

An Experimental Investigation on a Mobile Solar Tracker using GPS

by

Alkaabi SAIF^{*1} and Ryu-ichiro OHYAMA^{*2}

(Received on Mar. 14, 2024 and accepted on May 20, 2024)

Abstract

This paper describes the development of a mobile solar panel tracker. Unlike most other solar trackers with optical sensors, this mobile device does not rely on optical sensors. The tracker improves solar energy efficiency by effectively guiding panels to align with the sun's path throughout the day without being affected by weather factors. The instrument uses several equations to determine the position of the sun relative to the instrument's location. The device can directly determine its position and the direction of the sun, allowing it to be carried on slow moving vehicles, such as ships. Finally, the device smoothly aligns the solar panels with the sun.

Keywords: Solar tracker, Solar declination, Solar elevation, Solar azimuth

1. Introduction

Technologies like photovoltaics (PV) and concentrated solar power (CSP) plants are projected to increase global solar power capacity to 1,500 gigawatts by 2027 ^{1,2)}. Solar capacity is expected to rise from 1 terawatt today to 60 terawatts by 2050, positioning PV as a central technology in the global energy transition towards a decarbonized, sustainable economy ³⁾.

Solar trackers are devices in PV and CSP installations that orient panels or mirrors to follow the sun's path, enhancing power output by up to 40% compared to fixed-tilt mounts ⁴⁾. Trackers adjust panels to the sunlight's changing angles, maximizing direct and diffuse irradiance capture throughout the year. Single-axis trackers follow the sun's east-west arc, while dual-axis trackers also adjust for seasonal shifts, optimizing energy yield by maintaining orthogonal alignment with incident rays. This technology increases annual energy production, reduces the levelized cost of energy, and allows for higher density panel arrangements by eliminating interrow shading. Trackers are crucial for maximizing return on investment and competitiveness in renewable energy, making solar projects more bankable. They play an essential role in optimizing yields, reducing solar electricity prices, and are considered indispensable for modern solar facilities to harness the sun's energy cost-effectively. Solar trackers are key to the industry's future and the global solar power expansion to terawatt-scale.

Over time, researchers have been able to increase the accuracy of solar trackers designed to increase the efficiency of solar panels, thanks to advances in computer technology.

The reliance of solar trackers on sunlight to determine the direction of movement may be one of the reasons for low tracking accuracy when the weather is not clear. Many solar trackers use light sensors to track the sun, so the less light that shines on these sensors, the less accurate the tracking will be.

In this research, the aim was to find a method for tracking the sun that is not affected by any weather factors. Therefore, the optical sensors that are usually used to track the sun and that are affected by weather factors will be dispensed. This research also aims to contribute to the development of sun tracking systems and increase the accuracy of tracking. Another aim of this research is to open people's eyes to solar trackers as a comprehensive solution to the problems of solar panels.

2. Background and history

2.1 Development of solar trackers

The genesis of solar trackers traces back to John Ericsson in the 19th century, who designed a sun-powered engine ⁵⁾. This innovation spurred further development in solar energy technologies, laying the foundation for solar tracking mechanisms. Significant advancements occurred from the early 20th century, culminating in the 1950s with the first patents for sun-following devices. The pivotal development of mechanical solar trackers began with Finster in 1962, which evolved into more sophisticated systems through subsequent enhancements and the integration of digital technologies ⁶⁾. The 1960s and 1970s saw further innovations, notably influenced by space research and the advent of computerized control, leading to the creation of automatic solar tracking systems. These systems, refined over time, now effectively optimize panel orientation to maximize energy capture, demonstrating the critical role of solar trackers in the renewable energy landscape.

^{*1} Master's Program, Department of Electrical and Electronic Engineering, Graduate School of Engineering

^{*2} Professor, Department of Electrical and Electronic Engineering, Faculty of Engineering

2.2 Basic principles

Solar trackers increase energy absorption and yields by continuously orienting PV panels or mirrors to face the sun directly, minimizing angle-of-incidence optical losses. They operate on the sun's predictable motions, adjusting panels in one or two axes to stay perpendicular to incoming irradiation. Single-axis trackers follow the sun's east-west path, while dual-axis trackers also adjust for the sun's seasonal elevation changes. The trackers' operation relies on precise tracking through photosensors and astronomical computations, with system automation and high-torque motors enhancing pointing accuracy and platform stability. Modern trackers use programmable logic controllers and closed-loop feedback for autonomous monitoring and alignment, incorporating smart features to increase reliability and reduce component counts.

2.3 Components and design

Solar trackers consist of mechanical, electronic and software components that work together to follow the sun. Core components include photosensors for light detection, programmable logic controllers for data processing, and slew drives and gearboxes for precise mechanical motion. Structural design choices, such as materials and load optimization, affect durability and efficiency. Advanced technologies in trackers allow for remote diagnostics and predictive maintenance, leveraging cloud computing and machine learning to enhance reliability and optimize performance.

2.4 Integration with solar panels

Trackers provide the structural support for PV panels and control their orientation to maximize solar irradiation capture. Integration involves mechanical linkages for support and electrical connections for power transmission. Designs accommodate various panel sizes and shapes, with electrical connectivity ensuring seamless power flow. Utility-scale plants may use microinverters for distributed power optimization and remote controllability for efficient operation and protection against severe weather. Trackers enhance the electrical and mechanical foundations of solar installations, contributing to global solar proliferation by maximizing the energy capture from natural daily sunlight cycles.

2.5 Benefits of solar trackers

Solar trackers enhance solar panel energy output by continuously orienting panels towards the sun, reducing losses and maximizing irradiation absorption. These devices can increase energy collection by up to 40% annually, with single-axis trackers boosting productivity by 25-30% and dual-axis trackers adding an additional 3-8% to yields⁴⁾. This efficiency is particularly beneficial in densely packed urban areas, where self-shading losses can significantly reduce energy generation. Trackers enable panels to capture sunlight from low angles, increasing productivity by mitigating mutual shading.

The implementation of solar trackers results in a 25-40+% increase in clean energy production yearly compared to stationary panels. This efficiency makes trackers critical for optimizing land use in solar projects, especially in locations

with limited space or suboptimal solar exposure. By allowing more compact spacing between panels, trackers enhance the total energy density of an area, enabling the generation of more megawatts per acre. Their adaptability also makes previously unsuitable sites viable for solar energy generation, supporting the global shift towards multi-terawatt solar capacity and contributing significantly to achieving sustainability goals.

3. Method

3.1 Equations used to find the position of the sun

The sun's position can be determined using two coordinates of azimuth and elevation. The solar azimuth represents the direction of the sun along the horizontal plane. The solar altitude represents the height of the sun in the sky. For every coordinate, there is an equation that enables us to calculate it, but we also need to compensate for some variables in each equation.

First, there are six essential variables that we need to find:

1. Local solar time (*LST*); Adjusts the local time to consider the longitudinal position concerning the standard time longitude.

$$LST = LT + \frac{TC}{60}, \quad (1)$$

where *LT* refers to local time and *TC* refers to time correction factor.

2. Local standard longitude (*LSTM*); The reference longitude for standard time zones.

$$LSTM = 15^\circ \cdot \Delta T_{GMT}, \quad (2)$$

where ΔT_{GMT} is the difference of the local time (*LT*) from Greenwich mean time (*GMT*) in hours.

3. Equation of time (*EoT*); Represents the discrepancy between solar time and clock time.

$$EoT = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B), \quad (3)$$

where *B* represents the Earth's orbital position as an angle, which is used in further calculations to correct solar time for the eccentricity of the Earth's orbit. We can calculate *B* by a following equation.

$$B = \frac{360}{365}(d - 81). \quad (4)$$

In this calculation, *d* is the number of days since the start of the year.

4. Time correction factor (*TC*); Adjusts the time equation and the difference between local and standard time longitudes.

$$TC = 4(Longitude - LSTM) + EoT. \quad (5)$$

The factor of 4 minutes comes from the fact that the Earth rotates 1° every 4 minutes.

5. Solar declination (δ); The angle between the sun and the equator.

$$\delta = 23.45^\circ \sin \left[\left(\frac{360}{365} \right) (d - 81) \right]. \quad (6)$$

6. Hour angle (HRA); The sun's position relative to its highest point in the sky.

$$HRA = 15^\circ (LST - 12). \quad (7)$$

The sun's position equations have been used from the PV Education website⁽⁷⁾. After finding the six variables, the solar elevation equation has been used, which calculates the sun's height in the sky. It uses the observer's latitude, the sun's declination, and the hour angle to find the sun's vertical angle above the horizon.

7. Solar elevation (Solar altitude α); The sun's angular height in the sky as measured from the horizon. We can calculate the solar elevation by using the equation:

$$\alpha = \sin^{-1}[\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos(HRA)], \quad (8)$$

where φ is the latitude of the observer's position, while (HRA) is the sun's position relative to its highest point in the sky. The equation can be simplified by using the zenith angle, but found first by using the equation:

$$\zeta = \cos^{-1}[\sin \varphi \sin \delta + \cos \varphi \cos \delta \cos(HRA)]. \quad (9)$$

After finding the zenith angle, the simplified solar elevation is:

$$\alpha = 90^\circ - \zeta. \quad (10)$$

8. Solar Azimuth; The angle of inclination of solar radiation from the geographical north.

$$\text{Azimuth} = \cos^{-1} \left[\frac{\sin \delta \cos \varphi - \cos \delta \sin \varphi \cos(HRA)}{\cos \alpha} \right]. \quad (11)$$

The sun's exact position concerning the device's location has been found by using these equations. These equations are going to be calculated by the device once every second, so the device is going to update the sun coordinates every second for more accuracy.

3.2 Hardware

The equipment used in this research is divided into two sections according to use. The first section is for the equipment in the tracking device, and the second section is for

the measuring device. Fig.1 shows the system configuration, where the solar tracker is represented by green, and the measuring device represented by blue.

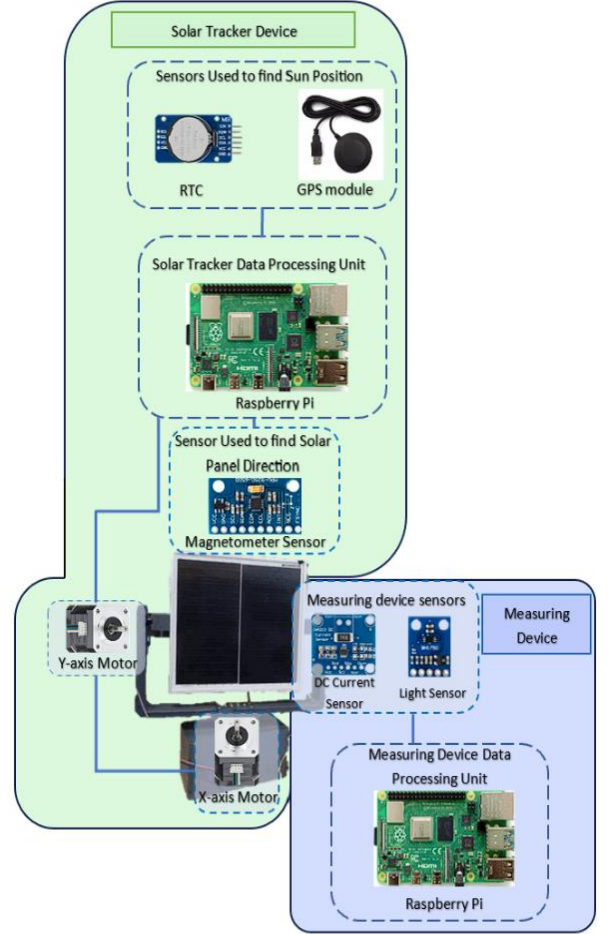


Fig.1 System configuration.

3.2.1 Tracking device equipment

The basic equipment includes a solar panel (dimensions: L277×H264×W17 mm, output: 12W, 18.8V, 0.64A) and Raspberry Pi 4. The device needs to find several variables throughout the tracking period, some of which are used to find the sun's position, and others are used to direct the device in the sun's direction.

3.2.1.1 Equipment used to find the position of the sun

The local time, latitude and longitude are variables that the device needs to find the position of the sun, and to find them, these sensors have been used:

- Real-time clock (RTC) finds the real-time at the device's location as well as the time range of the device's location.
- GPS Module finds the longitude and latitude of the device's location. Using GPS as a sensor responsible for directing the solar panel to the direct position of the sun represents a solution that contributes to avoiding any external influences that may affect tracking accuracy. Unlike the tracking method that is used in this research, the tracking methods that are usually utilized rely on optical sensors, the accuracy of which is affected by surrounding factors. Covering the

optical sensor with the shadow of nearby objects causes the device to point in the wrong direction. This drawback makes optical sensor tracking methods unsuitable for mobile devices. On the other hand, external factors do not affect the GPS tracking device, as it does not depend on the light directed at it to track the sun.

After finding these variables, the sun's position can be found using the equations in the above chapter of equations used to find the sun's position.

3.2.1.2 Equipment used to find the orientation of a solar panel

After finding the position of the sun (azimuth and elevation), we need to find the current direction of the solar panel, for that we used:

- Magnetometer (mpu 9250) is a 9-axis motion tracker that combines a 3-axis gyroscope, 3-axis accelerometer, 3-axis magnetometer, and a digital motion processor (DMP). The (mpu 9250) sensor has been installed on the solar panel and used to find the inclination angle and direction of the solar panel.

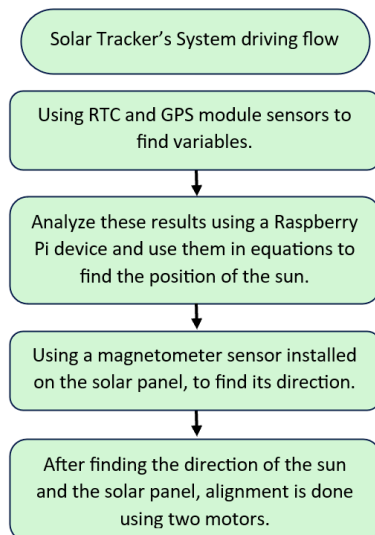


Fig.2 Solar tracker's driving system flow.

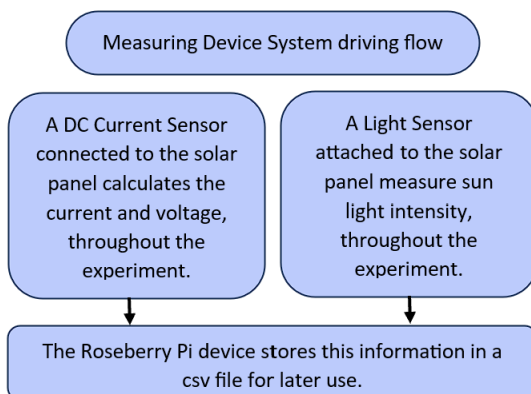


Fig.3 Measuring device's driving system flow.

3.2.1.3 Tools used to direct the device towards the sun

After knowing the position of the sun (azimuth and elevation), as well as the direction of the solar panel, represented by the direction of the solar panel and the angle of inclination, it remains for us to direct the solar panel toward the sun. To do this, the has been used is:

- Two Stepper Motors (Nema 17) convert electrical pulses into precise mechanical movement so that the rotating part of the motor rotates in intermittent steps and depends on the electrical pulses applied to the motor. Fig.2 shows the driving system flow of the solar tracker device.

3.2.2 Measuring device equipment

After completing the tracking device, to collect comprehensive information about the change in energy extracted by the solar tracker throughout the experiment, as well as the change in the intensity of the sun's brightness during that period, a measuring device has been created. In the measuring device, the parts that have been used:

- Raspberry Pi 4,
- Current shunt and power monitor (INA219), the power monitor sensor module can calculate the power from a solar panel up to 26V and 2.3A,
- Light intensity sensor (BH1750),
- 50W 30Ω Resistance.

The sensors were connected to the Raspberry Pi and then a wire from the solar panel were connected to the sensor (INA219). In addition, the light intensity sensor (BH1750) was installed on the solar panel. The light sensor has been added to the measuring device to calculate the amount of sunlight shining on the solar panel throughout the experiment, which represents an additional step to ensure the accuracy of the results. Fig.3 shows the driving system flow of the measuring device.

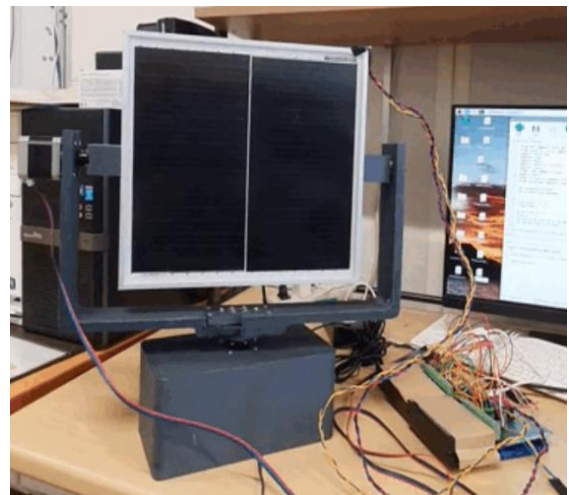


Fig.4 Overview of the manufactured solar tracker.

3.3 Device design

In this research, several designs of solar trackers were made that use dual motors to direct solar panels. The device parts were printed using a Creality ender-3 S1 printer and PLA

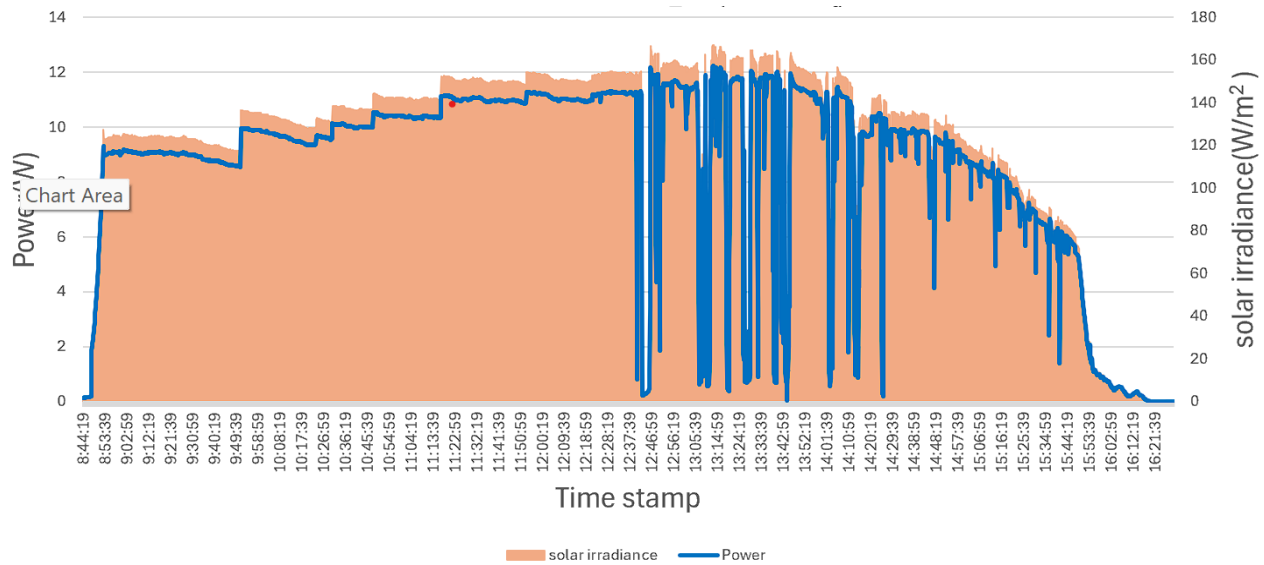


Fig.5 Solar Panel's Power Output and Solar Irradiation.

filament. This printer has a printing area of 220*220*270mm (L*W*H). The device will carry a solar panel with dimensions of 277×264×17 (L×H×W) mm, so in order to maintain the balance of the device, two arms was designed to carry the solar panel, and one of these arms has the motor responsible for changing the inclination of the solar panel added to it as shown in Fig.4.

4. Results

The speed of alignment when operating the tracking device depends on the extent to which the direction of the device differs from its direction to the sun, but after directing the device in the direction of the sun, it can then continue to track the sun smoothly. The tracking device was placed on the roof of a tall building (the Shonan campus's first building, Tokai University) so that the surrounding buildings did not block sunlight. The sun's position can be found using two coordinates: angular elevation (altitude) and azimuth. The sun direction coordinates obtained by the tracking device have been compared with the actual sun direction coordinates, which can be found through websites specialized in calculating the sun direction. After comparing them, it became clear that the coordinates calculated by the tracking device were similar to those shown by the sites. As for the theoretical results that have been obtained after testing the tracking device on the ground, it has been noticed that the device tracks the position of the sun well enough so that the solar panel remains facing the sun. After experimenting with the solar tracker from 8:45 a.m. to 4:30 p.m. with the solar panel connected to the measuring device, the solar panel's outputs have been measured throughout the experiment. The measuring device can find the voltage and current of the solar panel, as well as the brightness of the sun. The measuring device generates these three outputs every ten seconds during the experiment and then saves them as a CSV file that can be used later in

Fig.5 explains the relationship between the energy coming out of the solar panel, which we found by multiplying voltage and current, represented in blue, and the solar irradiation, represented in orange. The figure shows the change in the solar panel's power output and the change in solar irradiation throughout the experiment. The solar panel rated at 12W has been used in the experiments. As solar irradiation increases, the solar panels' outputs increase. The experiment can be divided into two periods that can be observed in Fig.5. In the first period, which begins with the beginning of the experiment until 12:30, the weather was clear, so the tracking device maintained high outputs, as represented by the voltage table between 16.5V and 18.8V, which is the largest output for the solar panel that have been used. As for the second period of the experiment, which started from 12:30 until near the end of the experiment, the sky was covered with clouds that blocked the sunlight for specific periods, so sharp declines in the intensity of the sun's brightness could be observed, as well as in the outputs of the solar panel of current, voltage, and power.

The output from a solar panel is highest when the panel is perpendicular to the sun; that is, the azimuth angle and the elevation angle of the device are the same as the sun's angles. In this experiment, the tracking device has been adjusted so that there are 10 degrees of error in the alignment of the azimuth angle as well as the elevation angle in order to reduce the unnecessary movement that the device makes to track sunlight and reduce the energy used in tracking. This thing can be observed in the first period of the experiment. In the first period of the experiment, it can be observed in Fig.5 that there is a gradual pattern in the increase of the solar panel's outputs. This is because the tracking device realigns with the sun once

there is a ten-degree difference between the azimuth angle of the device and the azimuth angle of the sun, as well as the elevation angle.

5. Conclusion

The research goal was to invent a sun-tracking device based on a new tracking technology that increases solar-tracking efficiency and reduces the cost of tracking. One of the reasons that reduces the efficiency of most solar trackers is their reliance on optical sensors to track the sun. Therefore, when the sun's radiation weakens, this causes poor tracking accuracy. When creating the tracking device, avoiding using any sensor whose accuracy might be affected by weather factors was important in order to maintain the accuracy of the device's tracking under any condition.

In this research, an idea of a new tracking device that would increase tracking accuracy has been proposed and implemented. The strength of this device is that it is not affected by weather factors. The question now is whether there is a significant difference in the solar panel outputs when tracking the sun when the weather is cloudy. If there is a difference, it may be small, but more importantly, continuing to innovate new methods of tracking the sun will contribute to the cost of its production and highlight it as an approved solution to increase the efficiency of solar panels. Innovation in the field of solar trackers also drives technological progress in the field of renewable energy in general, opening the door to new discoveries and applications that may be useful in other fields.

After completing the device experiment, it has been

noticed that the angle of error that has been included in the programming of the device may be significant. The error angle that has been set to the device is estimated at 10 degrees, and this caused a slight difference in the solar panel outputs, as can be observed in Fig.5. One of the suggestions whose effect could be studied might be to reduce the degree of error so that the device can maintain the highest outputs that the power board can produce throughout the experiment without any decrease, even if it is slight. It can be determined whether it is feasible to reduce the degree of error in the device by comparing the power output concerning the power consumed to track the sun.

References

- 1) Gromicko, N. Advantages of solar energy. International Association of Certified Home Inspectors.(2023) <https://www.nachi.org/advantages-solar-energy.htm>
- 2) International Energy Agency. Solar PV. (2023) <https://www.iea.org/energy-system/renewables/solar-pv>
- 3) Hemetsberger, W., Schmela, M., & Cruz-Capellan, T. Global market outlook for solar power 2023-2027. (2023)SolarPower Europe.
- 4) Oriaifo, A. P., & Akahomen, I. E. Performance evaluation of a PV solar tracker panel. NIPES Journal of Science and Technology Research, 4(4), 107-121. (2022)
- 5) Saurabh, A., Atheaya, D., & Kumar, A. Study of hybrid photovoltaic thermal systems. IOP Conference Series: Materials Science and Engineering, 748(1), 1-7. (2020)
- 6) Nsengiyumva, W., Chen, S. G., Hu, L., & Chen, X. Recent advancements and challenges in solar tracking systems (STS): A review. Renewable and Sustainable Energy Reviews, 81(Part 1), 250-279. (2018) <https://doi.org/10.1016/j.rser.2017.06.085>