularly for smaller solar panel configurations.
- In their research, Ceyda Aksoy Tirmikci and Cenk Yavuz (2015) [26]addressed the critical challenge of sustainable energy provision by exploring solar tracking technologies and introducing an innovative sensorless dual-axis solar tracking system. Recognizing the imperative to optimize solar energy capture, the researchers devised a system controlled by a low-power microcontroller, guided by precise solar mathematics. Their approach capitalized on the inherent predictability of solar movement based on latitude and time of day, obviating the need for costly sensors. Two linear actuators were employed to achieve dual-axis movement, enabling precise adjustments of solar panel orientation. The researchers meticulously designed the mechanical and electronic components, aiming for an economical, flexible, and efficient solution.
- In the research conducted by Hassan Fathabadi in 2016[64], a comparative study between two novel solar tracking systems was undertaken. The study aimed to enhance the efficiency of solar energy conversion by designing and constructing two distinct dual-axis solar trackers. Notably, the first tracker was a sensorless dual-axis solar tracker, boasting an exceptionally low tracking error of merely 0.43 degrees. This degree of accuracy surpassed that of most other sensorless and sensor-based solar trackers documented in the literature. Conversely, the second tracker was a sensor-based dual-axis solar tracker, exhibiting a tracking error of at most 0.14 degrees, which was

notably superior to state-of-the-art sensor-based trackers. A noteworthy contribution of this work was the rigorous comparison of the performances of these two trackers in terms of energy conversion efficiency and cost-effectiveness.

- In the year 2020, Chan Men Loon and Muhamad Zalani Daud [28]embarked on an innovative research endeavor focused on advancing solar energy harvesting through the development of a novel sensorless dual-axis solar tracker. Departing from conventional methods that utilize sun position algorithms, their approach is centered around a distinctive concept that leverages current sensors to detect optimum azimuth and tilt angles. This cutting-edge algorithm operates by identifying the positions at which the solar panel exhibits maximum current generation, which corresponds to its most efficient alignment with the sun's rays.

- In 2016, Hassan Fathabadi [27]introduced a novel and highly accurate sensorless dual-axis solar tracking system that was controlled by the ubiquitous maximum power point tracking (MPPT) unit present in photovoltaic systems. This system aimed to optimize solar energy extraction by dynamically adjusting the orientation of the solar panels based on real-time calculations of the maximum power output. Unlike traditional sensorless trackers, Fathabadi's system was designed as a closed-loop setup, utilizing current sun direction data for precise tracking. The core concept involved calculating the optimal output power of the photovoltaic module and employing deviations in altitude and azimuth angles to precisely track the sun's path. By leveraging the advantages of both sensor-based and sensorless tracking approaches, this system aimed to offer improved accuracy without the limitations commonly associated with each method

- In the year 2023, a pioneering advancement in solar photovoltaic (PV) technology was introduced by Alongkorn Pirayawaraporn and collaborators[29]. Their research focuses on augmenting PV energy generation through the implementation of a unique sensorless dual-axis solar tracking system. This innovative system utilizes a particle filter (PF) algorithm as its core methodology, aimed at overcoming the limitations inherent in existing solar tracking systems. Unlike conventional approaches, which often rely on historical meteorological data or complex mathematical models, the proposed system integrates PF to iteratively estimate the sun's position. This circumvents the need for such resource-intensive elements, marking a significant leap forward in the realm of PV energy optimization.

- In 2019, Soroush Ghabusnejad and his collaborators introduced an innovative approach to solar tracking through their research on a power and light sensor-less P&O (perturbation and observation) based single-axis tracking method [65]. This methodology presents a cost-effective alternative for both solar power stations and standalone systems, such as buildings or water pumps. The system employs a stepper motor to continuously adjust the angle of incidence, while a controller assesses the maximum received power at each angle. This enables the system to accurately determine the sun's direction without the need for conventional sensors. The proposed algorithm is closed-loop and adaptable to various locations. Unlike traditional methods that rely on light-dependent resistors (LDRs), geographical equations, or time-based positioning, this methodology offers robust performance under different weather conditions, including cloudy skies.

- Hassan Fathabadi conducted two groundbreaking studies in the field of solar tracking, each proposing innovative sensorless dual-axis sun tracking systems [66, 27]. In 2017, Fathabadi introduced a novel online sensorless dual-axis sun tracker that utilizes the maximum power point tracking (MPPT) unit to continuously calculate the maximum output power of photovoltaic modules. The tracker uses deviations in altitude and azimuth angles to determine the sun's direction with the highest output power value. Unlike conventional open-loop sensorless trackers, this system operates as a closed-loop, tracking the actual sun direction in real-time. By combining advantages from both sensor-based and sensorless approaches, this methodology eliminates their drawbacks.

- In 2022, Chien-Hsing Wu, Hui-Chiao Wang, and Horng-Yi Chang introduced a novel dual-axis solar tracking system equipped with a satellite compass and inclinometer for automated sun positioning and tracking [67]. The system was designed to optimize solar energy harvesting by accurately aligning solar panels with the sun's trajectory throughout the day. The research aimed to overcome challenges related to low sunlight incident angles and manual orientation calibrations. To achieve this, the proposed tracker employed two Global Positioning System (GPS) receivers with Real-Time Clock (RTC) functionality, forming a satellite compass, and integrated an inclinometer. This combination eliminated the need for manual alignment of the system's heading to the North-South orientation, ensuring precise sun tracking. A microcontroller unit (MCU) controlled the dual-axis instrument, coordinating servo-motors, the satellite compass, and the inclinometer. The embedded Solar Position Algorithm (SPA) utilized data from the satellite compass to determine accurate sun vector angles based on geographical information.

- In 2014, M.H.M Sidek, W.Z.W Hasan,and others undertook the design and development of a GPS-based portable dual-axis solar tracking system utilizing astronomical equations [68]. The primary objective was to create a versatile and mobile solar tracking solution. The study's focus was on the design aspects, the electronic control system, and the algorithm implementation using astronomical equations. The tracking system's core components included a GPS module for location determination and a digital compass sensor for heading feedback. A microcontroller-based system integrated with a PID (Proportional-Integral-Derivative) controller was employed to enhance the positioning accuracy of photovoltaic (PV) panels, leveraging feedback from an absolute encoder. The research also entailed a comparison between the performance of the developed portable solar tracking system and fixed-tilted PV panels.

- In 2021, Neelam Verma, Manish Kumar, and Shivam Sharma introduced a real-time solar tracking system that utilizes GPS technology to optimize power output from solar energy systems, particularly on moving platforms [69]. The system addresses the challenge of maximizing power output from solar installations that experience varying sunlight angles due to changing locations. The authors discussed various subsystems within the proposed system and highlighted its advantages over existing techniques.
- The research conducted by Nadia AL-Rousan, Nor Ashidi Mat Isa, and Mohd Khairunaz Mat Desa in 2020 [70] introduces innovative solar tracking system controllers based on the Adaptive Neural Fuzzy Inference System (ANFIS) principle. The aim of their study is to design and implement efficient single and dual-axis solar tracking control systems that enhance solar tracker performance, accurately predict the sun's trajectory across the sky, minimize errors, and thereby maximize energy output. The proposed ANFIS models are trained and tested using experimental data, utilizing input variables such as month, day, and time to predict optimal solar tracking positions (tilt/orientation angles). The results demonstrate the controllers' efficacy in achieving high prediction rates and low error rates, thereby enhancing solar tracking systems' performance and energy capture.
- The research conducted in 2019 by the authors [71] presents a novel discrete single-axis solar tracking system that actsuates only three times a day in the azimuthal plane to track the sun. The system's tracking angles are determined based on simulations that incorporate weather data for optimal discrete tracking angles.

1.10.2 Key Research Findings

- The findings from M.H.M. Sidek's research in 2017 [23]revealed that the sensorless solar tracker presented significant benefits. It achieved an impressive 26.9% increase in energy gain and maintained a low energy consumption of just 14.4 Wh. Even when faced with challenging heavy overcast conditions, the tracker managed to produce a notable 12.8% higher power output, highlighting its versatility across various scenarios. The system's precision was evident, boasting a ±0.5° accuracy, which emphasized its ability to precisely track solar positioning.
- The research conducted by Sebastijan Seme and Gorazd Stumberger[24] unveiled a remarkable breakthrough in the realm of energy optimization. Through a meticulously

designed open-loop approach, the researchers achieved heightened energy production levels, all without relying on solar sensors. Their pioneering algorithm for solar radiation prediction enabled precise estimation of potential energy output. Merging this with data on energy consumption and power output from the tracking system, and employing the prowess of the Differential Evolution algorithm, they successfully pinpointed the optimal azimuth and tilt angles. Notably, the results presented in the paper demonstrate that this innovative procedure significantly increased the efficiency of energy production within the photovoltaic system, boasting enhancements of 10–50%.

- The findings from Nazir, Refdinal and Hadi, Muhammad and others's research in 2015[25] unveiled a substantial enhancement in solar power generation efficiency through their sensorless dual-axis solar tracking algorithm. By comparing the electrical power output of a solar panel positioned flat versus upright to catch sunlight, the researchers observed a significant increase in energy capture. In a span of seven hours, the energy harvested from the flat position was measured at 166.4 Watthour. However, with the implementation of the solar tracker algorithm, this output escalated to 225.05 Watthour, representing a remarkable boost of 26% in solar power generation efficiency. This augmentation in efficiency is independent of weather conditions; even on cloudy days, the solar panel's positioning remained optimized to capture the maximum available sunlight, thereby consistently maximizing electricity generation
- The research conducted by Ceyda Aksoy Tirmikci and Cenk Yavuz (2015) [26]underscored the prominence of dual-axis solar trackers in enhancing energy generation efficiency. Through rigorous analysis, they established that dual-axis trackers outperformed single-axis counterparts and fixed panels, offering up to 40% greater efficiency in optimal scenarios. The unique dual-axis design allowed for precise adjustments in both azimuth and elevation angles, optimizing solar panel orientation. Despite being more intricate and expensive compared to single-axis trackers, dual-axis trackers demonstrated superior performance gains. The study also advocated for a sensorless approach, utilizing solar mathematics to calculate sun angles. This method eliminated the need for costly sensors and ensured a cost-effective yet efficient solution adaptable to various weather conditions.
- The research outcomes by Hassan Fathabadi[64] showcased the remarkable performance of both sensorless and sensor-based dual-axis solar trackers in augmenting solar energy conversion efficiency. The findings revealed that the application of the sensor-based solar tracker to a photovoltaic (PV) panel aligned with the sun's noon position yielded substantial benefits. Notably, the average daily captured solar energy increased by approximately 27.7%, 32.5%, 37.3%, 42.7%, and 35.22% during winter, spring, autumn, summer, and over the course of a year, respectively. The sensorless tracker, while still offering improved performance, exhibited relatively lower

increases in energy capture, at 19.1%, 22.4%, 26.1%, 30.2%, and 24.59% for the same seasonal periods. It is noteworthy that the sensorless tracker tracked the sun's direction across the sky, while the sensor-based version identified the sky direction with maximum solar irradiance absorption. Despite the significant energy gains achieved by the sensor-based tracker, it was acknowledged that its complexity and higher cost posed certain disadvantages compared to the sensorless counterpart.

- The results of the 2020, Chan Men Loon and Muhamad Zalani Daud research [28] were indeed enlightening. By optimizing solar panel alignment to maximize current output rather than relying on sun position calculations, the proposed sensorless dual-axis tracker consistently outperformed both fixed panel systems and trackers employing the traditional Sun Position Algorithm (SPA). Notably, the proposed algorithm exhibited a 17.96% improvement in energy harvesting efficiency compared to fixed systems, and a 6.38% enhancement over SPA-based trackers. Despite these impressive findings, a noteworthy observation emerged during the experiment—a sudden change in weather conditions led to significant fluctuations in results. Precisely at 12:50 PM, the algorithm's performance experienced a drastic drop in alignment accuracy due to rapidly changing cloud cover. This observation highlights the algorithm's sensitivity to abrupt environmental changes and the need for strategies to mitigate such disruptions.

- Fathabadi's [27] innovative solar tracking system yielded remarkable findings that underscored its superiority over existing solutions. The key highlight was the minimal tracking error of just 0.11 degrees, a remarkable achievement compared to the errors associated with other solar tracking systems. This level of accuracy was made possible by the closed-loop nature of the system, which harnessed real-time sun direction data. Moreover, the system demonstrated a significant increase in energy efficiency. Depending on the season, the proposed system outperformed fixed systems by enhancing energy efficiency by 28.8% to 43.6%.

- Pirayawaraporn et al.'s research [29] yielded significant findings regarding the performance of their sensorless dual-axis solar tracking system. Through a comparative study conducted over 60 days under various weather conditions, the proposed system demonstrated remarkable enhancements in energy generation efficiency. The experimental results showed that the innovative tracking system improved energy generation performance by an impressive 20.1% compared to a fixed flat-plate system.

- Ghabusnejad et al.'s research [65] yielded valuable findings concerning their sensorless P&O based single-axis solar tracking method. By integrating perturbation and observation techniques into their tracking strategy, the researchers achieved significant enhancements in solar energy capture. The proposed method's adaptability to different weather conditions, including cloudy skies, was demonstrated through simulations and experiments. Importantly, the methodology's closed-loop design eliminated the reliance on conventional light or current sensors. The experimental results showcased exceptional accuracy, with the error of the optimum angle limited to a maximum of 1.5 degrees, comparable or even superior to previous research efforts.

- Fathabadi's work in 2017 [66] showcased significant findings related to the novel online sensorless dual-axis sun tracker. By exploiting the MPPT unit and a closed-loop system design, the tracker achieved exceptional tracking accuracy with a minimal error of 0.11°. Moreover, the tracker's unique combination of advantages from both sensor-based and sensorless trackers resulted in enhanced solar energy capture. On a similar note, Fathabadi's research in 2016 [27] presented an offline sensorless dual-axis solar tracker. This tracker harnessed offline data from solar map equations to determine sun direction, achieving an impressive increase of 19.1%–30.2% in captured solar energy depending on the seasons. Its innovative structure and offline technique differentiated it from traditional sensor-based trackers, providing accurate tracking with a remarkably small error of 0.43°.
- The study's findings [67] revealed the impressive performance of the proposed dual-axis solar tracker. Comparative analyses against a fixed-tilted photovoltaic (PV) tracker were conducted under various scenarios, including fixed, rotating, and moving conditions. The proposed solar tracker, leveraging the satellite compass and inclinometer, consistently outperformed the fixed-tilted tracker. Specifically, the field measurements demonstrated energy capture improvements of 35.91% in mostly clear weather under fixed locations, and up to 38.72% and 38.40% in different locations with clear days. Notably, the tracker's efficiency soared to 60% in heading variation conditions and an astonishing 113.70% in moving conditions compared to the fixed-tilted system. These results underscore the system's ability to dynamically and accurately track the sun's movement, leading to substantial energy gains.
- In the 2014 study by M.H.M Sidek and colleagues [68], the integration of a PID control algorithm was found to play a pivotal role in enhancing the precision of PV panel positioning. This resulted in a remarkable improvement in tracking angle accuracy, allowing the system to locate the elevation and azimuth angle with a high level of precision, up to ± 0.2 degrees.Additionally,the research demonstrated the successful utilization of a GPS module and a digital compass sensor for real-time location determination and heading feedback. This integration enabled the development of a portable dual-axis solar tracking system with the ability to accurately follow the sun's trajectory throughout the day.
- The findings of the Neelam Verma et al [69] research showcase the effectiveness of the proposed real-time solar tracking system. By integrating GPS technology and a

two-axis tracker, the system achieves improved solar energy capture by dynamically adjusting the orientation of solar panels based on the sun's position. This innovative approach results in a significant enhancement in power output efficiency compared to fixed solar installations. The authors reported that the proposed system demonstrates its capabilities effectively in real-world scenarios, ensuring optimal power generation even on moving platforms with varying geographical positions .

- The findings of the study [70] underscore the efficiency of the proposed ANFIS-based solar tracking controllers. These controllers exhibit superior predictive capabilities, achieving high prediction rates and low error rates in determining optimal tilt and orientation angles for both single-axis and dual-axis solar tracking systems. By utilizing five membership functions, the ANFIS models demonstrate optimal efficiency, outperforming other fuzzy and neural network principles. The research concludes that ANFIS effectively drives solar photovoltaic systems to track the sun's trajectory across the sky, resulting in enhanced energy generation and improved solar tracker control.
- The findings from this study [71] showcase that the discrete single-axis solar tracking system, with its unique actuation three times a day, offers promising results. Simulation outcomes reveal comparable solar energy generation using tracking angles from isotropic or anisotropic models.Moreover, experimental results which closely aligned within 11-17% of simulation data during the summer season demonstrate that the proposed discrete tracking system achieves approximately 91-94% of the solar energy collection obtained by a continuous single-axis solar tracker that moves every hour based on solar calculations. This indicates potential energy savings and calls for further investigation into the system's efficiency and motor energy consumption trends.

1.10.3 Identified Research Gaps

- Starting with M.H.M. Sidek's research in 2017, their developed sensorless solar tracker system, while innovative, does present certain drawbacks. The complexity arises due to the integration of multiple components like microcontrollers, sensors, and actuators, potentially leading to challenges during installation, maintenance, and troubleshooting. However, it's worth noting that their study doesn't fully address the complexities of system deployment and management. Additionally, the costs associated with the development, fabrication, and implementation of this automated dual-axis solar tracking system might exceed those of fixed-tilted PV systems. Maintenance becomes a key concern as automated systems often require regular upkeep to ensure smooth tracking mechanism and electronics operation. The system's reliability hinges on the dependability of its electronic components, sensors, and software algorithms, raising questions about its long-term performance. Moreover, while the system is engineered to enhance energy generation during overcast days, its effectiveness could be constrained in scenarios of heavy cloud cover or low lighting conditions. Thus, while offering innovative solar tracking solutions, this approach prompts consideration of these potential challenges for practical deployment and sustained efficiency.

- The approach presented in the Sebastijan Seme and Gorazd Stumberger[24] 2011 research offers advantages in optimizing energy production within a photovoltaic system, yet it also comes with inherent disadvantages. These include the computational complexity of the optimization process, sensitivity to model parameters, potential inaccuracies in energy production and consumption models, limited capture of real-world variability, and the reliance on clear sky assumptions for solar radiation prediction. Additionally, the method's practical implementation may introduce challenges in translating optimized angles into real-world control, and the approach's effectiveness could be constrained to specific locations and time intervals. The complexities of the Differential Evolution algorithm, system cost, and maintenance requirements further contribute to the limitations of the approach.
- Although the approach presented in Nazir, Refdinal and Hadi, Muhammad and others's 2015 [25]research offers noteworthy advantages in terms of increased solar power generation efficiency and consistent panel orientation, it does exhibit inherent disadvantages. Notably, the effectiveness of the sensorless solar tracker is less pronounced in cloudy weather due to diminished variations in sunlight direction. The algorithm's dependence on linear interpolation for sun position calculations might introduce inaccuracies during rapid changes in sunlight angle. Additionally, the proposed system assumes a fixed solar panel orientation, which might not be ideal for large-scale installations or environments with complex shading patterns. Furthermore, while the research highlights an impressive 26% efficiency improvement, the specific conditions under which this enhancement occurs should be further investigated, as variations in geographic location and environmental factors could influence the actual performance gains.
- While the sensorless dual-axis solar tracking system proposed by Ceyda Aksoy Tirmikci and Cenk Yavuz (2015)[26] offers remarkable benefits, certain limitations and research gaps warrant consideration. The reliance on linear actuators for movement raises challenges related to positional feedback. Although the study addressed this concern by incorporating cost-effective linear potentiometers, the algorithm's complexity increased. Moreover, the study showcased the system's efficacy under specific wind and pressure conditions, indicating the need for broader environmental robustness testing. The authors acknowledged the higher complexity and cost associated with dual-axis trackers and suggested further exploration of strategies to mitigate these factors.

- While the research by Hassan Fathabadi [64]demonstrated promising advancements in solar tracking technology, it also illuminated certain limitations and trade-offs associated with the two types of trackers. The sensor-based dual-axis solar tracker, although delivering superior energy efficiency improvements, involved greater intricacy and cost due to the necessity of incorporating an irradiance sensor with a radiance limiting tube and additional mechanical components. Conversely, the sensorless dual-axis tracker, while achieving commendable energy enhancements, showcased reduced performance gains compared to its sensor-based counterpart.

- While the proposed the 2020, Chan Men Loon and Muhamad Zalani Daud research[28] introduced a groundbreaking approach to energy optimization, certain limitations and research gaps surfaced during the investigation. Notably, the algorithm's sensitivity to environmental factors, particularly swift changes in weather conditions, underscores the need for further refinement. The algorithm's effectiveness relies on real-time current measurements, rendering it susceptible to sudden fluctuations caused by cloud cover or other unforeseen factors. Additionally, the study did not elaborate on the specific calculation methods employed to determine the optimal azimuth and tilt angles based on maximum current output. Furthermore, while the sensorless approach alleviates the need for dedicated sun position sensors, it employs current sensors instead, prompting questions about the broader applicability and scalability of this method.

- While Fathabadi's work [27]showcased remarkable advancements in solar tracking technology, a few potential research gaps and disadvantages deserve attention. The paper highlighted the advantages of the system, particularly its accuracy and efficiency gains. However, it might have been beneficial for Fathabadi to delve into potential challenges or limitations of the proposed method. For instance, the system's reliance on real-time sun direction data could potentially face challenges in scenarios with frequent cloud cover or rapid weather changes. Additionally, while Fathabadi's work succeeded in demonstrating the feasibility and benefits of the system, further studies could explore the system's performance across a broader range of geographic locations, weather conditions, and types of photovoltaic modules. Such investigations would provide a comprehensive understanding of the system's robustness and suitability for diverse applications.

- Despite the remarkable achievements of Pirayawaraporn et al.'s sensorless dual-axis solar tracking system [29], certain research gaps and limitations remain evident. The proposed system's reliance on the particle filter (PF) algorithm for tracking, while innovative, may introduce computational complexity that requires optimization to minimize operational energy consumption. Additionally, further exploration of alternative sampling-based algorithms could offer avenues to reduce the number of particles and energy consumption. Moreover, a comprehensive techno-economic analysis is necessary to assess the economic feasibility of implementing this novel tracking system..

- While the sensorless P&O based single-axis tracking method by Ghabusnejad et al. [65] presents promising advantages, certain research gaps and limitations merit attention. The paper highlights the methodology's independence from azimuth, altitude angles, and geographical equations, making it adaptable to diverse weather conditions. However, further investigation could be undertaken to explore the system's performance under extreme weather scenarios or dynamic environments. Moreover, the proposed method's reliance on the inner and outer layers of P&O methods introduces a layered approach that could benefit from optimization to improve convergence speed and accuracy. Additionally, exploring the potential application of this innovative system as a guiding mechanism for groups of solar panels could expand its practical utility and impact.

- While Fathabadi's research [66, 27] presents notable advancements, certain gaps and considerations arise. In the case of the 2017 study [66], the system's performance under extreme weather conditions and dynamic environments remains a potential avenue for further exploration. Additionally, a comparative analysis of the system's robustness against other sensorless and sensor-based trackers could provide deeper insights into its efficacy. The 2016 research [27] highlighted the offline sensorless dual-axis solar tracker's strengths, such as cost-effectiveness and independence from feedback signals. Nevertheless, further investigations could delve into the tracker's response to varying solar conditions and potential improvements in tracking accuracy.

- While Chien-Hsing Wu et al.'s research [67] introduced a highly innovative dual-axis solar tracking solution, certain avenues for further exploration and consideration arise. The study's focus on automated sun positioning using a satellite compass and inclinometer addresses critical challenges in solar energy harvesting. However, potential research gaps may involve investigating the system's performance under extreme weather conditions and assessing its adaptability to various geographical locations and climatic variations. Furthermore, in-depth analyses of the system's reliability and robustness in practical scenarios, such as mobile vehicles, floating solar power systems, or remote locations, could provide insights into its real-world feasibility and application potential.

- The 2014 study by M.H.M Sidek and colleagues [68] introduces a portable dual-axis solar tracking system with emphasis on the open-loop astronomical equation and PID control integration. However, the research lacks a comprehensive analysis of potential inaccuracies in trajectory calculations due to atmospheric conditions and the mechanical reliability of the system during adverse weather. Moreover, economic feasibility and scalability aspects are not fully explored, leaving gaps in understanding the system's real-world viability for larger-scale installations.

- the Neelam Verma et al research [69]reveals certain research gaps and limitations. While the proposed real-time solar tracking system holds promise for moving platforms, its application in large-scale installations or environments with specific operational constraints might need further investigation. Potential disadvantages might include increased system complexity, maintenance requirements, and initial setup costs. These potential drawbacks could be areas for future research and development to enhance the system's applicability and scalability across diverse scenarios. The research in 2021 by Verma, Kumar, and Sharma opens up avenues for further exploration into optimizing solar energy generation in dynamic environments and addressing the challenges associated with moving solar installations .

- However, the research by AL-Rousan et al. [70] also suggests potential research gaps and limitations. While the ANFIS-based controllers showcase promising performance, further investigations may be needed to explore their applicability in complex scenarios, large-scale installations, and environments with specific constraints. Additionally, challenges related to the implementation, maintenance, and scalability of ANFIS controllers for solar tracking systems could warrant further attention. These aspects offer opportunities for future research endeavors to optimize and refine ANFIS-based solar tracking systems for a broader range of applications and scenarios.

- in the [71] research, a noteworthy limitation arose due to the absence of Maximum Power Point Tracking (MPPT), which led to a partial loss of the system's energy potential. The authors highlighted the potential of MPPT integration in discrete tracking systems to unlock higher photovoltaic (PV) power production. This observation points toward future avenues for improving the performance of discrete tracking systems, offering the potential for enhanced efficiency in PV energy generation. Moreover, the study recommended further investigation through accelerated life cycle testing of the tracking system's motors.

The research conducted by various scholars in the field of sensorless solar tracking systems reveals common gaps and limitations that deserve attention. Despite the innovative proposition of reducing costs and complexity, many of these studies resort to the incorporation of sensors, such as irradiance sensors, inclinometers, and current sensors, which can escalate the overall complexity and expenses. Complex optimization algorithms requiring data storage and energy consumption add further intricacy to these systems. Moreover, the continuous movement of sensorless trackers to locate optimal angles for maximum power collection introduces the risk of heightened energy consumption and potential mechanical strain. The impact of weather conditions on these trackers is noteworthy, as they might be more susceptible to adverse weather. It's notable that these novel approaches could end up being more intricate and costly than their sensor-based counterparts. As these research studies showcase the potentials of sensorless tracking, the recurring reliance on sensor technologies and complex optimization approaches raises concerns about practical feasibility, scalability, and reliability. These shared gaps include concerns regarding installation, maintenance, system performance in varying weather conditions, and economic viability.

1.11 Practical Applications and Implementation

In recent years, sensorless solar tracking systems have gained significant attention due to their potential to enhance solar energy capture without relying on external sun-tracking sensors. This section showcases practical applications and case studies where sensorless solar tracking has been successfully implemented.

Sunflower-Inspired Solar Tracking System

Researchers have drawn inspiration from sunflowers to design a biomimetic solar tracking algorithm[72, 73]. By analyzing the pattern of light and shadows on solar panels, this system accurately determines the sun's position and adjusts panel orientation. This approach eliminates the need for traditional sun-tracking sensors, making it suitable for off-grid solar installations.

Computer Vision-Based Solar Tracking

Computer vision techniques have been used to enable sensorless solar tracking[74, 75]. Cameras capture images of the sky and surroundings, and advanced image processing algorithms identify the sun's position. This technology has been deployed in residential solar installations to enhance energy yield.

Machine Learning-Driven Solar Tracking

Machine learning algorithms predict the sun's movement patterns based on historical data and real-time inputs. These algorithms analyze weather conditions, time of day, and location to optimize solar panel positioning. This approach adapts to changing conditions and achieves higher energy output[76, 77, 78].

Distributed Sensor Network for Solar Tracking

Distributed networks of light sensors are strategically placed around solar panels. These sensors measure incoming light intensity and direction, enabling the system to estimate the sun's position. This approach has been used in large-scale solar farms to improve energy production efficiency[79].

IoT-Integrated Solar Tracking

IoT technology has been integrated into solar tracking systems to enable real-time data collection and analysis[80, 81, 82, 83, 84]. IoT devices gather environmental information, which influences panel orientation. This data is transmitted to a central control unit that calculates optimal panel angles.

Optical Sensors and Shadow Analysis

Optical sensors [85]detect shadows cast by objects, and by analyzing shadow movement patterns, the system estimates the sun's position. This technique is valuable in urban environments where shading from surrounding structures impacts solar energy generation.

Cloud-Imaging Solar Tracking

Cloud movements indirectly indicate the sun's position. Cloud-imaging systems use cameras to capture images of the sky and track cloud movements[86, 87]. By analyzing cloud motion, the system estimates the sun's location and adjusts solar panels.

The successful implementation of sensorless solar tracking systems demonstrates their potential to optimize solar panel positioning and enhance energy production efficiency across various scenarios. Innovative technologies such as computer vision, machine learning, distributed sensor networks, and IoT integration have enabled these advancements in solar tracking.

1.12 Research insights

1.12.1 Problematic

The existing literature extensively explores solar tracking systems, emphasizing the dichotomy between sensor-based and sensorless approaches. However, a critical gap remains, demanding an innovative solution that not only optimizes energy output but also aligns with the overarching goals of cost reduction and system simplification. The drawbacks of sensor-based trackers, including high costs, susceptibility to adverse weather conditions, and demanding maintenance, necessitate a shift towards sensorless tracking. While sensorless approaches show promise, they often diverge from the essential objective of achieving global feasibility with reduced costs and complexities. The challenge lies in developing a solar tracking system that combines the advantages of sensorless tracking while mitigating the limitations associated with sensor-based counterparts. This research aims to address this gap by proposing a simple, cost-effective, and industrially viable solar tracking solution that caters to both small and large-scale PV systems. Leveraging insights from the literature, the goal is to design a solar tracker that ensures optimal energy capture without compromising on accessibility and practicality on a global scale.

1.12.2 Research Objectives

The primary objective of this research is to enhance the efficiency of solar power generation by eliminating the reliance on specific sensors in solar tracking systems. The central focus is to revolutionize the conventional paradigm of solar tracking, aiming for an innovative approach that delivers efficient energy generation with a host of benefits.

Through this study, we aim to achieve the following goals:

1. **Enhanced Efficiency:** The research seeks to optimize the efficiency of solar power generation by precisely aligning solar panels with the sun's trajectory. By dynamically tracking the sun's movement using a ZIP code-based approach, we intend to achieve higher energy capture rates and overall system efficiency.

2. **Cost-Effectiveness:** Our objective is to significantly reduce the cost of solar tracking systems by eliminating the need for dedicated sensors. This approach has the potential to make solar tracking technology more accessible and affordable, opening doors for broader adoption across various socio-economic contexts.

3. **Simplicity and Low Complexity:** We aim to simplify solar tracking systems by removing intricate sensor components. The research intends to streamline the overall system architecture, making it less complex and easier to install, operate, and maintain.

4. **Adaptivity to Weather Conditions:** Weather conditions can impact the performance of solar tracking systems. Our research aims to enhance system adaptability, ensuring optimal tracking even under varying weather conditions, without the vulnerability of sensor malfunctions.

5. **Smooth Operation:** Unlike continuous motion in sensor-based solar tracking, our goal is to achieve smooth operation with controlled, periodic adjustments. The system is designed to rotate the solar tracker every 15 minutes for precise alignment, contributing to stable energy generation.

6. **Reduced Energy Consumption:** By eliminating specific sensors, we aim to reduce the energy consumption associated with sensor operations and maintenance. This reduction contributes to a more sustainable and efficient energy production process.

7. **Wider Applicability:** We aspire to create a solar tracking solution that can be implemented in diverse geographical locations and weather environments. The goal is to develop a technology that adapts to different settings without compromising accuracy, efficiency, or smooth operation.

In summary, the overarching aim of this research is to redefine solar tracking systems by introducing a novel approach that enhances energy generation efficiency without the need for specific sensors. By achieving these objectives, we anticipate contributing to the advancement of renewable energy solutions and addressing the challenges associated with conventional solar tracking methods.

1.12.3 Research Questions

The research is guided by the following research questions, which provide a clear focus on the study's objectives and expected outcomes:

1. How can solar power generation efficiency be optimized without relying on specific sensors for solar tracking?
2. What are the advantages and disadvantages of utilizing sun position algorithms for solar tracking compared to traditional sensor-based systems?
3. What is the impact of the proposed sensor-less solar tracking approach on the overall cost-effectiveness of solar tracking systems?
4. How does the novel sensorless solar tracking approach address the challenges of smooth operation, adaptability to weather conditions, and reduction in energy consumption?
5. How can the proposed system be practically implemented and integrated into existing PV setups across varying geographic locations and weather environments?
6. How can the proposed system be resilient to Algerian weather conditions and how it can be properly implemented?

These research questions will guide the investigation, experimentation, and analysis to address the gaps in the field and contribute to the development of a sensorless solar tracking system that enhances energy efficiency in PV systems.

1.12.4 Significance and Contributions

The significance of this research is profound and extends to the realms of solar energy systems and solar tracking technology. By delving into and implementing more accurate and adaptable tracking algorithms, this study takes a bold step towards addressing the limitations inherent in traditional tracking methods, offering fresh perspectives on how we can enhance the efficiency of solar tracking systems. The amalgamation of environmental factors and the application of cutting-edge techniques such as machine learning and image processing showcase innovative approaches for optimizing solar panel angles and fine-tuning tracking mechanisms.

The outcomes of this research furnish us with invaluable insights into augmenting energy output and maximizing the overall performance of solar tracking systems. Furthermore, these findings underscore the critical importance of incorporating real-time environmental data into tracking algorithms, illustrating their capability to achieve optimal efficiency under diverse and evolving conditions.

The contributions of this research extend well beyond the laboratory or the theoretical realm. They manifest as tangible advancements in the development of more efficient and reliable solar tracking systems. These advancements, in turn, propel the broader adoption and utilization of solar energy as a sustainable and environmentally friendly power source. As we stand on the precipice of a renewable energy revolution, the fruits of this research provide a vital boost to our efforts in harnessing the boundless potential of solar power for a greener and more sustainable future.

1.12.5 Limitations

While this research unquestionably delivers valuable insights and noteworthy contributions to the realm of solar tracking systems, it is prudent to acknowledge and reflect upon certain inherent limitations. These limitations serve as important signposts guiding us towards further exploration and refinement in this field.

First and foremost, it's crucial to recognize that the experimental setup and validation tests were executed within specific environmental conditions and geographical locales. Consequently, there may be constraints on the extent to which the findings can be generalized to diverse settings. Future endeavors should aspire to expand the scope of experimentation to encompass a broader array of environments, ensuring that the insights gained can be universally applicable.

Additionally, it's worth noting that this study primarily concentrated on the development and assessment of tracking algorithms that do not rely on specific sensors. While this approach showcases considerable promise, it inadvertently sidesteps the potential advantages that sensor-based tracking systems may bring to the table. Future research should consider the merits of sensor-based technologies in conjunction with the innovative sensorless approaches presented herein, fostering a more comprehensive understanding of the available options.

Furthermore, the research predominantly delved into the performance of solar tracking systems through the lens of energy output and efficiency. While these are undeniably critical metrics, a holistic evaluation should also encompass factors such as cost-effectiveness and maintenance requirements. Future studies can expand their purview to explore these multifaceted aspects, thereby offering a more comprehensive perspective on solar tracking system performance.

Lastly, while considerable efforts were invested in optimizing the tracking algorithms, there remains room for further refinement and enhancement. The quest for ever-improved performance should be an enduring pursuit, inspiring future research to continue pushing the boundaries of what solar tracking systems can achieve.

1.13 Conclusion

In conclusion, our comprehensive literature review delves into solar tracking systems, specifically emphasizing the efficacy of sensorless solar tracking in optimizing energy output. The exploration covers both sensor-based and sensorless technologies, revealing gaps in the literature and underscoring the importance of solutions aligning with the goals of enhanced performance, cost minimization, and system simplification. The review underscores the drawbacks of sensor-based trackers, such as high costs and susceptibility to weather conditions, contrasting them with the promising potential of sensorless tracking, which relies on the inherent clarity of the sun's position. Past research, while innovative, sometimes deviates from the goal of global feasibility, often substituting solar sensors with other types. Leveraging these insights, we have developed a simple, cost-effective, and industrially viable solar tracking solution, avoiding the pitfalls associated with sensor-based approaches and catering to both small and large-scale PV systems.

Chapter 2

A New Sensorless Solar Tracking Strategy using ZIP Codes

2.1 introduction

This chapter presents the methodology employed in the study, which encompasses the development and implementation of an innovative and cost-effective sensorless solar tracking system. The methodological framework serves as the roadmap for how the research is designed, conducted, and analyzed, ensuring the validity and reliability of the findings. In this chapter, we will provide a comprehensive overview of the principles and procedures involved in harnessing country ZIP codes to precisely determine the sun's position. Our exploration will extend to the intricate design and simulation processes, laying the foundation for a detailed understanding of the system's functionality.Furthermore, we will elucidate the step-by-step details of the experimental procedure, enabling readers to replicate the system with a straightforward and comprehensive guide. This chapter, therefore, serves as a pivotal milestone in the study, offering readers a guiding path through the methodology that underlies the creation and evaluation of the sensorless solar tracking system.

2.2 Research Design

2.2.1 Research Philosophy and Approach

Through this research, our primary objective is to overcome the current limitations in solar tracking technology and enhance overall solar energy efficiency by developing an innovative, cost-effective, and sensor-free solar tracker. Traditional solar trackers, typically rely on sensors for accurate sun tracking. However, their complexity, inaccuracy, and delayed response times pose significant drawbacks. Additionally, these sensor-based trackers face challenges such as reliability issues in harsh environmental conditions, increased costs associated with high-quality sensor implementation, and the need for regular calibration and maintenance. The energy consumption of sensors in solar-powered systems also requires careful consideration, as it may offset the efficiency gains achieved through improved tracking. In response to these challenges, the main goal of this thesis is to design a novel solar tracker that not only enhances solar power efficiency but also prioritizes simplicity and affordability. Unlike conventional trackers, our proposed solution eliminates the need for sensors and feedback loops. Instead, we suggest a revolutionary approach that utilizes sun position algorithms and geographic coordinates for accurate sun tracking.

To demonstrate the efficacy and accuracy of our approach, comprehensive testing of the proposed method will be conducted . This testing will involve rigorous data collection, recording precise measurements of energy output, solar tracker angles, and energy consumption. We will employ both quantitative and qualitative data collection techniques to gain a comprehensive understanding of the system's performance.

Quantitative data will be gathered through precise testing and measurements, providing empirical evidence of the system's efficiency. Simultaneously, qualitative data will be obtained through surveys and user observations, offering valuable insights into user experiences and system behavior. Observations will focus on factors such as reduced vibrations and smoother operation of the solar tracker.

To validate the system's performance, we will adhere to the IEC:62817 standard, which enables a comprehensive comparison with other solar tracking systems and validates our approach's feasibility. Based on the gathered data and rigorous analysis, our research will lead to evidence-based conclusions and practical recommendations for further system improvements and real-world implementation. Ultimately, our study aims to contribute to the advancement of solar energy technology and promote sustainable and efficient photovoltaic systems worldwide.

2.2.2 Timeframe and Temporary Horizon of the Research

The research was conducted over a 12-month period, from January 2022 to January 2023. During this time, both simulated testing and separate real-world testing on specific days were carried out to evaluate the sensorless solar tracking system's efficacy.

Simulated testing was performed using software tools like Proteus and MATLAB Simulink. These simulations modeled the behavior of the sensorless solar tracking system under various conditions, considering changes in solar position, weather parameters, and geographical factors. Simulated testing provided valuable insights into the system's response and allowed for algorithm refinement to optimize accurate sun position determination and tracking.

In addition to simulated testing, separate real-world testing took place on specific days. These testing sessions were conducted in outdoor environments, allowing the system to operate under natural sunlight and real-time variations. Days with diverse weather patterns, solar irradiance levels, and daylight hours were selected to capture a wide range of scenarios.

The combination of simulated and real-world testing provided comprehensive insights into the sensorless solar tracking system's performance. Simulated testing helped refine the system's algorithms, while real-world testing offered valuable data on its behavior in dynamic outdoor conditions. By conducting testing throughout the 12-month period, the research covered a representative range of conditions and ensured a robust evaluation of the system's capabilities and practical applicability.

The data obtained from both types of testing were thoroughly analyzed to draw meaningful conclusions about the system's efficacy. The research successfully enhanced the energy efficiency of photovoltaic systems without relying on specific sensors, and the results informed evidence-based recommendations for further system improvements and real-world implementation.

2.2.3 Sampling Strategy for Data Collection

For data collection, a purposive sampling strategy was meticulously implemented, targeting diverse geographic regions across Algeria with varying solar irradiance levels and distinct weather conditions. The selection of these regions was thoughtfully based on their locations across different latitudes, encompassing areas with high solar potential and those with comparatively lower solar energy availability. This strategic approach aimed to ensure a representative sample, facilitating a comprehensive evaluation of the sensorless solar tracking system's efficacy under various environmental contexts and geographical locations.

The selected regions included both residential and Sahara sites. While the coordinates of all 58 Wilaya (provinces) and 2425 municipalities of Algeria were utilized to simulate the sensorless solar tracking system, the real experimental testing was conducted in Tiaret city. Tiaret, located in the Tell Atlas area of Algeria, presented an ideal location for the experimentation, with a latitude of 35.3673553 and longitude of 1.3220322. The city experiences hot, sometimes extremely hot, summers, and cold winters, with minimal precipitation, making it a suitable spot for the comprehensive evaluation of the system's performance.

To ensure the reliability of the data and minimize bias, we diligently documented the characteristics of each testing site, including ZIP codes, accurate latitude, and longitude corresponding to each specific region represented by a particular ZIP code. This meticulous data collection was accomplished using Google Map data as a reference. Such information proved crucial for accurately analyzing the system's performance under specific environmental contexts.

Throughout the research, we ensured that the sample size was substantial enough to draw meaningful and robust conclusions. The data gathered from multiple sites with diverse conditions facilitated a comprehensive assessment of the ZIP code-based solar tracking system's performance and reliability.

The collected data from this diverse sample were subjected to rigorous analysis, employing statistical methods for quantitative data and thematic analysis for qualitative data. The integration of quantitative and qualitative data allowed for a holistic understanding of the system's effectiveness and user experiences.

By diligently following this purposive sampling strategy, our research successfully obtained reliable data and valuable insights into the sensorless solar tracking system's performance across a range of real-world scenarios. The evidence-based conclusions and recommendations derived from the data analysis significantly contribute to advancing solar tracking technology and its potential widespread implementation in photovoltaic systems.

2.3 Data Collection

2.3.1 Data Collection Methods

The data collection phase of this research involved acquiring essential parameters required for accurate sun tracking. To enable the sensorless solar tracking system to calculate the sun's position based on ZIP codes and geographical factors, we employed the following data collection methods:

User Input through Keypad and LCD Display

To create a user-friendly interaction, we have incorporated a keypad and an LCD display as the means for users to input their location details into the sensorless solar tracking system. The keypad prompts users to enter the date, time, and ZIP code corresponding to their location. As the user enters the information, the LCD display provides real-time feedback, displaying each entry for verification and ensuring accuracy. This seamless integration of the keypad and LCD display streamlines the data input process, allowing users to effortlessly interact with the system. By collecting the necessary date, time, and location details through this intuitive interface, the solar tracker can precisely calculate the sun's position, optimizing solar energy generation effectively.

User Input through Mobile App

We developed a mobile app that allows users to input their location details conveniently. The app prompts users to enter their ZIP code, date, and time, which are vital parameters for calculating the sun's position. The app interface was designed to be intuitive and accessible, ensuring seamless data input.

User Input through user intefrace

We designed an online interface using MATLAB App Designer, which allows users to input their location details effortlessly. The interface prompts users to provide their ZIP code, date, and time, essential parameters for precise sun position calculations. The intuitive and accessible design of the interface ensures a seamless data input process, enhancing the overall usability of the system. With this online MATLAB App Designer interface, users can conveniently access and input their location information, facilitating the sensorless solar tracking system's operation and optimizing solar energy generation.

Geographic Data Retrieval

To support the user input mechanism, we integrated an extensive database of ZIP codes and their corresponding geographical coordinates, including latitude and longitude information. This database allows the solar tracking system to obtain the necessary location data based on the user's provided ZIP code. The geographic data retrieval process is automated, ensuring accurate and real-time access to location-specific details.

Geographic Data Accuracy

To ensure the accuracy of the geographic data used in the calculations, we relied on reliable and up-to-date databases, specifically Google Maps. By utilizing the geocoding feature in Google Sheets, we were able to determine the latitude and longitude of each region specified by a particular ZIP code. The precision of the geographic data is crucial for the sensorless solar tracking system's accuracy, as even slight deviations can impact the orientation of solar panels and subsequently affect energy generation.

Through these data collection methods, we enable seamless and precise functioning of the sensorless solar tracking system. Users can effortlessly input their location details through the mobile app, and the system uses ZIP codes to retrieve the corresponding geographic coordinates for accurate sun position calculations. This streamlined data collection process significantly enhances the solar tracking system's overall efficiency and effectiveness in maximizing solar energy generation. Table 2.1 serves as a comprehensive reference, providing essential information, including ZIP codes, latitude and longitude coordinates, provinces, and municipalities. This data serves as the foundation for precise sun tracking calculations and subsequent adjustments of solar panels, ensuring optimal energy capture.

Utilizing ZIP Codes for Sun Position Determination

Our solar tracker design was inspired by prayer watches commonly found in Saudi Arabia(see Figure 2.1[88]). These watches use city codes to provide Qibla direction and prayer times through sun position algorithms and geographic coordinates. Building on this idea, we

Table 2.1: Geographic Data for Selected Locations - ZIP codes, Latitude, Longitude, Provinces, and Municipalities.

ZIP code	Latitude	Longitude	provinces	municipalities
9000	36.473571	2.832315	Blida	Blida
9002	36.458546	2.849169	Blida	Sidi Kebir
16000	36.779443	3.061738	Alger	Alger Gare
16081	36.694293	2.973317	Alger	Baba Hassen
14191	35.373814	1.315758	Tiaret	Ouarsenis el Beida
14200	35.185742	1.493502	Tiaret	Sougueur
13016	34.878963	-1.348694	Tlemcen	Mansourah
13111	34.931076	-1.324027	Tlemcen	Ain el Houtz

developed a solar tracker system using a tracking code based on ZIP codes. The decision to use ZIP codes as the primary input for sun position determination was driven by their widespread use and ease of accessibility. ZIP codes serve as well-known location identifiers globally, allowing users to conveniently specify their geographic location. By incorporating ZIP codes, our system utilizes sun position algorithms and geographic coordinates to accurately determine the sun's position. This innovative approach enables dynamic sun tracking and optimal solar panel alignment, resulting in enhanced energy generation.

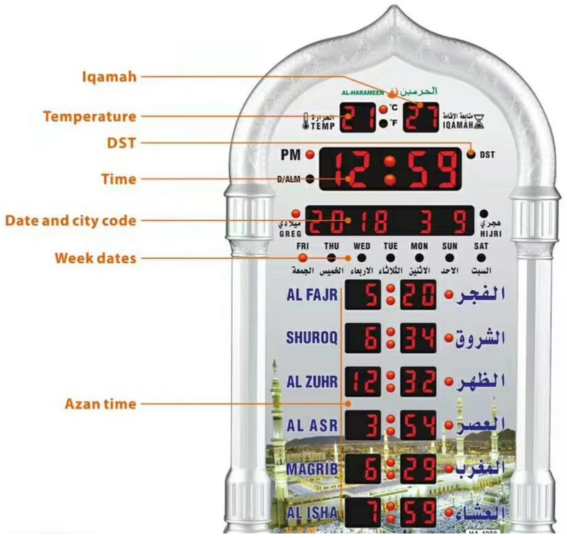


Figure 2.1: The appearance of an Islamic prayer clock [86]

2.3.2 ZIP Codes to Geographic Coordinates Conversion

The sensorless solar tracker system we designed takes geographical factors such as latitude and longitude into account, recognizing their significant role in determining the sun's position. To avoid using sensors in our system, we adopted an innovative approach by utilizing ZIP codes to obtain latitude and longitude coordinates for specific locations. This decision was inspired by the Azan prayer watches used by Muslims, which employ city codes to provide accurate prayer times and Qibla direction through the implementation of sun position algorithms and geographic data. By leveraging this concept, we have developed a sensorless solar tracker that harnesses the power of geographic data to optimize the orientation of solar panels for enhanced energy generation.For our study conducted in Algeria, we employed Algerian ZIP codes, leveraging the administrative divisions of the country. Algeria is subdivided into 58 provinces, each representing a county, and further segmented into 2,324 municipalities, as depicted in Figure 2.2[89]. Our control algorithm facilitates the retrieval of latitude and longitude data for all provinces and municipalities across Algeria, encompassing 2,324 distinct regions.

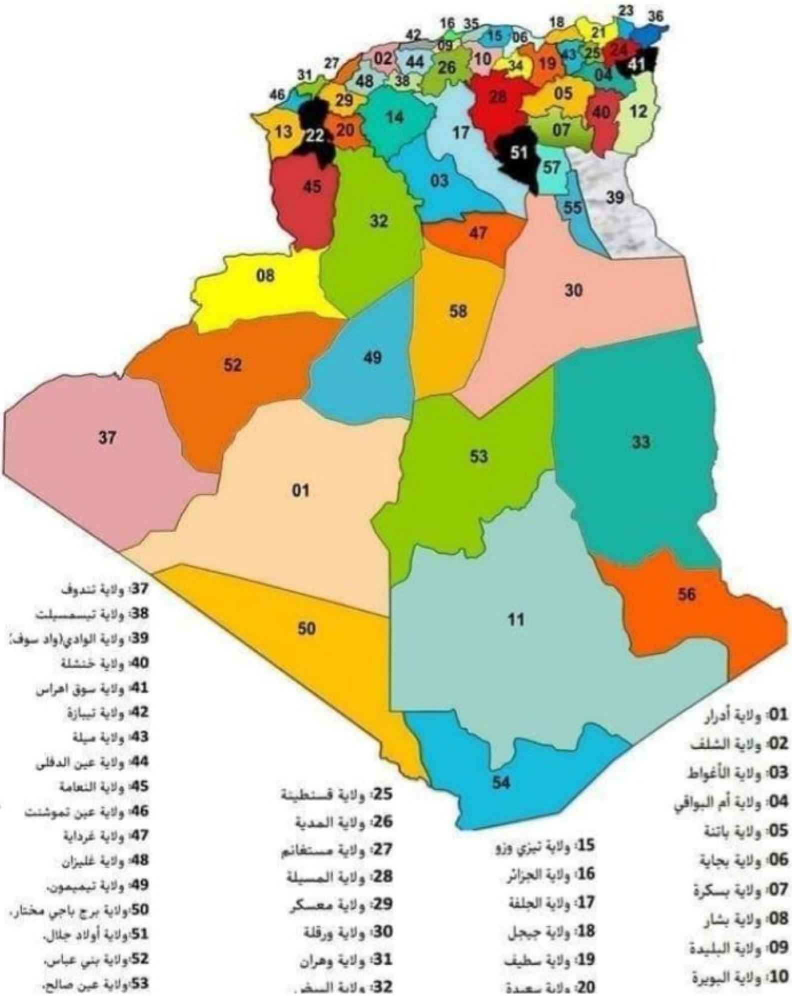


Figure 2.2: Administrative divisions of Algeria [87]

2.4 Data Analysis

2.4.1 Data Analysis Techniques

The data analysis process involved utilizing several software tools and measurement devices to analyze various aspects of the sensorless solar tracking system. We used MATLAB, a powerful computational software, to process and analyze the data output, including power generation, tracker angles, irradiance, and voltage. Through MATLAB, we conducted statistical calculations, visualizations, and comparisons to gain insights into the system's performance metrics.

Furthermore, we employed Simulink, a simulation tool within MATLAB, to examine the system's behavior. Simulink allowed us to create a dynamic model, enabling us to observe the system's response under different conditions and inputs. This simulation phase provided valuable predictions and insights into the system's behavior, aiding in identifying potential issues and optimizing the design before conducting physical experiments.

Proteus, another simulation software, played a pivotal role in evaluating the system's behavior before experimental testing. By simulating the sensorless solar tracking system within Proteus, we assessed its functionality and performance under varying scenarios. This pre-experimental analysis facilitated the refinement of the system's design and ensured a smoother experimental process.

The combination of MATLAB data analysis, Simulink and Proteus simulations allowed us to conduct a comprehensive evaluation of the sensorless solar tracking system. These data analysis techniques enabled us to draw meaningful conclusions, validate the system's performance, and identify areas for further improvement. The results obtained from this extensive analysis were pivotal in shaping evidence-based recommendations and contributing to the advancement of solar tracking technology for enhanced energy generation.

2.4.2 Sun Position Calculation

The system relies on mathematical equations and astronomical principles to calculate the position of the sun based on geographical coordinates, date, and time. This involves determining the azimuth and altitude angles of the sun, which are crucial for tracking its movement. The solar tracker system utilizes astronomical equations to track the movement of the sun in the sky from any location on Earth, considering two angles: altitude and azimuth. The azimuth angle represents the angular displacement of the Sun reference line from the observer's point, while the altitude angle represents the angular height of the Sun in the sky from the same point. These equations, derived from Astronomical data, were employed with the Arduino microcontroller to calculate solar positions. Despite the limited precision of the Arduino's real number arithmetic, the calculations of solar elevation and azimuth based on location ZIP code, date, and time exhibited a high level of accuracy. The calculated values agreed within a deviation of less than 0.002° when compared to online calculations. The equations used in this study were sourced from Jean Meeus renowned book, Astronomical Algorithms[90] as follows: Julian Date:

$$JD = 365.25(y+4716) + 30.6001(M+1) + d + B - 1524.5 \tag{2.1}$$

Where :

$$A = \frac{y}{100} \tag{2.2}$$

$$B = 2 - A + fracA4 \tag{2.3}$$

Modified the Julian date :

$$MJD = JD - 2400000.5 \tag{2.4}$$

Time in Julian centuries :

$$T = \frac{(JD - 2451545)}{36525} \tag{2.5}$$

Mean longitude of the Sun:

$$L_0 = 280.46646 + 36000.76983T + 0.0001537T^2 \tag{2.6}$$

Mean anomaly of the Sun :

$$M = 357.5291 + 35999.0503T - 0.0001537T^2 \tag{2.7}$$

Eccentricity of Earth’s orbit :

$$e = 0.016708617 - 0.000042037T - 0.0000001267T^2 \tag{2.8}$$

Equation of the center of earth:

$$\begin{aligned} C = {} & (1.914602 - 0.004847T - 0.000014T^2)\sin(M) \\ & + (0.019993 - 0.000101T)\sin(2M) + 0.00029\sin(3M) \end{aligned} \tag{2.9}$$

True longitude of the Sun :

$$\theta = C + L_0 \tag{2.10}$$

True anomaly of the Sun :

$$v = M + C \tag{2.11}$$

Earth-Sun distance:

$$R = \frac{1.000001018(1-e^2)}{1+e\cos(v)} \tag{2.12}$$

The apparent longitude of the Sun :

$$\lambda = \theta - 0.00569 - 0.00478 \sin(\Omega) \tag{2.13}$$

Where :

$$\Omega = 125.04 - 193.136T \tag{2.14}$$

Obliquity of the equator:

$$\varepsilon = 23 + \frac{26}{60} + \frac{21.448}{3600} - \frac{46.815}{3600}T - \frac{0.00059}{3600}T^2 + \frac{0.001813}{3600}T^3 \tag{2.15}$$

Right ascension of the Sun :

$$\tan(\alpha) = \frac{\cos(\varepsilon)\sin(\theta)}{\cos(\theta)} \tag{2.16}$$

Declination of the Sun :

$$\sin(\delta) = \sin(\varepsilon)\sin(\theta) \tag{2.17}$$

Greenwich Hour angle of the Sun :

$$\begin{aligned} w_G = {} & 280.46061837 + 360.98564736629(JD - 2451545) \\ & + 0.000387933T^{2\smile}\frac{T^3}{38710000} \end{aligned} \tag{2.18}$$

Hour angle of the Sun :

$$w = GHA + \theta - \alpha \tag{2.19}$$

Elevation angle of the Sun :

$$\sin(\theta) = \sin(\Phi)\sin(\delta) + \cos(\Phi)\cos(\delta)\cos(w) \tag{2.20}$$

Azimuth angle of the Sun:

$$\tan(\gamma) = \frac{\sin(w)}{\cos(w)\sin(\Phi) - \tan(\delta)\cos(\Phi)} \tag{2.21}$$

By employing these calculations, a two-axis solar tracker can be controlled with an appropriate stepper motor and gearing arrangement. This allows for precise alignment of the solar panels with the sun's position, optimizing energy generation throughout the day. Figure2.3 illustrates the sun angles, namely the azimuth and altitude angles, which were precisely calculated using the astronomical equations detailed in Section II.4.2. When determining the sun position angles, the solar radiation also plays a pivotal role in optimizing the efficiency of solar energy systems. These angles dictate the precise orientation of solar panels with respect to the sun, a critical factor for maximizing energy capture. In this context,

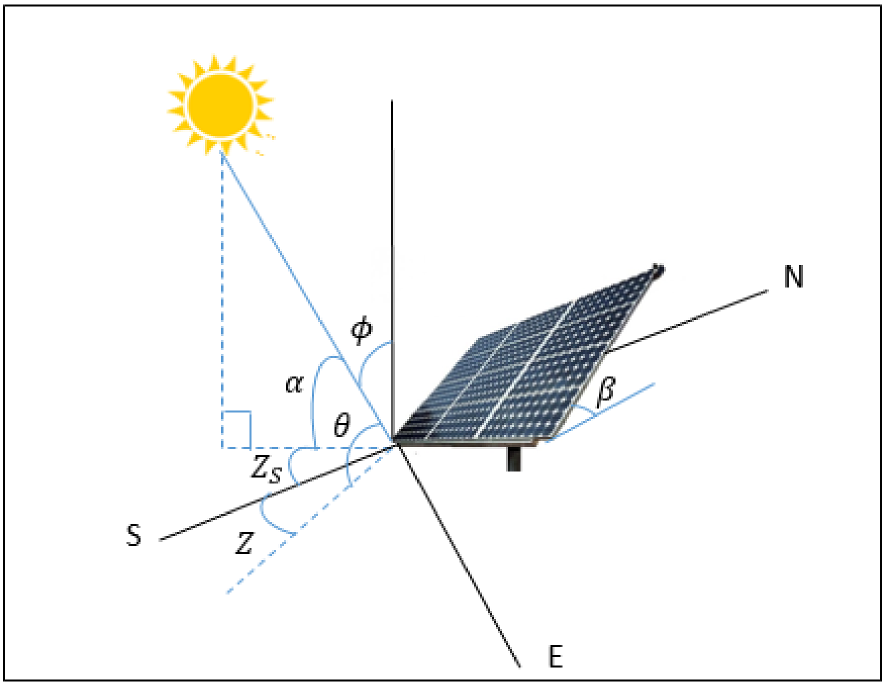


Figure 2.3: the designed solar tracker system diagram.

understanding the radiation incident on a tilted surface, often referred to as "global irradiance" (denoted as $G_(T,\beta)$), is paramount. Global irradiance encompasses a composite of several key components, including direct, diffuse, and reflected irradiance. Direct irradiance signifies the portion of solar radiation that reaches the surface without undergoing scattering or reflection. Its intensity varies based on dynamic factors like solar position and surface orientation. Conversely, diffuse irradiance accounts for scattered radiation, ensuring consistent energy generation even on overcast days. Moreover, reflected irradiance, influenced by surface characteristics, adds to the overall solar energy received. This holistic consideration of radiative components underscores the critical importance of accurately determining sun position angles. It empowers us to unlock the full potential of clean and sustainable solar energy, taking into account the intricate interplay of these factors within solar energy systems. As depicted in Figure 2.4, the radiation on a tilted surface visually encapsulates this vital aspect of solar energy optimization.The expression for global irradiance is as follows[91]:

$$G_(T,\beta) = G_{B,\beta} + G_{D,\beta} + G_R \tag{2.22}$$

Which can be rewritten as :

$$G_(T,\beta) = G_B R_B + G_D R_D + G_T \rho R_R \tag{2.23}$$

Where:

$$R_B = \frac{\cos(L-\beta)\cos(\delta)\sin(w_{ss}) + w_{ss}\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(w_{ss}) + w_{ss}\sin(L)\sin(\delta)}$$

(2.24)

$$R_B = \frac{\cos(L+\beta)\cos(\delta)\sin(w_{ss}) + w_{ss}\sin(L+\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(w_{ss}) + w_{ss}\sin(L)\sin(\delta)} \tag{2.25}$$

$$R_R = \frac{1-\cos(\beta)}{2} \tag{2.26}$$

$$R_D = \frac{1+\cos(\beta)}{2} \tag{2.27}$$

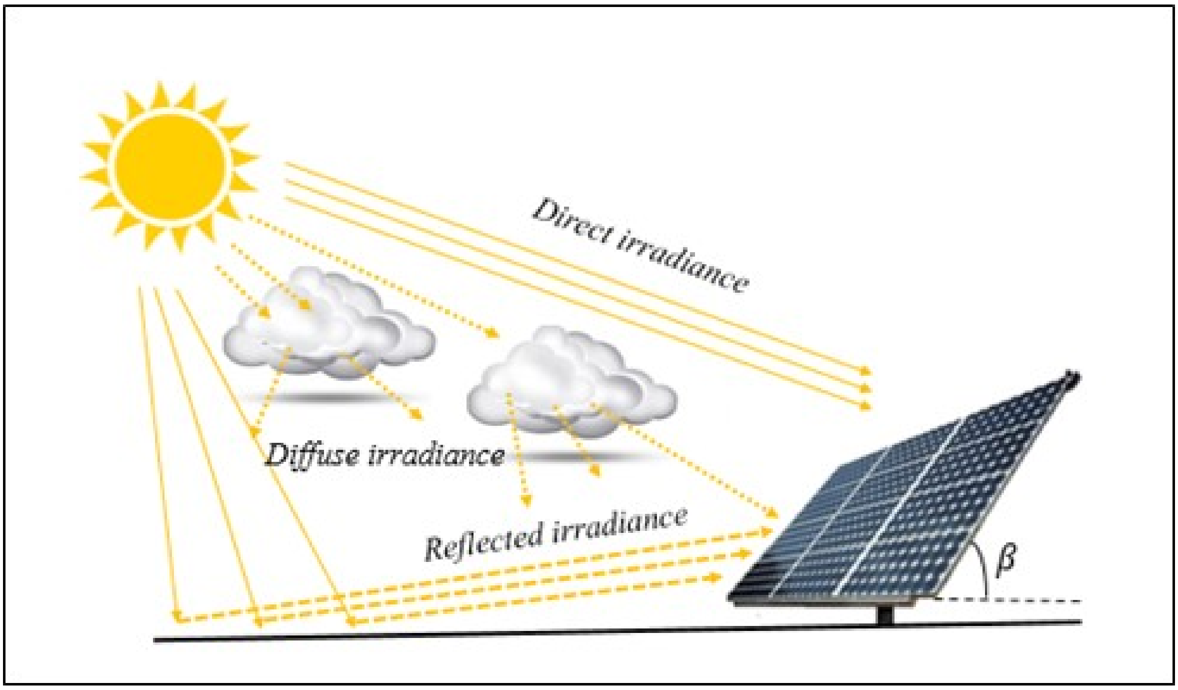
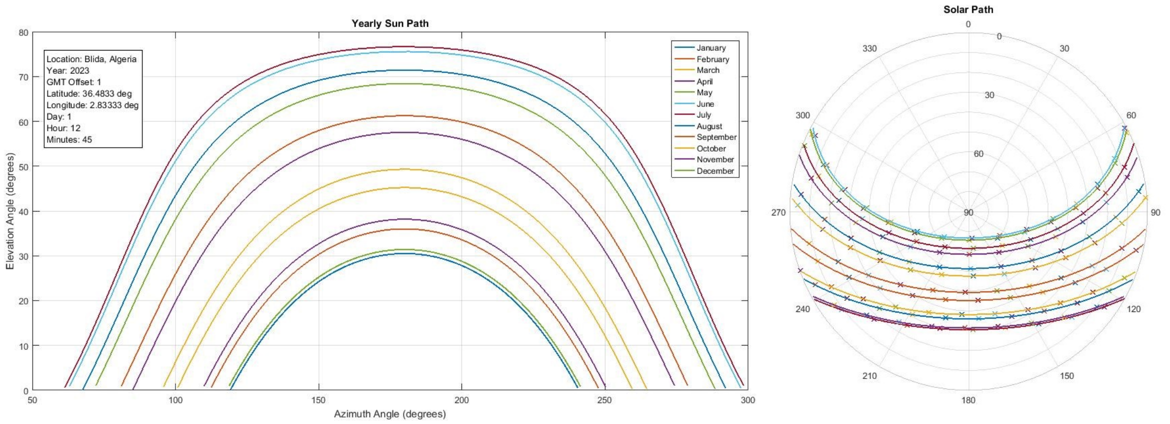


Figure 2.4: Solar radiation on a tilted surface

In our meticulously designed solar tracking system, we employ calculated sun positions at a specific location for continuous alignment of solar panels. This alignment isn't just a daily affair; our system performs intricate yearly calculations, ensuring its adaptability to the sun's dynamic path as it changes across the seasons. The key to this adaptability lies in our ability to comprehensively study and analyze the sun's trajectory, accounting for its daily, monthly, and yearly variations. Figure 2.5 provides a visual representation of our system's predictive capabilities, showing the generated sun path diagram, which reflects the sun's movement throughout the entire year. These calculations and predictions enable our solar tracking system to maintain precise solar panel alignment and optimize energy capture, regardless of the season, ultimately increasing energy efficiency and ensuring consistent performance in a variety of environmental conditions.



(a) (b)

Figure 2.5: Yearly Sun Path in 2023, Blida: (a) Cartesian Plot, (b) Polar Plot

2.4.3 Proper Alignment for Sensorless Solar Tracking

Accurate alignment is critical for sensorless solar trackers, especially during the initial setup, as misalignment at this stage can lead to increased tracking errors. Achieving precise alignment is essential, and the best time for this task is around noon when the azimuth angle is guaranteed to be zero.

However, we must consider the observer's location on Earth, as the sun's position differs for those in the northern hemisphere compared to the southern hemisphere. At sunrise, the sun is positioned with an azimuth angle of around 90 degrees, marking its eastern location. The elevation angle starts at zero and gradually increases as the sun rises, while the azimuth angle increases towards the south.

Conversely, observers in the northern hemisphere see the sun in the southern sky, whereas those in the southern hemisphere witness the sun in the northern sky(as shown in Figure 2.6). For southern hemisphere observers, the azimuth angle decreases and crosses zero degrees, indicating a northward direction.

In the northern hemisphere, after noon, as the sun descends, the elevation angle decreases, and the azimuth angle increases towards the west. At sunrise in the northern hemisphere, the azimuth angle is approximately 90 degrees, and the elevation angle is at its lowest at noon. However, precisely at noon, the azimuth angle reaches around 180 degrees, with the elevation angle reaching its peak,as shown in Figure2.7.

Therefore, we made sure to set the solar tracker exactly at noon using a compass because at that moment, we know precisely where the sun is, as well as the exact azimuth and elevation angles, ensuring accurate alignment.Since Algeria is located in the northern hemisphere, the offset of the solar tracker was set at noon with an azimuth angle of 180 degrees and an elevation angle of 75 degrees. This adjustment ensures optimal alignment for solar tracking in this region.

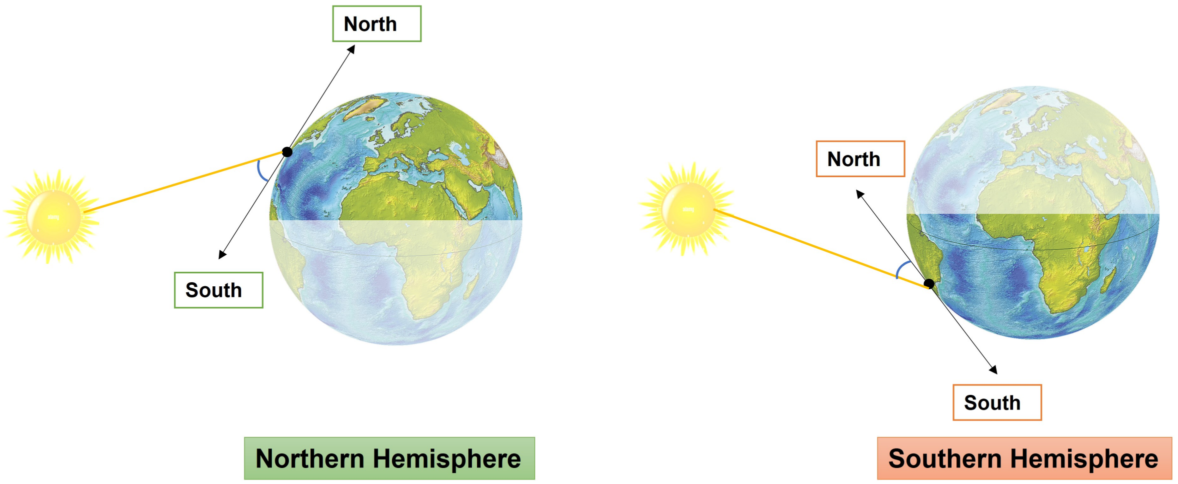


Figure 2.6: The Sun's position relative to the observer's location

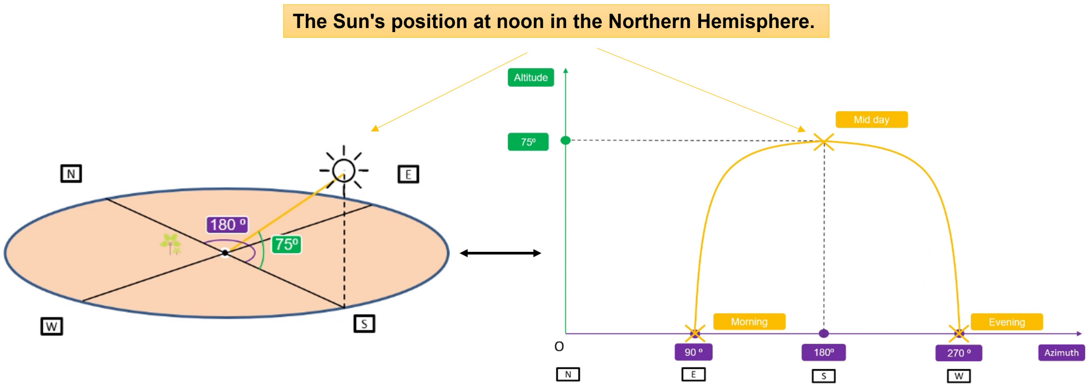


Figure 2.7: The Sun's position in the Northen Hemisphere at noon

2.4.4 Designed Solar Tracker performance

Power output

To calculate the power output of the designed solar tracker system using the used solar panel spesifications and the gathered irradiance data, a comprehensive approach was employed. The initial data included azimuth and elevation angle calculations(Eq(2.21) and Eq(2.20)), which determined the orientation of the solar panel throughout the day. Solar insolation data was then obtained for these specific angles(Eq(2.22). Additionally, the technical specifications of the used solar panel were considered, which included a Rated Maximum Power (Pmax) of 50W, Current at Pmax (Imp) at 2.93A, and Voltage at Pmax (Vmp) at 17.4V.

To calculate the area of the solar panel, the panel's dimensions were converted to square meters. The panel's dimensions are 665 mm in length, 631 mm in width, and 30 mm in height. After converting these dimensions to meters (0.665 meters, 0.631 meters, and 0.03 meters, respectively), the area was calculated as the product of length and width, resulting in an area of approximately 0.42 square meters .

Furthermore, to estimate the panel's efficiency (η), standard test conditions (STC) were taken into account. These conditions specified a solar insolation (E) of 1000 W/m², a temperature (Tc) of 25°C, and a Rated Maximum Power (Pmax) of 50W. The efficiency was calculated using the formula :

$$\mu = \frac{P_{\text{max}}}{E_{\text{STC}} \cdot A} \tag{2.28}$$

To estimate the power output of the solar panel at each time interval during the day, utilize the following formula):

$$P = A \cdot I \cdot \mu \tag{2.29}$$

Sum up the power outputs over the course of the day to estimate the total energy generated. Ensure you consider temperature effects if necessary due to the TNOCT value. Please note that this is a simplified estimation, and for more precise results, specialized simulation software may be used.

energy production

The energy output of a solar tracker system over the course of a day is a critical metric in evaluating its performance. This energy represents the total power generated by the system during daylight hours and can be a key factor in assessing its efficiency and economic viability. To quantify this energy production, we employ a fundamental equation:

$$E = \int P(t)\, dt \tag{2.30}$$

In this equation, E denotes the total energy produced, and $P(t)$ represents the instantaneous power output of the solar tracker as a function of time t. The integral sign ($\int$) signifies the accumulation of power over time, essentially summing up the power output at each moment throughout the day. This mathematical approach allows us to calculate the integral of the power curve, providing a comprehensive and precise measure of the energy produced by the solar tracker system. It's important to note that this method accounts for variations in power output over the entire day, offering a robust understanding of the system's energy generation capabilities.

energy consumption

The statement that the energy consumption of a solar tracker should be 2% to 3% of the increased energy in a solar power generation system was a crucial factor that we considered when designing our solar tracker. Therefore, in addition to calculating the energy produced by our solar tracker, energy consumption was an important factor to consider in order to evaluate the performance of our solar tracker. To calculate the daily energy consumption of our designed solar tracker, we considered the power consumption of each component and the duration of operation. Here are the energy consumption calculations for the components we've used: to calculate the power consumption, we used the formula:

$$P_{\text{consumed}} = V \cdot C \tag{2.31}$$

This formula helps you determine the power consumption of each electrical component by multiplying the voltage and current it operates at. operation duration: our solar tracker operates every 15min from sunrise to sunset about 8 hours a day. the energy consumption:

NEMA 23 Stepper Motor: First, calculate the power consumption of the motor:

$$\begin{aligned} P &= V \cdot C \\ &= 3.2 \cdot 2.8 = 8.96\text{W} \end{aligned} \tag{2.32}$$

$$\begin{aligned} E_{\text{consumed}} &= P \cdot T \\ &= 8.96 \cdot 8 = 71.68\text{Wh} \end{aligned} \tag{2.33}$$

So, the NEMA 23 stepper motor consumes approximately 71.68 watt-hours per day.

NEMA 17 Stepper Motor:

$$\begin{aligned} P &= V \cdot C \\ &= 12 \cdot 1.2 = 14.4W \end{aligned} \tag{2.34}$$

$$\begin{aligned} E_{\text{consumed}} &= P \cdot T \\ &= 14.4 \cdot 8 = 115.2Wh \end{aligned} \tag{2.35}$$

The NEMA 17 stepper motor consumes approximately 115.2 watt-hours per day.

L298N Motor Driver: The L298N motor driver's power consumption is relatively low, approximately 36 mA (milliamperes) at 5 V. To calculate daily energy consumption:

$$\begin{aligned} E_{\text{consumed}} &= P \cdot T \\ &= 0.036 \cdot 5 \cdot 8 = 1.44Wh \end{aligned} \tag{2.36}$$

The L298N motor driver consumes approximately 4.32 watt-hours per day Additional Components:

- 16x2 I2C LCD Display: The power consumption of the display is variable based on the supply voltage. The required supply voltage is from 4.7V to 5.3V, and the LCD can operate either in 8-bit mode or in 4-bit mode. The exact power consumption depends on the voltage supplied and the mode of operation. Please consult the display's documentation for detailed power information.

- Arduino Mega 2560: The power consumption of the Arduino Mega 2560 is relatively low, typically around 50-100 mA. The precise current rating depends on the specific operating conditions and connected peripherals. Please refer to the Arduino Mega 2560's documentation for detailed power specifications.

By calculating the energy consumption of each component and accounting for their daily operation times, we can determine the total daily energy consumption of our solar tracker system:

$$E_{\text{total}} = 71.68Wh + 115.2Wh + 4.32Wh = 191.2Wh \tag{2.37}$$

ensuring that it remains within the recommended range in relation to the increased energy production. This analysis allows us to assess the overall efficiency and cost-effectiveness of our solar tracker design.

2.5 System Components

2.5.1 Electrical setup

The sensorless solar tracking system comprises a range of carefully selected electrical components, each playing a crucial role in its efficient operation. At the core of the system lies the Arduino board, functioning as the central control unit. This versatile microcontroller serves as the system's brain, executing complex algorithms and orchestrating the seamless coordination of various components.

To achieve accurate and smooth tracking movements, the system employs two high-performing stepper motors. The NEMA23 motor is dedicated to azimuth control, while the NEMA17 motor handles elevation control. These motors are equipped with LN298N motor drivers, which offer reliable and efficient control over their rotational motion, ensuring precise solar panel alignment throughout the day.

To provide an intuitive and user-friendly interface, the system features a 3x4 keypad that enables users to input vital information, including their location details specified by ZIP code, as well as the date and time. This user input is crucial for the system's calculations of the sun's position and subsequent tracking algorithm execution, ensuring optimal solar energy capture.

For seamless user feedback and information display, a 16x2 I2C LCD screen is thoughtfully integrated into the system. This display unit communicates essential data, such as the current tracking status, time, and other relevant system parameters. The LCD screen enhances user transparency and ease of operation, facilitating a smooth and interactive experience with the solar tracker system.

In Figure 2.8, a visual representation of the system's electrical components is presented, showcasing the harmonious integration of these components to create an efficient and user-friendly sensorless solar tracking system.

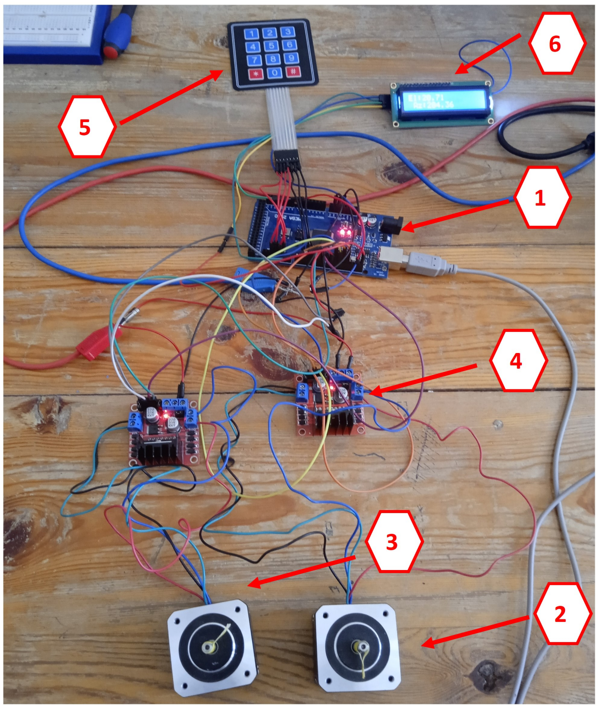


Figure 2.8: the electrical components of the designed solar tracker system.

Figure 2.9 presents a comprehensive diagram showcasing the intricate interconnections and strategic arrangement of essential electrical components.

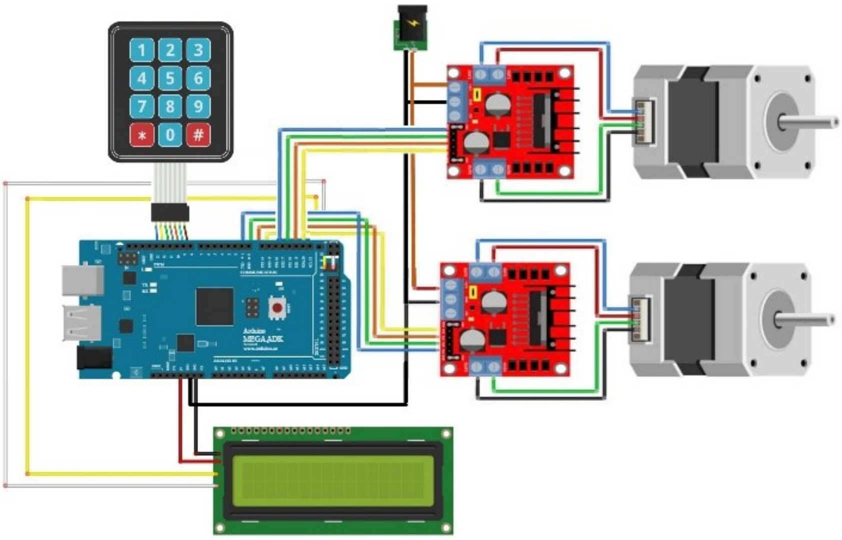


Figure 2.9: the designed solar tracker system diagram.

Table 2.2 provides a concise summary of the main components used in the electrical setup of our sensorless solar tracker system. It includes essential details such as the model names, specifications, and estimated costs for each component. This table serves as a quick reference for readers, offering a clear overview of the key components utilized in our system design.

Table 2.2: Main Specifications and Estimated Costs of Components Used in the Electrical Setup.

N°	Component	Model	Specifications	Cost
1	Arduino Board	Arduino Mega 2560	-Microcontroller:ATmega 2560 -Digital I/O Pins: 54 -Flash Memory: 256 -Communication Interfaces:4 UART serial communication ports	4700DA
2	NEMA23 Stepper Motor	1m-57HS76-3004	-Step Angle: 1.8° -Holding Torque: 4 Ncm -Current Rating: 1.68 A	6500DA
3	NEMA17 Stepper Motor	1m-42HS34-1334AC	-Step Angle: 1.8° -Holding Torque: 26 Ncm -Current Rating: 0.4 A	2900DA
4	LN298N Motor Driver	LN298N	-Maximum Motor Voltage:46V -Maximum Continuous Current: 2A -Motor Control Type: The dual H-bridge driver	1200DA
5	Keypad	3x4 Keypad	-Number of Keys: 12 -Keypad Output: Digital -Keypad Interface: Serial or Parallel	900DA
6	LCD Display	16x2 I2C LCD Display	-Display Size: 16 characters x 2 lines -Interface: I2C	1300DA

2.5.2 mechanical design

The solar tracker system's mechanical design (Figure 2.10)was carefully engineered to achieve peak performance while keeping costs low, ensuring simplicity, and enhancing durability. The system features a sturdy framework made from high-quality materials, offering excellent stability and support for the solar panels. Key factors considered included weight distribution, structural strength, and resistance to environmental conditions. The solar tracker's base is mounted on four wheels, facilitating flexible and easy movement during installation. We ensure the installation location is free from shading or issues, allowing for smooth relocation to different positions as needed. The mechanical components of the system consist of a linear screw actuator for elevation angle tracking and a belt drive system for azimuth tracking, as illustrated in Figure 2.11. The elevation linear actuator is responsible for tilting the solar panel vertically around the altitude axis, while the azimuth belt drive system rotates the PV module horizontally. To achieve this, the linear actuator is inclined and attached as a stand on the PV panel, enabling it to create angles ranging from 5 to 90 degrees, while the azimuth belt drive is placed at the base, allowing for a full 360-degree rotation. Both systems are powered by stepper motors: a NEMA 17 stepper for the elevation drive and a

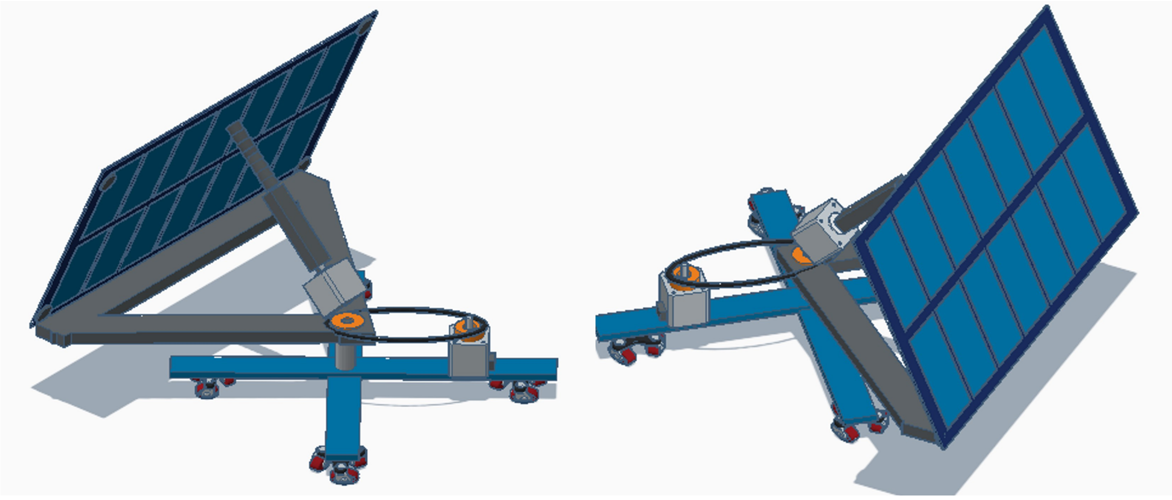


Figure 2.10: 3D design of the sensor-less dual axes solar tracker

NEMA 23 for the azimuth tracking. The decision to use a linear screw actuator for elevation tracking was based on the need for precision and the ability to handle moderate loads effectively. Meanwhile, the choice of a belt drive system for azimuth tracking was driven by its smooth motion and cost-effectiveness, as azimuth angle adjustments typically require lower precision. These component selections are carefully made to optimize the performance and cost-effectiveness of the solar tracking system for its specific purposes.

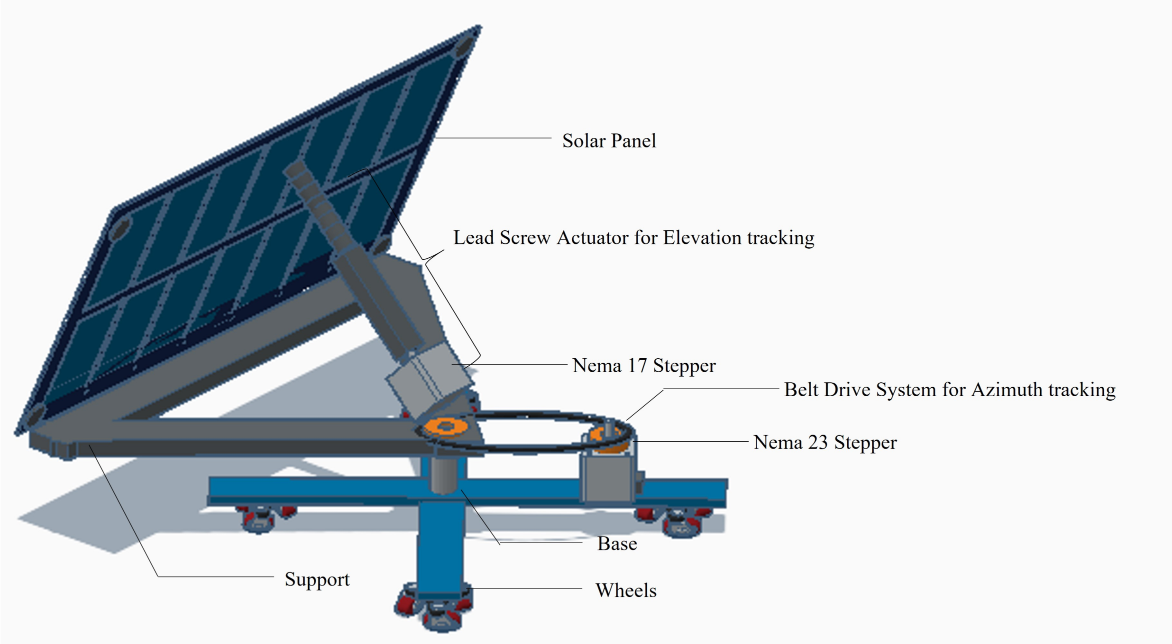
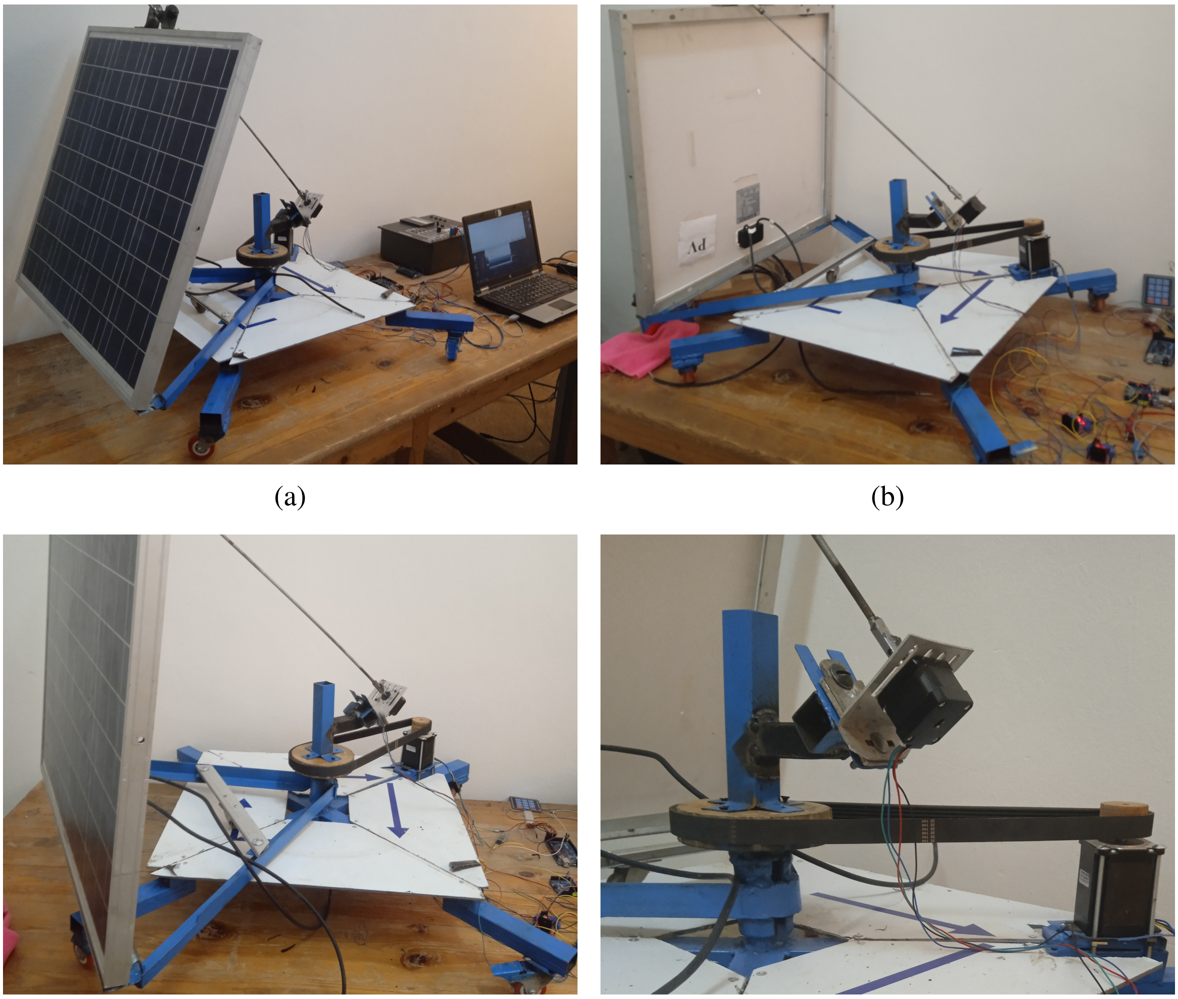


Figure 2.11: 3D design of the sensor-less dual axes solar tracker with labels

The NEMA 23 stepper motor has a step angle of 1.8 degrees. However, when coupled with a belt drive system that uses a large pulley with a 6 cm (0.06 meters) diameter, a belt length of approximately 1.2 meters, and a pulley ratio of 1/2, each rotation step of the stepper motor (1.8 degrees) is effectively converted into a rotation step of 0.1 degree on the secondary pulley connected to the PV panel. This results in a very small rotation step of only 0.1 degree for the panel's movement around the azimuth axe. Consequently, this significantly reduces tracking errors. For a lead screw actuator with a screw lead of 1 millimeter, a 1-degree rotation would require approximately 0.000008726 meters of linear distance. In this setup, the effective step angle for the NEMA 23 stepper motor is approximately 0.5 degrees, rather than the standard 1.8 degrees. This modification further decreases tracking errors and offers a mechanical advantage. It efficiently converts the rotary motion of the stepper motor into linear motion, allowing for the use of lower torque stepper motors while still achieving the required linear movement.

Utilizing a combination of a belt drive system and a linear actuator powered by stepper motors offers several advantages. It eliminates the necessity for a separate brake system or torque reducer, resulting in substantial cost savings and streamlining the design of the solar tracker. Additionally, this setup doesn't introduce any extra expenses or maintenance complications.Figure 2.12 represents the fully assembled mechanical components of the solar tracker with the PV module STP050D-12/MEA .



(a) (b)

(c) (d)

Figure 2.12: the designed sensor-less dual axes solar tracker

2.6 System Workflow

The sensorless solar tracking system is thoughtfully engineered to maximize the efficient harnessing of solar energy through a streamlined and highly accurate approach. Its operation starts with the utilization of tracking codes (ZIP codes) as inputs, enabling the system to pinpoint the exact geographic coordinates of a specific location. These coordinates serve as the foundational data for precise calculations, facilitated by advanced astronomical equations, which accurately determine the Sun's position.

Subsequently, the system employs the resulting azimuth and elevation angles to guide the actuators of the solar tracker, ensuring it attains the desired orientation. This process operates cyclically, with updates occurring at 15-minute intervals, thereby guaranteeing optimal alignment with the Sun's trajectory. The primary advantage of a solar tracking system based on tracking codes lies in its simplicity, cost-effectiveness, durability, and low maintenance requirements. In this context, our study has employed a ZIP code-based approach to pioneer an innovative sensorless solar tracking strategy, aimed at overcoming the previously mentioned limitations while ensuring consistent tracking performance.

This novel strategy eliminates the need for additional sensors by relying on ZIP codes, thereby establishing an open-loop, no-feedback control system. It remains unaffected by adverse weather conditions and conserves energy by operating exclusively during sunset and sunrise times. Furthermore, it replicates the intermittent manual rotation of solar panels while avoiding the undesirable vibrations or continuous movements often associated with traditional Light-Dependent Resistor (LDR) trackers.

What sets this approach apart is its utilization of administrative divisions represented by ZIP codes, ensuring coverage across diverse geographic features within the country. This adaptability enhances its applicability, facilitating efficient solar tracking in various locations and accommodating different terrains and climatic conditions. All of these features align with the global objective of finding cost-effective and straightforward methods for harnessing photovoltaic (PV) power. For a visual representation of this innovative tracking strategy using ZIP codes,An overview of the proposed tracking strategy is illustrated in Figure 2.13 .

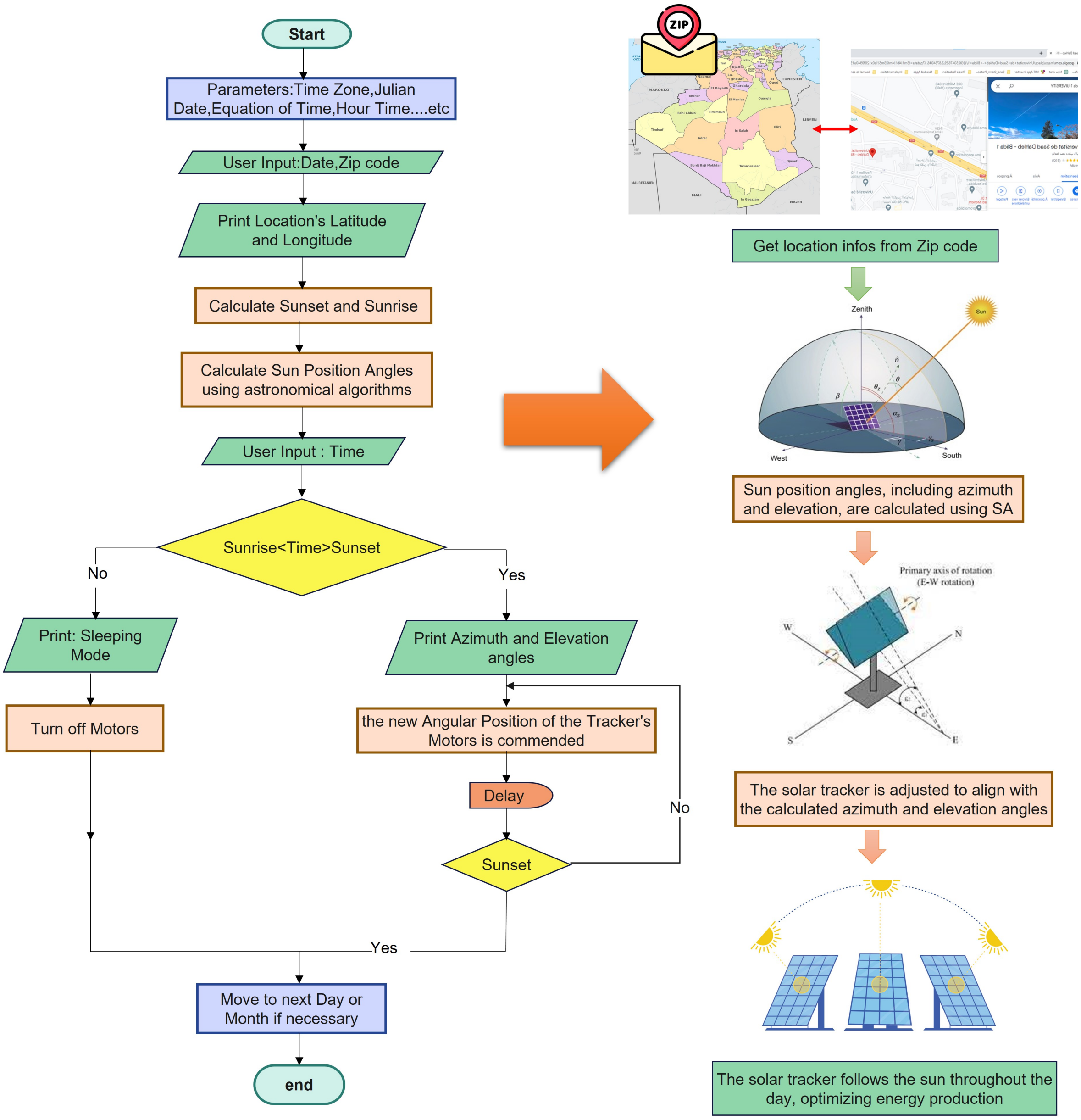


Figure 2.13: Overview of the designed Solar Tracker workflow

2.7 Simulation and Testing

2.7.1 Proteus Simulation

The Proteus software was utilized to simulate and validate the control schematic of the sensorless solar tracker system(see Figure 2.14). Proteus provides a virtual environment where the control circuitry and components can be accurately modeled and tested.

Using Proteus, the control schematic was translated into a simulated circuit, allowing for the evaluation of the control signals, interactions between components, and overall system behavior. This virtual simulation helped identify any potential issues, validate the functionality of the control schematic, and optimize the system's performance.

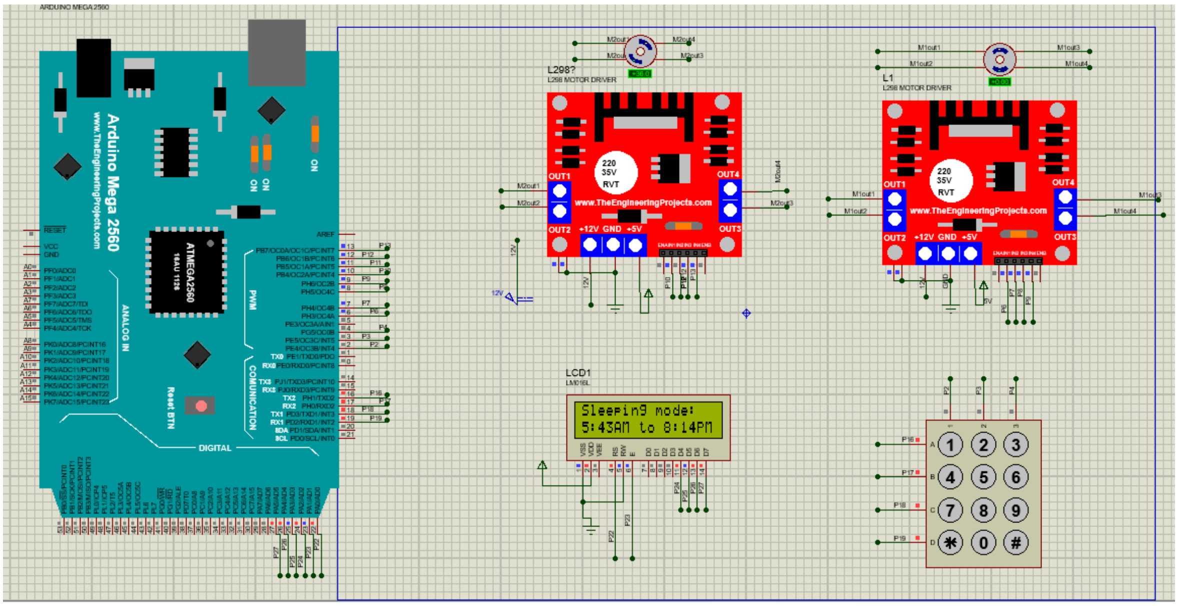


Figure 2.14: the control schematic of the ZIP code solar tracker system usin Proteus

2.7.2 MATLAB Simulink

Matlab Simulink was used as a robust simulation tool to model and analyze the sensor-less solar tracker system's performance. It provides a comprehensive environment for designing, simulating, and testing PV systems. Through Simulink, a dynamic model of the sensorless solar tracker system was created to capture interactions between components and subsystems. The control algorithm, based on astronomical equations and implemented in an Arduino microcontroller, was integrated into the Simulink model. The figure in reference (2.15) illustrates the schematic block diagram of the solar tracker designed in MATLAB 2016a Simulink, established using equations (Eq(2.21),Eq(2.20),Eq(2.22)). This model was developed to simulate real solar cell characteristics (see table 2.3), calculate collected radiation on both horizontal (Figure 2.16) and tilted surfaces (Figure 2.17)using equations(Eq(2.4.2), Eq(2.4.2),Eq(2.4.2)), predict power output for fixed versus tracking PV systems, and compare their performance. Emphasizing the significance of the developed solar tracking in maximizing solar radiation capture, the simulation aimed to enhance solar PV system efficiency without sensor reliance. The Simulink-derived simulation results facilitated the evaluation and optimization of the control algorithm, identifying potential issues or inefficiencies. This approach utilizing Matlab Simulink allowed for thorough analysis and refinement of the sensorless solar tracker system in a virtual environment. Iterative improvements ensured reliability and efficiency before real-world implementation.

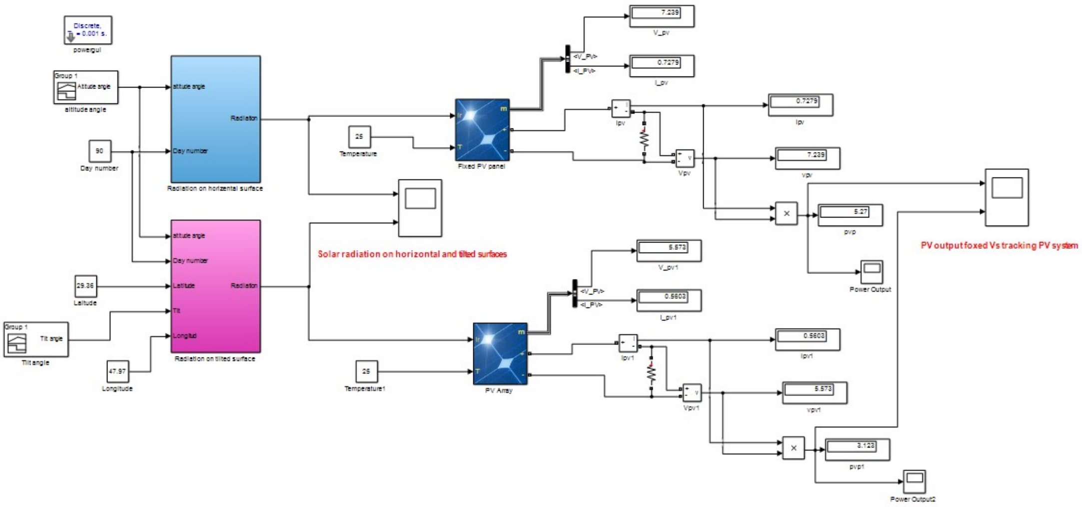


Figure 2.15: the schematic block diagram of the designed solar tracker

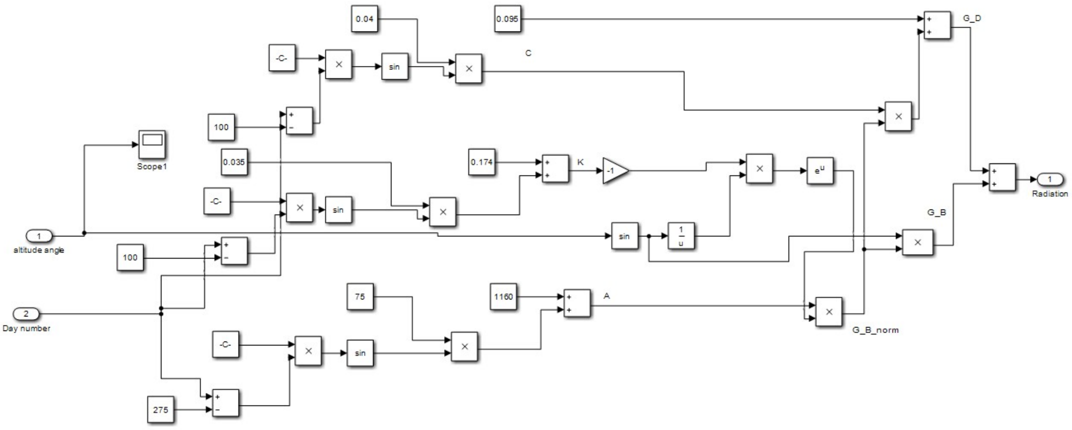


Figure 2.16: Solar radiation on a horizontal surface Simulink model

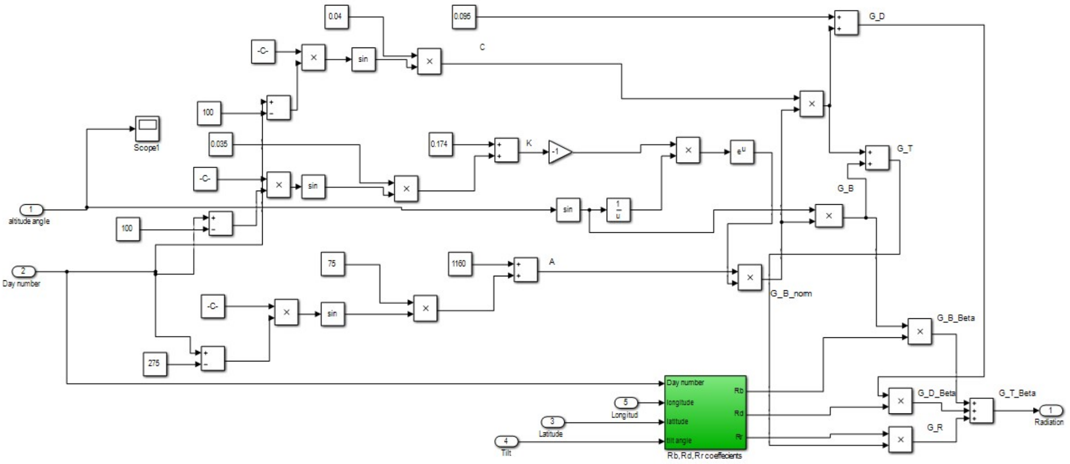


Figure 2.17: Solar radiation on a tilted surface Simulink model

2.8 Experimental procedure

2.8.1 Motor Type Selection

When determining the suitable motor for our application, the choice often boils down to Permanent Magnet DC (PMDC) motors and stepper motors(shown in Figure 2.18) for solar tracking systems. The decision between these two options hinges on the distinct requirements and priorities of the application. Below is a comparative analysis of PMDC motors and stepper motors tailored to the context of solar tracking:

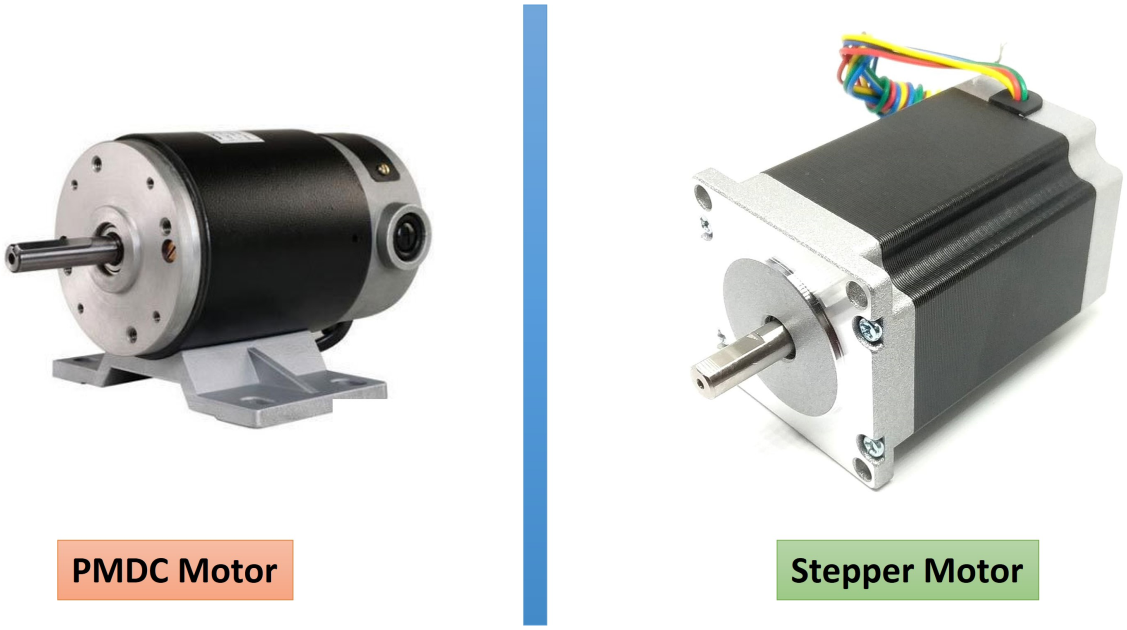


Figure 2.18: PMDC Motor vs Stepper Motor

PMDC Motors

PMDC (Permanent Magnet DC) motors present several advantages that make them well-suited for various applications. These motors are generally more efficient, boasting higher power-to-weight ratios compared to other types. They excel in achieving higher speeds and delivering smooth, continuous motion, making them ideal for applications requiring precision and rapid movement adjustments. PMDC motors come with simple control mechanisms, facilitating easy integration with microcontrollers or control systems. Their compact design, free from brushes and commutators, contributes to a more streamlined and space-efficient solution. Additionally, PMDC motors exhibit lower maintenance requirements. However, it's essential to consider certain factors. To accurately track the sun's position, PMDC motors may require additional feedback mechanisms, such as encoders. Furthermore, the cost of PMDC motors can vary depending on the specific motor and control system, emphasizing the importance of evaluating project-specific needs and budget constraints.

Stepper Motors

Stepper motors offer distinct advantages and considerations that cater to specific application requirements. These motors are renowned for providing precise control of angular position and rotation, offering built-in step-by-step motion that simplifies control without the need for additional feedback devices. Their ability to hold position without power is advantageous in certain scenarios. Stepper motors are particularly well-suited for applications where positional accuracy is paramount. However, it's crucial to consider certain factors. Stepper motors generally have lower power-to-weight ratios compared to PMDC motors and tend to offer lower speeds. Achieving smooth continuous motion may require more complex control algorithms, and they can be more susceptible to heat generation during prolonged operation. Evaluating the specific needs of a project and considering the trade-offs between precision and power is essential when choosing stepper motors for a particular application.

In solar tracking systems, the selection between stepper motors and PMDC motors hinges on specific priorities dictated by the project. Stepper motors are frequently preferred when pinpoint accuracy is paramount, capable of moving in discrete steps ideal for maintaining precise angles. However, achieving the desired speed may necessitate additional gearing, and they may be less efficient. Conversely, PMDC motors come into play when factors such as efficiency, compactness, and smoother continuous motion take precedence. They seamlessly provide the necessary motion for solar tracking without relying on discrete steps, potentially enhancing the solar panels' energy output through smoother transitions. Ultimately, the choice between PMDC motors and stepper motors depends on project-specific considerations, including cost, power efficiency, speed requirements, accuracy, and the overall design of the tracking system. In our particular case, our primary objective was to minimize cost and complexity, leading us to opt for stepper motors in our solar tracker design.

2.8.2 Motor sizing

Sizing and selecting the appropriate stepper motor for the solar panel application requires considering the torque and power requirements. The torque is essential to handle the weight of the solar panel and overcome the frictional forces, while the power specifies the amount of work the motor can perform per unit time. But first, we need to consider the drive mechanism for our equipment. In our case, we utilized the following given specifications to determine the required torque for each drive system:

- Maximum weight of the solar panel: 15 kg.
- Desired speed: 60 rpm.
- Estimated coefficient of friction: 0.1.
- Estimated Power loss: 10%.

To perform these calculations accurately, we employed Oriental Motor sizing software (shown in Figure 2.19), wherein we specified the driven system type as well as the tracker's exact dimensions. This software facilitated a comprehensive analysis, ensuring that the selected stepper motor meets the specific needs of our solar panel tracking system.

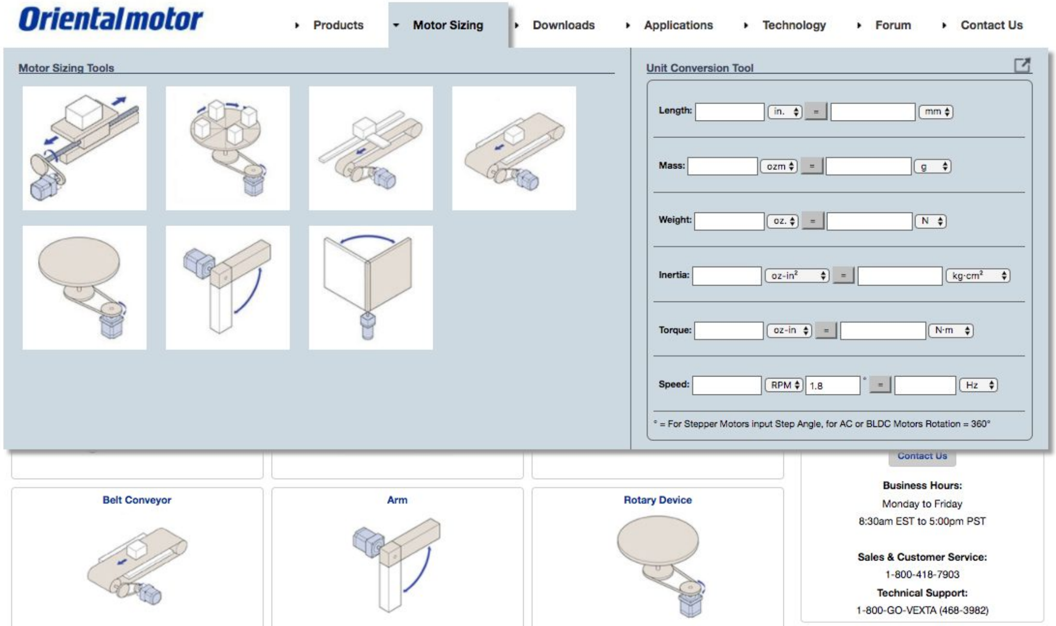


Figure 2.19: Oriental Motor sizing software

Azimuth Rotation Drive System

In the azimuth rotation drive system, a V-belt mechanism has been meticulously chosen for its efficiency and reliability in solar panel tracking applications. The drive pulley, featuring a 4 cm diameter, and the driven pulley, with a 12 cm diameter, are connected by a 2 cm wide belt. The 39 cm distance between the centers optimizes the system for azimuth movement. The selection of a V-belt drive system is based on its ability to provide smooth and precise rotational control. This choice facilitates the necessary torque to handle the weight of the solar panel and overcome frictional forces during azimuthal adjustments. To calculate the required torque accurately, a motor sizing software, as shown in Figure 2.20, was employed, ensuring optimal performance and longevity of the drive system.
The labeled components (1-6) represent key elements of the azimuth rotation drive system. Here is a breakdown of the numbered components:

1. Nema 23 Stepper Motor:This motor provides the necessary torque for precise azimuth and elevation adjustments.

2. Drive Pulley: The drive pulley, with a diameter of 4 cm, plays a pivotal role in transmitting motion to the belt system.

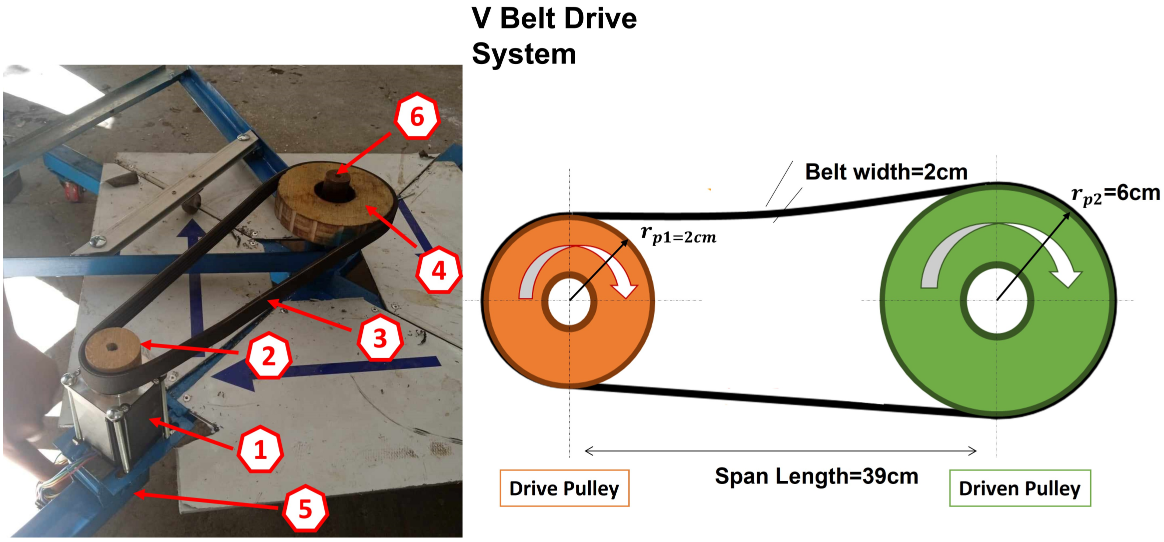


Figure 2.20: Azimuth Rotation Drive System

3. V-type Belt: This belt, with a width of 2 cm, efficiently transfers rotational energy from the drive pulley to the driven pulley.
4. Driven Pulley: With a diameter of 12 cm, the driven pulley is instrumental in converting the rotational motion from the belt into the desired panel movement.
5. Support for the Motor: This component ensures stability and proper alignment for the Nema 23 stepper motor during operation.
6. Rotation Axes for the Driven System: These axes provide the pivotal points for azimuth and elevation movements, contributing to the overall system's functionality.

Elevation Rotation Drive System

For the elevation rotation drive system, a linear actuator with a screw lead drive mechanism has been specifically chosen. This system incorporates a screw with a length of 69 cm and a nut with a length of 2 cm. The linear actuator design provides precise control over the elevation angle of the solar panel. This choice is motivated by the linear actuator's ability to convert rotary motion into linear motion, offering a straightforward and reliable means of adjusting the panel's tilt. The screw lead drive system ensures a smooth and accurate elevation adjustment, critical for optimizing solar exposure. Further analysis is required to determine the torque required for this drive system, taking into account factors such as the panel weight and elevation adjustments. The elevation drive system configuration is illustrated in Figure 2.21 providing a visual representation of the selected components and their arrangement.

The numbered elements (1-4) provide a detailed breakdown of the components comprising the elevation drive system, encompassing:

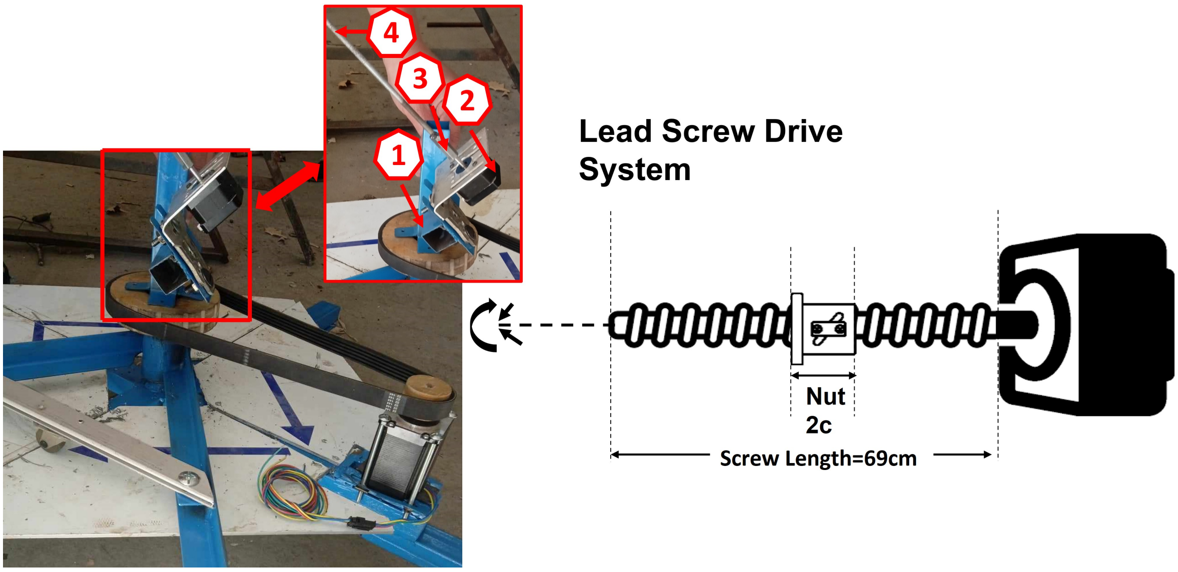


Figure 2.21: Elevation Rotation Drive System

1. Support for the Motor:This component provides stability and alignment for the Nema 17 stepper motor, ensuring reliable and controlled elevation adjustments.
2. Nema 17 Stepper Motor: Selected for its ability to meet the torque and precision requirements, this motor drives the elevation adjustments of the solar panel.
3. Nut:The nut, with a length of 2 cm, is an essential part of the linear actuator system, working in conjunction with the screw to facilitate smooth and precise elevation movements.
4. Screw: With a length of 69 cm, the screw is a key element in the linear actuator system, converting rotational motion into linear motion for accurate control of the solar panel's tilt.

Having calculated the required torque (T_{req}) to be approximately 0.2 Nm for the azimuth drive system and 1.1 Nm for the elevation drive system, our next step was to identify stepper motors that meet or exceed these torque specifications. Additionally, we specified a stepper motor with a step angle of 1.8 degrees per step to align with the precise needs of our application. After careful consideration, we found that Nema 17 and Nema 23 stepper motors fulfilled our requirements, leading to their selection. Figure 2.22 provides a visual representation of the motors integrated into the system.

Figure 2.22: The motors selected for the designed solar tracker system

2.8.3 Used Solar Panel

The heart of any photovoltaic system lies in the solar panel, which converts sunlight into electrical energy. In our study and simulated tracking system, we carefully selected a solar panel based on its specifications to ensure optimal performance within the sensorless solar tracking framework. Table 2.3 provides a comprehensive overview of the key specifications and data associated with the chosen solar panel.

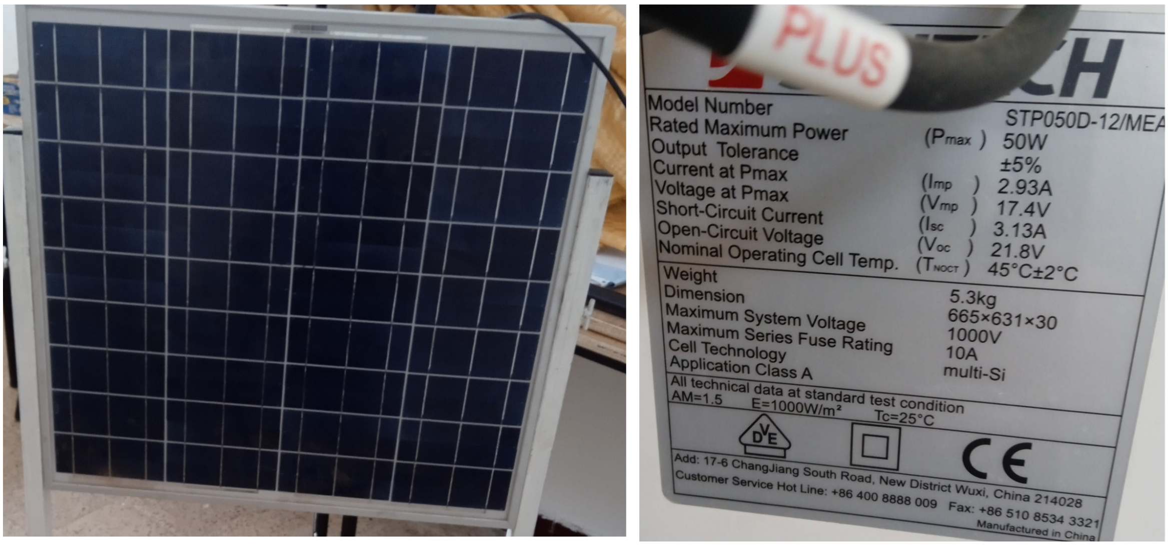
Table 2.3: Solar Panel Datasheet

Specifications	**Values**
Solar Panel Model Number	Suntech STP050D-12/MEA
Rated Maximum Power (P_{max})	50W
Output Tolerance	±5%
Current at P_{max} (I_{mp})	2.93A
Voltage at P_{max} (V_{mp})	17.4V
Short-Circuit Current (I_{sc})	3.13A
Open-Circuit Voltage (V_{oc})	21.8V
Nominal Operating Cell Temp (T_{NOCT})	45°C+2°C
Weight	5.3kg
Dimensions	665mm x 631mm x 30mm
Maximum System Voltage	1000V
Maximum Series Fuse Rating	10A
Cell Technology	Multi-Si
Application Class	A

Additional Information:

- All technical data at standard test condition: AM=1.5, E=1000W/m^2, Tc=25°C.
- Manufacturer: Suntech
- Manufactured in China
- Address: 17-6 Chang Jiang South Road, New District Wuxi, China 214028
- Customer Service Hot Line: +86 400 8888 009
- Fax: +86 510 8534 3321

The selection of this solar panel was driven by its compatibility with the sensorless solar tracking system and its ability to provide the necessary electrical characteristics for efficient energy conversion. The desirable short circuit current (I_{scn}) and open circuit voltage (V_{ocn}) values directly influence the power generation capacity of the panel. Moreover, the temperature-related constants (K_v and K_i) play a critical role in understanding the panel's behavior under varying environmental conditions.



Model Number		STP050D-12/MEA
Rated Maximum Power	(P_{max})	50W
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Short-Circuit Current	(I_{sc})	3.13A
Open-Circuit Voltage	(V_{oc})	21.8V
Nominal Operating Cell Temp.	(T_{NOCT})	45°C±2°C
Weight		5.3kg
Dimension		665×631×30
Maximum System Voltage		1000V
Maximum Series Fuse Rating		10A
Cell Technology		multi-Si
Application Class A		

All technical data at standard test condition
AM=1.5 E=1000W/m^2 Tc=25°C

Add: 17-6 ChangJiang South Road, New District Wuxi, China 214028
Customer Service Hot Line: +86 400 8888 009 Fax: +86 510 8534 3321
Manufactured in China

Figure 2.23: Visual Representation of the Used Solar Panel

The integration of this specific solar panel ensures a solid foundation for accurate tracking calculations and reliable energy generation throughout the experimental procedures. Its characteristics and performance contribute significantly to the overall effectiveness and success of the developed system.

2.8.4 Stepper Motor Angle Control

A meticulous control strategy is pivotal in achieving precise solar tracking, involving the coordinated control of NEMA 17 and NEMA 23 stepper motors. These motors, renowned for their reliability and precision, are governed by the LN298N motor driver, a high-performance device adept at managing their rotational motion. The control paradigm revolves around specifying an angle through the system's interface, facilitated via the Serial monitor. Upon inputting the desired angle, the intricate mechanics spring into action, adjusting the motors' positions in relation to their prior orientations.

Central to this control strategy is the utilization of the 28BYJ-48 stepper motor, a versatile component compatible with a wide range of applications. The motor's key parameters, gleaned from its datasheet, are as follows: rated voltage (5 VDC), number of phases (4), speed variation ratio ($\frac{1}{64}$), and stride angle ($\frac{5.625^\circ}{64}$). Notably, the real step angle of 5.625° is further finely-tuned to an astounding 0.0879° through the implementation of gears with a gear ratio of 1 : 64. This meticulous calibration yields a remarkable resolution of 4096 steps per revolution, a hallmark of precision.

The orchestrator of motor movement is the LN298N driver, a vital bridge between the motors and the control system. Its high-voltage, high-current Darlington transistor arrays empower the seamless management of motor rotation. To realize this control strategy, meticulous hardware connections are established. Specifically, the connections of the NEMA 17 and NEMA 23 motors to the LN298N driver are crucial for coordinated movement.

The algorithm that governs motor movement is encapsulated in the equation:

$$\text{steps} = (\text{eleva}[i] - \text{eleva}[i-1])0.555555556 \tag{2.38}$$

where *steps* represent the calculated movement required for precise motor adjustment. Subsequently, this algorithm is executed via the command:

$$\text{myStepper.step(steps)} \tag{2.39}$$

This intricate interplay of equations ensures that the motors respond dynamically to the user's input, guaranteeing accurate solar panel alignment.

In parallel with motor control, an informative feedback loop has been incorporated. The Serial monitor becomes the conduit through which elevation angle information is relayed to users, providing real-time insights into motor positional adjustments. This data is further echoed on an LCD display, offering a tangible visualization of the motors' rotation. Strategically introduced delays enhance the user interface's usability, optimizing the communication process.

In summation, the Stepper Motor Angle Control mechanism, facilitated by NEMA 17, NEMA 23 motors, and the LN298N driver, is at the heart of the solar tracking system's precision. By enabling users to effortlessly and accurately specify angles via the Serial monitor, and orchestrating complex motor movement via intricate algorithms, this mechanism is fundamental to the system's ability to maximize solar panel alignment and energy optimization.

2.9 Advanced Interface Development for Solar Tracking

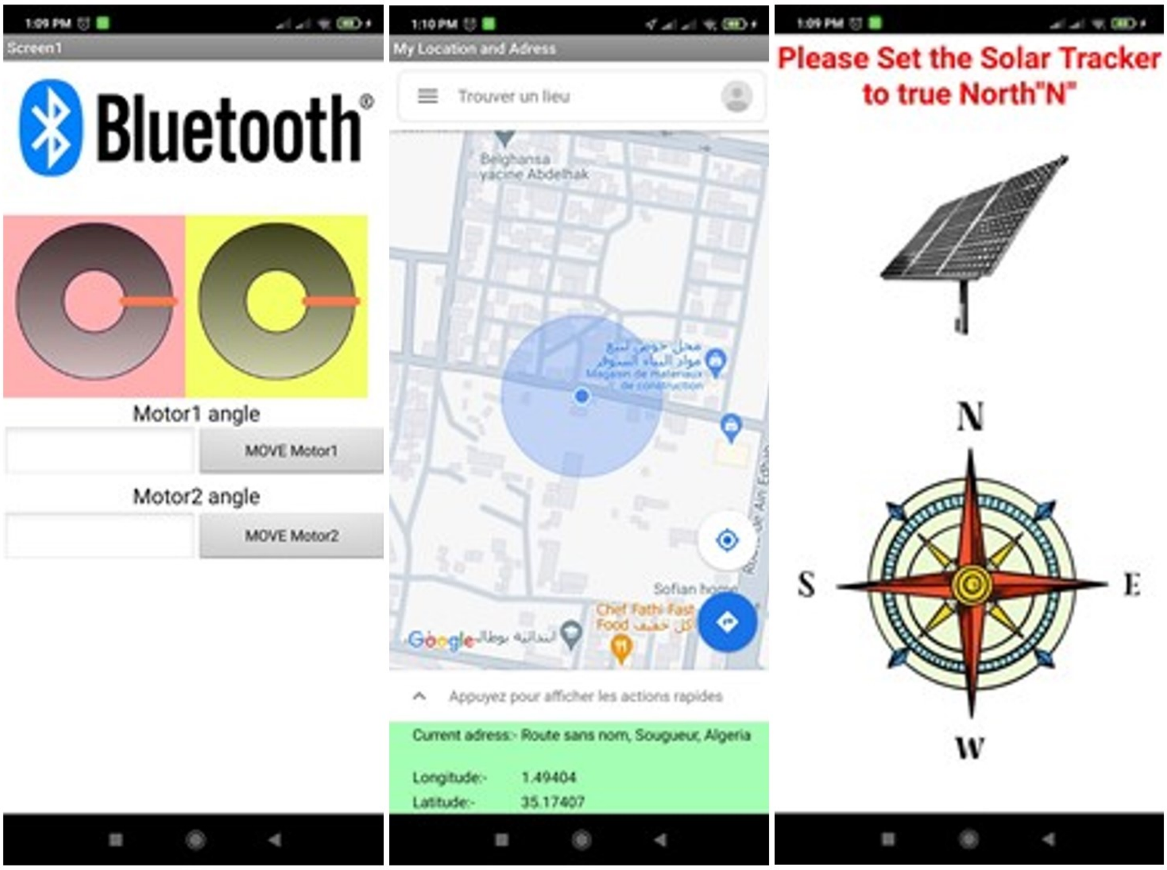
2.9.1 Mobile Application for Solar Tracking Control

The mobile application developed for the solar tracking system offers an intuitive and user-friendly interface, empowering users to efficiently control and monitor the solar tracker's movements.This app was developed using MIT APP Inventor for phone size(505,320). The app's functionalities are tailored to provide precise control over the azimuth and elevation angles of the solar tracker's motors. Users can manually adjust both motor angles using an interactive circular interface that facilitates angle selection. For azimuth control, a circle spanning from 0 to 360 degrees is provided, while for elevation control, a circle ranging from 0 to 90 degrees is available.

To enhance user convenience, the app features dedicated input boxes for each motor angle. These boxes allow users to directly input their desired angles, offering flexibility for specific panel cleaning, protection, or other operational requirements. This feature empowers users to easily achieve precise positioning for their solar panels.

In terms of interaction with the system, the app requires a WIFI connection and communicates with the solar tracker via Bluetooth connectivity. A Bluetooth module integrated into the electric circuit of the designed solar tracker establishes a connection between the app and the system. Once connected, users can input their desired angles, location details, and other parameters through the app's interface. These inputs are transmitted to the solar tracker using a serial connection. To distinguish between the azimuth and elevation angles, the app employs a clever strategy: it sends the elevation angle augmented by 360 degrees, and subsequently subtracts 360 degrees within the Arduino code of the solar tracker. This approach ensures accurate angle differentiation and control.

Figure2.24 illustrates the mobile app interface, showcasing its circular control interface, input boxes for angle adjustments, location detail inputs, and compass functionality. The app's user-friendly design and seamless interaction with the solar tracking system contribute to the overall efficiency and effectiveness of the system.



Current adress:- Route sans nom, Sougueur, Algeria

Longitude:- 1.49404

Latitude:- 35.17407

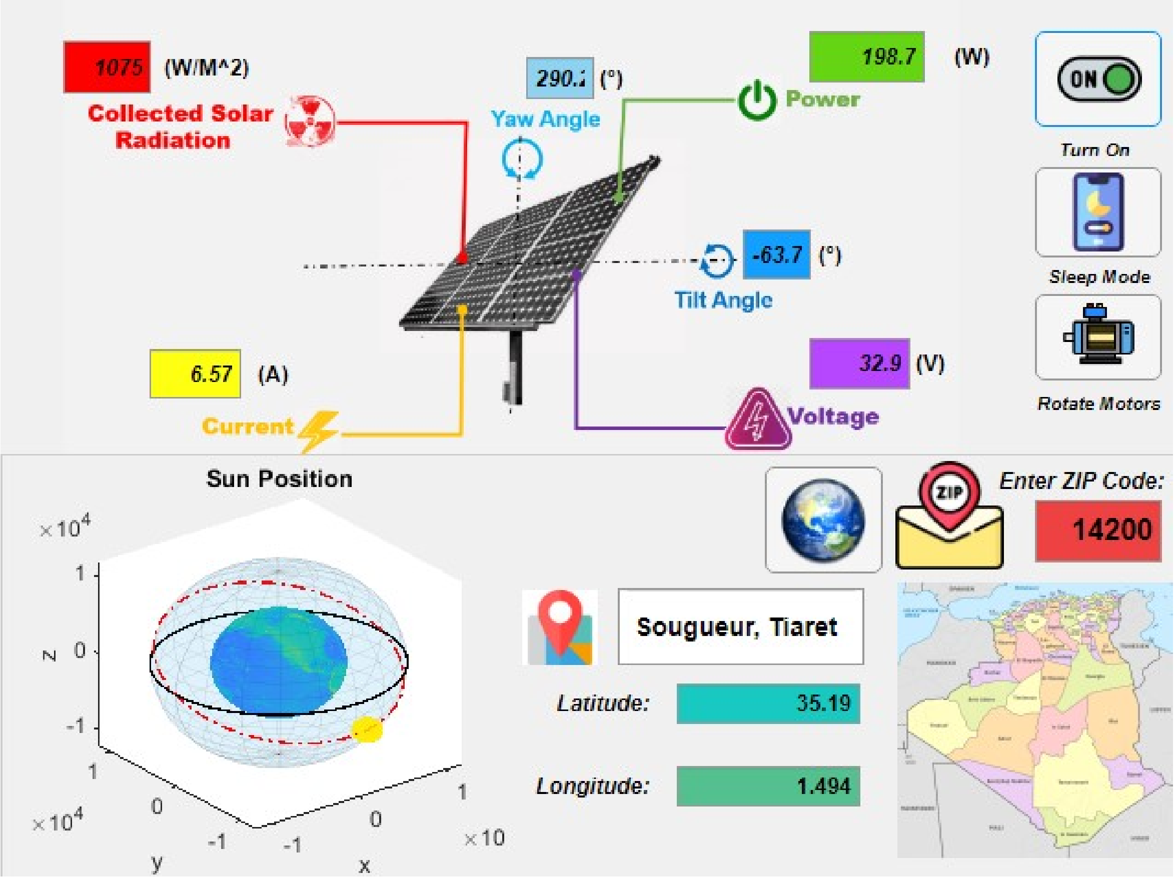
Please Set the Solar Tracker to true North"N"

Figure 2.24: the designed phone app

2.9.2 Online Interface for Solar Tracking Optimization

The MATLAB App Designer platform has been employed to craft a dynamic and user-friendly interface tailored for the solar tracking system. This interface complements the mobile app and offers an array of extended functionalities. Much like the mobile app, the online app allows users to conveniently control the solar tracker's azimuth and elevation angles. However, it further enriches the user experience by incorporating a host of additional features.

Figure 2.25 visually illustrates the MATLAB App Designer interface developed using MATLAB 2019b. This interface serves as an alternative means for users to interact with the system, offering an array of functionalities including solar panel angle control, data visualization, solar path analysis, and real-time monitoring. Through its user-friendly layout and comprehensive features, the interface provides a powerful tool for users to engage with the solar tracking technology and optimize its performance.



1075 (W/M^2)
Collected Solar Radiation

290. (°)
Yaw Angle

198.7 (W)
Power

-63.7 (°)
Tilt Angle

6.57 (A)
Current

32.9 (V)
Voltage

Enter ZIP Code: 14200

Sougueur, Tiaret

Latitude: 35.19

Longitude: 1.494

Figure 2.25: the designed user interface

In particular, the MATLAB App Designer interface offers users the capability to visualize crucial solar tracking parameters on a daily basis, including azimuth and elevation angles, collected irradiance, power output, and energy consumption. Furthermore, the interface facilitates monitoring and protection of the solar tracker, granting users a comprehensive insight into their selected location's solar characteristics.

2.10 Conclusion

In conclusion, this chapter has provided a comprehensive and insightful overview of the methodology employed in the development of our innovative sensorless solar tracking system based on ZIP codes. The methodology outlined here not only ensured the validity and reliability of our research findings but also demonstrated the feasibility and practicality of harnessing ZIP codes to accurately determine the sun's position. From the conceptual framework to the intricate design and simulation processes, and finally to the step-by-step experimental procedure, this chapter has served as a valuable roadmap for readers interested in replicating the system. By bridging the gap between theory and practice, this methodology chapter constitutes a crucial milestone in our study, setting the stage for the creation and evaluation of an efficient and cost-effective sensorless solar tracking system.

Chapter 3

Novel Approach to Sandstorm Resilient Solar Tracking System

3.1 introduction

The sun radiation level is considerably very high in Algeria since it occupies 75% of the Sahara territory, offering substantial potential for solar power generation. However, these areas face frequent sandstorms that could last up to three days, posing various challenges for solar PV systems, including dust accumulation, surface abrasion, structural stress, long-term degradation, and the potential for total panel deterioration.In this chapter we present an innovative approach to address these challenges and enhance solar power efficiency in desert environments . The innovation lies in integrating wind data readings into standard solar tracking tools for proactive sandstorm mitigation. The technique uses wind speed data to detect sandstorms once a predefined threshold is reached, automatically repositioning to an established angle based on wind direction data.

3.2 Philosophy and Approach

Our primary objective revolves around enhancing solar power efficiency without relying on solar sensors, a feat we achieved through an innovative approach utilizing geographic coordinates and ZIP codes, as thoroughly explained in Chapter 4. This groundbreaking method not only allows us to overcome the limitations associated with traditional solar sensors but also opens up new avenues for optimizing solar energy utilization in diverse geographic locations.

However, delving deeper into the pursuit of heightened efficiency reveals another critical aspect that demands our attention the profound impact of weather conditions on solar power effectiveness. Recognizing the pivotal role weather plays in the overall performance of solar energy systems, our research takes a comprehensive approach to address this variable.

Given that Algeria occupies a substantial 75% of the Sahara territory, our central focus naturally gravitates towards finding innovative solutions for the specific weather conditions prevalent in desert environments. Deserts, renowned for their arid and semi-arid climates, present immense potential for solar energy due to abundant sunshine. However, these areas are frequently susceptible to sandstorms, which can pose a significant challenge to installing PV systems in such regions. The Sahara Desert, contributing to 69% of global dust emissions [92], and other arid areas characterized by loose soil and uncultivated land [93] are particularly susceptible to these storms. Sand and dust storms arise when strong winds carry sand from exposed, dry surfaces. This meteorological phenomenon occurs, especially in temperate climate zones [94]. Concentrated in the Northern Hemisphere [95](see Figure 3.2), where the areas with the highest dust intensities are found [96](see Figure 3.1), frequent sandstorms affect 151 countries globally [97], especially in Africa and Asia, with 45 serving as source areas along the Tropics of Cancer and Capricorn [98].

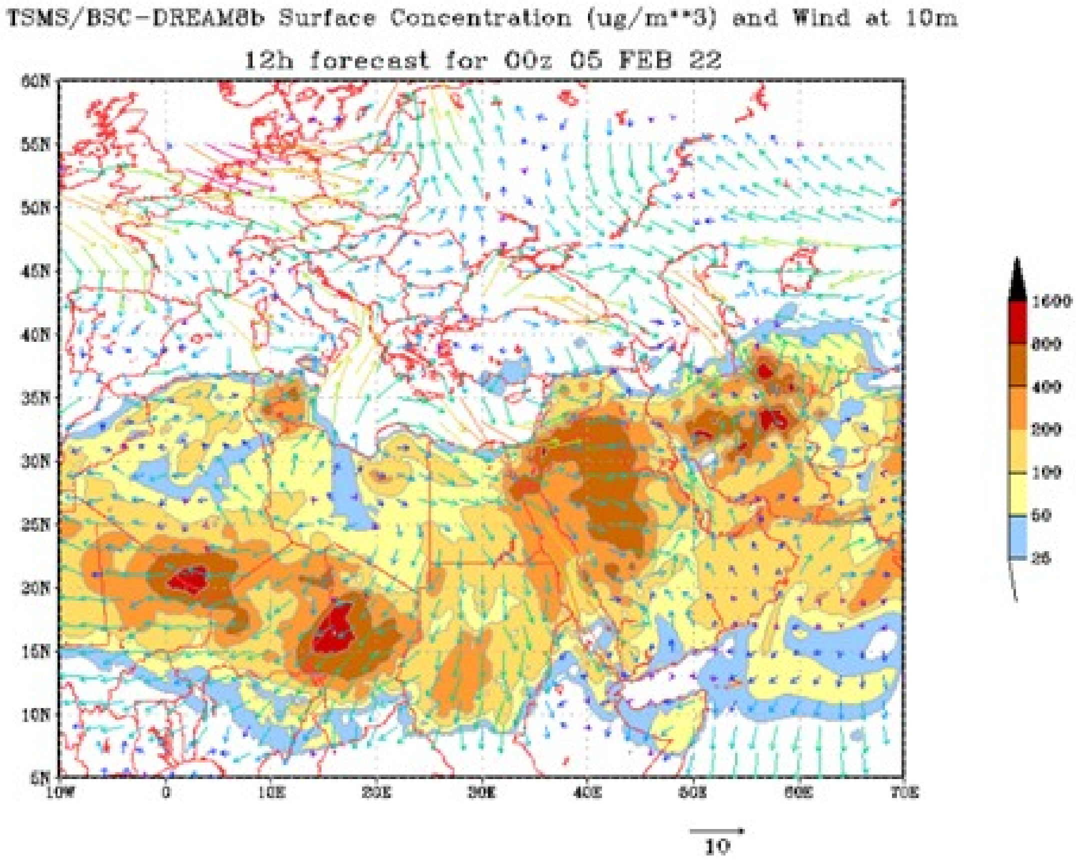


Figure 3.1: Sand Storm concentration and direction [93]

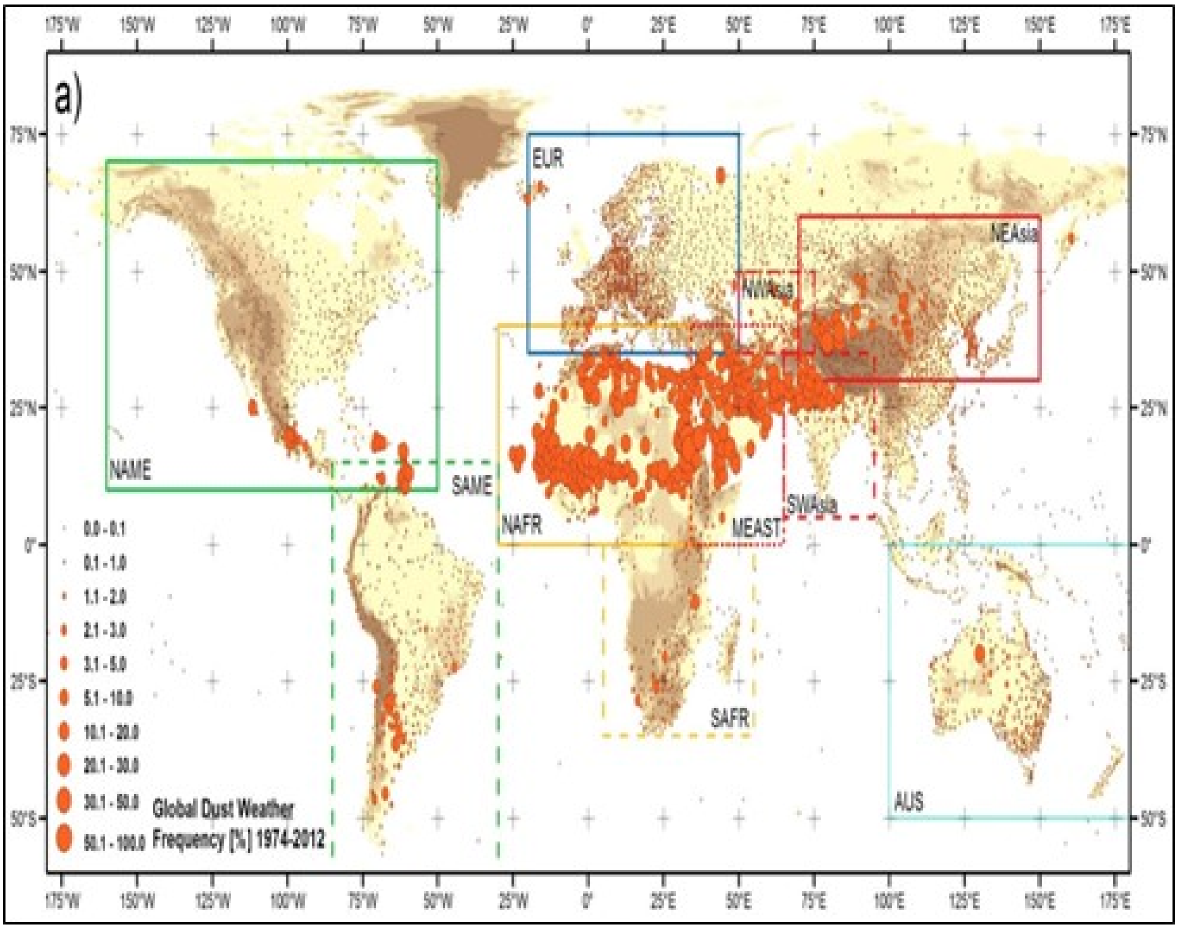


Figure 3.2: Global pattern of dust frequency [94]

Acknowledging these challenges, our research endeavors extend beyond merely eliminating sensor dependency; we strive to amplify the efficiency of solar power systems specifically tailored for desert climates. This involves the development of cutting-edge technologies designed to effectively counteract the adverse effects of sandstorms. Our comprehensive, multi-faceted approach seeks not only to bolster the resilience of solar energy systems but also to enhance their overall efficiency within the challenging context of desert environments.

This holistic strategy aims to unlock the full potential of these regions for sustainable and renewable energy solutions. By addressing the intricacies of desert climates and their unique challenges, we aspire to position solar power as a robust and dependable energy source in diverse environmental settings. Through our unwavering dedication, we contribute to the overarching objective of establishing solar power as a reliable and viable energy solution, adaptable to a wide array of geographical and climatic conditions.

3.3 Data Collection

3.3.1 Timeframe and Temporary Horizon of the Research

The testing phase conducted in June 2023 was deliberately chosen to align with the peak of summer in Tiaret, Algeria. This specific timeframe was selected to capitalize on the intense solar radiation typical of the summer season, providing optimal conditions for evaluating the performance of the sandstorm-resilient solar tracker. June also represents a period characterized by the prevalence of sandstorms in the region, offering a unique opportunity for a comprehensive assessment of the tracker's effectiveness under the challenging environmental conditions typical of desert climates. The decision to conduct the testing during this specific month enhances the relevance of the findings by simulating and assessing the solar tracker's response during the most demanding climatic conditions, encompassing both high solar radiation and the occurrence of sandstorms.

3.3.2 Sampling Strategy for Data Collection

The wind data utilized in this research was obtained from the NASA POWER Data Access Viewer[99]. This source was selected to ensure the use of authentic, reliable, and globally recognized information on wind patterns. The sampling strategy involved collecting real-time wind data relevant to the geographical coordinates of Tiaret, Algeria. By leveraging NASA POWER's comprehensive and up-to-date database, we aimed to obtain accurate information that aligns with the specific environmental conditions of the testing location. Table 3.1 provides detailed insights into the data used for simulating and testing our innovative approach, highlighting the meticulous approach to sourcing information critical to the validation and optimization of the sandstorm-resilient solar tracker.

3.4 Data Analysis

3.4.1 Sandstorm Affect on PV systems

Sandstorms pose severe threats to solar PV systems, resulting in substantial damage and economic losses. key consequence of sandstorms is the deposition of dust on various surfaces[100][101], a phenomenon extensively studied and documented [102] . This accumulated dust poses a significant challenge in desert climates, where studies reveal a notable reduction in the efficiency of photovoltaic modules [103, 104, 105] .

Research by Mostefaoui et al. (2019) [106]in the Adrar desert of South Algeria provides empirical evidence of diminished PV panel efficiency after prolonged exposure, particularly on days characterized by sandstorms. Similarly, Bouraiou et al. (2015) [107]explored partial shading and sand accumulation in Adrar, identifying substantial output reductions in PV

Table 3.1: Wind Speed and Direction Data for Tiaret Algeria June 2023

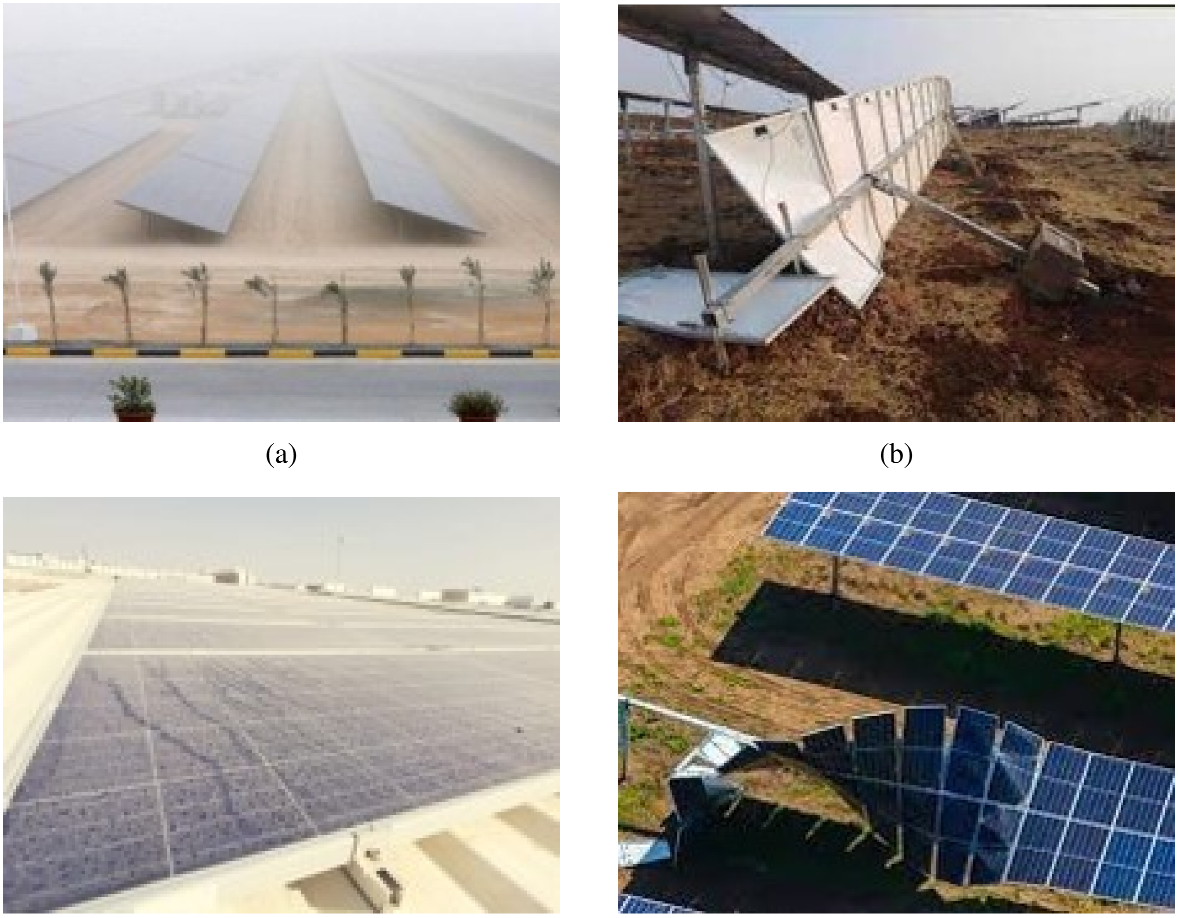
Date	**Hour**	**Wind Speed at 10M(m/s)**	**Wind Direction at 10M(°)**	**Wind Speed at 50M(m/s)**	**Wind Direction at 50M(m/s)**
1/6/2023	0	2.62	97.02	4.42	96.6
1/6/2023	1	2.77	109.25	4.78	109
1/6/2023	2	2.89	118.23	5.12	118.01
1/6/2023	3	2.92	127.94	5.26	127.76
1/6/2023	4	2.98	137.02	5.41	136.93
1/6/2023	5	2.81	143.7	5.45	143.39
1/6/2023	6	3.74	148.83	4.2	148.32
1/6/2023	7	2.19	159.75	2.24	164.66
1/6/2023	8	1.6	208.81	1.95	213.05
1/6/2023	9	2.11	237.25	2.55	236.12
1/6/2023	10	2.63	250.6	3.09	247.53
1/6/2023	11	2.94	258.21	3.39	254.49
1/6/2023	12	3.12	262.52	3.56	259.11

systems. The adverse effects of sandstorms extend beyond Algeria, as studies by Cabrera et al. (2016)[108] delved into the impact of sandstorms in Germany and Chile, revealing increased transmissivity, reflectivity, and short-circuit current losses.

Furthermore, investigations into the consequences of dust accumulation highlight daily power losses of up to 9% for dirty modules compared to their clean counterparts [109]. Additionally, projections involving a sand mass of 150 g resulted in a performance decrease ranging from 91.3% to 38.2% [110], and energy reductions varying from 4.4% to 80% [111]. However, it's noteworthy that solar trackers demonstrate lower power losses at 8.5% compared to the 31.4% power drop observed in fixed PV panels [112].

Beyond the immediate performance effects, the implications of dust settlement extend to the lifespan of PV modules. Gupta et al. (2019)[113] have demonstrated that dust accumulation can lead to elevated temperatures due to the reduction of solar panels' reflective properties, contributing to surface abrasion and shortening the overall lifespan of the modules. Moreover, the impact of sandstorms transcends the realm of energy infrastructure, as their contribution to desertification through soil erosion is well-documented in research studies (Akhlaq, Sheltami[92], and Mouftah 2012[114]; Wiesinger et al. 2020[115]; Karim et al. 2015[116]).

In addition to these challenges, the wind pressure accompanying sandstorms introduces further risks, including structural stress, torsional galloping[117], and the total deterioration of solar panels [117][118](see Figure 3.3). These multifaceted challenges underscore the pressing need for innovative solutions to mitigate the impacts of sandstorms on solar power systems in desert environments.



(a) (b)

(c) (d)

Figure 3.3: Sandstorm effect on solar power plant : (a) Sandstorm causing dust settlement on PV plant solar panels [98](b) Bhadla desert Solar Park damage due to sandstorm [116](c) Saharan dust accumulated on solar PV plant [99](d) the terror of torsional galloping due to windstorm in a solar PV plant in Queensland, AUS [115]

3.4.2 Sandstorm detection

Detection of sandstorms plays a pivotal role in mitigating their adverse impacts on solar photovoltaic (PV) systems. The significance of this lies in understanding the wind dynamics that lead to the entrainment of sand particles. Winds exceeding the threshold velocity create conditions for sand-driving winds, as observed by Tsoar in 1994[119]. It's crucial to note that higher wind speeds contribute to an exacerbation of dust accumulation, influencing sedimentological structures and, consequently, resulting in substantial drops in efficiency [120, 121, 115].

This complex interplay between wind dynamics and sand movement has been validated through various studies, including wind tunnel experiments conducted by Dale Gillette et al. in 1982[122], Nickling and Gillies in 1989[123], and Bouet et al. in 2015[124]. These experiments highlight three distinct modes of sand transport: creep, saltation, and suspension [125]. Distinguishing between mild and severe sandstorms hinges on the transport wind velocity, corresponding to the annual maximum sand transport rate [126]. Previous research has guided the selection of an appropriate wind threshold for detecting sandstorms.

Reports indicate that the lowest wind speed capable of initiating a 10-meter dust event above the soil is 4 m/s [127, 128]. Notably, Gillette proposed a threshold velocity of 6–7 m/s in 1977[129], while Park and In defined values of 6.0–9.5 m/s in 2003[130]. Tegen and Fung utilized a threshold of 6.5 m/s in 1994[131]. Adding to this body of knowledge, A. Benallal et N. Cheggaga reported that a wind speed threshold of 6.5 m/s triggers a dust event in the Algerian desert, aligning with the conditions under consideration in this study [132].

This comprehensive understanding of sandstorm dynamics and the associated wind thresholds is instrumental in the development of effective detection mechanisms. By precisely identifying the conditions conducive to sandstorms, we can implement timely measures to protect solar PV systems from the detrimental effects of dust accumulation, ensuring their sustained efficiency and longevity in the challenging desert environments.

3.4.3 Exciting Approaches

In the quest to address the complex challenges associated with dust accumulation and wind forces impacting solar panels, the literature presents a rich tapestry of strategies developed by dedicated researchers. A primary focus has been on mitigating the detrimental effects of dust on solar panels, prompting exploration into diverse and innovative methods. Solar trackers, renowned for their effectiveness, have emerged as a key solution. Strategies such as stowing trackers vertically at night or adjusting the tilt angle beyond 90° have demonstrated tangible success in reducing power drop [133, 134, 112]

Cleaning practices, another avenue of exploration, offer a pragmatic approach to addressing dust-related issues. Researchers, recognizing the importance of periodic maintenance, have suggested utilizing windy periods for partial cleaning, providing an opportunity to naturally alleviate dust accumulation [135, 134]. These strategies not only contribute to the efficiency of solar panels but also offer sustainable solutions by harnessing environmental conditions for system maintenance.

Moreover, alternative solutions have been investigated to enhance the resilience of solar panels in challenging environments. Covering panels with plain glass, coating modules with specialized films, or incorporating soda-lime glass into the panel structure are among the innovative approaches that have proven effective in minimizing the impact of dust on solar panels [136, 137, 138]. These materials and coatings act as protective shields, reducing the adherence of dust particles and thereby preserving the efficiency of the solar modules.

The literature not only unveils a plethora of strategies designed to tackle the challenges arising from dust accumulation and wind forces on solar panels but also illustrates the depth of innovation and research invested in optimizing solar energy systems. In the realm of dust management, researchers have explored a variety of multifaceted methods, each contributing to the arsenal of solutions. Solar trackers, as a prime example, have emerged as effective tools in minimizing power drop. Strategies like stowing trackers vertically at night or adjusting the tilt angle beyond 90° showcase the adaptability and ingenuity applied in addressing the specific challenges posed by dust [133, 134, 112]

Complementary to these approaches are cleaning practices that capitalize on environmental conditions. Utilizing windy periods for partial cleaning, as suggested in the literature, not only aids in dust removal but also aligns with a sustainable approach to maintenance [135, 134] . The literature also highlights alternative solutions that leverage various materials and coatings. Covering panels with plain glass, coating modules with specialized films, or integrating soda-lime glass into the panel structure have all demonstrated their efficacy in minimizing the impact of dust on solar panels [136, 137, 138]. These materials act as protective layers, creating barriers against dust adherence and thereby sustaining the efficiency of solar modules.

In the realm of wind forces, innovative designs have been introduced to fortify solar panels against their impact. Moth-eye anti-reflective structures[139], auto-folding reflectors in V-trough assemblies[140], and the use of waterproof boxes under strong wind conditions [141]showcase the diverse approaches taken to enhance the resilience of solar panels in adverse weather . Strategies like lowering the height of tracking PV arrays [142] and implementing fences and barriers have been proposed to minimize the adverse effects of wind forces [143, 144, 145] .

3.4.4 Gaps in exciting literature

The prevailing literature casts a spotlight on critical gaps that present formidable challenges to the extensive adoption and optimal functionality of solar energy systems, especially in arid regions. While existing studies diligently delve into the intricacies of dust accumulation and wind forces separately, a glaring void exists when it comes to comprehensive solutions for safeguarding solar PV systems from the dynamic duo of dust-laden sandstorms. These climatic events, characterized by a fusion of airborne dust particles and formidable wind forces, demand an integrated approach that seamlessly addresses both aspects, signaling a pivotal gap in current research endeavors.

One of the primary lacunae is evident in the realm of cost-effectiveness concerning cleaning mechanisms, coatings, and additional protective designs. The financial burden associated with the maintenance and periodic cleaning of solar panels often tips the scale, outweighing the cost savings derived from the energy they produce. This economic imbalance places a considerable constraint on the overall viability of solar systems, especially in regions prone to arid conditions. Bridging this gap requires innovative solutions that not only enhance the efficiency of cleaning mechanisms but also explore cost-effective protective measures, ensuring the economic sustainability of solar energy systems.

Another significant void emerges from the energy consumption associated with additional protective mechanisms against wind forces, such as V assemblies or protective boxes. In certain instances, the energy required for these protective measures can surpass the energy generated by solar trackers, introducing an imbalance that raises pertinent questions about the sustainability and overall efficiency of these protective interventions. Addressing this gap necessitates a nuanced examination of the energy trade-offs involved in implementing various protective measures, ensuring a harmonious balance that enhances rather than hinders the overall energy efficiency of solar systems.

Furthermore, the temporal and financial resources demanded for the frequent cleaning of solar panels present another challenge, affecting the practicality of solar systems in regions characterized by high dust accumulation. Developing strategies that minimize the frequency of cleaning while maintaining optimal efficiency becomes imperative to overcome this particular gap. Innovative solutions that promote self-cleaning or reduce the adherence of dust particles can significantly enhance the practicality and long-term viability of solar systems in challenging environmental conditions.

Additionally, the limited effectiveness of traditional fences against dust accumulation underscores the ongoing need for groundbreaking solutions in the realm of solar energy infrastructure. Recognizing this gap prompts the exploration of novel protective measures that extend beyond conventional approaches, ensuring a comprehensive defense against the challenges posed by dust-laden sandstorms.

3.4.5 Aims and perspectives

This research endeavors to bridge the identified gaps and elevate the efficiency of solar power generation in challenging desert environments, where sandstorms pose distinctive challenges to conventional solar panels. The innovative essence of this study lies in the seamless integration of wind data readings into standard solar tracking tools, presenting a proactive and dynamic approach to sandstorm mitigation. The core technique involves a meticulous analysis of wind speed data, with a keen focus on detecting sandstorms once they surpass a predefined threshold. Upon detection, the solar tracker autonomously repositions itself, utilizing established angles based not only on wind speed but also on wind direction data. This approach considers the azimuth rotation of the tracker, diverging from the conventional emphasis solely on tilt angles as observed in prior research. The result is an optimized protection mechanism during sandstorms, significantly mitigating their detrimental effects on the photovoltaic (PV) system.

This integrated approach not only serves as a robust safeguard during sandstorms but also carries notable economic advantages. By reducing operational costs, simplifying system complexity, and minimizing overall energy consumption, our approach stands out as a cost-effective and environmentally sustainable solution when compared to alternative protection mechanisms, cleaning practices, and traditional maintenance methods. The economic viability stems from the proactive nature of the system, enabling efficient utilization of resources and reducing the need for frequent manual interventions. Moreover, the integration of wind data readings into the solar tracking tools adds a layer of sophistication that enhances the overall resilience of the PV system, ensuring its continued functionality in the face of unpredictable desert conditions.

In summary, this research not only seeks to address the specific challenges posed by sandstorms in desert environments but also strives to redefine the approach to solar power generation in such regions. By integrating wind data into the solar tracking system, we aim to offer a comprehensive solution that not only safeguards the PV system but also contributes to the economic sustainability of solar power installations in desert regions. This research represents a significant step towards creating resilient, efficient, and economically viable solar energy systems in environments where sandstorms are a prevalent and disruptive force.

3.5 Sandstorm Impact Analysis

3.5.1 Wind Forecast

The impact of sandstorms on solar trackers is acknowledged as one of the most intricate challenges to address, primarily due to the multifaceted movements of the tracker parts in various directions simultaneously. Effectively preventing and minimizing the impact of sandstorms on trackers hinges on strategic preparedness, with a key element being the utilization of weather forecasts. Weather forecasts, which typically provide information about the direction and speed of the wind, play a pivotal role in anticipating and mitigating the potential adverse effects of sandstorms on solar tracker systems.

The complexity arises from the fact that the components of solar trackers move in diverse directions concurrently, making it essential to have precise information about the upcoming weather conditions. By leveraging weather forecasts, solar power facilities can anticipate the onset of sandstorms and take proactive measures to minimize the risk of damage to tracker components. Timely adjustments and repositioning of the solar tracker based on wind direction and speed data are crucial in ensuring that the system remains resilient and can withstand the challenges posed by sandstorms.

In the context of regions experiencing sandstorms, such as Algeria, where the wind dynamics play a significant role, understanding the wind patterns becomes particularly vital. The wind potential during specific seasons, holds paramount importance. In Algeria, the yearly average wind speed is recorded at 3.97 m/s, with a maximum recorded value reaching 14.6 m/s[146]. This data, illustrated in Figure 3.4), offers valuable insights into the prevailing wind conditions, allowing solar power facilities to tailor their sandstorm mitigation strategies according to the specific challenges posed by the region's climate.

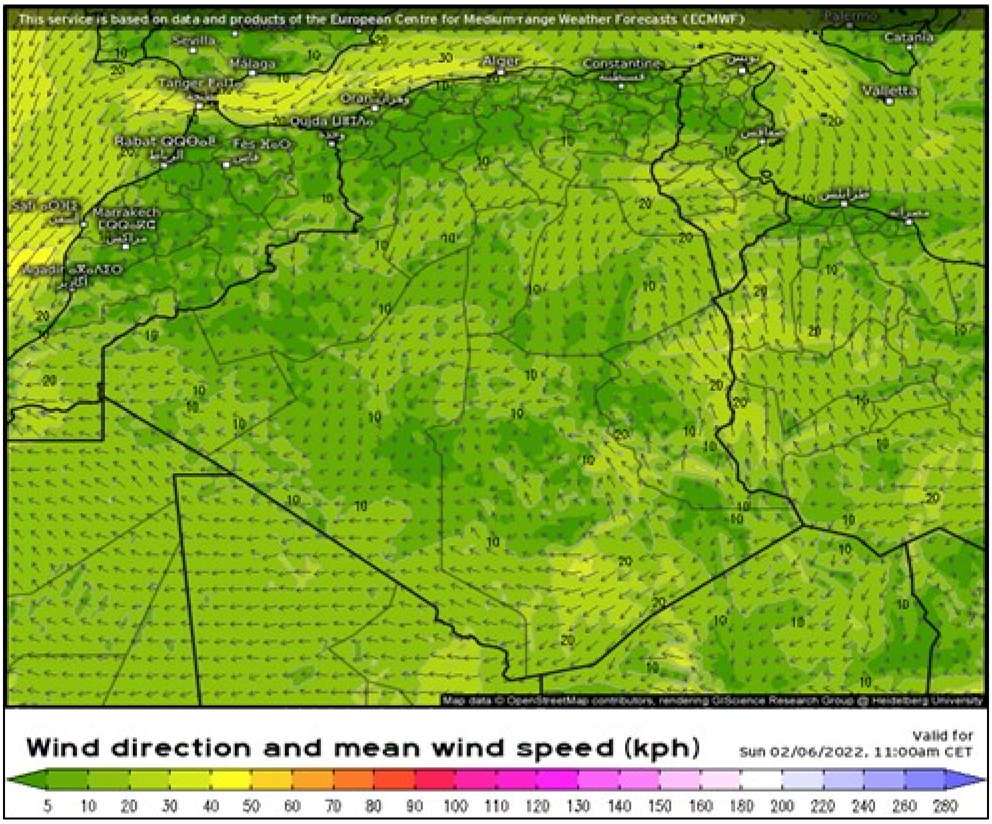


Figure 3.4: wind direction and speed in Algeria from January the 4th 2023 [144]

In essence, the proactive use of weather forecasts, coupled with a thorough understanding of wind dynamics, empowers solar power facilities to enhance the resilience of their tracker systems against sandstorms. By leveraging this knowledge, facilities can adopt preventative measures, such as adjusting tracker positions, optimizing system configurations, and fortifying components, to minimize the impact of sandstorms and ensure the uninterrupted performance of solar tracker systems in challenging environments.

3.5.2 Wind Dynamics

Understanding the impact of wind, including wind velocity and direction, is essential to assess the potential risks of sandstorms and implement appropriate protective measures [147]. Wind velocity threshold and sand transport rate help establish critical parameters for activating the sandstorm protection mode. This knowledge enables the solar tracker to adjust its position or deploy protective covers to minimize the impact of blowing sand and dust, ensuring the long-term functionality and durability of the system in sandy environments. Mathematical models describing the dynamics of wind and sand transport are essential for understanding the relationship between wind forces acting on the solar panels, dust transport by wind, and the impact of sandstorms, as presented below: The behavior of wind velocity at a given site can be specified using a probability distribution function, defined as [126]:

$$f_w(v,\lambda,k) = \frac{k}{\lambda}(\frac{v}{\lambda})^{k-1}e^{-(v/\lambda)^k} \tag{3.1}$$

Wind speed and direction(see Figure 3.5) can be estimated using the following equations[148]:

$$\vec{U}_{RV} = (\vec{u}^2+\vec{v}^2)^2 \tag{3.2}$$

$$\Theta_{RV} = \tan^{-1}(\frac{\vec{u}}{\vec{v}}) + \text{flow} \tag{3.3}$$

Where:

$$\text{flow} = \begin{cases} +180 & \text{for } \tan^{-1}\left(\frac{\vec{u}}{\vec{v}}\right) < 180 \\ -180 & \text{for } \tan^{-1}\left(\frac{\vec{u}}{\vec{v}}\right) > 180 \end{cases} \tag{3.4}$$

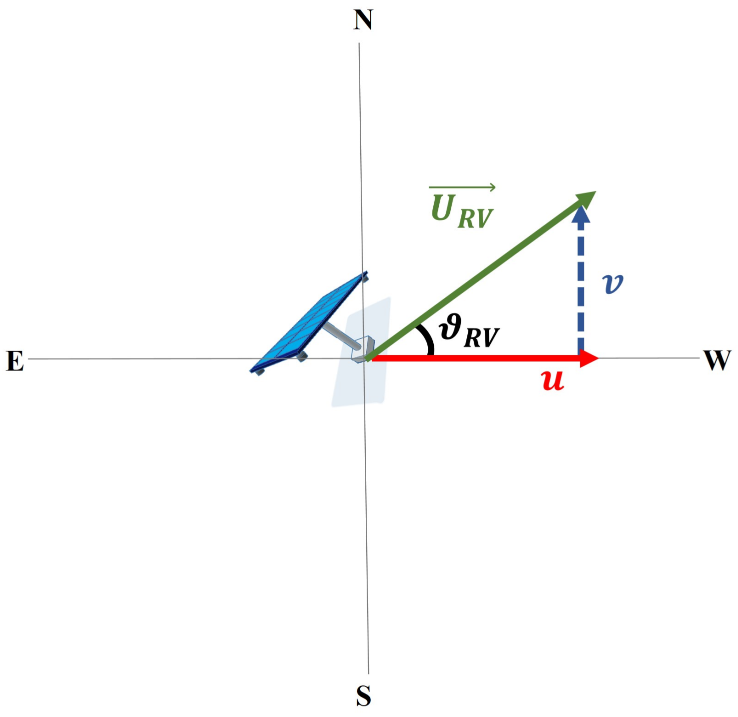


Figure 3.5: wind vector diagram

Given by Grange [148], the wind components u and v are expressed as:

$$\vec{u} = -u_i \sin(2\pi\frac{\theta_i}{360}) \tag{3.5}$$

$$\vec{v} = -u_i \cos(2\pi\frac{\theta_i}{360}) \tag{3.6}$$

3.5.3 Sands Transport by Wind

Sandstorms, characterized by the relentless winds carrying abrasive dust particles, present a formidable challenge to various structures, and among them, solar panels are notably susceptible. The forces exerted on individual sand grains, as elucidated in Figure 3.6, provide invaluable insights into the intricate dynamics between wind forces and the impact of dust on the structural integrity of solar panels. These forces encompass a range of factors, each playing a crucial role in the complex interplay between wind and dust, thereby influencing the potential harm inflicted on solar panels.

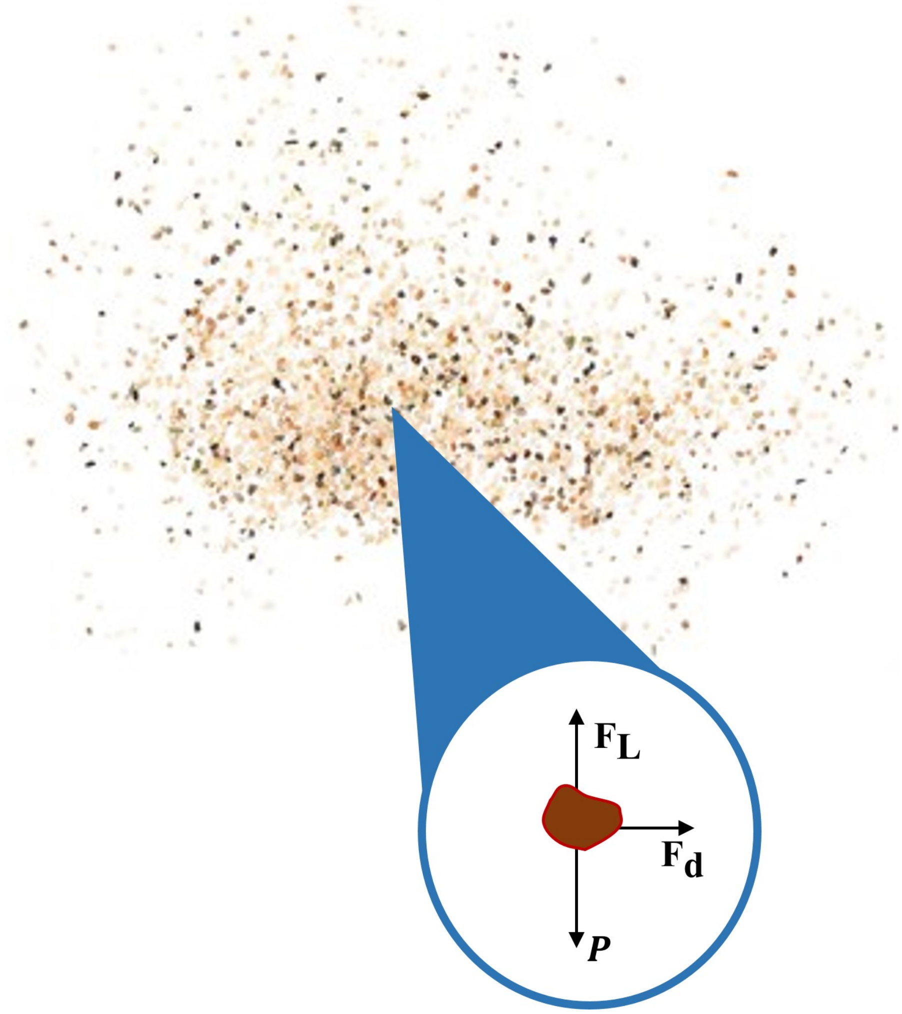


Figure 3.6: General forces acting on a grain of sand

First and foremost, the gravitational force (P) acts upon each individual sand grain, contributing to the downward pull that can result in dust settling on exposed surfaces. The reactions from neighboring grains (R) further complicate the scenario, introducing lateral forces that can lead to dynamic interactions between adjacent particles. Attractive forces (F) between particles also come into play, influencing their spatial arrangement and potential for aggregation. These forces collectively contribute to the intricate and often unpredictable behavior of airborne dust particles during sandstorms.

In the context of solar panels, it is crucial to recognize the additional impact of the wind's dynamic actions on the dust-laden air. The drag force (Fd) exerted by the wind plays a pivotal role in the transport and deposition of dust particles on solar panel surfaces. Simultaneously, the lift force (FL) may come into effect, especially in scenarios where strong winds lift particles from the ground, potentially causing abrasion and wear on exposed surfaces. These dynamic actions of the wind significantly influence the distribution and concentration of dust on solar panels.

Dust storm impact evaluation involves determining critical parameters like the threshold wind velocity (u*t) or the sand transport rate (q), as detailed by [126].These parameters are indicators for predicting dust storm occurrence and understanding the conditions favoring their development.

- **Threshold Wind Velocity (u*t):** This parameter represents the minimum wind speed required to initiate the movement of sand particles. Once the wind velocity surpasses this threshold, it signifies the potential for sand transport and the onset of a dust storm.

- **Sand Transport Rate (q):** The sand transport rate quantifies the amount of sand transported by the wind over a specific period. It measures the intensity of sand movement during a dust storm. Higher q values indicate more significant sand transport, suggesting a more severe impact of the dust storms. The threshold wind velocity u*t and sand transport rate q are given by:

$$u_*t \approx \sqrt{\frac{\rho_{\text{sand}} d_g}{\rho_{\text{air}}}} \tag{3.7}$$

$$q(u_*, C_L, \rho, g, d_g, D, u_{*t}) = \frac{\rho C_L}{g} \sqrt{\frac{d_g}{D}} u_*^2 (u_* - u_{*t}) \tag{3.8}$$

3.5.4 Wind forces acting on Solar Panel

The interplay between wind forces acting on a solar panel, as illustrated in Figure 3.7, and the impact of sandstorms on the panel constitutes a complex relationship. Wind forces, capable of exerting dynamic pressures and lift forces on the panel, introduce the potential for structural stress, torsional galloping, and overall deterioration. However, in the context of a sandstorm, the presence of airborne dust particles carried by the wind adds an additional layer of complexity to this dynamic interaction. The combined effect necessitates a comprehensive understanding of the mechanical stresses imposed by the wind and the potential degradation in performance due to the accumulation of dust on the panel.

Studying wind forces is paramount in the development of a strategy that optimizes the orientation of the solar panel to effectively mitigate the impact of wind forces, especially during sandstorms. The dynamic pressures and lift forces generated by the wind can induce mechanical stresses on the panel structure, potentially leading to structural issues and reduced efficiency over time. By comprehensively understanding these forces, solar panel installations can be designed and configured to minimize vulnerability to wind-induced stresses, ensuring the longevity and optimal performance of the system.

Moreover, the introduction of airborne dust particles during a sandstorm amplifies the challenges faced by solar panels. The accumulation of dust on panel surfaces not only affects the aerodynamics of the system but also diminishes the effectiveness of light absorption, thereby reducing energy conversion efficiency. Consequently, a holistic strategy must address both wind-induced stresses and the impact of dust accumulation to maintain the effectiveness and reliability of solar panels in challenging environmental conditions.

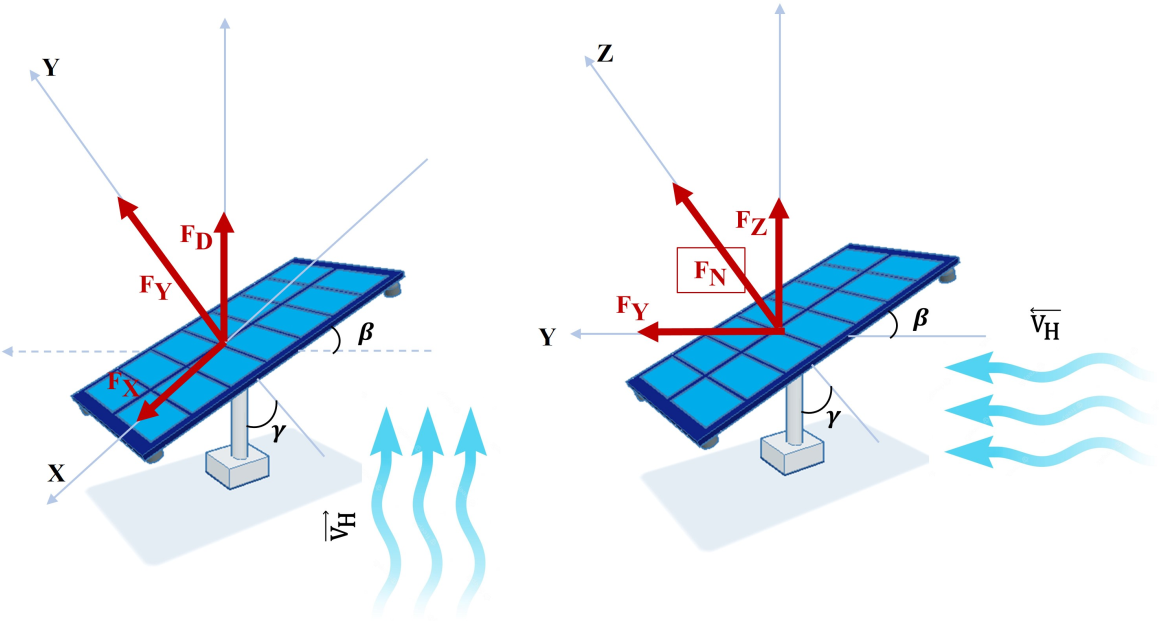


Figure 3.7: Wind forces acting on a solar panel

Wind forces and coefficients acting on the solar panel are given by [149]:

1. **Drag force:**The drag force is the resistance exerted by the air as it interacts with the surface of the solar panel in the direction of the wind. It influences dynamic pressures on the panel and is a crucial factor in assessing the aerodynamic effects.it can be given by:

   $$C_D = \frac{F_D}{\frac{1}{2}\rho V_H^2 A_{\text{ref}}} \tag{3.9}$$

   Where:

   $\mathrm{F}_D = F_y \cos(\theta) - F_x \sin(\theta)$(3.10)

2. **Lift force:**The lift force is the aerodynamic force perpendicular to the direction of the

wind, influencing structural stress and deterioration.It is given as :

$$C_L = \frac{F_L}{\frac{1}{2}\rho V_H^2 A_{\text{ref}}} \tag{3.11}$$

Where:

$$F_L = F_N \cos(\beta) - F_x \sin(\beta) \tag{3.12}$$

3. **Normal force:**The normal force is the force exerted perpendicular to the surface of the solar panel, contributing to the overall aerodynamic forces acting on the panel. It is given as:

$$C_{FN} = \frac{F_{FN}}{\frac{1}{2}\rho V_H^2 A_{\text{ref}}} \tag{3.13}$$

3.6 Sandstorm Mitigation Technique

3.6.1 Proposed protection strategy

Our proposed solar tracking strategy, complementing traditional sensor-based systems with additional features, is specifically designed to safeguard solar PV systems in desert environments against the challenges posed by sandstorms. Addressing mechanical stresses induced by wind and the potential performance degradation caused by dust accumulation on solar panels, this innovative approach integrates solar tracking tools with a wind-sensing technique to detect and proactively mitigate the impact of sandstorms.Figure 3.8 illustrates the sequential steps followed by the system, providing a visual representation of the designed sandstorm-resilient solar tracker's operational flow.

The operational sequence begins with the acquisition of location information, including latitude, longitude, date, and time. Utilizing astronomical equations detailed in Section 1, the system calculates the sun's position at various times throughout the day. Concurrently, wind speed and direction data are continuously monitored. If the wind speed remains below a predefined threshold, indicative of the absence of a sandstorm, and the time is within the sunrise-to-sunset range, the system optimizes energy consumption by calculating azimuth and elevation angles for that specific time. These angles are then converted into motor rotation angles and commanded to the actuators of the solar tracker, ensuring efficient solar tracking.

In the event of a detected sandstorm, characterized by wind speeds surpassing the predefined threshold, the solar tracker is stowed to a predefined angle, adopting a calculated attack angle based on wind direction data. These angles are proactively commanded to the actuators to ensure that the system is positioned optimally for sandstorm resilience. Regular tracking resumes once the wind speed falls below the defined threshold.

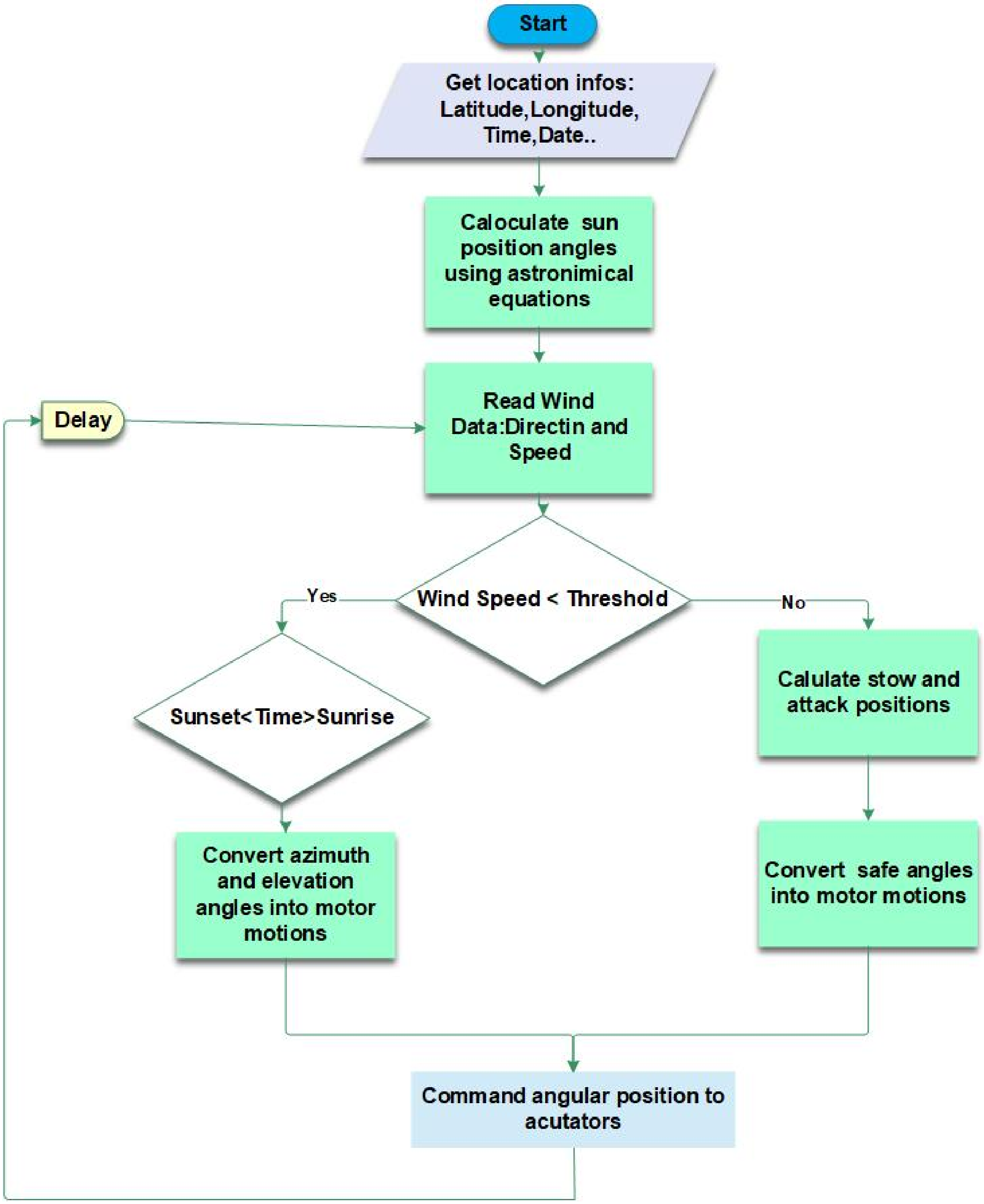


Figure 3.8: Flow chart of the daily sandstorm-resilient solar tracker

The wind-sensing process is repeated throughout the day and even at night, although solar tracking is confined to the period between sunrise and sunset. To conserve additional energy, the tracker freezes at the sunset position rather than adopting a specific night-stowing position.

This comprehensive strategy not only enhances the resilience of the solar tracker to sandstorms but also optimizes energy efficiency, minimizing operational costs and system complexity.

3.6.2 Optimum position for sandstorm resilience

The optimal position for the solar tracker to resiliently withstand sandstorms necessitates the consideration of several critical factors, including wind speed, direction, and dust accumulation. The stow angle, illustrated in Figure 3.9, is the angle at which the solar tracker tilts to minimize its profile and exposure to the wind during a sandstorm. This angle plays a crucial role in preventing structural stress and damage.

Conversely, the attack angle, also depicted in Figure 3.9, is the angle between the solar tracker and the wind direction during a sandstorm. It represents the angle at which the tracker presents itself to the oncoming wind. The specific stow and attack angles required depend on the panel's location and the desired level of protection. Notably, the literature provides specified stow angles aimed at shielding panels from the wind, as outlined in Table 3.2.

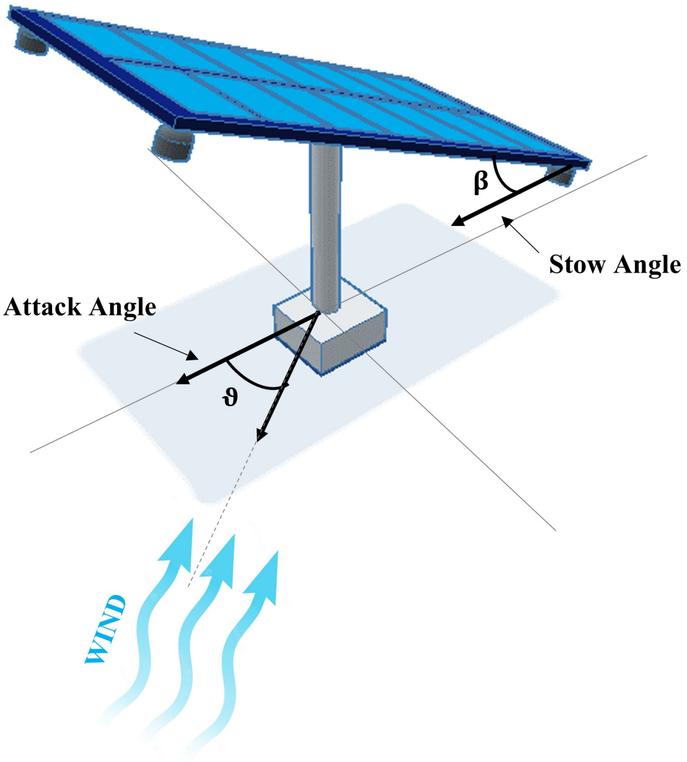


Figure 3.9: tracker's resilience configuration against sandstorm through optimized stow and attack angles.

Determining the optimum stow and attack angles is crucial for achieving effective protection against sandstorms, ensuring the structural integrity of the solar tracker, and mitigating potential performance degradation due to dust accumulation. As such, our proposed strategy employs these angles as key parameters for the proactive adjustment of the solar tracker's position during sandstorms, contributing to its overall resilience in challenging environmental conditions.

Table 3.2: Recommended stow angles from the literature to protect solar panels from wind forces

Reference	Stow Angle	Wind Direction	Comments
[150]	Not mentioned	65° to 75°	Stable for wind speeds 0 m/s to 33 m/s in Ottawa region
[109]	Not mentioned	0°	Lowest power drop compared to clean counterpart
[134]	30°	0°	Greatest resuspension when surface tilted 30° toward airflow
[149]	20°, 30°, 40°	Not mentioned	Drag coefficient highest at 40°, lift and vertical force coefficients not significantly affected by panel inclination
[151]	-15	Not mentioned	Recommended stow angle during wind events to reduce damage
[152]	0°	Not mentioned	Solar trackers susceptible to torsional galloping at 0°, prone to damage at wind speeds as low as 40 m/s
[153]	0°	Not mentioned	SATs prone to torsional galloping at 0° during wind events, even at low wind speeds
[154]	Not mentioned	Not mentioned	Wind load components vary with panel elevation, wind direction, and aspect ratio
[155]	30°	0°, 30°, 135°	Higher suction near upwind corner for 30°
[156]	Not mentioned	Not mentioned	Orientation with respect to wind direction and proximity to leading edge affect pressure distributions
[157]	< 30	Not mentioned	Critical wind loads observed at lower angles of incidence for panel tilt >30°
[158]	< 30	α (angle at which the panel is tilted)	Caution needed for wind loads on tilted panel at lower wind direction values when tilt angle >30°
[98]	0°	between 20° and 30°	It is recommended to stow the solar tracker at 0° and expose it to wind at an angle between 20° and 30°

In addition to structural stress caused by wind forces, sandstorm resilience requires considering the dust settlement on the panels and its impact on their efficiency. Even a minor dust storm can lead to particle buildup on the surface. The rate at which photovoltaic (PV) modules accumulate dust is significantly influenced by their tilt angle, with less dust settling on surfaces with steeper angles (see Figure 6). Research indicates that the lower the tracker's tilt angle is, the less wind loads are acting on the solar panel. However, it's crucial to acknowledge the inverse relationship between dust accumulation and tilt angle. Consequently, tilting the panel closer to the ground might not be the most effective strategy for

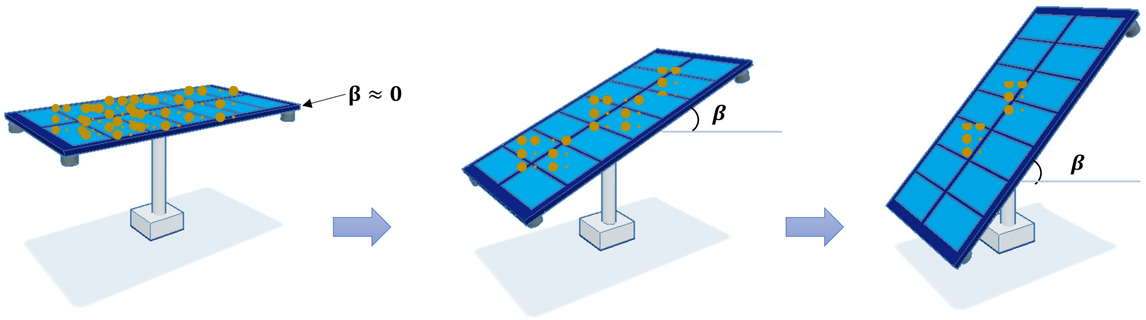


Figure 3.10: Dust accumulation on a solar tracker depending on the tilt angle

PV systems in desert environments. This positioning exposes the photovoltaic surface to repeated impacts from sand grains and the accumulation of dust propelled by the wind's kinetic energy. Additionally, a higher tilt angle proves advantageous for minimizing dust accumulation, while a lower tilt angle is preferable to reduce the impact of the wind. Moreover, the wind attack angle of the panel is crucial in protecting the panels from sandstorms. By carefully striking a balance between these considerations, we have identified an intermediate tilt angle that effectively addresses both wind resistance and dust accumulation, thereby ensuring the resilience of our solar panel system.

3.7 System Simulation and Modeling

Rigorous testing was conducted to ensure the performance, reliability, and adaptability of the smart solar tracker in sandstorm conditions. The testing involved simulations of the solar tracker's behavior, including the detection of sandstorms using wind speed data and the system's ability to respond swiftly by tilting to a calculated safe angle. The primary objective of the testing was to identify any potential weaknesses or areas for improvement in the system's design and functionality.

3.7.1 Proteus Software

One phase of the testing involved simulating the smart solar tracker in a virtual environment using Proteus software. The software allowed for a comprehensive simulation of the system's functionality and response to different parameters, such as wind data. The simulation accurately depicted the behavior of the solar tracker, showcasing its ability to adjust and respond to changes in wind conditions. Figure 3.11 illustrates the simulated system in Proteus, highlighting the proper functioning and interaction between the components.

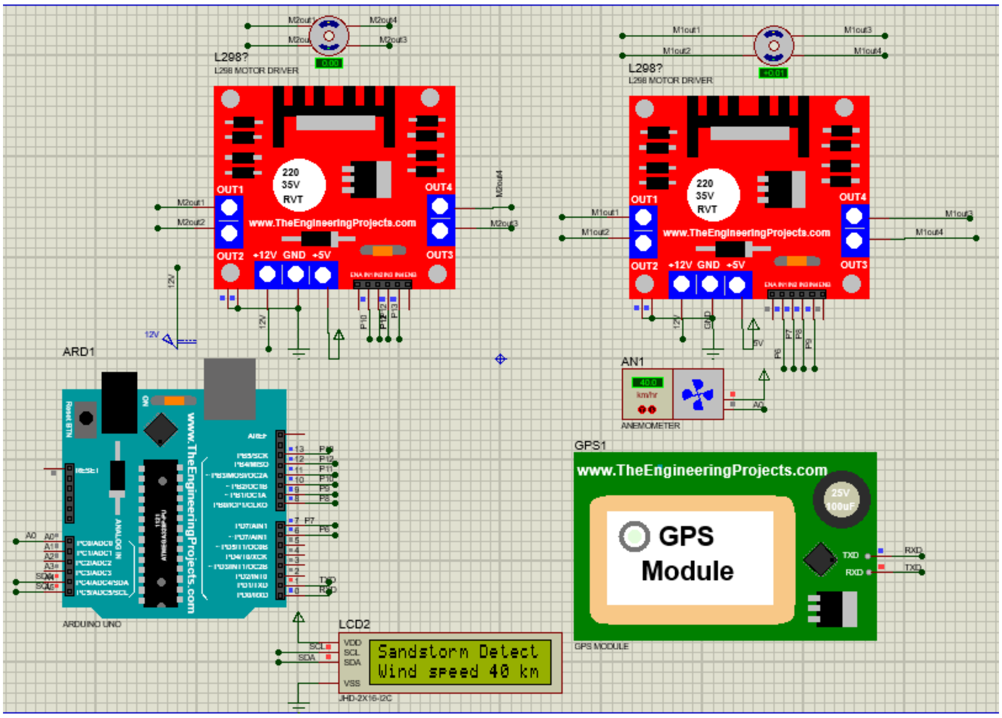


Figure 3.11: Proteus simulation of the designed system

3.7.2 MATLAB Simulink

Another phase of the testing process involved simulating the behavior of the solar tracker using Matlab. In this phase, the stepper motors were modeled, and real wind data was utilized for testing purposes. The wind data was obtained from NASA POWER Data Access Viewer [99], ensuring the use of authentic and reliable information. By incorporating the stepper motor models and integrating the real wind data into the simulation, the performance of the solar tracker under various wind conditions was assessed. The simulation results were then analyzed and interpreted. These results, along with their implications, will be presented and discussed in the results and discussion section. Figure 3.12 illustrates MATLAB simulation, providing the behavior and functionality of the solar tracker in response to real wind data.

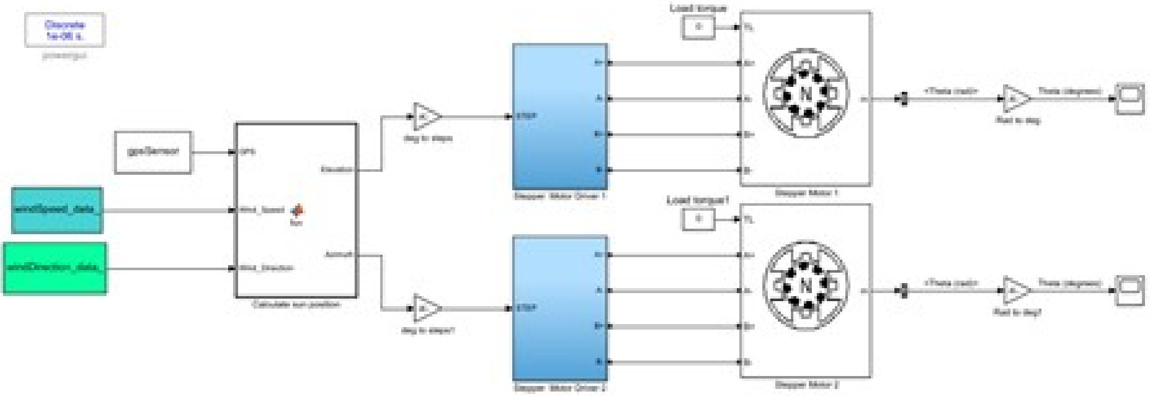


Figure 3.12: Matlab simulation of the system

3.8 Design and Implementation

3.8.1 Control unit

The control unit of the sandstorm-resilient solar tracker, as illustrated in Figure 3.13, consists of five key components, each playing a distinct role in enhancing the system's efficiency and responsiveness. First, a GPS sensor (1) captures precise geographic information, including latitude and longitude, crucial for calculating the sun's position. Second, an LCD Display (2) serves as the user interface, providing real-time information about sandstorm occurrences and other relevant data. The core processing unit is an Arduino Uno (3), responsible for calculating sun position angles, stow and attack positions, and commanding the actuators. The LN298N motor driver (4) facilitates the control of azimuth and tilt motors, ensuring seamless adjustments. Two stepper motors contribute to the mechanical operation: a NEMA 17 (5) controls the elevation rotation actuator, and a NEMA 23 (6) manages the azimuth rotation actuator. This integrated control unit ensures precise tracking and protection mechanisms against sandstorms, offering a comprehensive solution for challenging desert environments.

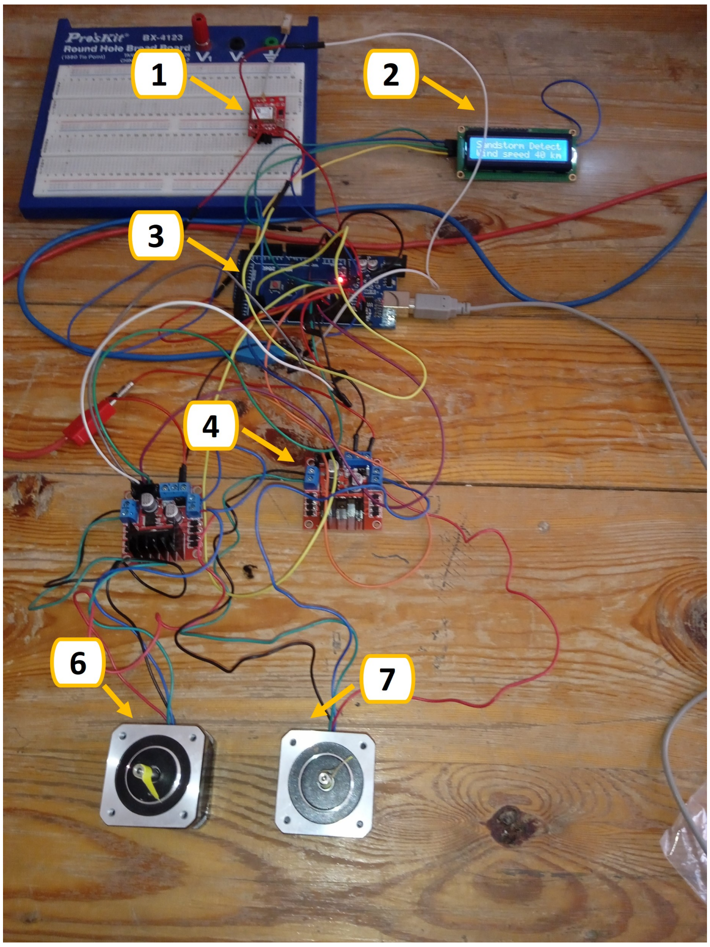


Figure 3.13: Control unit

3.8.2 Prototype

In implementing the sandstorm-resilient solar tracking approach, we seamlessly integrated wind data into the previously established solar tracker, which was thoroughly discussed in Chapter 2 (Figure 2.12). This involved refining the existing solar tracking tools to incorporate real-time wind information, enhancing the system's ability to respond dynamically to environmental conditions.

3.9 Advanced Interface Development for Solar Tracking

3.9.1 MATLAB App Designer

We've developed a streamlined user interface to facilitate user interaction with the solar tracker, enabling efficient monitoring of solar power generation processes. Our design addresses potential issues arising from sandstorms in the area, ensuring the reliability of the photovoltaic (PV) array. Additionally, the interface allows users to visualize the system's data. The choice of Matlab app designer was driven by our commitment to creating a professional app layout and programming its behavior without unnecessary complexity.

The user interface, illustrated in Figure 3.14, is organized into four panels:

Azimuth and Altitude Angles Calculator:

The core components of this program are structured as follows:

- Insert location coordinates (latitude and longitude), day number, and local meantime.
- Calculate the angle of declination, equation of time, and Local Mean Sidereal Time (LMST).
- Compute Apparent Solar Time (AST) and hour angle.
- Determine azimuth and altitude angles by clicking the designated button.

Solar Panel Orientation:

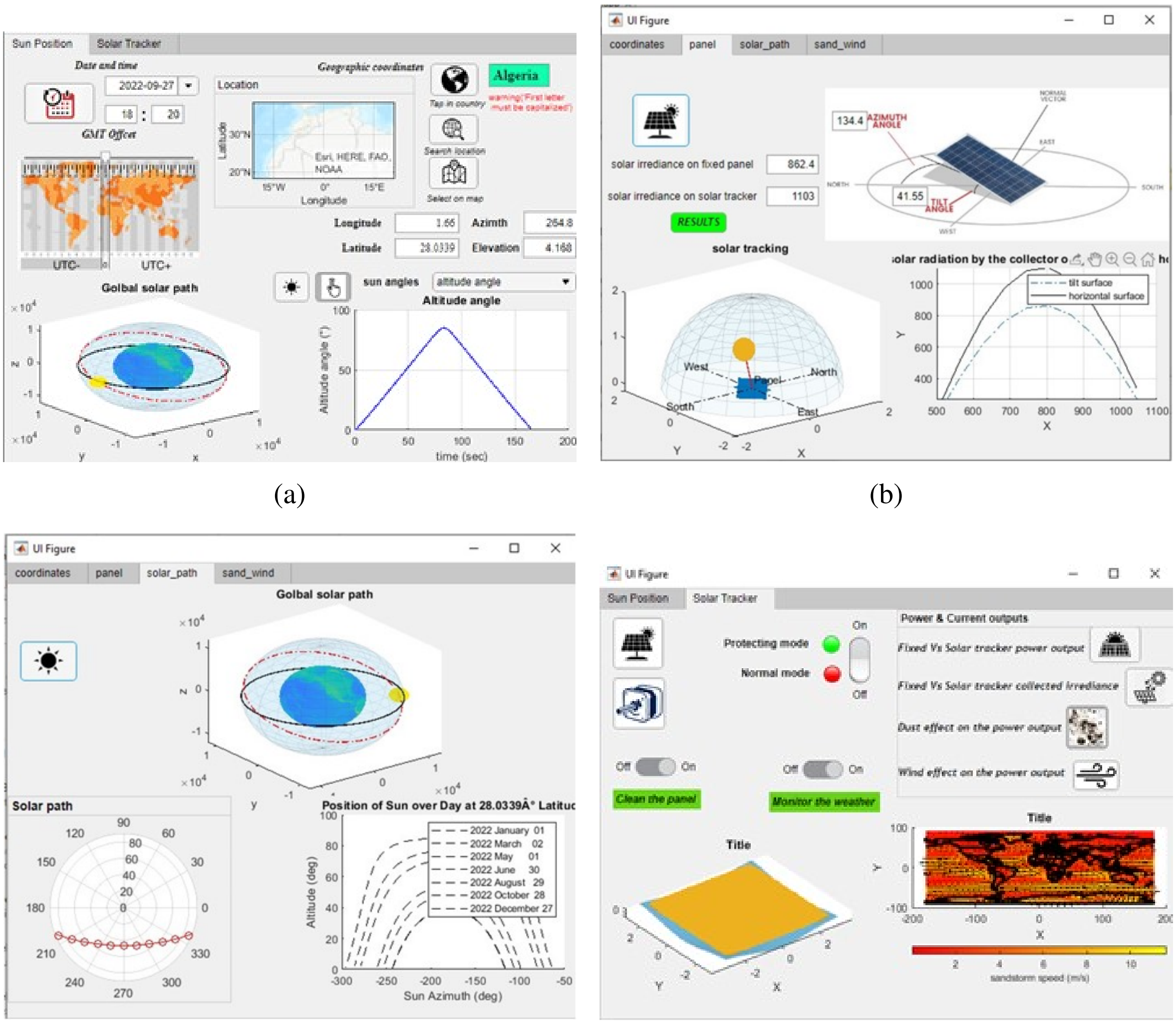
This program predicts the sun's trajectory to ascertain its position and solar radiation on a tilted surface at a specific location and time (Figure x). It also calculates the optimal tilt angle required to orient the PV panels toward the sun.

Sun Path:

By visualizing various plots (polar plot, globe-based reference frames, and elevation/azimuth graphs), this program simulates the solar path (Figure x d).

Protecting Solar Panels from Sandstorm:

This program focuses on safeguarding solar panels during adverse weather conditions, particularly sandstorms. It achieves this by monitoring wind speed and direction and automatically stowing the tracker in a secure position during such events.



Date and time: 2022-09-27, 18 : 20

Longitude: 1.66 Azimth: 264.8

Latitude: 28.0339 Elevation: 4.168

sun angles: altitude angle

solar irrediance on fixed panel: 862.4

solar irrediance on solar tracker: 1103

134.4 AZIMUTH ANGLE

41.55 TILT ANGLE

(a) (b)

(c) (d)

Figure 3.14: MATLAB app designer solar tracker user interface

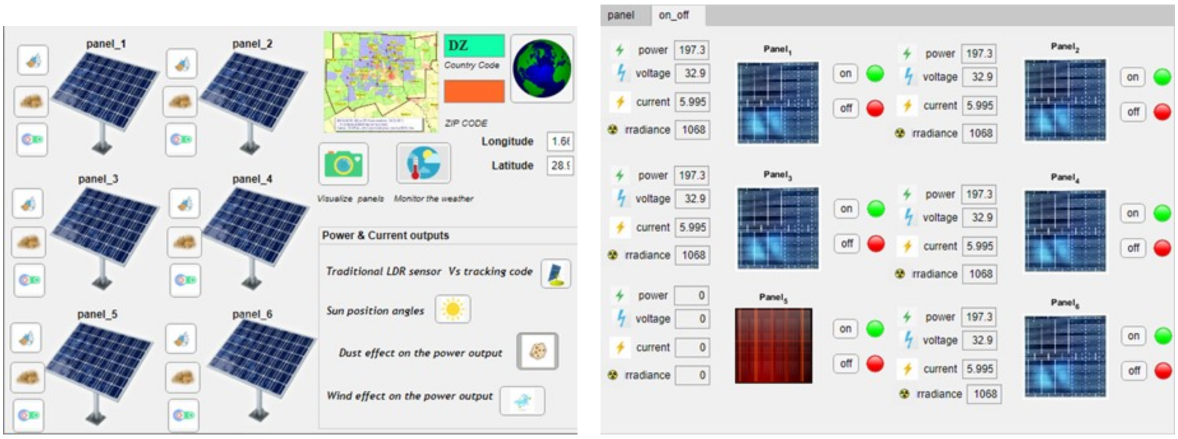
We have also designed a user interface for a solar tracker array (see Figure 3.15), incorporating two distinct interfaces for seamless control and management:

Solar Monitoring Interface

This interface allows remote control and monitoring of six individual solar panels. Its primary functions include optimizing energy production by aligning panels with the sun, converting calculated tracker angles into motor motion, inspecting panels through cameras, monitoring weather conditions for panel protection, and utilizing a vibration effect for panel cleaning during sandstorms. Additionally, it offers weather forecasting capabilities to enable users to take appropriate actions to safeguard and maintain optimal performance.

Turn On and Off System Interface

Designed for users to assess individual solar panel performance, this interface provides information on collected irradiance and generated power for each panel. The interface incorporates a rapid shutdown system, allowing users to quickly turn off one or all solar panels with a single button press, cutting off the current supplied to the system. This feature provides users the flexibility to manage panels in emergencies, during cleaning with water, or to protect against adverse conditions such as excessive heat or lack of light (nighttime or due to weather), which can significantly impact the output of the PV system.



(a) (b)

Figure 3.15: MATLAB app designer solar array user interface

3.9.2 Control Unit

To connect the developed user interfaces to the solar tracker, an electrical setup was implemented, incorporating a Bluetooth module (HC-05) and an Arduino Uno. The stepper motors employed for the solar tracker's movement include a NEMA 17 for elevation rotation and a NEMA 23 for azimuth rotation. These motors are driven by LN298N motor drivers, ensuring precise control and efficient operation. The integration of Bluetooth technology facilitates wireless communication between the user interfaces and the Arduino Uno, enabling remote control and monitoring of the solar tracker. This setup not only enhances user convenience but also ensures the seamless execution of commands from the interfaces to the physical movement of the solar tracker, aligning it with the sun for optimal energy harvesting.Figure 3.16 serves as a visual representation of the system's electrical components, showcasing the harmonious integration of these components to create an efficient and user-friendly sensorless solar tracking system.

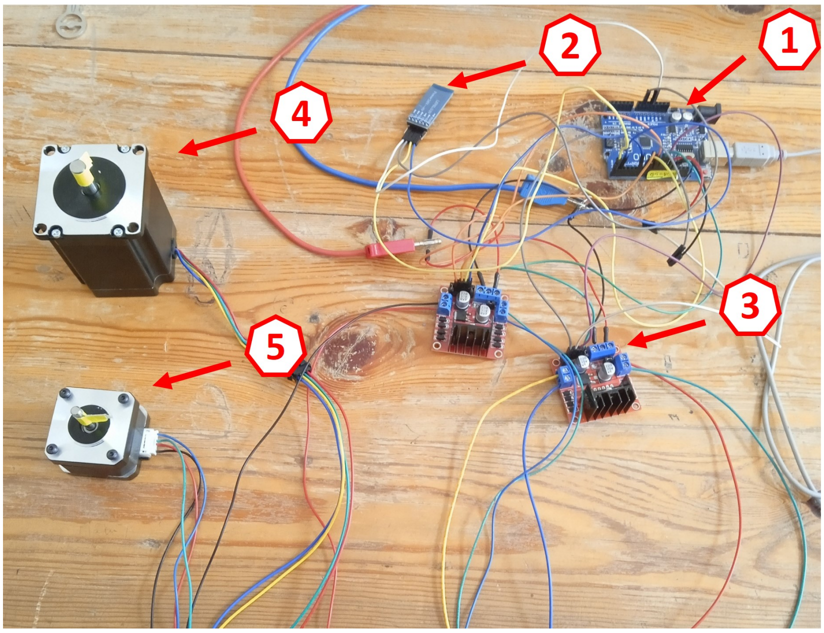


Figure 3.16: the electrical components of the solar tracker system connected to user interface

Table 3.3 provides a concise summary of the main components used in the electrical setup of our sensorless solar tracker system. It includes essential details such as the model names, specifications, and estimated costs for each component. This table serves as a quick reference for readers, offering a clear overview of the key components utilized in our system design.

Table 3.3: Specifications and Estimated Costs of Used Components

N°	Component	Model	Specifications	Cost (DA)
1	Arduino Board	Arduino Uno	-Microcontroller: ATmega328P -Digital I/O Pins: 14 -Flash Memory: 32 KB -Communication Interfaces: UART, I2C, SPI	2500
2	NEMA23 Stepper Motor	NEMA 23 17HS3004	-Step Angle: 1.8° -Holding Torque: 4 Ncm -Current Rating: 1.68 A	6500
3	NEMA17 Stepper Motor	NEMA 17 42HS1334AC	-Step Angle: 1.8° -Holding Torque: 26 Ncm -Current Rating: 0.4 A	2900
4	LN298N Motor Driver	LN298N	-Maximum Motor Voltage: 46V -Maximum Continuous Current: 2A -Motor Control Type: Dual H-bridge	1200
5	Bluetooth Module	HC-05	-Communication Range: 10m -Bluetooth Version: 2.0	1200

3.10 Validation Process

A critical aspect of our research involved validating the effectiveness and accuracy of the proposed sandstorm-resilient solar tracker. To accomplish this, we established a rigorous validation process that involved comparing the collected data with expected results. The validation process encompassed two key aspects:

1. **Dust Accumulation:** To determine the optimal tilt angle, we conducted a comprehensive analysis of dust accumulation on solar panels. This involved estimating the amount of dust accumulated for different tilted angles, as detailed in Table 3.2.
2. **Wind Pressure:** Another crucial parameter for validation was assessing the impact of wind forces on the solar panel. We systematically analyzed the wind forces acting on the solar panel and selected the minimal wind coefficient attack angle to enhance the resilience of the system.

By rigorously examining both dust accumulation and wind pressure on solar panels, we were able to select the optimum position during sandstorms. Through systematic analysis of the impact of different tilt angles on dust accumulation, we identified the tilt angle that minimizes the accumulation of dust particles on the solar panels. Simultaneously, by evaluating the wind forces acting on the panels and choosing the minimal wind coefficient attack angle, we ensured that the solar tracker maintains optimal resilience in the face of varying wind conditions during sandstorms.

3.11 Advantages of the Sandstorm-Resilient Solar Tracker

By leveraging standard solar tracking tools with integrated wind data, this study presents an innovative solution to mitigate sandstorm impacts on PV systems and optimize solar power generation in challenging desert environments. The research illuminates advancements in renewable energy within arid and hot climates, offering significant advantages as follows:

1. **Effective Sandstorm Mitigation:** The strategy of stowing the solar panel at a low tilt and considering the attack angle proves effective in minimizing sandstorm impacts, addressing both dust accumulation and structural stress.
2. **Continuous Protection:** The protective approach remains operational even during inactive nighttime periods, ensuring continuous safeguarding against potential sandstorms.
3. **Cost-Effective Solution:** The designed solar tracker stands out for its cost-effectiveness by integrating solar tracking tools with wind sensing, eliminating the need for additional proactive mechanisms.

4. **Real-Time Monitoring:** Utilizing wind data for sandstorm prediction and solar tracker protection represents a novel approach, enabling real-time monitoring and proactive defense against sandstorms.
5. **Extended PV System Lifespan:** By minimizing wind forces and dust accumulation, the approach extends the PV system's lifespan, offering protection from surface abrasion, structural stress, long-term degradation, and the risk of total panel deterioration.
6. **Holistic Environmental Protection:** Beyond sandstorms, this approach contributes to advancing solar energy generation in deserts by safeguarding panels from excessive heat through misalignment with the sun during stowing and reducing dust accumulation that retains temperature.
7. **Enhanced Efficiency:** The strategy significantly enhances the solar tracker's efficiency in desert environments, achieving minimal energy consumption through the utilization of tracking tools without additional mechanisms.
8. **Versatility in Storm Protection:** This approach holds promise for broader applications, extending its utility to various storm types, not limited to sandstorms, and offering protection against wind storms.
9. **Reduced Maintenance Costs:** The proactive approach to sandstorm mitigation minimizes the accumulation of dust on solar panels, reducing the frequency and intensity of cleaning requirements. This leads to lower maintenance costs over the operational lifespan of the solar installation.
10. **Increased Lifespan of Solar Panels:** By minimizing exposure to abrasive dust particles during sandstorms, the solar tracker contributes to the prolonged lifespan of solar panels. This not only enhances the return on investment but also promotes sustainable and long-term energy production.
11. **Optimized Energy Production in Challenging Environments:** The adaptability of the solar tracker to changing environmental conditions ensures optimal energy production even in the face of sandstorms. This makes it particularly suitable for deployment in arid regions with frequent dust and sandstorm events.

The sandstorm-resilient solar tracker emerges as a multifaceted solution that not only addresses sandstorm challenges but also enhances the overall performance, durability, and adaptability of PV systems in demanding environmental conditions.

3.11.1 Limitations of the Sandstorm-Resilient Solar Tracker

The sandstorm-resilient solar tracker, while presenting significant advantages, is subject to certain limitations that warrant acknowledgment. Firstly, the system's efficacy hinges on the precision of real-time wind data. Inaccuracies in measurements related to wind speed and direction could potentially compromise the tracker's ability to proactively respond to impending sandstorms. Secondly, the initial setup and calibration of the sandstorm-resilient solar tracker demand meticulous attention to ensure proper functionality. The intricacies involved in the setup process may present challenges during the system's deployment. Lastly, the tracker's design is intricately tailored for desert environments, and its effectiveness may exhibit variations in regions characterized by different climatic conditions. Adapting the system for diverse environments might be necessary to optimize its performance across varied geographical locations. These considerations highlight the importance of addressing specific challenges related to wind data accuracy, initial setup procedures, and geographical variations for the sandstorm-resilient solar tracker.

3.12 Future work

In the realm of future research, our focus will extend towards refining and expanding the protective approach to address sandstorms across all three levels of intensity: mild, moderate, and severe. The forthcoming investigation aims to comprehensively evaluate the efficacy of the proposed strategy under varying sandstorm conditions. This endeavor involves the fine-tuning and optimization of the solar tracking system's response algorithms to different degrees of sandstorm severity, enhancing its resilience and protective capabilities. Key areas of exploration include severity-specific optimization of response parameters, integration of advanced sensors for accurate sandstorm detection, geographical adaptation to diverse climates, long-term durability studies, economic viability assessments, and the exploration of energy storage integration for uninterrupted energy production. This holistic approach anticipates making the sandstorm-resilient solar tracker a robust and adaptable solution capable of thriving in a range of environmental conditions and sandstorm intensities.

3.13 Conclusion

In conclusion, this chapter has presented a comprehensive methodology for the development of a sandstorm-resilient solar tracker tailored for optimal performance in desert environments. By integrating geographic coordinates, astronomical equations, and real-time wind data, our innovative approach aims to proactively address the challenges posed by sandstorms. This meticulous methodology not only mitigates potential damage but also optimizes energy efficiency, contributing to the overall viability of solar power generation in Algeria and arid regions in general. As we move forward, this robust foundation sets the stage for the implementation and testing phases, marking a significant step towards the realization of a resilient and efficient solar PV system in the face of challenging desert climates.

Chapter 4

Results and Discussion

4.1 Introduction

In this chapter, we analyze the outcomes of our research, focusing on evaluating the performance of the designed solar tracker and presenting our findings.This chapter aims to demonstrate the system's ability to significantly enhance solar power efficiency while circumventing the drawbacks associated with traditional sensor-dependent trackers. By relying on sun position algorithms and geographic coordinates, our innovative solution validates its feasibility and efficacy in diverse weather conditions, particularly in arid and hot regions.

4.2 Descriptive Statistics

4.2.1 Geographic Location Data

The precise mapping of geographic locations to latitude and longitude coordinates is indispensable for the optimal performance of the sensor-less solar tracking system.We present a comprehensive mapping of ZIP codes to latitude and longitude coordinates, establishing the groundwork for accurate sun tracking. This meticulous mapping allows the solar tracker to fine-tune its orientation based on the sun's position, making a substantial contribution to the overall efficiency of the system. In our study conducted in Algeria, the determination of the solar tracker's location is achieved by selecting the ZIP code corresponding to the region where the tracker is installed. Given Algeria's administrative division into 58 provinces, each representing a county, and further subdivided into 2324 municipalities, our solar tracking system utilizes Algerian postal codes. Table 4.1 provides an extensive dataset of Geographic Coordinates for Various ZIP Codes in Algeria. This dataset facilitates the retrieval of latitude and longitude information for all provinces and municipalities across Algeria, encompassing a total of 2324 distinct regions.The incorporation of Algerian postal codes represents an innovative approach we employed to facilitate and make the use of the developed solar tracker feasible across the country.

Table 4.1: Geographic Coordinates Data for Various ZIP Codes in Algeria

ZIP_CODE	ADDRESS	LATITUDE(°)	LONGITUDE(°)
1000,00	Adrar	27,88	-0,29
9035,00	AHL EL OUED ETHENIA	35,97	4,16
44000,00	Ain - Defla	36,26	1,96
46000,00	Ain - Temouchent	35,30	-1,14
14039,00	AIN BEIDA	35,80	7,39
14040,00	AIN BOUCHEKIF	35,36	1,51
14007,00	AIN DEHEB	34,85	1,55
14017,00	AIN DZARIT	35,35	1,67
14008,00	AIN EL HADID	35,06	0,89
14009,00	AIN KERMES	34,91	1,11
14041,00	AIN MERIEM	37,30	9,87
14042,00	AIN RADJAH	36,17	1,05
9004,00	BLIDA BAB DJAZAIR	36,47	2,83
9026,00	BLIDA BEN ACHOUR	36,48	2,86
9016,00	BLIDA BEN BOULAID	36,49	2,83
9005,00	BLIDA BEN MOKADEM	36,50	2,83
9017,00	BLIDA BOUNAAMA DJILLALI	36,47	2,83
14016,00	TIARET BENAMARA DJILLALI	35,37	1,32
14031,00	TIARET BOUHENNI	35,37	1,32
14032,00	TIARET CITE CHAIB MOHAMED	35,37	1,31
14033,00	TIARET MED BOUDIAF	35,37	1,32
14000,00	TIARET RP	35,37	1,32
14034,00	TIARET TAHRI BOUABDELLAH	35,36	1,32
14035,00	TIARET UNIVERSITE	35,37	1,32

To understand geographic location effects on accurate sun position determination, we conducted sun position calculations for different ZIP codes on the same day. Figure 4.1 illustrates the daily variation in Sun Position Elevation and Azimuth across various ZIP codes on March 21, 2023. The selected regions exhibit diverse geographical and weather conditions across Algeria.

From the figure, distinct sunrise and sunset times are evident for each location, highlighting the influence of geographical variations and diverse weather patterns. Notably, the maximum elevation angle differs for each location due to variations in solar noon timings. For instance, in Tindouf, the solar noon occurs at nearly 660 minutes (11 AM), while in Blida, Algiers, and other locations, it is around 780 minutes (1 PM). This discrepancy influences both azimuth and elevation angles, as observed in the figure.

Furthermore, the maximum elevation angle reaches approximately 70 degrees for Tindouf, Tammnrasset, and Tlemcen, whereas for Blida, Algiers, Tiaret, and similar locations, it hovers around 50 degrees. A similar pattern is observed in azimuth angles, with differences of up to 100 degrees. These variations stem from differences in latitudes and longitudes, as detailed in Table 4.1.

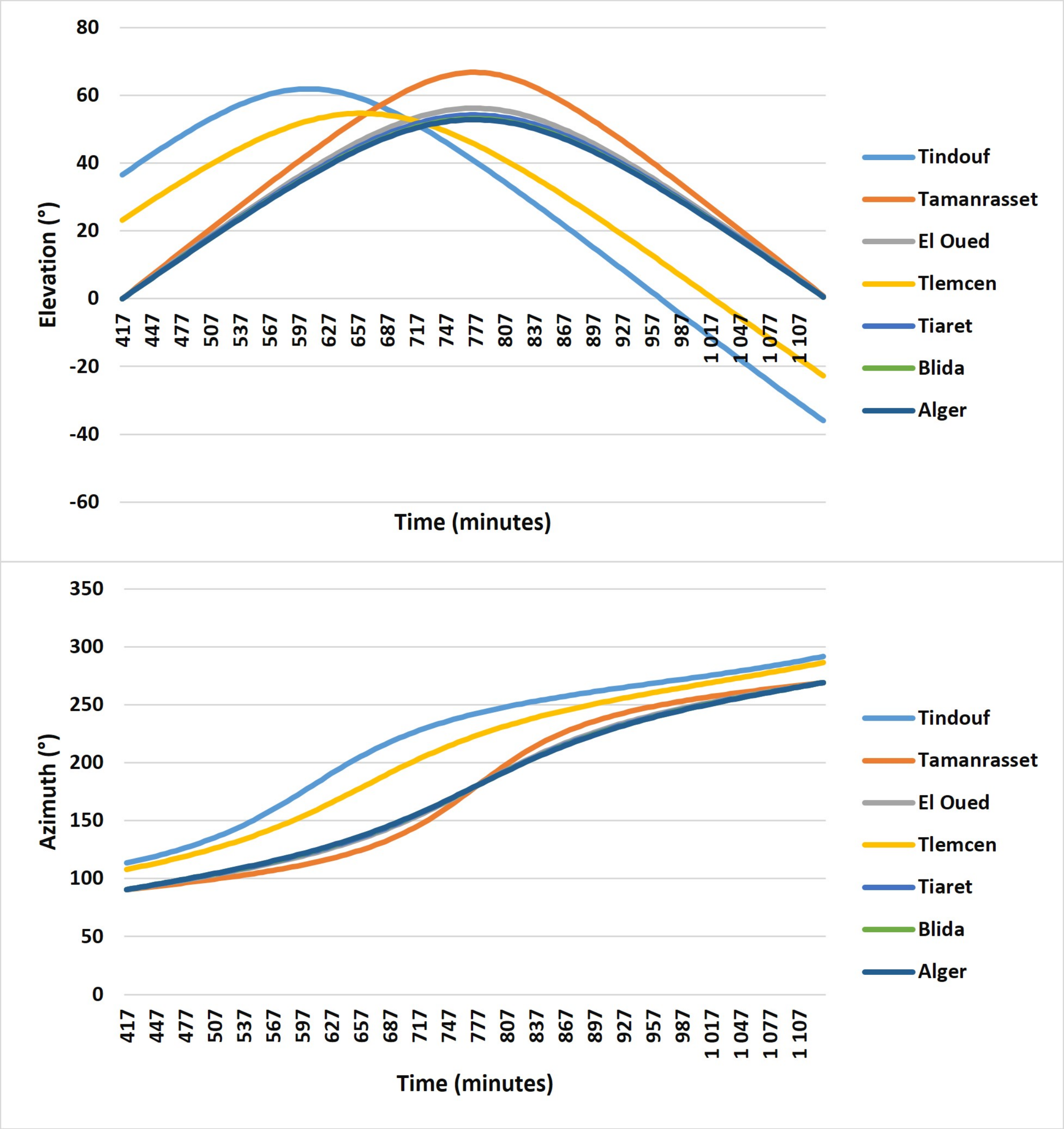


Figure 4.1: Daily Sun Position Elevation and Azimuth Variation Across Various ZIP Codes on a Single Day

Essentially, alterations in location exert a substantial influence on both azimuth and elevation angles, profoundly affecting the collected radiation(as shown in Figure 4.2. This underscores the critical importance of factoring in geographic considerations for effective solar tracking, highlighting the necessity of adapting tracking systems to the specific conditions of different locations to optimize solar energy collection.

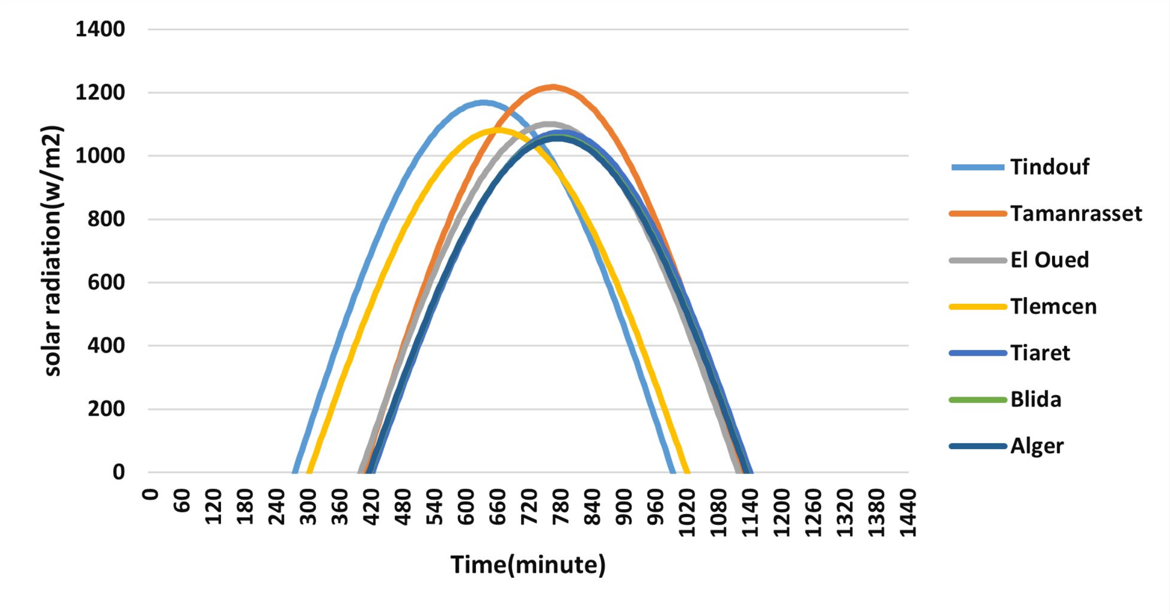


Figure 4.2: Solar Radiation Variation Across Various ZIP Codes on a Single Day

The sun's position is not solely influenced by geographic coordinates; it also varies within the same location throughout the year due to the Earth's orbit around the sun. Figure 4.3 illustrates Sun Position Variations in Blida across different months throughout the year.

The elevation angle in Blida is at its lowest on December 21st and highest on January 21st, representing the winter solstice and summer solstice, respectively. These dates mark the longest and shortest days of the year. The elevation angle exhibits a range from 0 to 80 degrees, while the azimuth spans from 50 to 300 degrees.

Notably, at noon around 1 PM, the elevation angles differ significantly by approximately 10 degrees between each month. This variation is attributed to the changing position of the sun in the sky throughout the year. Despite the azimuth angle remaining constant at 175 degrees at noon, differences of 16 degrees are observed before and after noon between each month in the azimuth angle.

These fluctuations in both elevation and azimuth angles underscore the seasonal variations in the sun's position, emphasizing the need for a solar tracking system that can dynamically adapt to these changes for optimal efficiency.

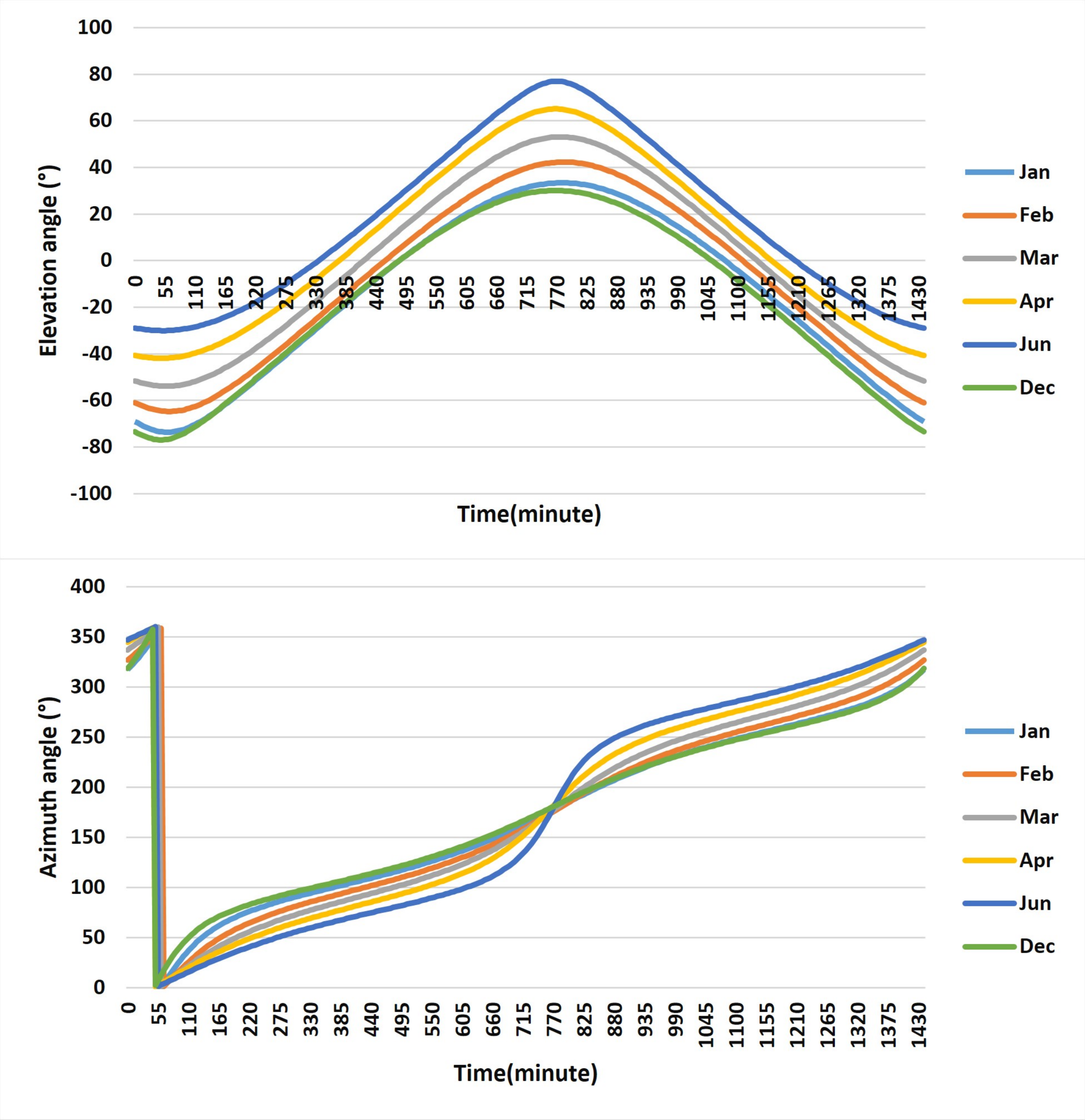


Figure 4.3: Sun Position Variations in Blida on Different Dates

Understanding the seasonal variations in solar radiation is crucial, given that it constitutes the primary objective of the tracking system. Figure 4.4 illustrates the solar radiation results in Blida for the year 2023. Notably, the maximum incoming solar radiation occurs between 12:45 and 13:45, varying throughout the year. In the hotter months (March, April, June), the solar radiation hovers around 1300 W/m², while in the colder months (December, January, February), it peaks at about 700 W/m², reflecting a significant rate of change at 47%. This insightful analysis provides a comprehensive view of how solar radiation fluctuates over the course of the year, crucial information for optimizing the performance of solar tracking systems.

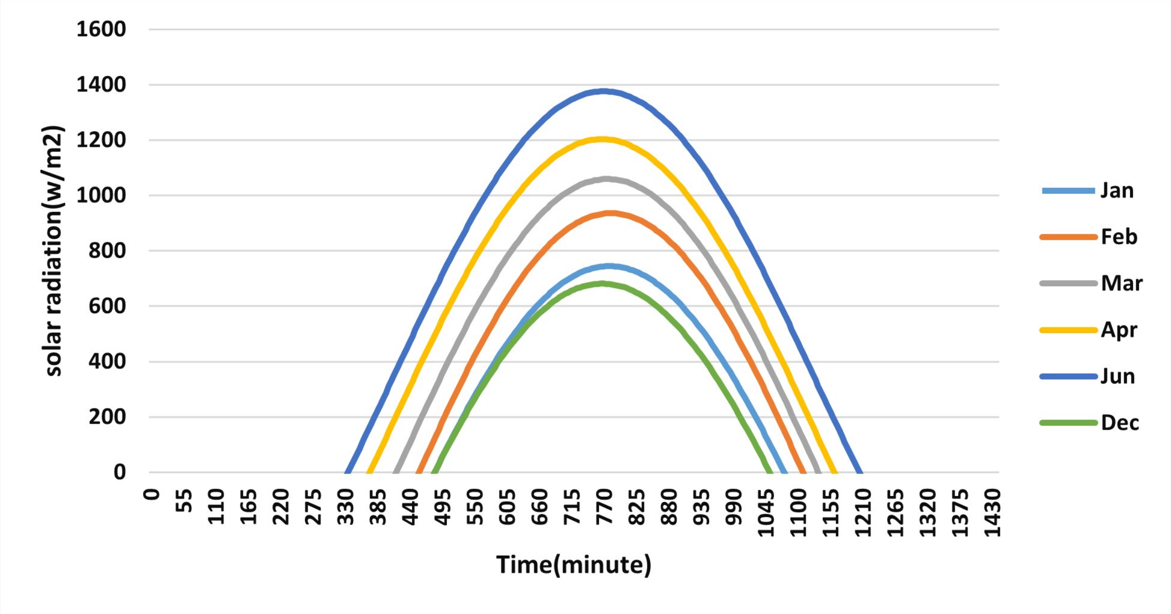


Figure 4.4: Yearly Solar Radiation Trends in Blida for the Year 2023

4.2.2 Solar Radiation Data

Solar radiation data plays a pivotal role in evaluating the system's performance. The purpose of any solar tracking system is to maximize solar radiation exposure, ensuring optimal energy capture. By examining variations in solar radiation across different locations, dates, and months, we gain insights into the system's adaptability to diverse environmental conditions. These statistics are essential for gauging the efficiency of our sensor-less solar tracker in harnessing solar energy under various scenarios. Table 4.2 illustrates the daily variation in solar radiation for Blida in March 2023. In Figure 4.5, a column chart depicts the average daily solar radiation variation for the same location during the same period. The chart provides a visual representation of patterns and trends in daily solar radiation values throughout the month, revealing an average sunlight fluctuation from 600 W/m² to 750 W/m² , occurring approximately every 5 days with a consistent pattern and a rate of 20%.

Moreover, the table includes information on sunrise and sunset times, offering insights into the duration of daylight. The fluctuation in the length of daylight over the month is notable, impacting the solar radiation reaching the surface. Observing the table reveals that sunset and sunrise times can vary by up to 40 minutes in a month. When the sunrise time advances, the sunset time tends to be later. From these results, we note that the maximum and minimum values of monthly solar radiation in Blida city are 1200 W/m² on the first day of March and 800 W/m² on the last day, showcasing the monthly variability in solar radiation intensity.

Table 4.2: Daily Average Sunlight, Sunrise, and Sunset Time for Blida in March 2023

Date	Sunrise	Sunset	Daily Average Sunlight (W/m²)
01/03/2023	7:26	18:37	599.9
02/03/2023	7:25	18:38	605.3
03/03/2023	7:24	18:39	622.9
04/03/2023	7:22	18:40	647.3
05/03/2023	7:21	18:41	657.5
06/03/2023	7:20	18:42	644.7
07/03/2023	7:18	18:43	630.8
08/03/2023	7:17	18:44	624.5
09/03/2023	7:15	18:44	641.9
10/03/2023	7:14	18:45	663.8
11/03/2023	7:13	18:46	681.0
12/03/2023	7:11	18:47	673.8
13/03/2023	7:10	18:48	659.2
14/03/2023	7:08	18:49	646.0
15/03/2023	7:07	18:50	656.7
28/03/2023	6:47	19:01	705.5
29/03/2023	6:46	19:02	728.7
30/03/2023	6:44	19:03	748.5
31/03/2023	6:43	19:04	742.0

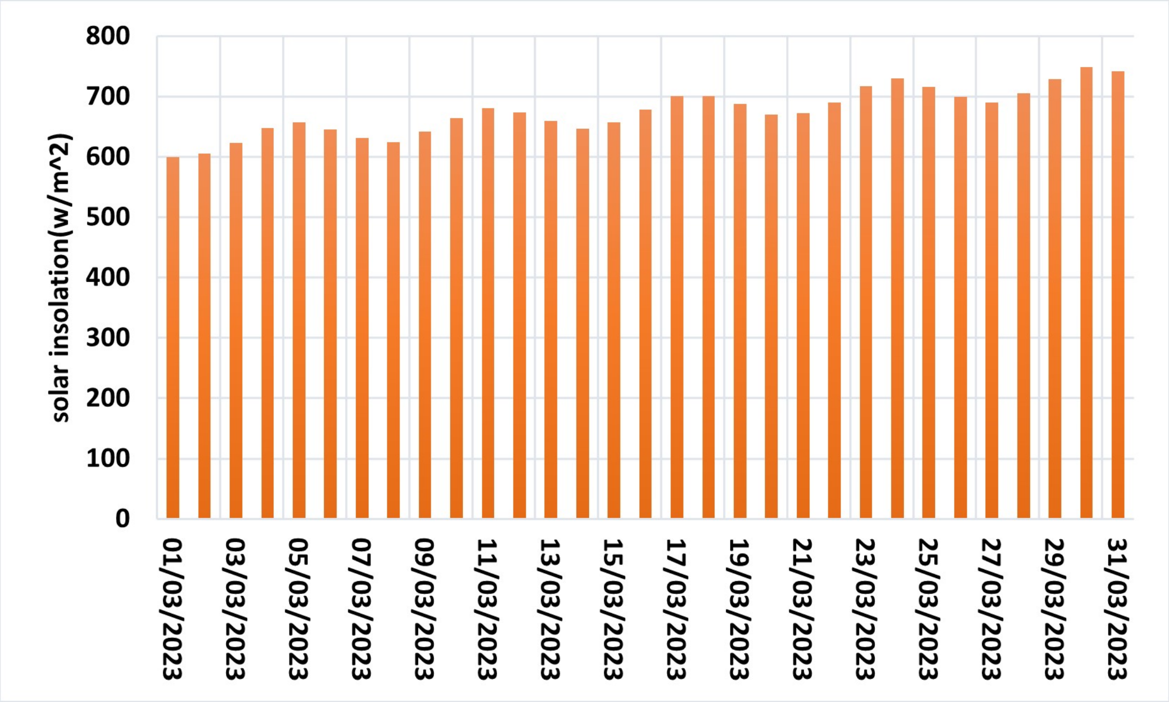


Figure 4.5: Daily Average Sunlight Variation in Blida for March 2023

4.3 Data Presentation

4.3.1 Fixed PV vs. Designed Solar Tracker

To evaluate the performance of our solar tracker, a comprehensive comparison was conducted against a fixed PV panel faced south. This thorough analysis considers key metrics, including collected irradiance, power generation, and energy generation.This comparative overview allows a nuanced understanding of how our system enhances power generation without reling on spesific sensors. By delving into these results, we gain valuable insights into the added efficiency and performance benefits that our designed solar tracker contributes to the overall power generation capabilities

Collected irradiance

The collected irradiance serves as a crucial metric for comparing between fixed PV panels and tracking systems. Figure 4.6 illustrates the collected irradiance from the designed tracker versus fixed PV panels. From the results, notable differences emerge in the maximum collected irradiance values. Specifically, the fixed PV system collected a maximum irradiance at 680 W/m², whereas our designed solar tracker surpassed it with a peak irradiance of 1120 W/m², observed at noon around 1:15 PM. These results underscore the superior performance of the solar tracker in optimizing sunlight exposure and, consequently, enhancing energy capture efficiency in comparison to fixed PV panels.

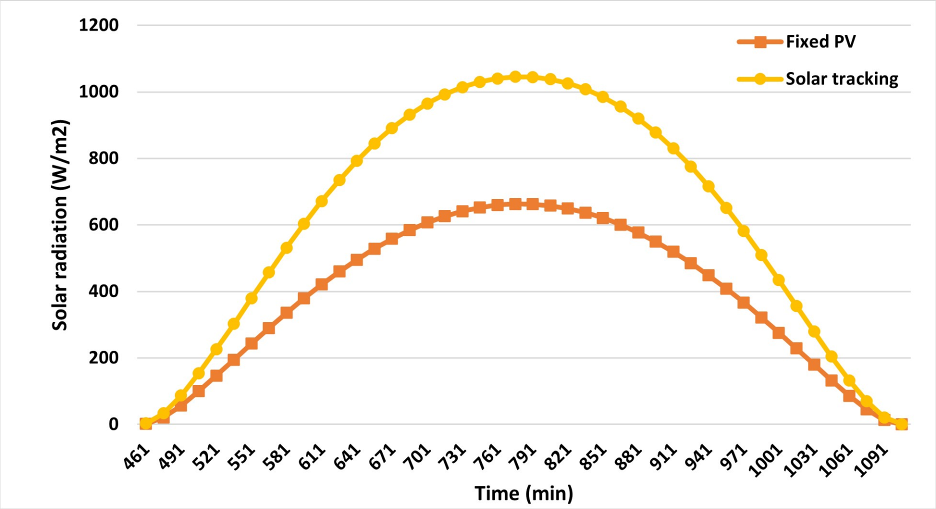


Figure 4.6: Collected radiation Solar Tracker versus Fixed

Power outputs

Examining the generated power further underscores the advantages of our solar tracker. Figure 4.7 delivers a comprehensive comparative analysis of the power output of a fixed PV panel and our designed solar tracker. The fixed PV system produced 160 W, the tilted at latitude PV panel generated 240 W, while our designed solar tracker excelled with an output of 270 W. This examination reveals crucial insights into the implications for energy capture, unraveling the performance disparities between stationary PV panels and the dynamic tracking capabilities embedded in our innovative solar tracking system.

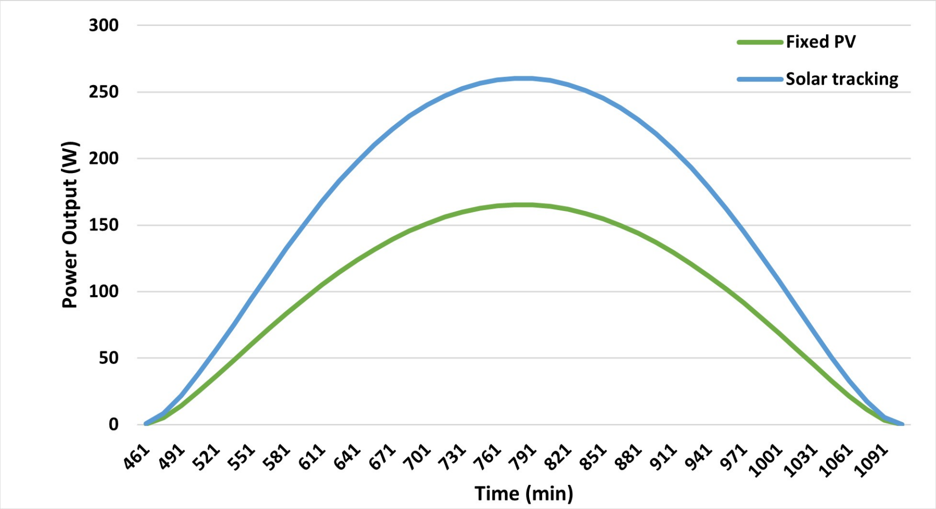


Figure 4.7: Performance Comparison of Solar Trackers versus Fixed PV panel

Energy generation

Figure 4.8 presents a visual depiction of the energy dynamics between fixed PV and our designed solar tracker. The chart provides a clear representation of their comparative energy generation performances. Notably, the designed solar tracker demonstrates robust energy generation, producing 1691,13 Wh. In comparison, the fixed PV system generates 1067,08 Wh. The results reveal a remarkable performance difference, showcasing the designed solar tracker's ability to generate substantially more energy. Specifically, our solar tracker produced 36.9% more than the fixed PV system, highlighting its superior efficiency in harnessing solar power.

4.3.2 Optimal Tracking Time

To determine the optimal tracking time for our solar tracking system, we tested the tracker's performance under different tracking intervals and analyzed the collected data. Table 4.3 presents the results, offering insights into the variations in energy capture efficiency. By examining the data, we aim to pinpoint the optimal tracking duration. The analysis of optimal tracking time is crucial for maximizing energy output while minimizing energy consumption, ensuring the efficient operation of the solar tracking system.

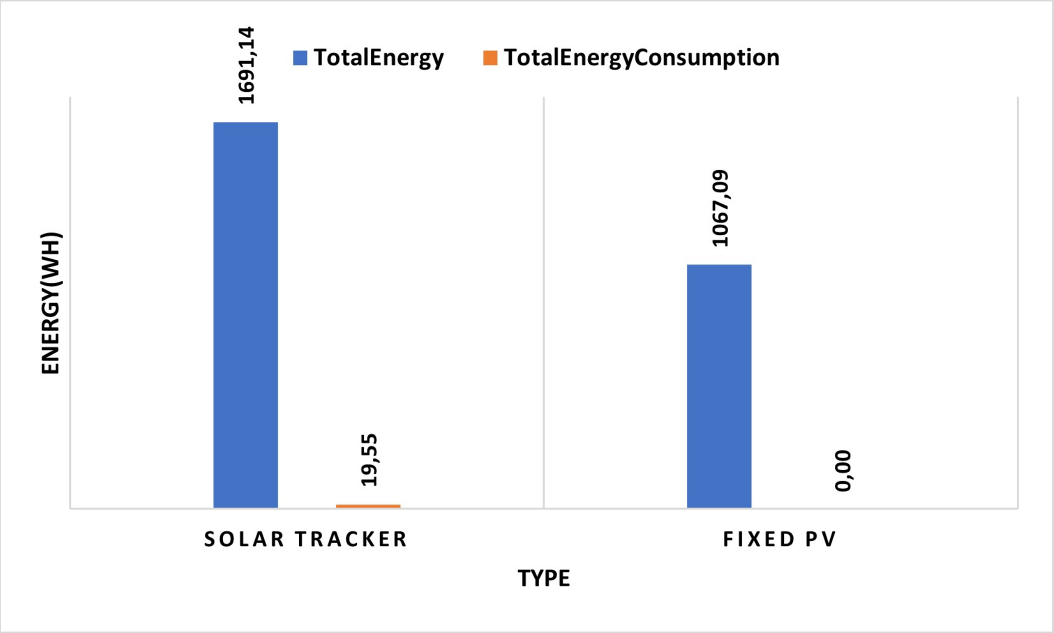


Figure 4.8: Energy Generation of the Designed Solar Tracker versus Fixed and Tilted Configurations

Table 4.3: Tracking Intervals Performance Comparison

Tracking Time	**Total Energy (WH)**	**Total Energy Consumption (WH)**	**Consumed E vs Generated (%)**	**Power (%)**
5 min	1683.2	71.97	4.28%	100.0%
15 min	1683.2	23.99	1.43%	100.0%
1 hr	1682.9	6.00	0.36%	99.98%
2 hrs	1673.9	3.00	0.18%	99.44%
2 hrs 20 min	1671.8	2.57	0.15%	99.32%
2 hrs 30 min	1682.4	2.40	0.14%	99.95%
3 hrs	1646.8	2.00	0.12%	97.84%
5 hrs	1670.2	1.20	0.07%	99.22%

Power and irradiance outputs

Figure 4.9 provides an insightful exploration into the performance of the solar tracker concerning power and irradiance under various tracking intervals, ranging from 5 minutes to 5 hours. Notably, the analysis reveals that these intervals primarily influence the elevation angle rather than the azimuth angle.

For the elevation angle, we observed a consistent value of 57 degrees for tracking intervals from 15 minutes to 2 hours and 30 minutes. However, a subtle change occurred with a tracking interval of 2 hours and 30 minutes, leading to a reduction to 52 degrees. Notably, a more significant difference was observed with a tracking interval of 3 hours, resulting in an angle of about 45 degrees.

Conversely, the azimuth angle remained relatively constant until the 3-hour interval, exhibiting a slight change of 2 to 3 degrees. The collected irradiance and power output showed uniform values for tracking intervals from 15 minutes to 2 hours and 20 minutes, registering at 970 W/m² and 230 W, respectively. Yet, with a tracking interval of 2 hours and 30 minutes, a slight drop in power to 215 W and collected irradiance to 900 W/m² was noted. The most substantial drop occurred with the 3-hour interval, where the power decreased to 60 W and the collected irradiance to 700 W/m². This comprehensive analysis unveils the nuanced impact of tracking intervals on the solar tracker's performance metrics.

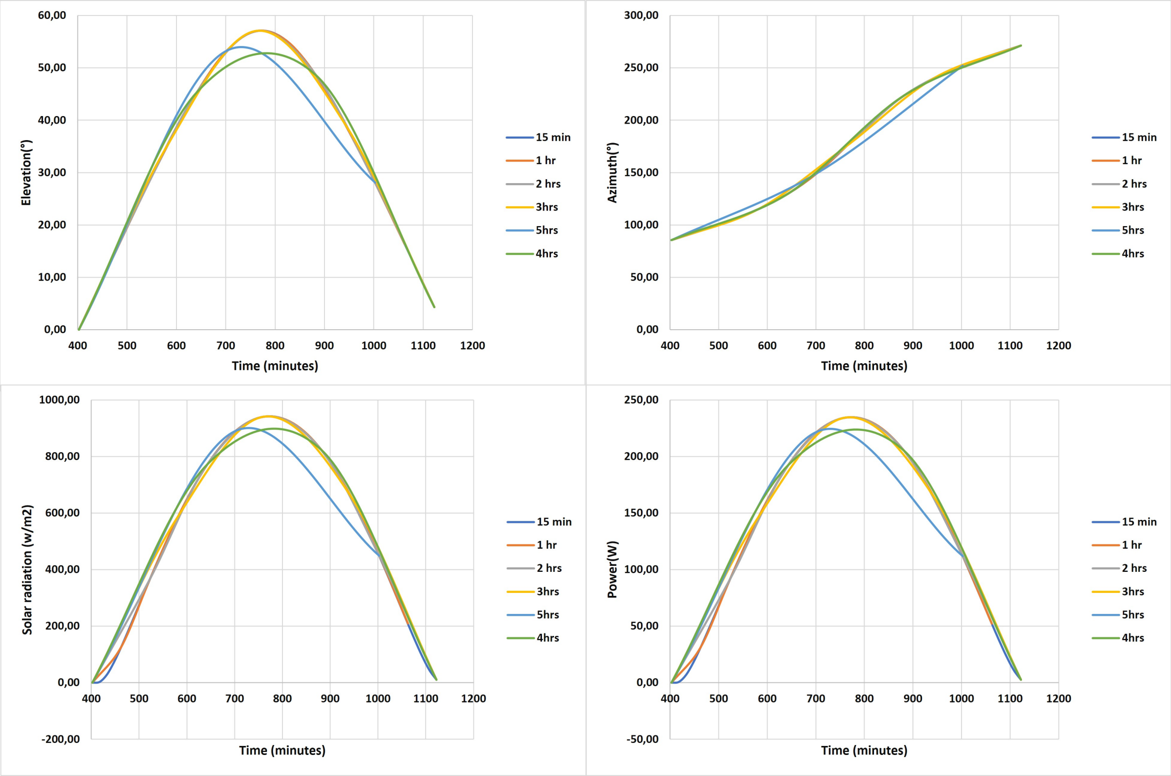


Figure 4.9: Evaluating Performance at Different Tracking Intervals

Energy generation

Figure 4.8 illustrates the energy generation profile for different solar tracking intervals unveils the system's adaptability to diverse temporal resolutions. The produced energy values (in Wh) for each interval exhibit both variations and consistencies, providing a nuanced understanding of the system's performance.The system generated 1683.24 Wh over a 5-minute interval, showing a minimal increase of 0.01 Wh when compared to the subsequent 15-minute period. This trend continued as the interval extended to 1 hour, where a decrease of 0.36 Wh was observed. Further, the system generated 1682.89 Wh over a 1-hour interval, marking a reduction of 10.04 Wh as the tracking timeframe increased to 2 hours.A slight decrease of 1.99 Wh was noted when comparing the 2-hour interval to the subsequent 2 hours and 20 minutes, where the system produced 1673.85 Wh. Interestingly, there was a notable increase of 10.55 Wh as the tracking interval extended to 2 hours and 30 minutes, resulting in an energy generation of 1671.85 Wh.A more significant decrease of energy (35.58 Wh) when tracking the sun every 2 hours and 30 minutes then tarcking it every 3 hours, where the system generated 1682.40 Wh. The final interval of 3 hours exhibited a slight increase of 23.37 Wh in comparison to the 5-hour period, with an energy generation of 1646.82 Wh.These fluctuations in energy production underscore the system's responsiveness to varying tracking intervals, offering valuable insights into its operational dynamics across different timeframes.

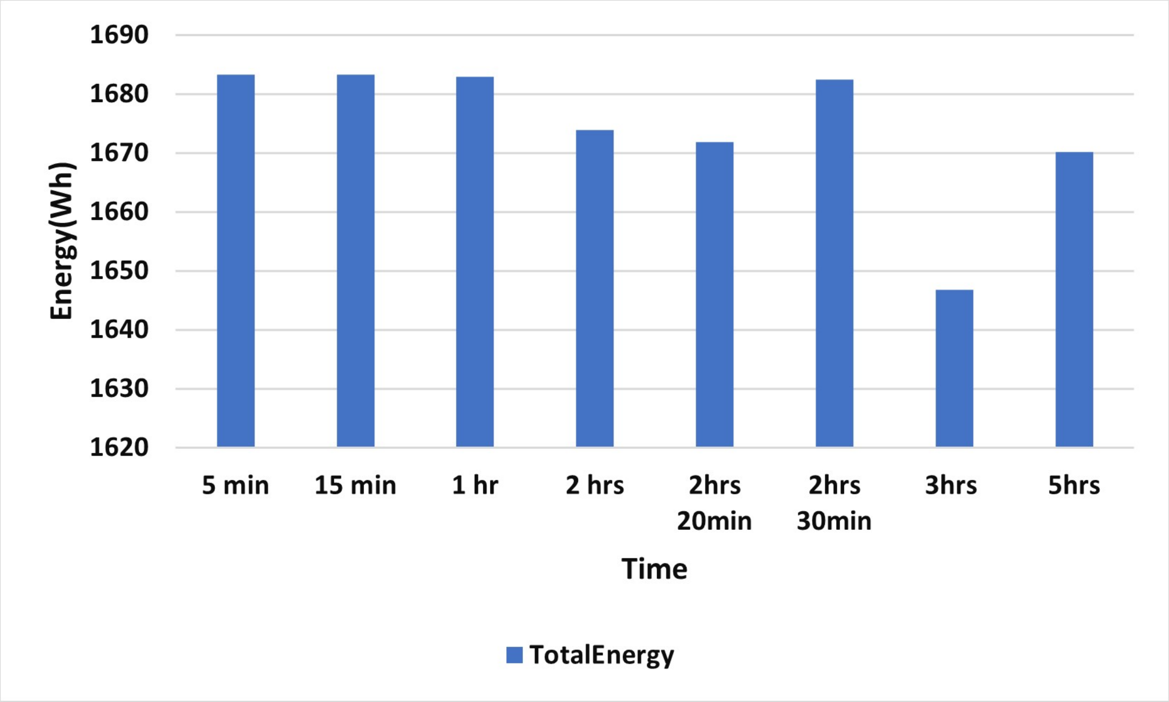


Figure 4.10: Produced Energy for Different Solar Tracking Intervals

Energy consumption

In Figure 4.11, the energy consumption pattern demonstrates notable variations across different solar tracking intervals. From 5 minutes to 15 minutes, there is a significant drop in consumption, decreasing from 71,969.36 Wh to 23,989.79 Wh. This trend continues as the tracking interval extends to 1 hour, where consumption further reduces from 23,989.79 Wh to 5,997.45 Wh.

However, from 1 hour onwards, the energy consumption values exhibit more stability. The consumption remains almost the same from 1 hour to 2 hours, ranging from 5,997.45 Wh to 2,998.72 Wh. Similarly, the following intervals, 2 hours to 2 hours 20 minutes and 2 hours 30 minutes, demonstrate marginal changes, fluctuating from 2,998.72 Wh to 2,570.33 Wh and 2,570.33 Wh to 2,398.98 Wh, respectively.

This consistency persists in the intervals from 2 hours 30 minutes to 5 hours, where the energy consumption values remain relatively steady. From 2,398.98 Wh to 1,999.15 Wh and finally, to 1,199.49 Wh, the consumption exhibits minimal fluctuations, indicating a consistent energy usage pattern in the latter tracking intervals.

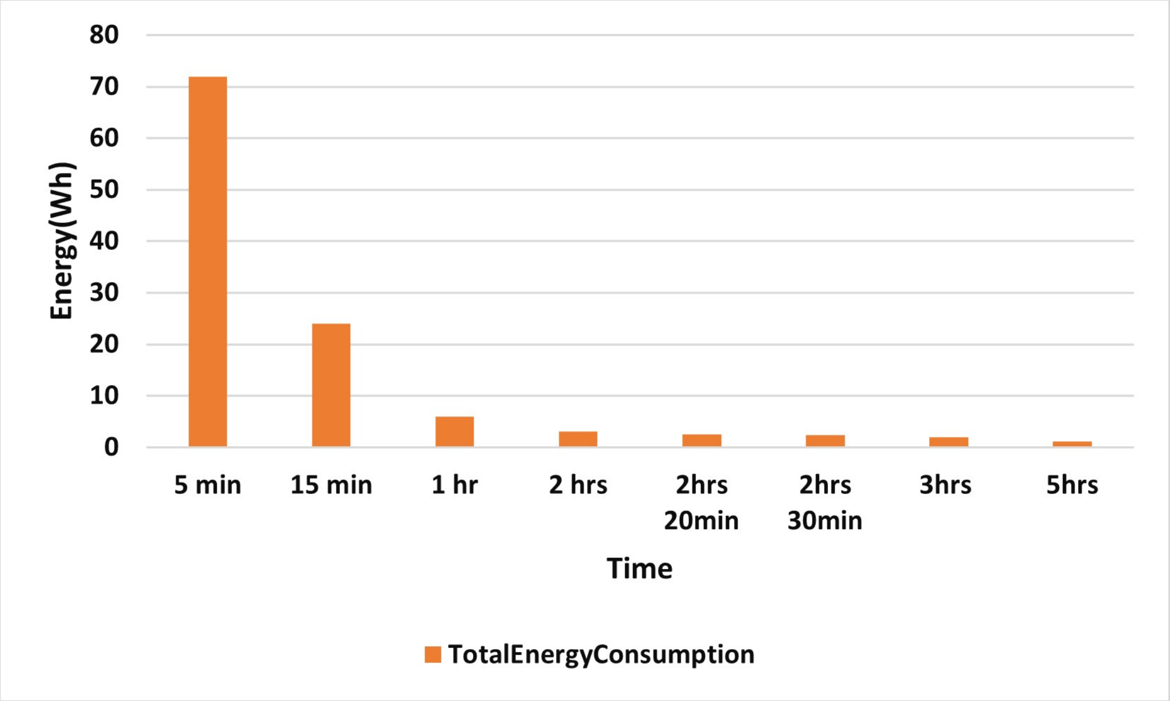


Figure 4.11: consumed Energy for Different Solar Tracking Intervals

Energy efficiency

In Figure 4.12, the generated power percentage for distinct solar tracking intervals showcases a substantial decrease from 4,276% for the 5-minute interval to 1,425% for the 15-minute period. This trend continues with a notable drop to 0.356% for the 1-hour interval, indicating a significant reduction in generated power percentage as the tracking timeframe increases.

From 1 hour onwards, the generated power percentage values exhibit a gradual decline. The values decrease from 0.356% to 0.179% for the 2-hour interval, and then further reduce to 0.154% for the 2 hours and 20 minutes interval. The downward trend persists with values of 0.143% for the 2 hours and 30 minutes interval, 0.121% for the 3-hour interval, and finally, 0.072% for the 5-hour interval.

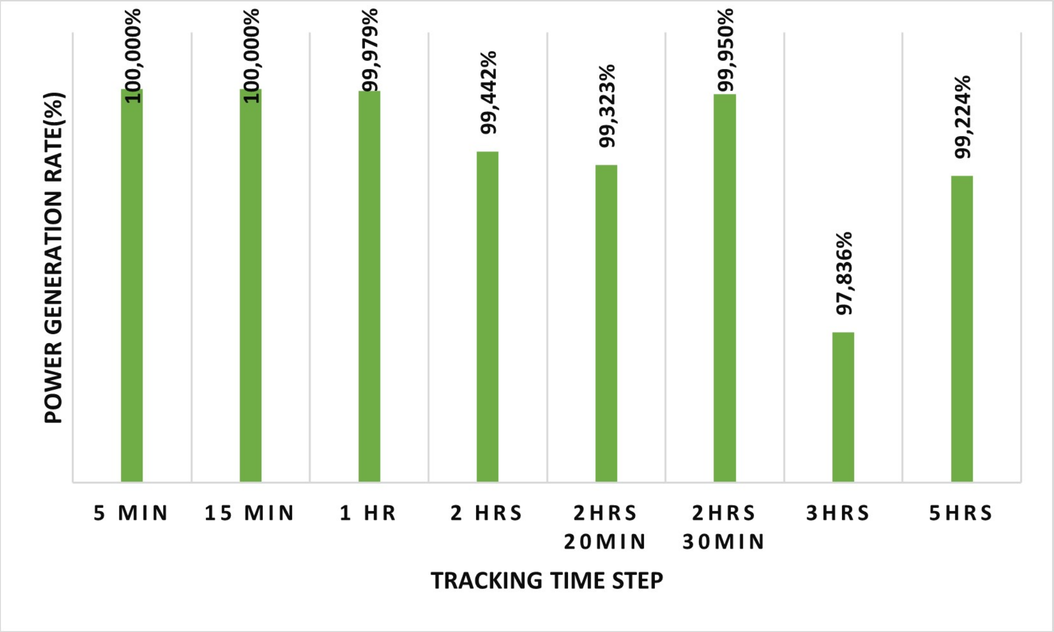


Figure 4.12: Generated Power Percentage for Different Solar Tracking Intervals

In Figure 4.11, the comparison of consumed energy by the solar tracker to the generated rate across different tracking intervals provides insights into the system's efficiency. Notably, the consumed energy closely aligns with the generated rate, consistently remaining at 100% for the 5-minute and 15-minute intervals. A marginal decrease is observed for the 1-hour interval, where the consumed energy stands at 99.979%.This trend continues with a slight decrease to 99.442% for the 2-hour interval, 99.323% for the 2 hours and 20 minutes interval, and 99.950% for the 2 hours and 30 minutes interval. A more noticeable decrease is noted for the 3-hour interval, with consumed energy registering at 97.836%. The trend then stabilizes with values of 99.224% for the 5-hour interval, emphasizing the system's effective utilization of the generated energy across varying tracking intervals.

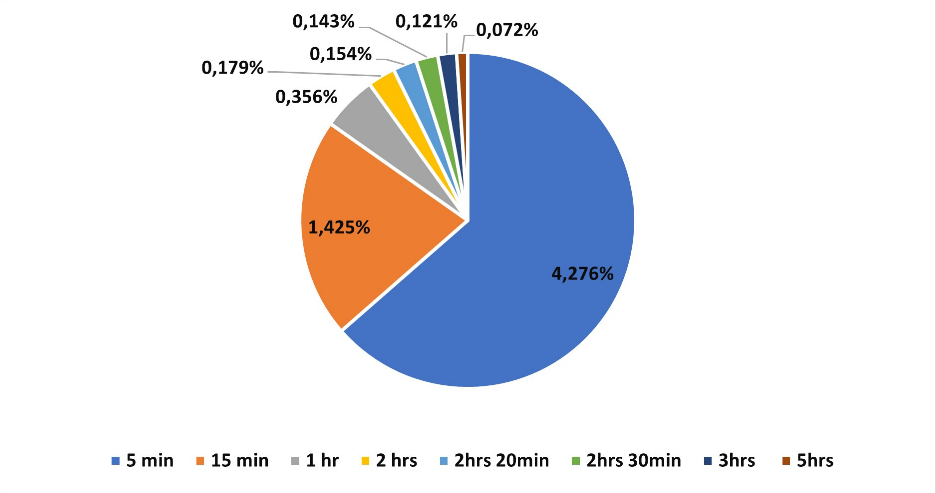


Figure 4.13: Comparing Consumed Energy by Solar Tracker to Generated Rate Across Various Tracking Intervals

4.3.3 Tracking Error Impact on Solar Tracker Performance

This section investigates the influence of tracking errors on the solar tracker's efficiency. Through a series of experiments introducing varying error percentages, we evaluate how these deviations affect the system's performance. The analysis focuses on energy generation, power output, and overall system efficiency, providing insights into the solar tracker's adaptability to tracking inaccuracies. This exploration aims to uncover the system's robustness in real-world scenarios, where tracking errors may arise from environmental or mechanical factors.Table 4.4 summarizes the results, offering insights into how different tracking errors impact key performance metrics. The findings provide valuable information for understanding the solar tracker's resilience and guiding strategies to mitigate the effects of tracking errors on overall performance.

Table 4.4: Produced Energy for Different Tracking Error Percentages

Traking Error	**Energy (WH)**	**Energy Consumption (WH)**	**Energy Consumption (%)**	**Power (%)**
1°	1621,56	64,85	4,00	96,00
6°	1590,92	64,85	4,08	95,92
12°	1540,25	64,85	4,21	95,79
18°	1474,96	64,85	4,40	95,60
24°	1395,74	64,85	4,65	95,35

Collected irradiance

Figure 4.15 illustrats the collected irradince for each tracking error

Power outputs

Figure 4.15 presents the solar tracker's performance under various tracking errors, ranging from 1° to 24°, inclusive, with a focus on power output . The results highlight the system's resilience to tracking errors within the 1° to 24° range, where minimal impact is observed. Specifically, with tracking errors from to 0° to 12°, the tracker consistently collects around 970 W/m² of irradiance and produces approximately 230 W of power.

However, as the tracking error increases from 12° to 24°, a discernible decline in performance becomes evident. A 5% reduction in irradiance, equivalent to 10 W/m², and a 5% drop in power, representing 5 W, are observed. Beyond a tracking error of 24°, the tracker significantly misses a substantial portion of solar irradiance, resulting in a minimal power output.

These findings underscore the solar tracker's robustness to moderate tracking errors but emphasize the increasing impact on performance as errors escalate beyond a certain threshold. The insights gleaned from Figure 4.15 contribute to a nuanced understanding of the

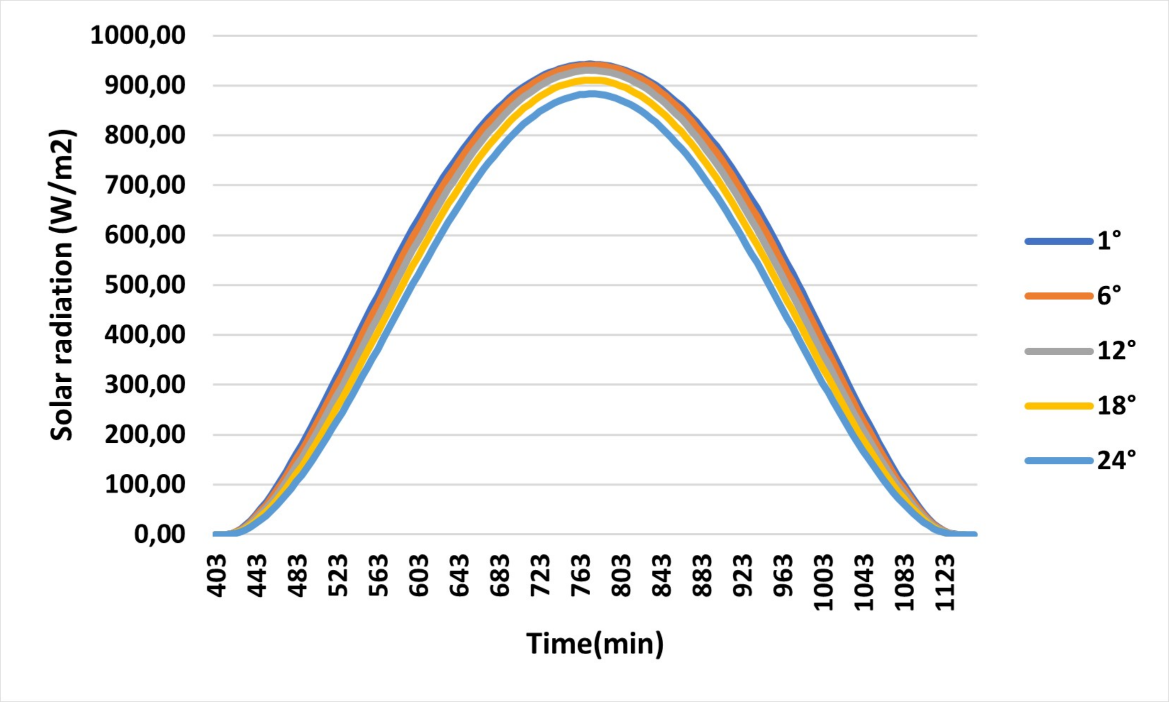


Figure 4.14: Collected irradiance at Different Tracking Errors

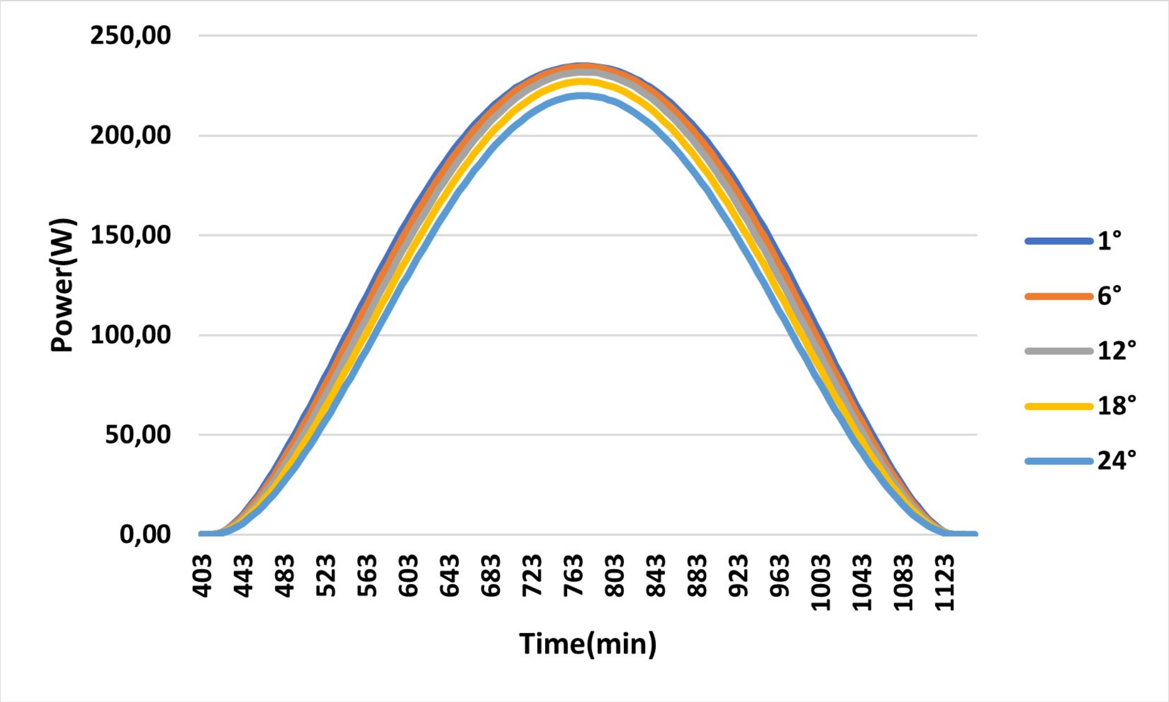


Figure 4.15: Evaluating Performance at Different Tracking Errors

system's response to tracking inaccuracies, informing potential optimization strategies for enhanced solar tracker performance.

Energy generation

Figure 4.16 provides a comprehensive analysis of the produced energy under different tracking errors, offering insights into the system's energy generation capabilities in the face of inaccuracies. The results discernibly showcase the impact of tracking errors on energy production.

For tracking errors ranging from 1° to 12°, the energy production remains remarkably consistent. The system consistently produces energy within a narrow range, varying from 1626.401 Wh to 1607.49 Wh. This stability in energy production suggests the solar tracker's robustness in maintaining a reliable output even when subjected to moderate tracking errors.

Conversely, as the tracking error percentage increases from 12° to 24°, a noticeable reduction in energy production becomes apparent. The produced energy drops from 1579.279 Wh to 1440.79 Wh, indicating a distinct decrease in output with each successive 6° increase in tracking error. This finding underscores the system's sensitivity to larger tracking errors, emphasizing the need for careful calibration and precision to optimize energy production.

The detailed insights provided by Figure 4.16 contribute significantly to understanding how tracking errors impact the energy production efficiency of the solar tracker, informing strategies for system optimization and performance enhancement.

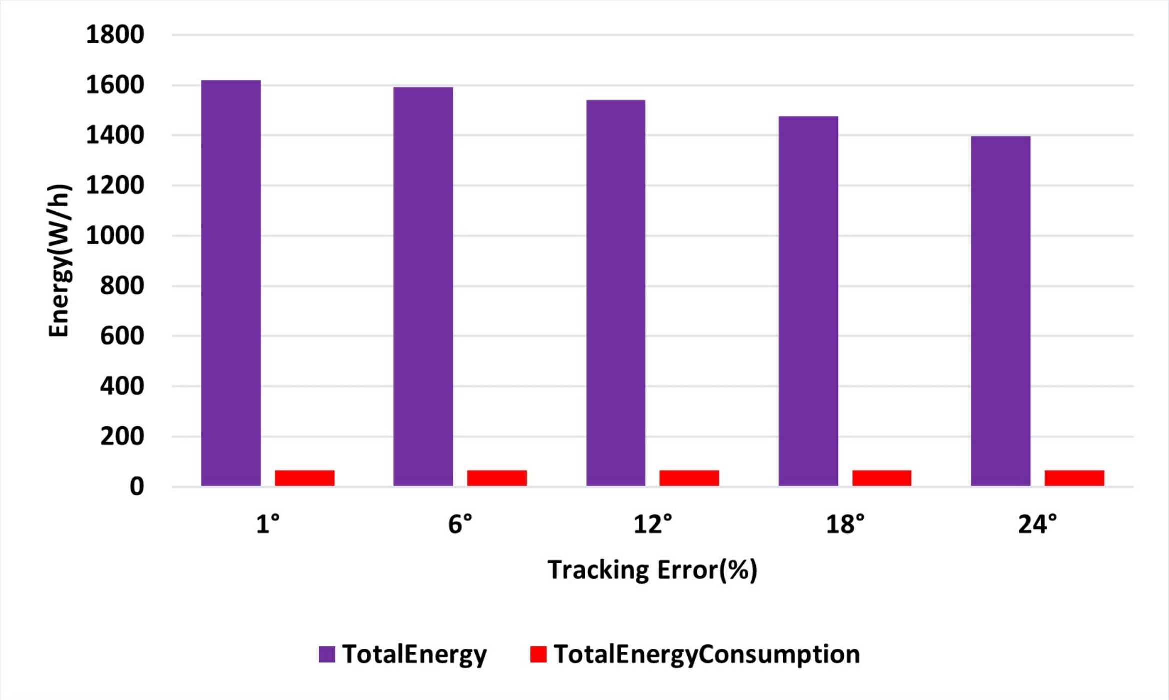


Figure 4.16: Analysis of Produced Energy for Varied Tracking Error Percentages

Energy efficiency

Figure4.17 illustrates the generated power percentage for varying tracking error percentages, providing insights into the system's power production rate under different degrees of inaccuracy. The results highlight the system's ability to maintain a high power production rate even with moderate tracking errors.

- For tracking errors from 1° to 12°, the power production rate remains consistently at 100%. The minor drop to 99% for a 6° error and 98% for a 12° error signifies a minimal impact on power generation.

- With a 18° tracking error , the power rate is 97%, still considered acceptable for efficient solar tracking.

- In the range of 18° to 24° tracking errors, the power rates experience a gradual decline from 95% to 89%. While this represents a reduction, it remains within acceptable bounds for practical solar tracking systems.

These findings suggest that a 6° tracking error is negligible, and a 12° error is acceptable for maintaining efficient power production in a solar tracking system.

Figure 4.17: Generated Power Percentage for Different Tracking Error Percentages

4.4 Statistical Analyses

4.4.1 Effect of Latitude on the solar tracking system

In this section, we explore the profound influence of latitude variations on the performance of our sensor-less solar tracking system. Latitude, being a key determinant of the sun's position in the sky, plays a crucial role in the efficacy of solar tracking technologies. Table 4.5 encapsulates a comprehensive summary of the system's performance across diverse latitudes, shedding light on how changes in geographical positioning impact its ability to capture solar energy. Through a systematic examination of the results for different latitudes, we aim to unravel patterns, trends, and insights that illuminate the system's responsiveness to varying solar conditions across a spectrum of locations. This exploration will contribute not only to the technical understanding of the solar tracker but also inform practical considerations for its deployment in regions characterized by distinct latitudinal coordinates.

Table 4.5: Energy Data at Different Latitudes

Latitude	**Energy (WH)**	**Energy Consumption (WH)**	**Energy Consumption (%)**	**Power (%)**
36.4816	1683.2	71.97	4.28%	100.00%
37.4816	1679.6	72.05	4.29%	99.78%
38.4816	1675.7	72.13	4.30%	99.55%
40.4816	1667.0	72.29	4.34%	99.03%
46.4816	1632.3	72.85	4.46%	96.98%

Power and irradiance outputs

In this analysis(Figure 4.18), we scrutinize the impact of varying latitudes, ranging from 36.48 to 46.48, on the performance metrics of our sensor-less solar tracking system. The results spotlight key aspects of the system's behavior in response to latitude differences. Notably, the maximum elevation angle demonstrates a consistent trend, maintaining approximately 57 degrees for a latitude difference of 2 degrees. However, as the latitude difference increases to 4 degrees, the elevation angle slightly decreases to 53 degrees. A more substantial drop to 47 degrees is observed for a 10-degree difference in latitude, indicating a linear relationship between elevation angle and latitude change.

The azimuth angle, on the other hand, exhibits negligible variations with latitude changes, especially within the specified range. A 10-degree difference in latitude does not significantly impact azimuth, suggesting the system's stability in maintaining its orientation.

Examining the collected irradiance reveals a consistent 970 w/m² maximum for latitudes from 36.48 to 40.48, despite a 4-degree difference. The power output similarly remains stable at 230 watts within this range. However, a 10-degree difference in latitude introduces a decline, reducing power output to 220 watts and irradiance to 950 w/m². This finding underscores the sensitivity of the solar tracker's performance to latitude variations, with a notable decrease in power beyond a 10-degree latitude difference. Consequently, it emphasizes the importance of considering specific geographical locations when deploying solar tracking systems due to their distinct solar power capabilities.

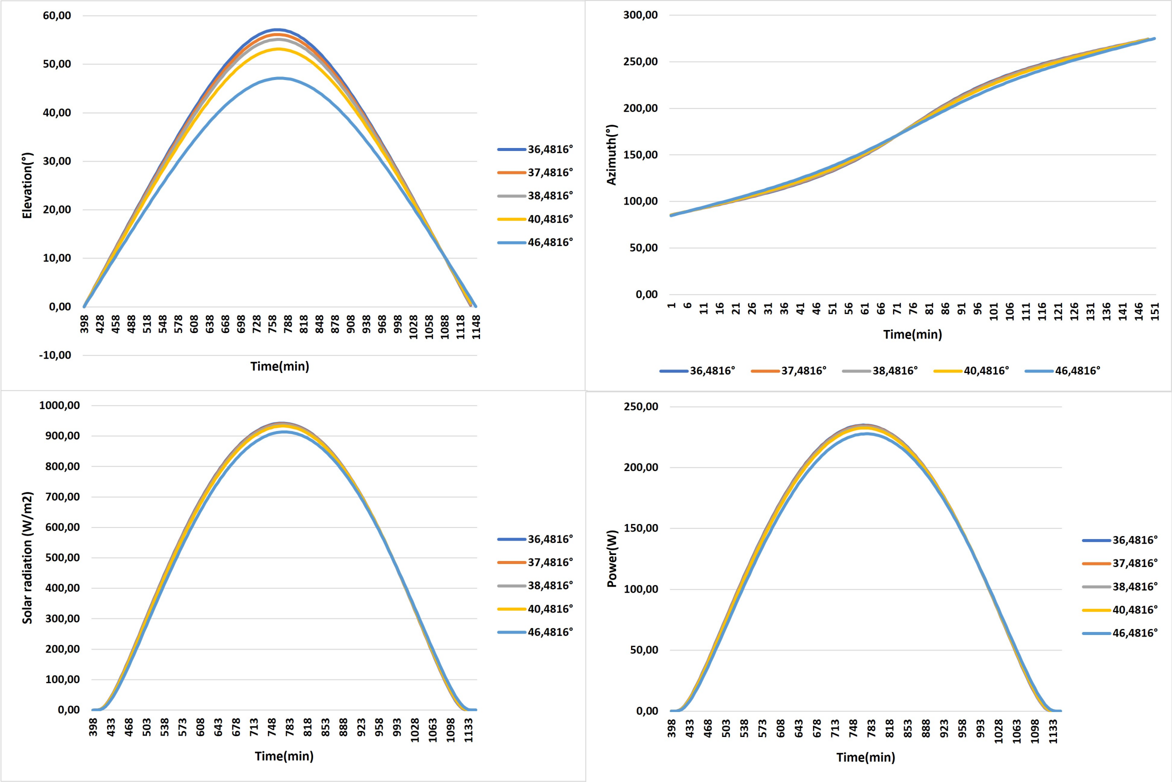


Figure 4.18: Evaluating Performance at Different Latitudes

Energy generation

In this exploration of energy generation, Figure 4.19illustrates the dynamic performance of our sensor-less solar tracking system across varying latitudes. The data points, including latitude and total energy production, provide a clear depiction of how the system responds to geographical changes.

As the latitude increases from 36.4816 to 46.4816, a discernible trend emerges. The system achieves its peak energy production at the lowest latitude, yielding 1683.24618 Wh. Moving towards higher latitudes, there is a gradual decrease in total energy generation, with values of 1679.605934 Wh, 1675.688883 Wh, 1666.961353 Wh, and 1632.349853 Wh for latitudes 37.4816, 38.4816, 40.4816, and 46.4816, respectively.

This observed pattern aligns with earlier findings on power output and irradiance, further emphasizing the intricate relationship between latitude variations and the solar tracker's energy generation capacity. These insights into energy production across diverse latitudes are crucial for optimizing the deployment and performance of the solar tracking system in different geographical locations.

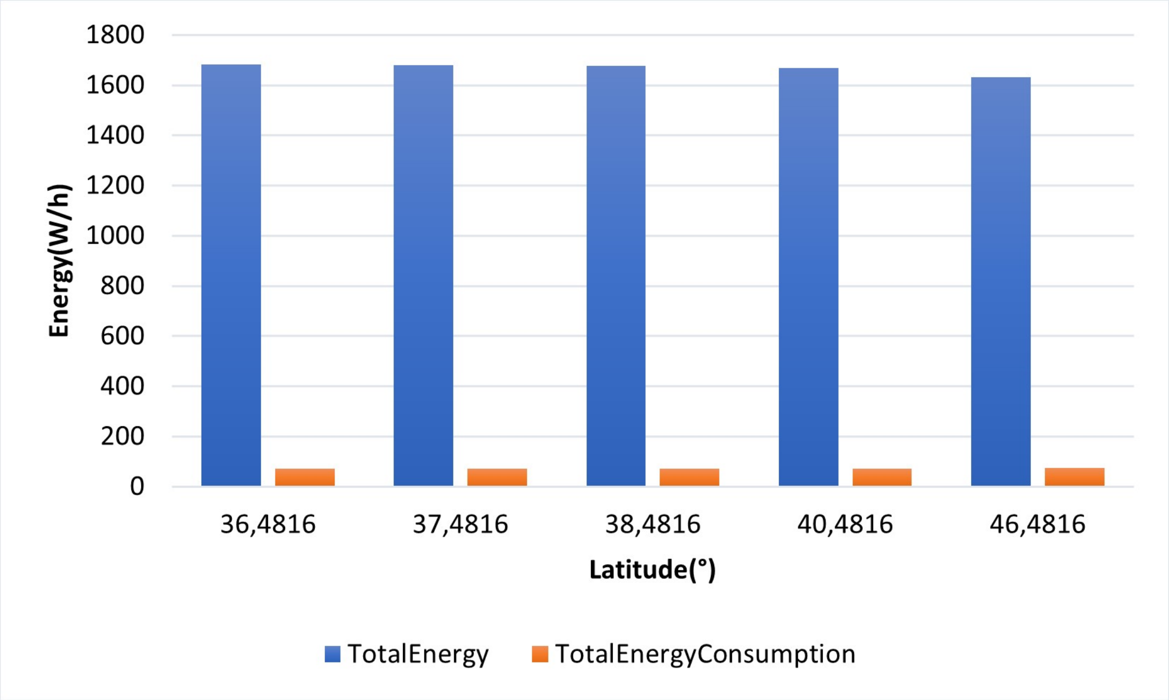


Figure 4.19: Analysis of Produced Energy for Varied Latitudes

Energy efficiency

Figure 4.20 provides a comprehensive overview of the power generation efficiency of our sensor-less solar tracking system at varying latitudes. The generated power percentage indicates the system's ability to convert sunlight into electrical energy.The data points reveal a gradual decline in power generation efficiency as latitude increases. The percentages, ranging from 4,276% at the lowest latitude to 4,463% at the highest latitude, showcase the impact of geographical changes on the solar tracker's effectiveness. This nuanced understanding of power generation efficiency across different latitudes is vital for optimizing the system's performance in diverse geographical locations.

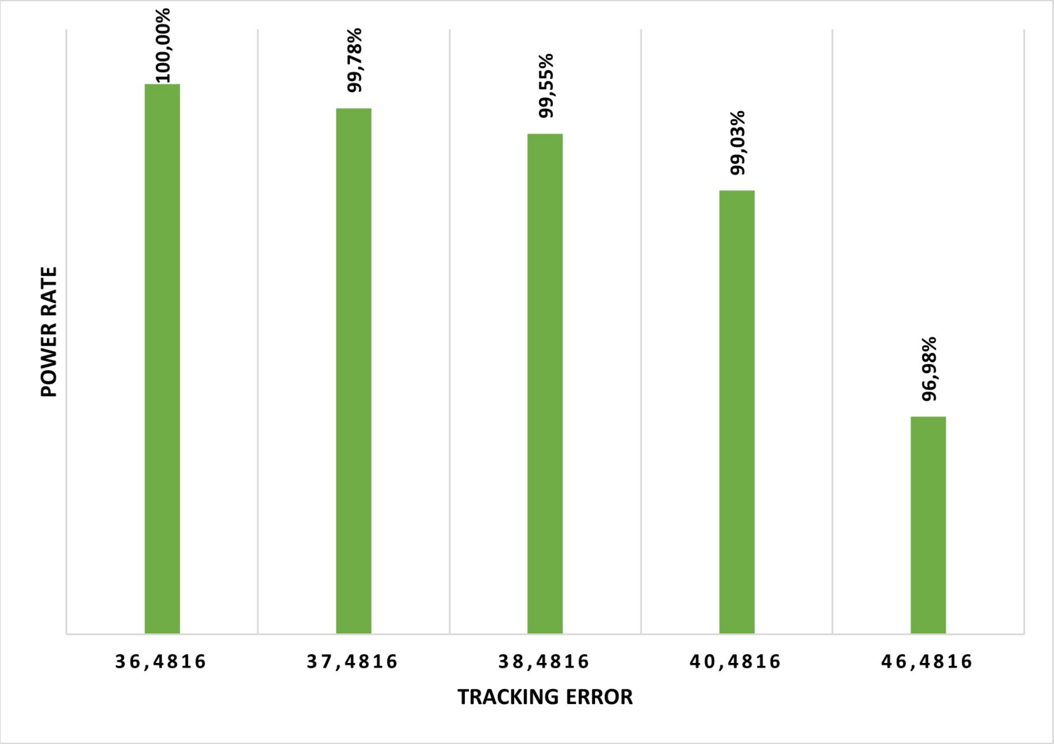


Figure 4.20: Generated Power Percentage for Different Latitudes

Figure 4.21 illustrates the energy consumption rate at various latitudes. The power percentages highlight the proportion of consumed energy compared to the generated rate, providing insights into the overall efficiency of the solar tracking system. For latitudinal differences of less than 10 degrees, the power rate remains consistently high at 99%.However, as the latitude difference exceeds 10 degrees, a noticeable drop in power efficiency occurs, reaching 96.98%.This finding underscores the importance of considering latitude variations for optimizing the overall efficiency and energy consumption of the solar tracking system in real world applications.

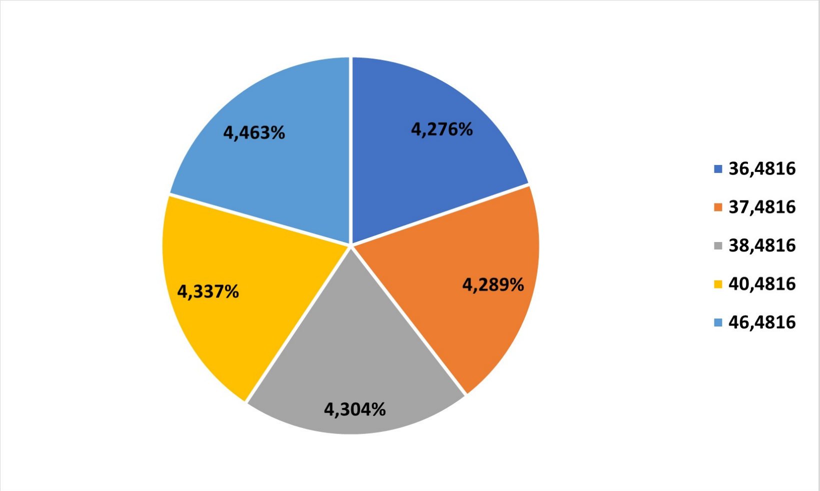


Figure 4.21: Comparing Consumed Energy by Solar Tracker to Generated Rate for for Different Latitudes

4.4.2 Effect of Longitude on the solar tracking system

Exploring the influence of longitude on our sensor-less solar tracking system, Table 4.6 serves as a comprehensive representation of the energy data at various longitudes. This analysis aims to unravel how changes in longitude affect the system's performance in terms of energy generation and efficiency.

Table 4.6: Energy Data at Different Longitudes

Longitude	**Energy (WH)**	**Energy Consumption (WH)**	**Energy Consumption (%)**	**Power (%)**
2.8389	1683.2	71.97	4%	100%
4.8389	1683.2	71.97	4%	100%
6.8389	1683.2	71.97	4%	100%
8.8389	1683.2	71.97	4%	100%
10.8389	1683.2	71.97	4%	100%

Power and irradiance outputs

Figure 4.22 provides a comprehensive evaluation of the solar tracker's performance at different longitudes, revealing intriguing findings about the system's adaptability to longitudinal changes. The analysis considers key parameters such as irradiance, power, elevation, azimuth, and tracking time.

From the results, it is evident that changes in longitude do not significantly affect the maximum power output and irradiance. The solar tracker consistently maintains an irradiance of 970 W/m² and a power output of 230 W, emphasizing its stability across different longitudes. The elevation angle also remains constant at 57 degrees, showcasing the tracker's robust performance.

However, a notable observation lies in the azimuth angle, where a 2-degree difference occurs for every 2-degree change in longitude, ranging from 187.5 degrees to 200 degrees. This suggests a linear relationship between azimuth and longitude, providing valuable insights into the tracker's orientation variations.

Moreover, an intriguing finding is the impact on tracking time, with a 7-minute shift for every 2 degrees of longitude change. This temporal difference highlights the influence of longitudinal variations on the solar tracker's operational timing, a crucial consideration for optimizing energy capture.

In summary, while the solar tracker's core performance remains consistent across different longitudes, the temporal aspects, particularly tracking time, showcase notable variations. These findings contribute to a deeper understanding of how longitude influences the solar tracking system's functionality in real-world applications.

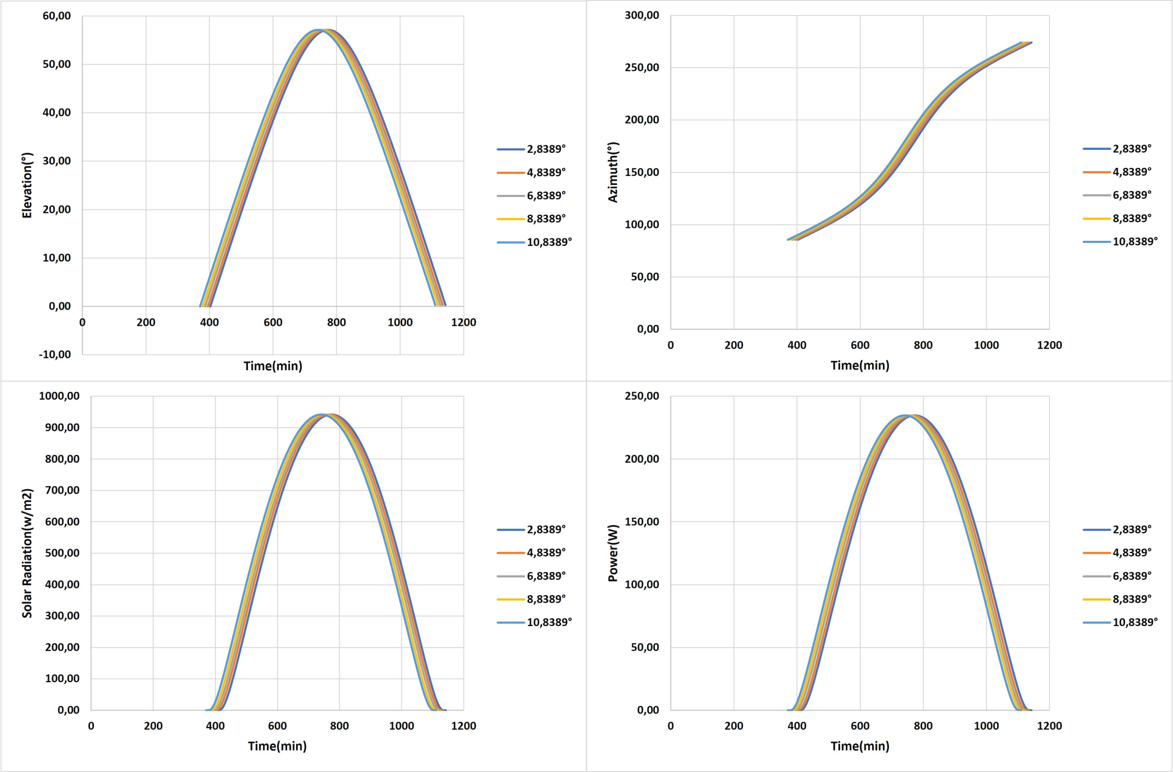


Figure 4.22: Evaluating Performance at Different Longitudes

Energy generation

The analysis of produced energy across various longitudes, as depicted in Figure 4.23, reveals intriguing insights into the solar tracker's performance in different geographic locations. The study encompasses a range of longitudes, spanning from 2.83 to 10.83.

Surprisingly, the energy production remains consistently uniform within this longitudinal range, maintaining a steady output of 1683.246 Wh. This finding suggests that the solar tracker's ability to generate energy is relatively insensitive to changes in longitude within the specified range.

Moreover, the energy consumption of the solar tracker remains constant across the considered longitudes, registering at 71.96 Wh. This consistency in energy consumption further emphasizes the stability and efficiency of the sensor-less solar tracking system, reinforcing its suitability for diverse geographic locations.

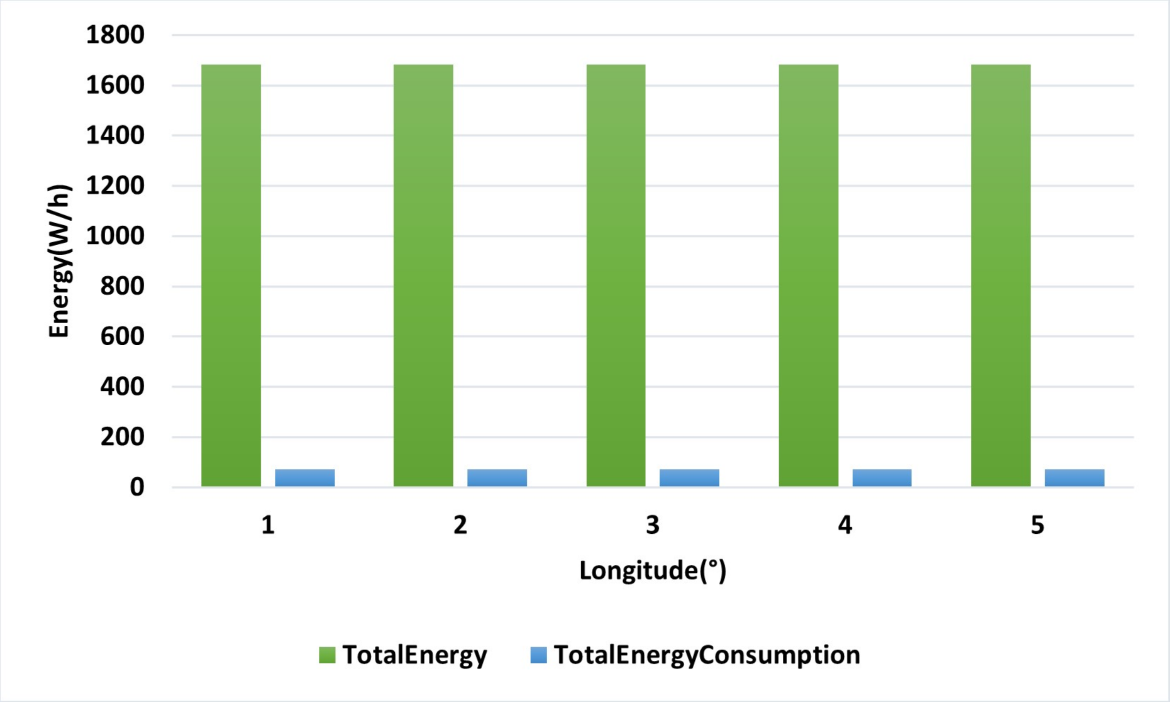


Figure 4.23: Analysis of Produced Energy for Varied Longitudes

Energy efficiency

In assessing the energy efficiency of the sensor-less solar tracking system across various longitudes, two essential factors were considered.illustrating the generated power percentage, remains constant at 4.276% across the examined longitudes. This consistent power generation percentage indicates that the solar tracker maintains a reliable level of efficiency in converting solar irradiance into usable power, unaffected by variations in longitude.

Furthermore, comparing the consumed energy by the solar tracker to the generated rate for different longitudes, reveals a stable power percentage of 100%. The unchanging power percentage underscores a crucial insight: the solar tracker's energy consumption is independent of longitudinal variations within the specified range. This consistency is attributed to the fact that longitudes primarily impact time intervals rather than the positions of the sun.

4.5 Sandstorm Resilience

A sandstorm-resilient feature was incorporated into our designed solar tracker and subjected to testing in Tiaret city, Algeria—a region renowned for its solar power potential but susceptible to sandstorms, especially during the summer. This addition addresses the specific environmental challenges prevalent in the area, aiming to enhance the durability and performance of the solar tracker in adverse conditions.The innovative approach integrates solar tracking tools and wind-sensing techniques to detect sandstorms and reduce their impact on solar PV systems, considering both wind forces and dust accumulation. We have conducted comprehensive tests to demonstrate the effectiveness of the proposed sandstorm-resilient solar tracker in minimizing structural stress, mitigating wind effects, and reducing dust settlement on solar panels.

A reliable threshold for sandstorm detection is crucial for designing an effective sandstorm-resilient solar tracker. Therefore, we calculated the sand transport rate (see Figure 4.24) from recorded wind data for Tiaret City in June 2023(see Figure 12). We observed a proportional increase between wind velocity and sand transport rate, affirming the theoretical concept that higher wind speeds lead to the transportation of more sand particles. For wind velocities below 8.5 m/s, the sand transport rate remains nearly negligible due to the low speed of the wind. However, a distinct shift occurs when the wind velocity surpasses 8.5 m/s. The sand transport rate gradually increases between 8.5 and 13m/s, peaks moderately between 10.5 and 13 m/s, and sharply accelerates from 13 m/s and beyond. This observation establishes that 6.5 m/s serves as the threshold for a mild sandstorm, 13 m/s for a medium sandstorm, and 16 m/s for a strong sandstorm in Tiaret City during the summer.

These findings suggest that adopting a 8.5 m/s threshold ensures complete protection for the solar tracker, as even a minor sandstorm has the potential to cause dust accumulation on solar panels.

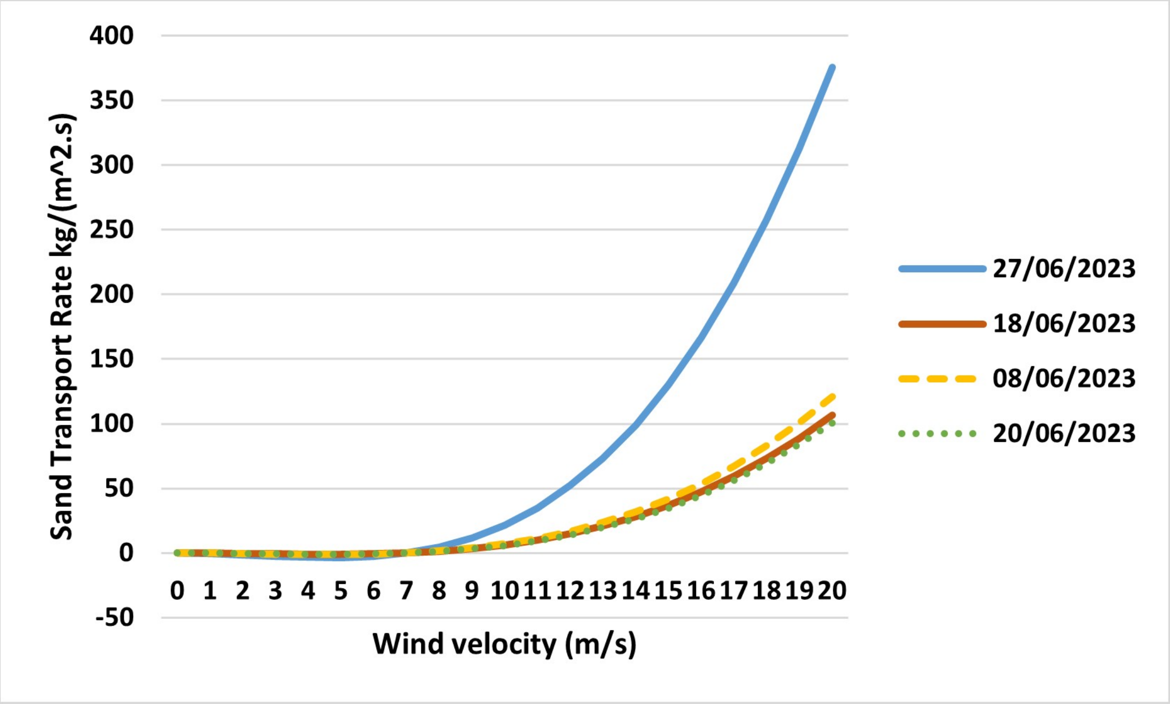


Figure 4.24: The sand transport rate varying with wind speed on June 2023.for Tiaret City, Algeria

Figure4.25 and Figure 4.26 illustrate the hourly wind speed and direction data recorded in Tiaret - Algeria, for 4 days of June 2023. The data underscores the dynamic nature of wind conditions, with speeds ranging from 1.1 m/s to 11.95 m/s, surpassing the 8.5 m/s threshold and indicating a mild sandstorm occurrence throughout the month. The fluctuation in wind direction emphasizes the necessity for an intelligent solar tracking system capable of adjusting panel orientation to minimize sand deposition and potential damage.

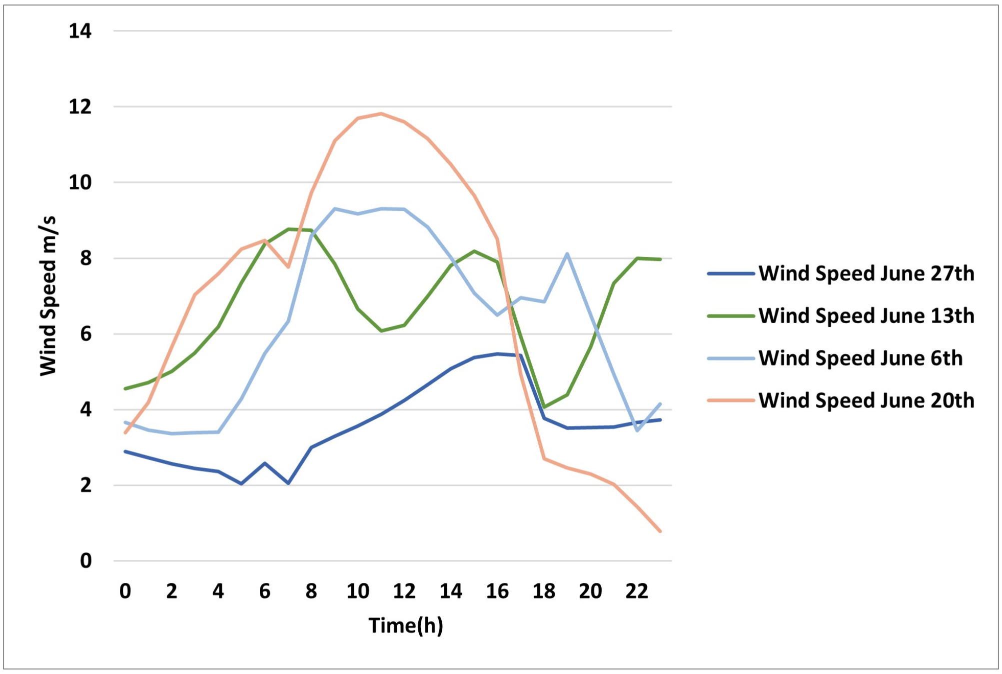


Figure 4.25: Hourly Wind Speed Data for Tiaret City, Algeria - June 2023.

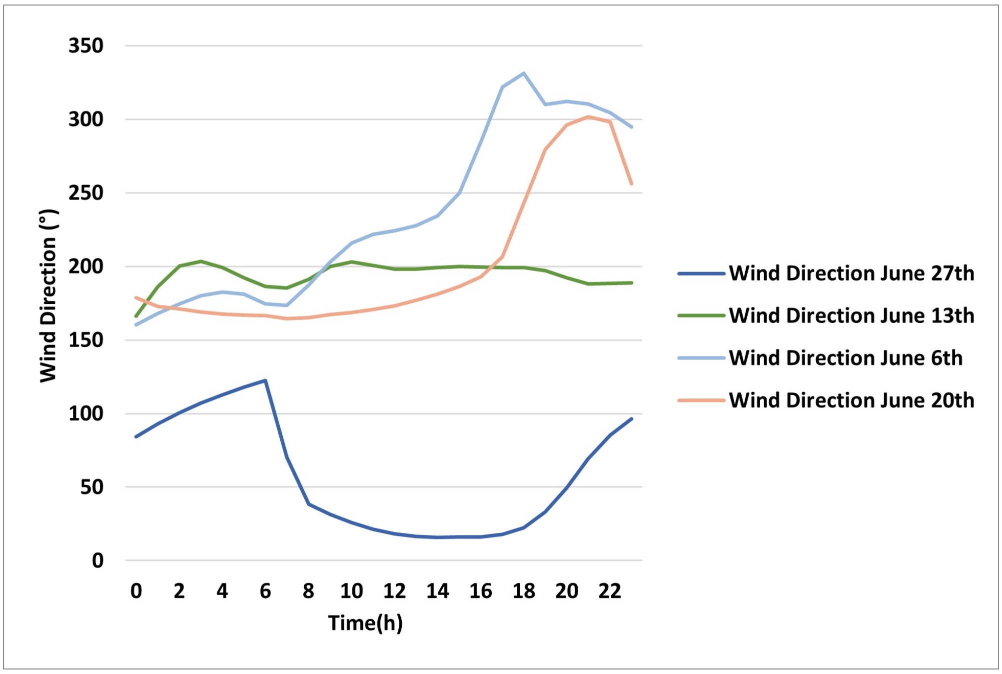


Figure 4.26: Hourly Wind Direction Data for Tiaret City, Algeria - June 2023.

The main factor for the success of this designed solar tracker lies in identifying the optimum position at which the tracker experiences minimal wind force and reduced dust accumulation. First, we have determined the optimal stow angle by analyzing dust particle accumulation for various stow angles (see Figure 4.27) recommended in the literature for wind resilience. The results show that the highest dust accumulation occurs at tilt angles of -15° and 0°. The -15° tilt exposes the panel directly to the wind, subjecting the photovoltaic surface to repeated impacts from sand grains. Meanwhile, the 0° tilt angle leads to the adherence of dust particles onto the panel's surface. Conversely, the 40° and 30° tilt angles experienced minimum dust accumulation. However, opting for these angles could result in higher wind forces impacting the solar panel. Consequently, after careful consideration, we identified the 20° tilt angle as the optimum stow position.

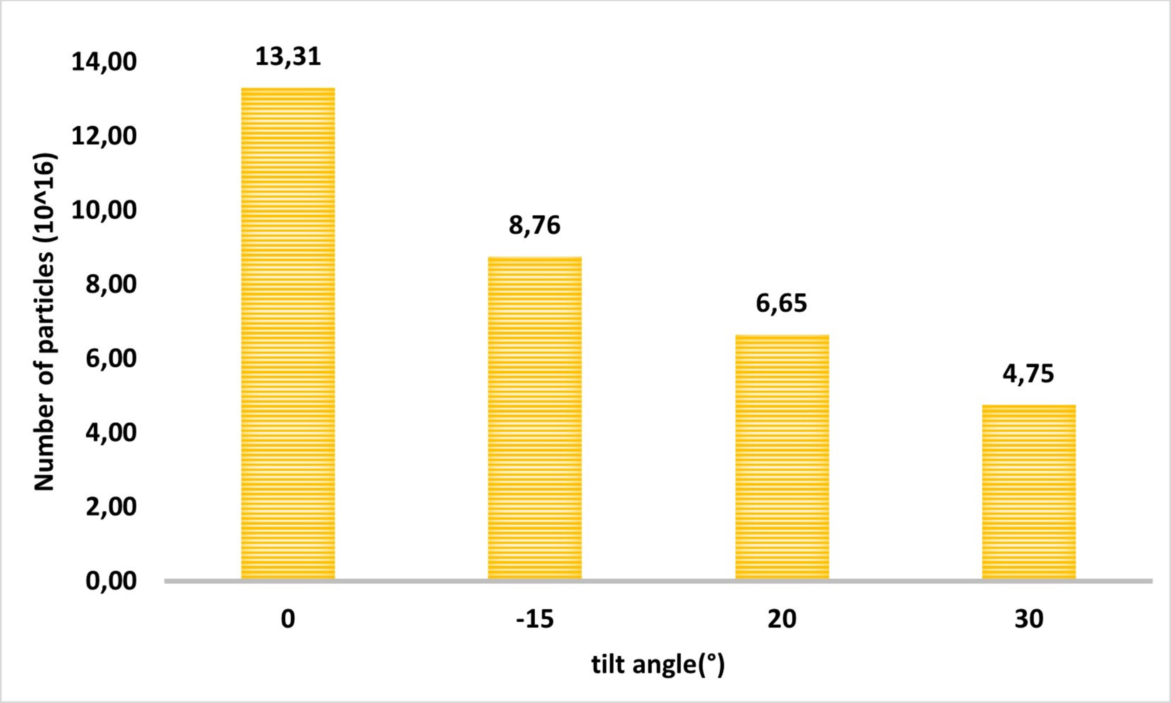


Figure 4.27: Estimated number of dust particles accumulated on the solar panel for different stow angles

The optimal position to prevent structural stress on the solar panel is not solely affected by the tilt angle; Rather, it depends on the attack angle, indicating the direction of the wind flow. To demonstrate this, we analyzed the lift and drag forces acting on the solar tracker when stowed at a 20° angle (see Figure 4.28). As wind speed increases, both lift and drag forces exhibit a corresponding rise. Notably, our observations reveal that the increase in drag force with escalating velocity surpasses the increase in lift force. This disparity is because drag force acts parallel to the wind flow, depending on the tracker's attack angle relative to the wind direction. While lift force hinges on the tilt angle of the solar panel, emphasizing the need to consider both the tilt and azimuth angles to safeguard solar panels from structural stress and potential deterioration.

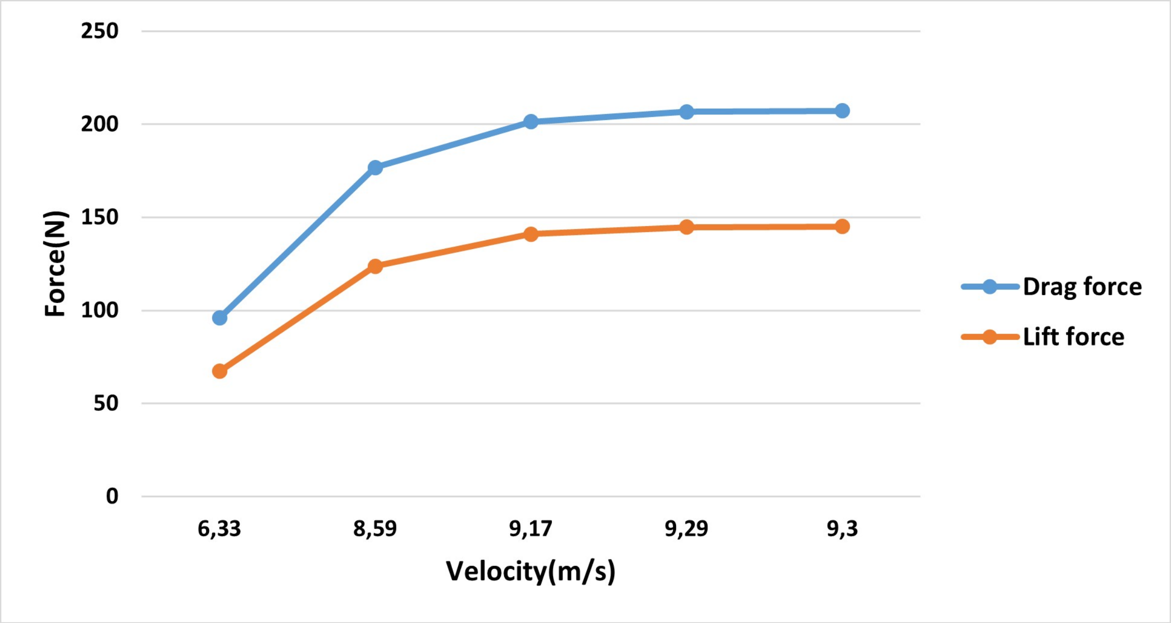


Figure 4.28: Lift and drag forces against velocity for a 20° stow position of the solar tracker

In evaluating the optimal attack angle for the tracker during sandstorms, we examined the wind force coefficient of the solar tracker when stowed at a 20° angle in June 2023 (see Figure 4.29).

Notably, when the wind direction is at 0°, impacting the back of the panel, and at 200°, affecting the front of the solar panel, drag coefficients are consistently observed to range between 0 and 1.6. It is because of the heightened forces acting on the solar panel when the tracker is parallel or facing the wind directly. The normal force coefficient exhibits similar values at wind directions of 0° and 250°, suggesting that these coefficients are less affected by wind. Conversely, drag, lift, and normal coefficients reach their minimum values at wind directions of 50° and 100°. Meaning the solar panel experienced less wind pressure at these side angles. The most significant wind coefficients for changes in wind direction are at 250° and 360°. Notably, apart from a headwind of 0°, the most wind coefficient is distributed between 200° to 230° and 300°, emphasizing the substantial impact of headwind direction on the wind load of solar panels. Therefore, it is crucial to consider rotating the panel to align with a 50° or 100° wind attack relative to the wind hitting at side angles and avoid maintaining a perpendicular orientation to the wind or facing it directly.

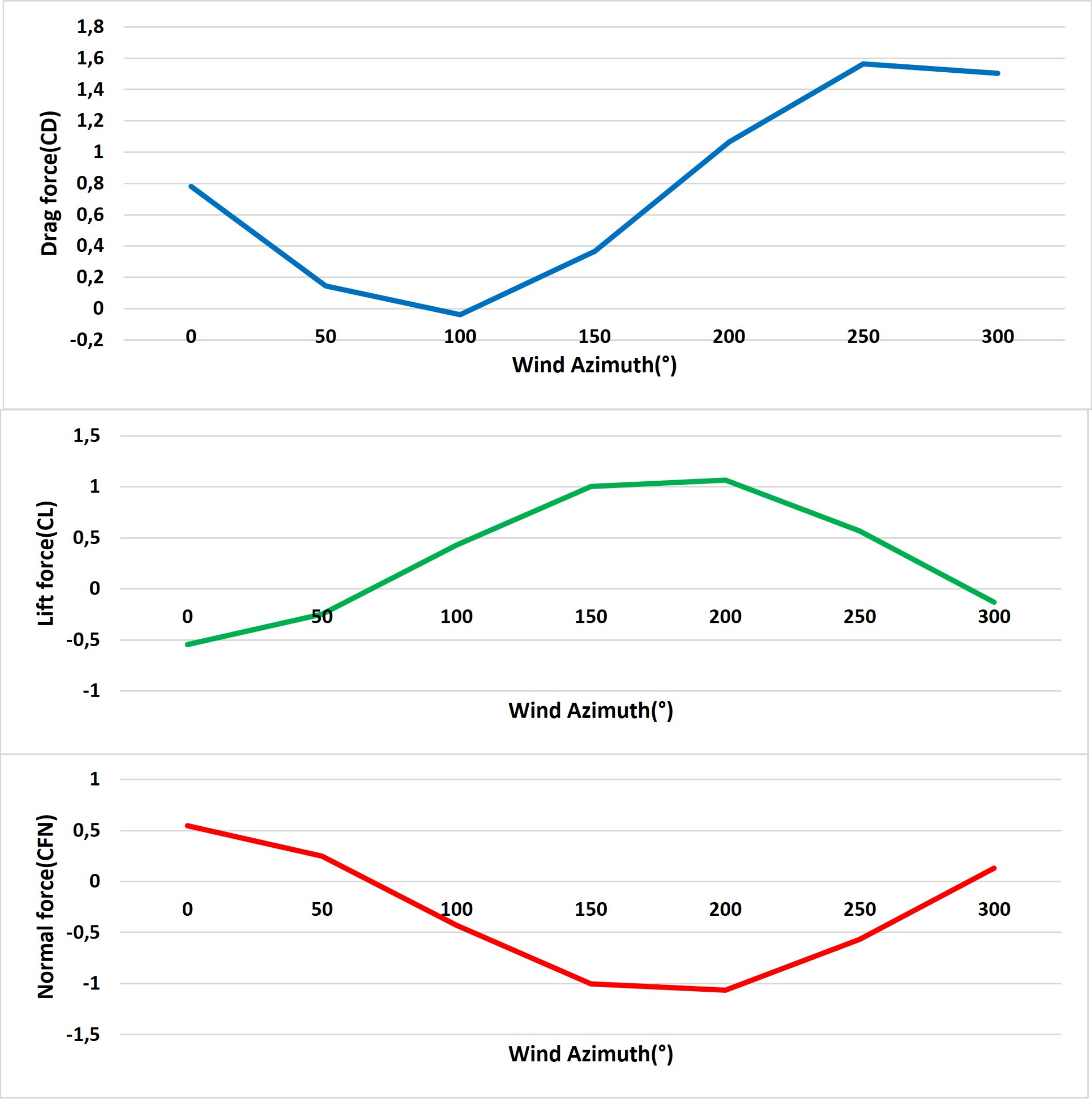


Figure 4.29: Wind force coefficient of the solar tracker tilted at 20° on June 2023

The performance of the solar tracker was assessed under various sandstorm conditions throughout a month, examining its robustness and functionality. Weekly observations of the tracker's behavior in response to sandstorms were conducted from June 6th to June 27th .Figure 4.31 illustrates the stow position of the solar tracker during sandstorm occurrences on various days in June.ANd figure 4.30 represents the attack angles in relation to wind direction during sandstorm events. The figures provide a clear visualization of the solar tracker's stow position, strategically adapting to varying wind directions encountered on different days in June. By showcasing the system's ability to align itself with wind patterns, this results underscores the practicality and reliability of our solar tracker in mitigating the impact of adverse weather conditions.

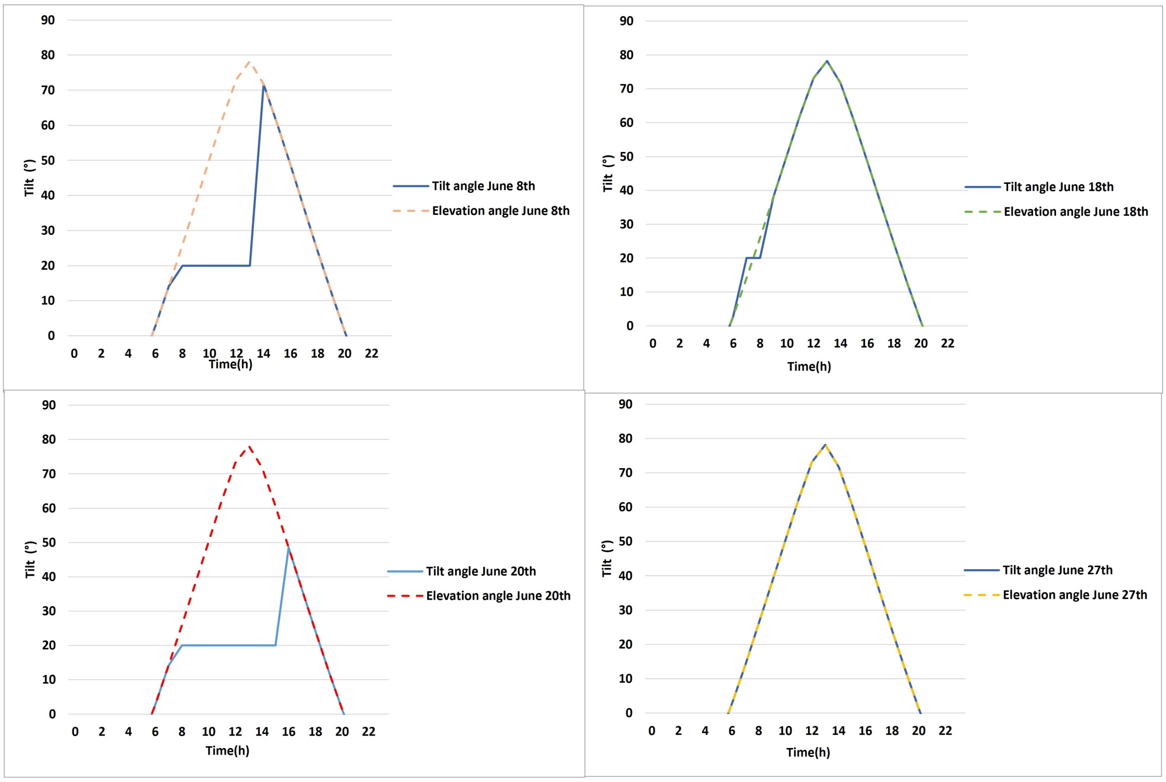


Figure 4.30: Stow angles response of the designed solar tracker to sandstorm occurrences on June 2023 for Tiaret, Algeria: (a)June the 6th (b) June 13th (c) June 20th (d) June 27th.

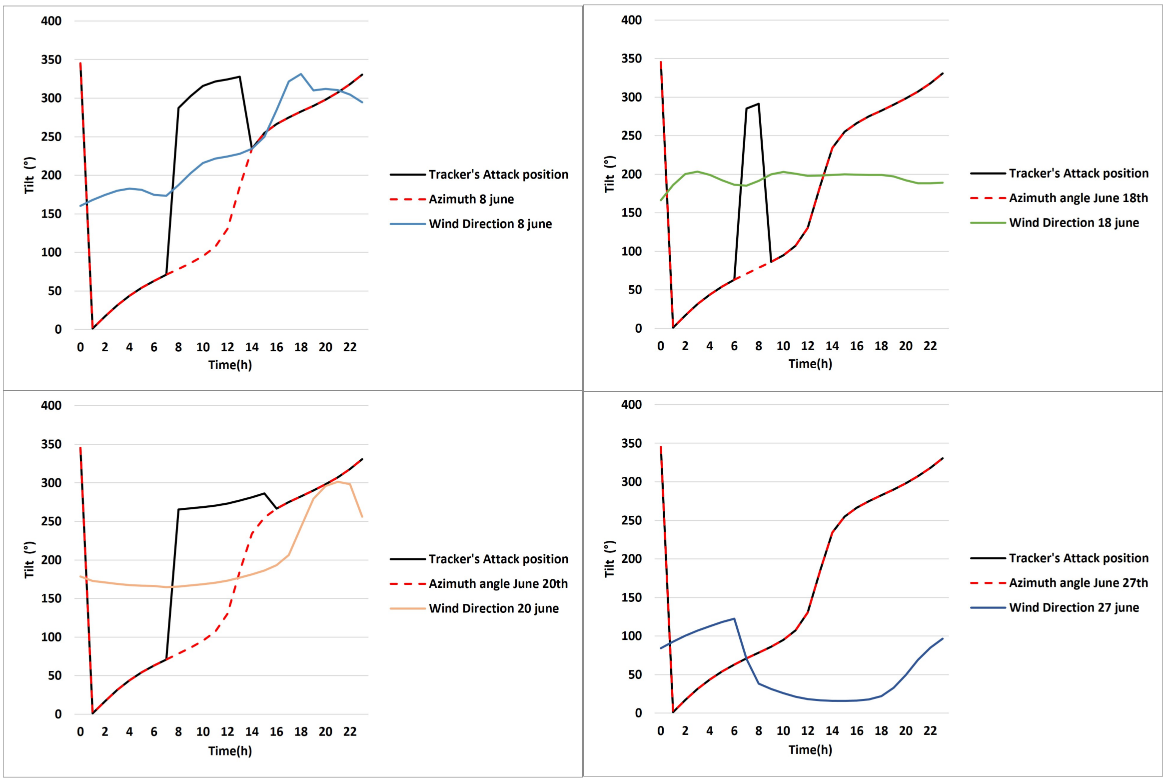


Figure 4.31: Attack angles response of the designed solar tracker to sandstorm occurrences on June 2023 for Tiaret, Algeria: (a)June the 6th (b) June 13th (c) June 20th (d) June 27th.

On June 8th, the tracker stowed its position to 20° and faced the wind at 100° from 8 AM to 13 PM, coinciding with the sandstorm occurrence, as supported by wind speed data (see Figure 4.25), where it exceeded 8.5 m/s. The tracker resumed tracking the sun once the sandstorm subsided. On June 18th, a sandstorm occurred around 7 AM, disappeared by 8 AM, lasing for an hour only. The solar tracker swiftly adapted to both occurrences, indicating its response to sandstorms even at night. On June 20th, the sandstorm was observed from 8 AM to 15 PM, prompting the tracker to adjust to the stowing position. Lastly, on June 27th, no sandstorm was detected, and the solar tracker precisely followed the sun's elevation and azimuth angles, demonstrating its efficiency and effectiveness in maximizing solar energy capture. These results highlight the robustness and quick response of the tracker to sandstorms.

As a primary objective, we have ensured that the tracker energy consumption remains minimal compared to the increased energy. This consideration was crucial as it is the main factor in any solar power generation system. Figure 4.32illustrates the energy produced versus consumed by the solar tracker on four different days in June during a sandstorm occurrence. On June 8th, due to a 5-hour sandstorm, the tracker energy production was 649.78 WH, and consumption was 15.53 WH, resulting in a consumption rate of 2.39%. On June 18th, despite a sandstorm occurrence for 1 hours, energy production was the lowest at 216.59 WH, as the storm was the strongest,causing unclear day and affecting overall energy production. However, energy consumption was low on that day at 11.65 WH, constituting 5.38%. The energy production on June 20th was at 974.67 WH,the consumption was the highest at 15.53 WH due to an 7-hour lasting sandstorm.The maximum energy production was noticed on June 27th, reaching 1475.84 WH, due to clear weather and sandstorm absence. The tracker consumed 7.77 WH of energy, constituting 0.53% of the produced energy. It is worth noting that the designed solar tracker operates only from sunset to sunrise and freezes at its sunset position rather than having a stow position at night, reducing, even more, the consumed energy. Throughout all days, energy consumption remained below 5.5% of the produced energy, which is very low compared to exciting designs from literature, demonstrating the efficiency of the designed solar tracker.

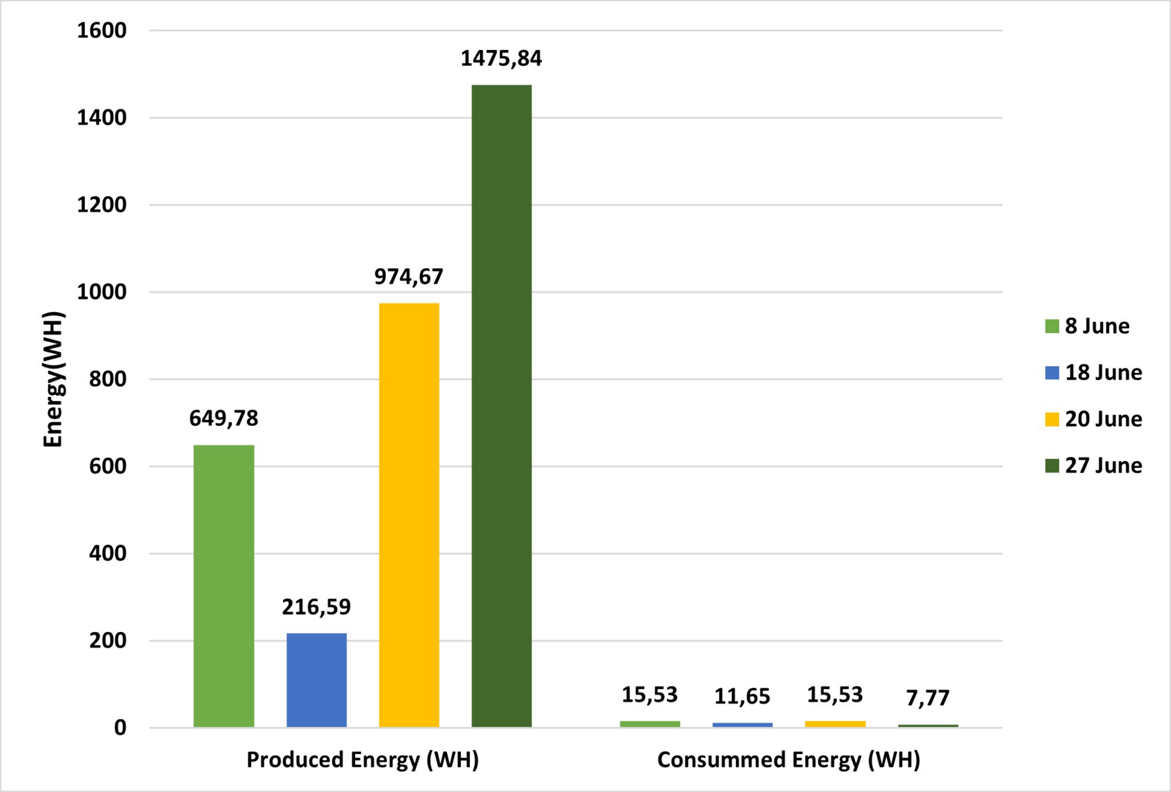


Figure 4.32: Tracker's Response of a Sandstorm occurrence on 27th June 2023 for Tiaret City, Algeria.

Figure 4.33 represents the energy consumption rate during sandstorms for different days in June. This visual representation allows for a detailed analysis of how the solar tracker responds to sandstorm events, particularly in terms of energy consumption.

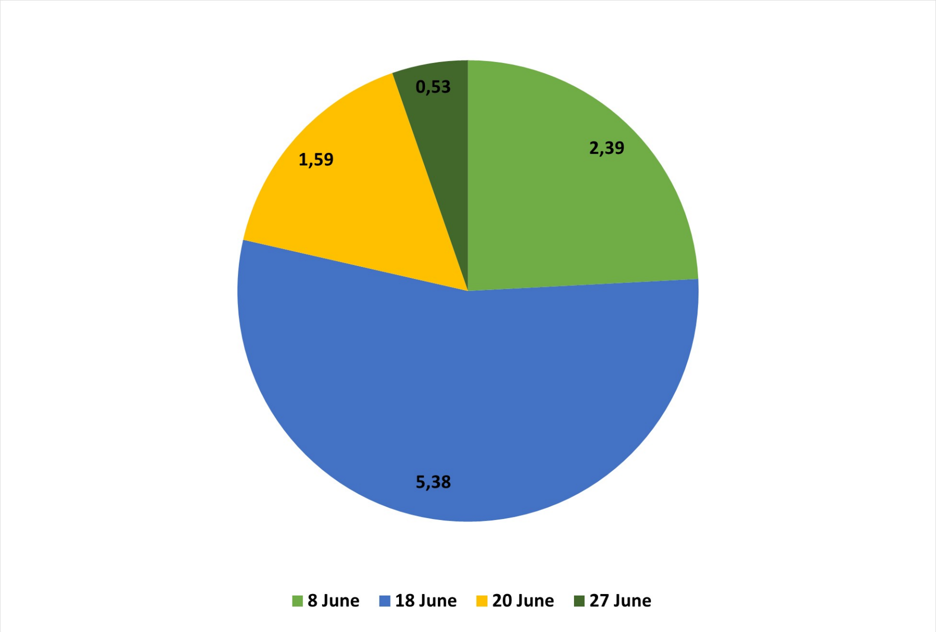


Figure 4.33: Tracker's Energy Consumption rate during Sandstorms

The results affirm the designed solar tracker's efficacy in withstanding sandstorms and optimizing PV solar systems in desert environments. By leveraging conventional solar tracking with wind data integration and stowing the tracker at a 20° angle while facing it into the wind at a 100° attack angle during sandstorms, we effectively reduced structural stress caused by wind and dust accumulation, addressing key sandstorm challenges. This approach not only protects panels from deterioration and enhances efficiency but also guards against excessive heat due to the misalignment in the stowing position and the reduction of dust that holds temperature. With minimal energy consumption ranging from 0.53% to 5.38% relative to production, the tracker significantly boosts solar power generation efficiently, with simplicity and cost-effectiveness. The designed solar tracker is a promising solution, integrating efficient energy generation with reliable sandstorm protection for sustainable energy production in desert regions.

4.6 Cost Breakdown

In our pursuit of designing an efficient and cost-effective sensorless solar tracker, we meticulously breakdown the cost of implementation into various components. Table 4.7 provides a comprehensive overview of the key elements and their associated expenses. The control unit, comprising an Arduino Mega, stepper motors (23 and 17), LN298N motor drivers, LCD I2C display, and a 3x4 keypad, serves as the brain of our solar tracker system. The prototype includes a screw-nut linear actuator, a v-belt drive system with two pulleys, a base with four wheels, a support structure for the solar panel, and a Suntech STP050D-12/MEA solar panel. Additional components encompass the necessary materials for the tracker's structure, such as paint for coating. The table delineates the quantity, unit, and cost for each item, allowing a detailed analysis of the overall expenses. Our commitment to designing a low-cost solar tracker is evident in our strategic cost breakdown, emphasizing efficiency and affordability in the pursuit of sustainable energy solutions

Table 4.7: Cost Breakdown for the Implementation of the Sensorless Solar Tracker Components

Category	**Item**	**Quantity**	**Unit (DA)**	**Cost (DA)**	**Cost (USD)**	**Cost (€)**
Control Unit	Arduino Mega	1	4832.02	4832.02	35.99	32.75
	L298N Motor Drivers	2	652.50	1305.01	4.86	4.42
	LCD I2C Display	1	1196.26	1196.26	8.91	8.11
	3x4 Keypad	1	965.33	965.33	7.19	6.54
Azimuth Rotation System	V-Belt	1	388.01	388.01	2.89	2.63
	Wooden Pulley	2	537.04	1074.08	4.00	3.64
	NEMA 23 Stepper	1	12349.23	12349.23	91.98	83.70
Elevation Rotation System	Lead Screw	1	1529.22	1529.22	11.39	10.36
	NEMA 17 Stepper	1	2760.39	2760.39	20.56	18.71
Structural Elements	Base with Four Wheels	1	1609.78	1609.78	11.99	10.91
	Support Structure for Solar Panel	1	1342.60	1342.60	10.00	9.10
	Suntech STP050D-12/MEA Solar Panel	1	9343.15	9343.15	69.59	63.33
Power Supply	12V Power Source	1	923.71	923.71	6.88	6.26
Others	Paint for Structure Coating	2	827.04	1654.08	6.16	5.61
	Resemblance Cost	1	2000.47	2000.47	14.90	13.56
Total Cost				43273.34	307.29	279.63

4.7 Discussion of Results

4.7.1 Narrative Description

In this section, we delve into the key findings derived from the comprehensive evaluation of the sensor-less solar tracking system. As we unfold the narrative, our aim is to not only present factual observations but to provide a nuanced interpretation of the results, contextualized within the framework of our initial research questions and hypotheses. This exploration extends beyond the mere identification of outcomes; it involves a critical analysis of how these findings align with or challenge our anticipated outcomes. Unexpected discoveries, if any, will be carefully scrutinized, and plausible explanations will be probed.Here are the key Findings from the Solar tracker evaluation:

ZIP code Sensor-less Solar Tracker

In this research we have designed a new, high-precision, low-cost and simple solar tracking system based on a tracking code that uses countries ZIP codes as an alternative for sensors. From the results we have found that :

- Solar tracking system using ZIP codes has proven effective,producing 36.9% energy more then fixed PV panel.

- The designed solar tracker can accurately track the sun with high response time, without getting effected if the weather is cloudy or rainy.
- This tracker can reduce energy consumption, as it consumes 1.16% of the produced solar power for tracking every 15 minutes and 0.36% for tracking every 1 hour. These figures align with the recommended energy consumption range for a solar tracker, which should be between 2% and 3% of the increased energy in a solar power generation system, as outlined by Mousazadeh in the review [38].
- This design demonstrates cost-effectiveness by eliminating the need for sensors and employing an open-loop, no-feedback control system. This approach not only reduces the initial installation costs but also minimizes ongoing maintenance expenses.
- This innovative design is suitable for both large and small-scale solar generation, offering versatile applicability across a range of solar power systems.
- It is simple and flexible, requiring only the location's ZIP code as input parameters.
- It has the potential to be suitable for any country worldwide. As part of our future perspective, we aim to expand our control program to incorporate 246 different countries, encompassing ZIP codes and administrative divisions for each one. This broadens the adaptability and global applicability of our solar tracker design.

Optimal Tracking Interval

By analyzing the performance of the tracker at different tracking intervals, we have found that:

- The assessment of various tracking intervals showed that the solar tracker's performance remained consistently stable for intervals spanning from 5 minutes to 2 hours, with a marginal power decrease of 0.66% and an energy consumption reduction of 4%.
- Beyond the 2-hour mark, a gradual decline in power output and collected irradiance was observed, indicating diminishing returns for longer tracking intervals.
- The optimal tracking interval for elevation tracking is identified as 2 hours. It is important to note that the azimuth angle tracking interval can be extended to every 5 hours, providing flexibility in the tracking system.
- These findings suggest that real-time tracking may not be as effective, as it can consume more energy without yielding the desired power outcome. This emphasizes the unnecessary use of sensors in solar tracking systems, indicating that optimized tracking intervals can achieve desired outcomes more efficiently.

Tracking Error Impact

In the aim of lowering cost and complexity, our designed solar tracker employs an open-loop, no-feedback control system. We conducted tests to assess the impact of various tracking errors on the performance of the solar tracker, and here are our findings:

- Tracking errors up to 12° had a minimal impact on the solar tracker's performance, with both energy production and power output experiencing a slight decline.
- A tracking error of 6° demonstrated an even more negligible impact, with a 0.8% drop, indicating that the tracker can effectively produce power even with a tracking error of 6 degrees.
- As tracking errors increased beyond 12°, a noticeable decline in performance was observed, resulting in a linear decrease in both energy production and power output.
- These findings underscore the unnecessary use of closed-loop control in solar tracking systems, as even an error of 6° doesn't significantly impact overall production. This emphasizes the need to focus on making solar tracking systems feasible and low-cost rather than prioritizing increased accuracy.

Sandstorm Resilient

Since this study was conducted in Algeria, a country occupying 75% of desert territory, known for its arid and hot climate, with significant potential for solar power but susceptible to sandstorms, the findings hold particular relevance. By integrating standard solar tracking tools with wind data, this study provides an innovative solution to mitigate sandstorm effects on PV systems and enhance the efficiency of solar power generation in desert environments. Through a thorough analysis of the results obtained, several key findings emerge:

- The strategy of stowing the solar panel at 20° and exposing it to a wind attack angle of 100° during sandstorms has proven to be effective in minimizing the impact of sandstorms, considering both dust accumulation and structural stress.
- The protective approach remains effective even at night when the tracker is inactive, ensuring continuous safeguarding against sandstorms that may occur during nocturnal hours.
- The designed solar tracker stands out for its cost-effectiveness, as integrating solar tracking tools with wind sensing reduces costs, eliminating the need for additional proactive mechanisms.
- Using wind data to predict sandstorms and protect the solar tracker represents a novel approach, providing real-time monitoring and proactive protection against sandstorms.

- By minimizing wind forces and dust accumulation, this approach extends the lifespan of the PV system, ensuring protection from surface abrasion, structural stress, long-term degradation, and the potential for total panel deterioration.

- This approach holds promise for advancing solar energy generation in desert regions, not only by providing a resilient solution to the challenges posed by sandstorms but also by safeguarding the panels from excessive heat through the misalignment with the sun in the stowing position and the reduction of dust that holds temperature.

- It significantly enhances the efficiency of the solar tracker in desert environments by achieving minimal energy consumption, ranging from 0.5% to 5.5% relative to energy production, and reducing dust settlement.

- This study establishes a foundation for future research in power generation in the Algerian desert. The findings reveal crucial thresholds for sandstorms in the Algerian desert during the summer, indicating that 6.5 m/s serves as the threshold for a mild sandstorm, 10.5 m/s for a medium sandstorm, and 14 m/s for a strong sandstorm.

These key findings collectively highlight the effectiveness and adaptability of the sensorless solar tracking system, providing valuable insights for optimizing its performance in real-world applications.

4.7.2 Key Findings from Analyses

The inspiration behind using ZIP codes as an alternative for sensors stemmed from the fact that the country has diverse latitude and longitude features. We investigated the influence of latitudes and longitudes on the solar tracking system, which yielded several key findings:

Latitude Variations Impact

- Elevation angles are significantly influenced by latitude changes, reflecting the varying angle of the sun's elevation in the sky as one moves closer to or farther from the equator. However, unlike elevation angles, azimuth angles, representing the compass direction of the sun, are relatively unaffected by latitude changes. This distinction in the impact of latitude on elevation and azimuth angles is a crucial consideration for optimizing solar tracker configurations in different geographic locations.

- the power percentage remains consistently high at 99% for latitude differences less than 10 degrees. However, beyond a 10-degree difference in latitude, there is a slight decrease in power percentage, reaching 96.98%. This suggests that the solar tracker's efficiency in capturing solar energy remains robust for moderate variations in latitude but experiences a modest reduction as the latitude difference becomes more pronounced.

- For latitude differences up to 4 degrees, the elevation angle exhibits a notable degree of stability, showing minimal variation. This suggests that within this range of latitude differences, the impact on the elevation angle is relatively constant, providing insights into the consistent behavior of the solar tracking system under slight changes in latitude.
- A 10-degree latitude difference results in a discernible decrease in both the elevation angle and power output. This finding indicates that larger variations in latitude significantly affect the solar tracker's performance, leading to a reduction in the elevation angle and, consequently, a noticeable decline in power output. It underscores the importance of fine-tuning solar tracking parameters to accommodate substantial latitude differences for optimal energy capture efficiency.

Longitude Variations Impact

- Longitudes were observed not to affect the elevation or azimuth angles, thereby having no notable impact on the production of the solar tracker. However, there was a temporal shift, indicating that longitudes influence the timing of the sun's position rather than the angles. This emphasizes the role of longitudes in determining when the solar tracker optimally aligns with the sun, without substantial alterations in its angular orientation.
- The tracking time, which spans from sunrise to sunset, experiences a shift of 7 minutes for every 2-degree change in longitude. This observation indicates a linear relationship between the solar tracker's tracking time and variations in longitude, providing valuable insights into the temporal aspects of solar tracking influenced by changes in geographic location.
- This implies that longitude variations play a crucial role in determining the timing of the solar tracker's alignment with the sun, offering practical insights for optimizing tracking systems based on geographic locations. It underscores the importance of considering temporal aspects alongside angular parameters for effective solar tracking.

These findings suggest that for locations that have a latitude difference of up to 10 degrees and longitude variations of 2 degrees, the same solar tracking configuration can be employed. This eliminates the need for location-specific adjustments in solar tracking systems, streamlining the implementation process and potentially reducing overall system complexity and costs.

4.7.3 Comparison with Literature

To assess the effectiveness of our solar tracking system, we compared it with similar systems existing in the literature. Here are the findings that we discovered:

Tracking Efficiency

To assess the efficiency of our designed solar tracker, we conducted a thorough comparison with studies from existing literature, examining both sensor-based and sensor-less solar tracking systems, as well as those specifically comparing with fixed PV systems. In the realm of sensor-based tracking, Morón et al. (2017) reported an 18% increase in energy output [19], while Hoffmann et al. (2018) indicated monthly gains ranging from 17.2% to 31.1% [21]. Shifting focus to sensor-less systems, Tirmikci and Yavuz (2015) advocated for dual-axis trackers, noting up to a 40% increase in efficiency [26]. Fuentes et al. (2020) demonstrated a 17.96% improvement [28], and Pirayawaraporn et al. achieved a remarkable 20.1% improvement [29]. The 35.91% boost in energy capture was specifically credited to the dual-axis solar tracker proposed by Wu et al. [67].

Significantly, our sensor-less solar tracking system consistently competes with and often surpasses reported efficiencies especially for sensor-based systems. The introduction of our dual-axis solar tracker stands out, showcasing a substantial 36.9% improvement in energy capture compared to fixed-tilted trackers. These findings underscore the effectiveness of our innovative sensor-less solar tracking system, offering significant advancements in energy efficiency compared to traditional sensor-based counterparts, establishing it as a powerful solution in the field.

Sensor reliance

Traditional solar trackers have conventionally relied on sensors to ensure precise sun tracking, yet the inherent complexities, inaccuracies, and delayed response times associated with sensor-based systems present significant drawbacks. The reliance on sensors introduces challenges such as reliability issues in adverse environmental conditions, escalated costs linked to the implementation of high-quality sensors, and the necessity for regular calibration and maintenance . Moreover, the energy consumption of sensors within solar-powered systems warrants careful consideration, as it may counteract the efficiency gains achieved through enhanced tracking capabilities .

In the sensor-based solar tracking paradigm, Morón et al. (2017) employed photodiodes as sensors in their photovoltaic solar tracker prototype [19]. Garcia and Alejandro (2010) utilized a commercial webcam as a sensor element in their solar tracking system [20]. Hoffmann et al. (2018) implemented Light Dependent Resistors (LDRs) as sun movement sensors in their dual-axis solar tracking system, [21]. While sensorless solar tracking systems are designed to operate without explicit sensors, some studies mentioned the use of certain sensors for auxiliary purposes. For instance, Sidek et al. (2017) incorporated GPS data and a Honeywell HMC6352 digital compass sensor module in their sensorless solar tracker [23]. Seme and Stumberger (2011) used pyranometer data for solar radiation prediction in their sensorless solar tracking system [24]. Loon and Daud (2020) utilized current sensors for detecting optimum azimuth and tilt angles [28], while Fathabadi (2016) employed a Maximum Power Point Tracking (MPPT) unit as a crucial component of the sensorless tracker [27]. Finally, Wu et al. (2022) integrated satellite compass, inclinometer, and GPS receivers as sensors in their dual-axis solar tracking system [67].

In comparison to the existing literature, where many sensorless systems still integrate sensors for supplementary functions, our design stands out as a true sensorless solution. By relying solely on geographic calculations and open-loop control, our solar tracker offers a robust and cost-effective alternative, contributing to a more sustainable and efficient utilization of solar energy resources.

Weather resilience

The existing literature highlights several critical gaps that pose challenges to the widespread adoption and effectiveness of solar energy systems, particularly in arid regions. While existing studies extensively address the issues of dust accumulation and wind forces separately, there is a distinct absence of comprehensive solutions for safeguarding solar PV systems from sandstorms. These climatic events combine dust particles and strong wind forces, requiring an integrated approach that simultaneously addresses both aspects. One prominent gap is the cost of cleaning mechanisms, coatings, and additional protective designs. The financial burden of maintaining and cleaning solar panels often outweighs the cost savings derived from the energy they produce, limiting the economic viability of solar systems. Another significant gap arises from the energy consumption of additional protective mechanisms against wind forces, such as V assemblies or boxes, which can surpass the energy generated by solar trackers. This imbalance raises concerns about the sustainability and efficiency of these protective measures. Further, the time and financial resources required for frequent cleaning present another gap, affecting the practicality of solar systems in regions with high dust accumulation. Additionally, the limited effectiveness of fences against dust accumulation underscores the need for innovative solutions. By introducing our innovative approach we were able to address these gaps and enhance the efficiency of solar power generation in desert environments, where sandstorms present unique obstacles to conventional solar panels. The innovation of integrating wind data readings into standard solar tracking tools for proactive sandstorm mitigation significantly reduces the detrimental effects of sandstorms on the photovoltaic (PV) system. The key to the success of this method lies in stowing the tracker at a specific angle of 20° and exposing it to the wind at an attack angle of 100°. These angles demonstrated minimal dust accumulation and reduced wind force on the panel. Through extensive testing, our research indicates that daily energy consumption during sandstorms ranges from 0.5% to 5.5% of the produced energy, showcasing the efficiency and reliability of this innovative sandstorm mitigation strategy. Importantly, this approach not only safeguards the PV system during sandstorms but also offers economic benefits by lowering operational costs, simplifying system complexity, and reducing overall energy consumption. Compared to alternative protection mechanisms, cleaning practices, and traditional maintenance methods, our integrated approach emerges as a cost-effective and environmentally sustainable solution for solar power installations in desert regions.

4.8 Limitations

While our study offers valuable insights into the performance of the sensor-less solar tracking system, it is important to recognize certain limitations that could influence the interpretation and broader application of our results. Our research is primarily focused on a specific geographical area defined by latitudinal and longitudinal ranges, potentially limiting the generalizability of our findings to regions with markedly different solar exposure patterns. Moreover, the accuracy of the solar tracker is contingent upon precise input parameters, such as latitude and longitude, and any inaccuracies in these inputs, whether due to measurement errors or changes over time, could impact the system's performance. Additionally, our investigation primarily addresses the short to medium-term performance of the system, with less emphasis on long-term stability and the potential effects of wear and tear on its components. Despite these acknowledged limitations, our study makes a significant contribution to understanding the feasibility and efficiency of sensor-less solar tracking systems. It is crucial for future research to carefully consider and address these limitations to advance the technology's comprehensiveness and applicability.

4.9 Implications for Practice or Theory

The findings of our study hold significant implications for both practical application and theoretical advancements in the field of solar energy systems. From a practical perspective, the demonstrated efficiency and adaptability of the sensor-less solar tracking system present a viable and cost-effective alternative to traditional sensor-based trackers. The consistent performance observed under various conditions, the flexibility in optimal tracking intervals, and the tolerance to certain tracking errors enhance the system's practicality for real-world applications. Moreover, the sandstorm reliance feather offers a pragmatic approach for enhancing solar power efficiency in desert environments.

On a theoretical level, our research challenges conventional assumptions about solar tracking systems. The flexibility observed in tracking intervals for elevation and azimuth angles introduces a nuanced understanding of system optimization based on specific requirements. The study contributes to the ongoing discourse on the trade-offs between accuracy, cost, and energy consumption in solar tracking technologies. By showcasing that the sensor-less solar tracking system can outperform sensor-based systems, especially in terms of energy capture, it adds a valuable dimension to the theoretical framework guiding solar energy research.

Overall, our findings contribute to the broader field of study by advancing the understanding of sensor-less solar tracking systems and their potential impact on improving the efficiency and accessibility of solar energy technology. The practical insights gained from this research can inform the development and implementation of solar tracking systems, while the theoretical implications stimulate further exploration and refinement of solar energy theories and technologies.

4.10 Future Research Recommendations

Our study has unveiled several avenues for future research that could enrich the understanding and development of solar tracking systems. Firstly, considering the geographical limitations of our study, future research could explore the performance of sensor-less solar trackers in diverse regions with distinct solar exposure patterns. This could provide a more comprehensive understanding of the system's adaptability and effectiveness in varying environmental conditions.

Future research can focus on extending the protective approach to address all three levels of sandstorms: mild, moderate, and severe, aiming to comprehensively evaluate the effectiveness of the proposed strategy across varying intensities of sandstorm conditions. This thorough exploration will involve refining and optimizing the solar tracking system's response to different degrees of sandstorm severity, enhancing its resilience and protective capabilities.

Additionally, future research could delve into the development of advanced algorithms for more accurate sun position calculations, reducing dependency on accurate input parameters. Exploring machine learning techniques or incorporating real-time data updates could address potential inaccuracies and ensure optimal performance over extended periods.

Long-term stability and durability of the sensor-less solar tracking system components could be a focus for future studies. Investigating the wear and tear effects and evaluating the system's performance over an extended period could contribute valuable insights for system optimization and maintenance practices.

Exploring the economic feasibility and cost-effectiveness of deploying sensor-less solar tracking systems on a larger scale is another area of interest. Assessing the long-term cost implications, including installation, maintenance, and potential energy savings, would provide stakeholders with valuable information for decision-making.

Finally, the theoretical implications of our study prompt questions about the optimal design parameters for solar tracking systems. Future research could delve into refining the theoretical framework, exploring new concepts, and considering alternative designs to further optimize the efficiency of solar energy capture. Addressing these research avenues would contribute to the ongoing evolution of solar tracking technology, fostering advancements in renewable energy systems.

4.11 Conclusion

In conclusion, this chapter substantiates the primary objective of this research, which is to overcome the existing limitations in solar tracking technology and enhance overall solar energy efficiency through the development of an innovative, cost-effective, and sensor-free solar tracker.The successful implementation of this sensor-less solar tracker holds the potential to play a pivotal role in advancing the efficiency and affordability of solar energy systems, aligning with the broader goal of fostering sustainable and renewable energy solutions. The key findings underscore the sensor-less system's effectiveness, adaptability, and resilience to tracking errors, positioning it as a robust alternative to traditional sensor-based trackers. The study's insights into optimal tracking intervals, latitude impact, and the system's performance under diverse conditions contribute valuable knowledge for both practical applications and theoretical advancements in solar tracking technology. These contributions collectively mark a significant step forward in harnessing solar energy more efficiently and sustainably.

CONCLUSION

This research aims to overcome the current limitations in solar tracking technology and enhance overall solar energy efficiency without using specific sensors. Traditional solar trackers, reliant on sensors for precise sun tracking, often face complexities, inaccuracies, and increased costs associated with maintenance and calibration. In response to these challenges, our primary objective is to design a revolutionary solar tracker that not only eliminates the need for sensors with a unique methodology based on ZIP codes but also presents an innovative approach to weather resilience.By prioritizing simplicity, cost-effectiveness, and accessibility, this research endeavors to contribute a novel solution to advance the efficiency and widespread adoption of solar energy systems in desert environments.

The comprehensive evaluation of the sensor-less solar tracking system yielded key findings that significantly contribute to the advancement of solar energy technology. The introduction of a high-precision, low-cost solar tracking system utilizing ZIP codes demonstrated a remarkable 36.9% increase in energy production compared to fixed PV panels. Additionally, the system showcased accurate sun tracking with a high response time, minimal energy consumption , and cost-effectiveness by eliminating the need for sensors. The optimal tracking interval for elevation tracking was identified as 2 hours, offering flexibility in the tracking system. Furthermore, tests on tracking errors revealed that deviations up to 12° had minimal impact, emphasizing the feasibility of an open-loop, no-feedback control system. The system's resilience to sandstorms in desert environments, achieved by stowing the solar panel and leveraging wind data, presented a multifaceted solution to mitigate dust accumulation and structural stress. Lastly, the impact of latitude variations on the solar tracker's efficiency showcased stability for latitude differences up to 10 degrees, while longitudes influenced tracking time linearly. These findings collectively underscore the effectiveness and adaptability of the sensor-less solar tracking system, providing valuable insights for optimizing its performance in real-world applications.

This research makes a substantial contribution to the field by introducing a viable and innovative sensor-free solar tracking solution that not only alleviates the challenges associated with traditional sensor-based trackers but also paves the way for increased accessibility and widespread adoption of solar power technology. By eliminating the reliance on sensors and implementing a novel approach based on ZIP codes, the proposed sensor-less solar tracker offers a cost-effective, simple, and efficient alternative. Furthermore, the integration of a weather-resilient feature, specifically designed for desert environments, enhances the system's durability and sustainability. The successful implementation of this sensor-less solar tracker not only addresses the drawbacks of existing solar trackers but also establishes a foundation for more efficient and affordable solar energy systems. This research contributes significantly to the broader goal of advancing sustainable and renewable energy solutions, particularly in regions susceptible to sandstorms and adverse weather conditions, thereby fostering the progress of solar technology on a global scale.

While our study provides valuable insights into the sensor-less solar tracking system's performance, it's essential to acknowledge limitations influencing result interpretation and broader applicability. Our research focuses on a specific geographic area, defined by latitudinal and longitudinal ranges, potentially limiting generalizability to regions with different solar exposure patterns. The solar tracker's accuracy relies on precise input parameters like latitude and longitude, and inaccuracies, whether due to measurement errors or changes over time, may impact system performance.Despite these acknowledged limitations, our study significantly contributes to understanding the feasibility and efficiency of sensor-less solar tracking systems. Future research should address these limitations to enhance the technology's comprehensiveness and applicability.

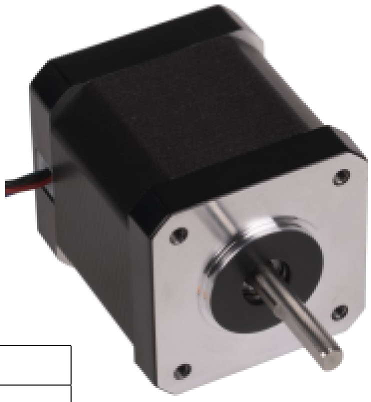
As a future perspective, our aim is to expand the control program to incorporate 246 different countries, encompassing ZIP codes and administrative divisions for each one. This expansion will enhance the adaptability and global applicability of our sensor-free solar tracker design, making it suitable for diverse geographic locations. Additionally, future research endeavors will focus on extending the protective approach to address all three levels of sandstorms: mild, moderate, and severe. The goal is to comprehensively evaluate the effectiveness of the proposed strategy across varying intensities of sandstorm conditions. This involves refining and optimizing the solar tracking system's response to different degrees of sandstorm severity, ultimately enhancing its resilience and protective capabilities. This comprehensive exploration will contribute to advancing the technology's suitability for deployment in desert environments and other regions prone to sandstorms.

APPENDIX A

NEMA17 STEPPER MOTOR - Datasheet

Main Features

- Shaft Ø 5 x 22 mm (4 mm flat spot)
- Interface connection 4 wire
- Dimensions 42 x 42 x 48 mm
- Items delivered: NEMA17 stepper, connection cable



Performance Specifications

Holding torque	0.59 Nm
Rated Voltage	3.6 V
Rated Current	2.0 A
Step Angle	1.8° ± 5%
No. of Phases	2
Phase Resistance	1.8 Ω
Phase Inductance	3.0 mH
Isolation Resistance	100 MΩ min. @500 V DC
Isolation Class	B (130° C)
Rotational Inertia	82 g·cm²
Detent Torque	0.02 Nm
Operating Temperature	-10° C - 50° C

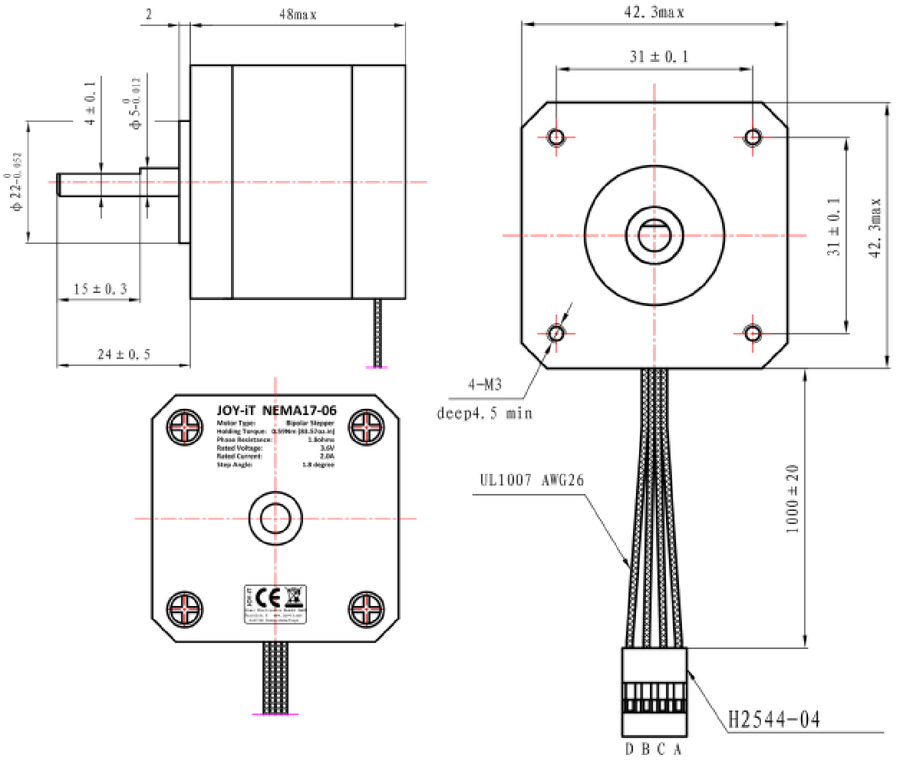
Max. Efficiency

- Efficiency: 98.3%
- Torque: 112.5 mNm
- Current: 0.842 A
- Speed: 1500 min^{-1}
- Output Power: 17.676 W

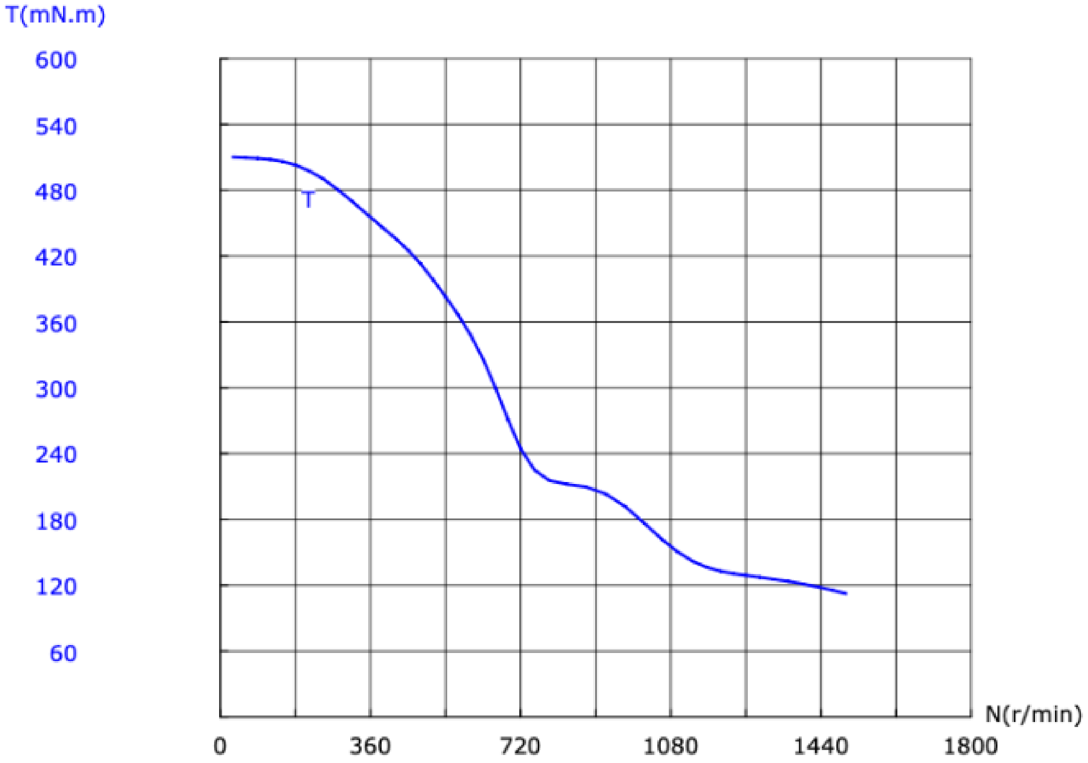
Further Details

- Article No.: NEMA17-06
- This is a small high torque stepper motor that can reach speeds of up to 3000 rpm.
- This stepper motor can be optimally used for tasks in the areas of Automation, CNC (e.g., engraving lasers, 3D printers, milling machines, etc.), or robotics.

Drawing and Wiring



Torque Diagram

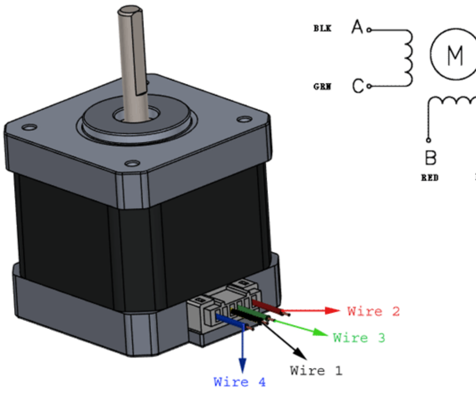


APPENDIX B

NEMA 23 STEPPER MOTOR - Datasheet

Overview

NEMA 23 is a high torque hybrid bipolar stepper motor with a 2.32.3 inch (58.458.5 mm) faceplate. This motor has a step angle of 1.8°, which translates to 200 steps per revolution. It is commonly used in applications such as printers, CNC machines, linear actuators, and hard drives.



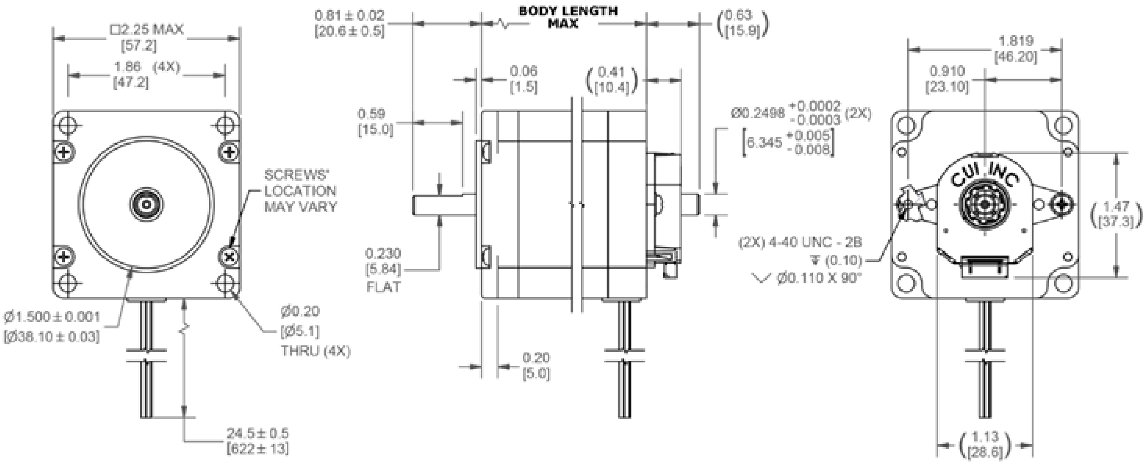
Electrical Specifications

Voltage Rating	3.2V
Current Rating	2.8A
Holding Torque	19 kg-cm
Step Angle	1.8°
Steps Per Revolution	200
No. of Phases	4
Motor Length	3.1 inches
No. of Leads	4
Inductance Per Phase	3.6mH

Pin Configuration

NO.	Pin Name	Wire Colour
1	Wire 1	Black
2	Wire 2	Green
3	Wire 3	Blue
4	Wire 4	Red

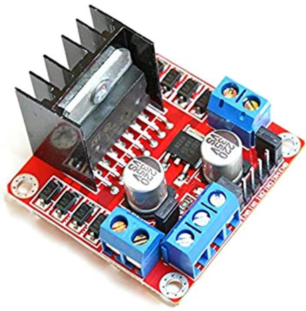
Dimensions



APPENDIX C

L298N MOTOR DRIVER MODULE - Datasheet

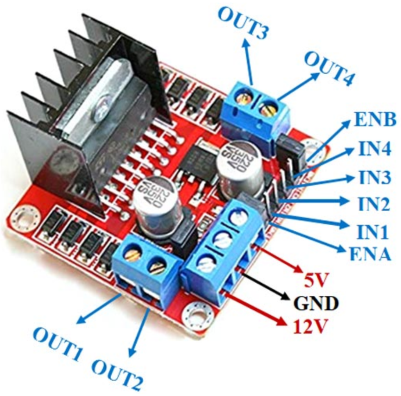
Overview



The L298N Motor Driver Module is a high-power motor driver designed for driving DC and Stepper Motors. The module incorporates an L298 motor driver IC and a 78M05 5V regulator. It has the capability to control up to 4 DC motors or 2 DC motors with directional and speed control.

Pinout Configuration

Pin Name	Description
IN1 & IN2	Motor A input pins. Control the spinning direction of Motor A
IN3 & IN4	Motor B input pins. Control the spinning direction of Motor B
ENA	Enables PWM signal for Motor A
ENB	Enables PWM signal for Motor B
OUT1 & OUT2	Output pins of Motor A
OUT3 & OUT4	Output pins of Motor B
12V	12V input from DC power source
5V	Supplies power for the switching logic circuitry inside L298N IC
GND	Ground pin



Features & Specifications

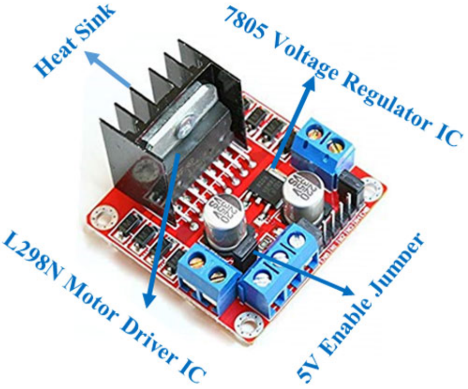
- Driver Model: L298N 2A
- Driver Chip: Double H Bridge L298N
- Motor Supply Voltage (Maximum): 46V
- Motor Supply Current (Maximum): 2A
- Logic Voltage: 5V
- Driver Voltage: 5-35V
- Driver Current: 2A

- Logical Current: 0-36mA
- Maximum Power (W): 25W
- Current Sense for each motor
- Heatsink for better performance
- Power-On LED indicator

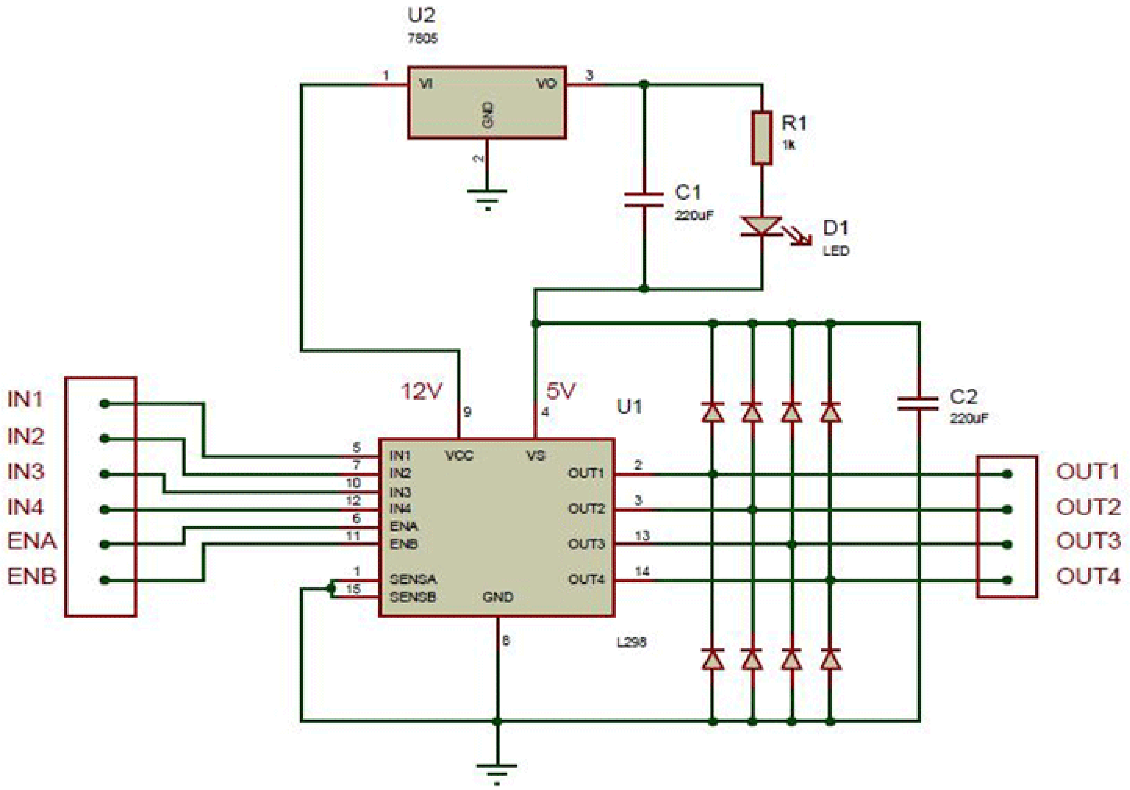
Brief about L298N Module

The L298N Motor Driver Module incorporates an L298 Motor Driver IC, 78M05 Voltage Regulator, resistors, capacitor, Power LED, and a 5V jumper in an integrated circuit.

The 78M05 Voltage regulator is enabled only when the jumper is placed. When the power supply is less than or equal to 12V, the internal circuitry is powered by the voltage regulator, and the 5V pin can be used as an output pin to power the microcontroller. The jumper should not be placed when the power supply is greater than 12V, and a separate 5V should be given through the 5V terminal to power the internal circuitry.



Circuit Diagram

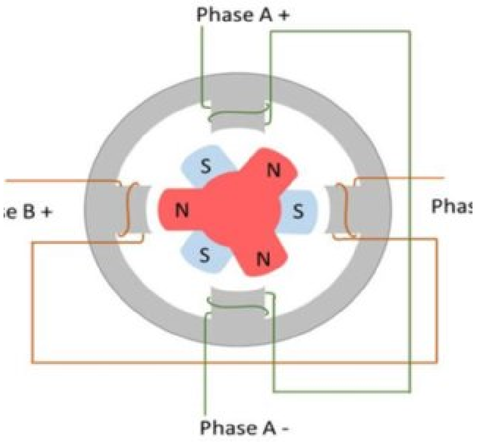


APPENDIX D

Mathematical Model of Stepper Motor

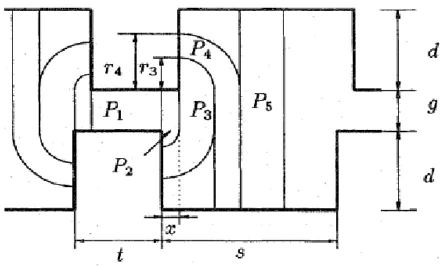
Inductance and Flux Linkage

$$
\begin{aligned}
P1(x) &= \mu_0 t - xg \\
P2(x) &= 2\pi\mu_0 \ln(2g + \pi x^2/g) \\
P3(x) &= (1/\pi)\mu_0 \ln(g + 2d - 0.5\pi xg + 0.5\pi x) \\
P4(x) &= 2\pi\mu_0 \ln(g + 2d + 2d - 0.5\pi x) \\
P5(x) &= (1/\pi)\mu_0 \pi s - \pi x - 4dg + 2d \\
Pt(x) &= Ns(P1(x) + 2(P2(x) + P3(x) + P4(x)) + P5(x))
\end{aligned}
$$



$$
\begin{aligned}
P_\alpha &\approx P_\theta + P_1\cos(p\theta) \\
P_\beta &\approx P_\theta + P_1\cos(p\theta - \pi/2) = P_\theta + P_1\sin(p\theta) \\
P_{\alpha'} &\approx P_\theta + P_1\cos(p\theta - \pi) = P_\theta - P_1\cos(p\theta) \\
P_{\beta'} &\approx P_\theta + P_1\cos(p\theta - 3\pi/2) = P_\theta - P_1\sin(p\theta)
\end{aligned}
$$

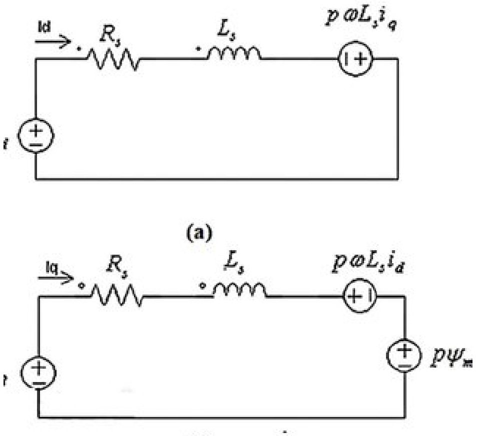
$$
\begin{aligned}
L_\alpha &= 2(P_\alpha + P_{\alpha'})N_s = 4P_\theta N_s \\
L_\beta &= 2(P_\beta + P_{\beta'})N_s = 4P_\theta N_s \\
L_s &= L_\alpha = L_\beta = 4P_\theta N_s
\end{aligned}
$$



$$
\begin{aligned}
\psi_{\alpha m} &= (P_\alpha - P_{\alpha'})N_s\Phi_m = 2P_1\cos(p\theta)N_s\Phi_m \\
\psi_{\beta m} &= (P_\beta - P_{\beta'})N_s\Phi_m = 2P_1\sin(p\theta)N_s\Phi_m
\end{aligned}
$$

Voltage Equations and Circuit Model

$$
\begin{aligned}
V_\alpha &= R_s i_\alpha + \frac{d}{dt}(L_\alpha i_\alpha + \psi_{\alpha m}) \\
V_\beta &= R_s i_\beta + \frac{d}{dt}(L_\beta i_\beta + \psi_{\beta m})
\end{aligned}
$$



(a)

(b)

$$
\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s + L_s\Delta & 0 \\ 0 & R_s + L_s\Delta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + p\psi_m \begin{bmatrix} 0 \\ -1 \end{bmatrix} \frac{d\theta}{dt}
$$

$$
\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s + L_s\Delta & pL_s - pL_s \\ -pL_s & R_s + L_s\Delta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + p\psi_m \begin{bmatrix} 0 \\ 1 \end{bmatrix}
$$

APPENDIX E

Sun Position Angles MATLAB Code

```
elevArray = zeros(1, 24);       % Elevation angles
azimuthArray = zeros(1, 24);    % Azimuth angles

% Loop through the hours and minutes of the day
for hourS = 0:23
    % Calculate the Julian date
    JD_whole = JulianDate(yearS, monthS, dayS);
    JD_frac = (hourS + zone + minuteS / 60. + secondS / 3600.) / 24. - .5;
    T = JD_whole - 2451545;
    T = (T + JD_frac) / 36525.;

    % Calculate the solar position
    L0 = DEG_TO_RAD * mod(280.46645 + 36000.76983 * T, 360);
    M = DEG_TO_RAD * mod(357.5291 + 35999.0503 * T, 360);
    e = 0.016708617 - 0.000042037 * T;
    C = DEG_TO_RAD * ((1.9146 - 0.004847 * T) * sin(M) + (0.019993 - 0.000101 * T
    * sin(2 * M) + 0.00029 * sin(3 * M));
    f = M + C;
    Obl = DEG_TO_RAD * (23 + 26 / 60. + 21.448 / 3600. - 46.815 / 3600 * T);
    JDx = JD_whole - 2451545;
    GrHrAngle = mod(280.46061837 + (360 * JDx), 360)+ 0.98564736629* JDx
    + 360.98564736629 * JD_frac;
    GrHrAngle = mod(GrHrAngle, 360.);
    L_true = mod(C + L0, TWOPI);
    R = 1.000001018 * (1 - e * e) / (1 + e * cos(f));
    RA = atan2(sin(L_true) * cos(Obl), cos(L_true));
    Decl = asin(sin(Obl) * sin(L_true));
    HrAngle = DEG_TO_RAD * GrHrAngle + Lon - RA;
    elev = asin(sin(Lat) * sin(Decl) + cos(Lat) * (cos(Decl) * cos(HrAngle)));

    % Azimuth measured eastward from north.
    azimuthS = PI + atan2(sin(HrAngle), cos(HrAngle) * sin(Lat) - tan(Decl)
    * cos(Lat));

    % Convert angles to degrees
    elev = elev / DEG_TO_RAD;
    azimuthS = azimuthS / DEG_TO_RAD;

    % Store the angles in arrays
    elevArray(hourS+1) = elev;
    azimuthArray(hourS+1) = azimuthS;

    fprintf('Time: %d:%d | Elevation: %.2f | Azimuth: %.2f\n', hourS, minuteS, el
    azimuthS);
```

```
end

% Plot the angles
figure;
subplot(2, 1, 1);
plot(elevArray, 'b.-');
xlabel('Hour');
ylabel('Elevation (degrees)');
title('Sun Elevation Angle');

subplot(2, 1, 2);
plot(azimuthArray, 'r.-');
xlabel('Hour');
ylabel('Azimuth (degrees)');
title('Sun Azimuth Angle');
```

APPENDIX F

C++ Code for ZIP Codes to Sun Position Angles

```
#include <Servo.h>
Servo myservo;

int i;

#define DEG_TO_RAD 0.01745329
#define PI 3.141592654
#define TWOPI 6.28318531
float eleva[65]={};

void setup() {

  // get coordinates
  float ZIPcode[3][5] = {
    {1000,1001,1100,1102,1103},
    {28.0174403,27.8683686,27.227286,28.0174403,28.0174403},
    {-0.2642497,-0.3016932,-0.1899704,-0.2642497,-0.2642497}
  };
  float targetValue = 1100;
  float lat,lon;
  int index_j = -1;

  for (int j = 0; j < 4; j++) {
    if (ZIPcode[0][j] == targetValue) {
      index_j = j;
      break;
    }
  }
  if (index_j != -1) {
    Serial.print("The ZIP code is: ");
    Serial.print(targetValue,0);
    Serial.println();
    lat=ZIPcode[1][index_j];
    lon=ZIPcode[2][index_j];
    Serial.print("Longitude and latitude "); Serial.print(lon,6);
    Serial.print("  "); Serial.println(lat,6);
  }
  else {
    Serial.print("The ZIP code ");
    Serial.print(targetValue);
    Serial.println(" was does not exist");
  }
```

```
  // calculate sun position
  int   counter = 0;
  myservo.attach(9);
  int hour,minute,second=0,month=6,day=26,year,zone=5;
  float Lon=lon*DEG_TO_RAD, Lat=lat*DEG_TO_RAD;
  float T,JD_frac,L0,M,e,C,L_true,f,R,GrHrAngle,Obl,RA,Decl,HrAngle,elev,azimuth;
  long JD_whole,JDx;
  Serial.begin(9600);
  year=2015;

  for (hour=8; hour<=20; hour+=1) {
    for (minute=0; minute<=60; minute+=15){
      JD_whole=JulianDate(year,month,day);
      JD_frac=(hour+minute/60.+second/3600.)/24.-.5;
      T=JD_whole-2451545; T=(T+JD_frac)/36525.;
      L0=DEG_TO_RAD*fmod(280.46645+36000.76983*T,360);
      M=DEG_TO_RAD*fmod(357.5291+35999.0503*T,360);
      e=0.016708617-0.000042037*T;
      C=DEG_TO_RAD*((1.9146-0.004847*T)*sin(M)+(0.019993-0.000101*T)*sin(2*M)+0.0
      f=M+C;
      Obl=DEG_TO_RAD*(23+26/60.+21.448/3600.-46.815/3600*T);
      JDx=JD_whole-2451545;
      GrHrAngle=280.46061837+(360*JDx)%360+.98564736629*JDx+360.98564736629*JD_fr
      GrHrAngle=fmod(GrHrAngle,360.);
      L_true=fmod(C+L0,TWOPI);
      R=1.000001018*(1-e*e)/(1+e*cos(f));
      RA=atan2(sin(L_true)*cos(Obl),cos(L_true));
      Decl=asin(sin(Obl)*sin(L_true));
      HrAngle=DEG_TO_RAD*GrHrAngle+Lon-RA;
      elev=asin(sin(Lat)*sin(Decl)+cos(Lat)*(cos(Decl)*cos(HrAngle)));
      azimuth=PI+atan2(sin(HrAngle),cos(HrAngle)*sin(Lat)-tan(Decl)*cos(Lat));

      counter++;
      eleva[counter-1]=elev/DEG_TO_RAD;
    }
  }
}

void loop() {
  for(i= 0; i<65; i++) {
    myservo.write(eleva[i]);
    Serial.print(eleva[i]);
    Serial.println();
    delay(10000);
  }
}

long JulianDate(int year, int month, int day) {
```

```
  long JD_whole;
  int A,B;
  if (month<=2) {
    year--; month+=12;
  }
  A=year/100; B=2-A+A/4;
  JD_whole=(long)(365.25*(year+4716))+(int)(30.6001*(month+1))+day+B-1524;
  return JD_whole;
}
```

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