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Intelligent Solar Tracker Designed to Optimize Photovoltaic Yield in Burundi

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Abstract

This research project concerns the development of an intelligent solar tracker designed to optimize the yield of photovoltaic systems in Burundi, one of the countries in the equatorial region, characterized by high variability in solar irradiation due to clouds, humidity and limited seasonal variations. During the day, the earth rotates around the sun continuously. Most photovoltaic generator installations are fixed, thus losing a considerable amount of energy, which could be available because the solar rays are not always perpendicular to the fixed solar panel. The aim of this paper is to design an automatically controlled device, using position and irradiance sensors, combined with a maximum power point tracking (MPPT) algorithm, to dynamically orientated the solar panels to capture the optimum amount of sunlight. Today's solar tracking systems differ from designer to designer and in the technology used to ensure good performance, high accuracy and a reliable, low-cost system. The solar tracker orientation technique in our study is based on an active method using two light sensors with photo-resistors placed in a crisscross pattern, which receive solar radiation and thus generate photoelectric control signals to a servomotor in azimuth. The method also involves capturing the current time and date using a real time clock RTC 3231 to control the second servomotor in East to West. The electronic control board is an Arduino UNO microcontroller, and the system studied enables intelligent management of energy consumption to minimize the tracker's self-consumption. The study includes modelling, mechanical design and programming using MATLAB 2020a, Proteus 8.13, Arduino IDE and SolidWorks 2023 software. The simulation results validate the experimental results. The energy gain of the single-axis solar tracker compared with the fixed solar panel varies between 29% and 41%. The energy gain of the dual-axis solar tracker compared with the fixed solar panel varies between 42% and 50%. The results show a significant improvement in photovoltaic electricity production, contributing to energy security and the energy transition in equatorial zones.

Keywords

Battery Management System, Solar Tracker, Solar Panel, Photovoltaic Yield, Control Algorithm

1. Introduction

The global energy transition is increasingly based on renewable energies, in particular photovoltaic solar energy, because of its abundance, modularity and low environmental impact. For a long time now, man has understood the benefits of exploiting renewable energy sources for providing the electricity the world needs. The electricity is one of the pillars for all income-generating activities. Discovered by the physicist Henri Becquerel in 1839, the principle of photovoltaic energy involves transforming sunlight into electrical energy [1]. A number of studies have been carried out to optimize the solar energy produced by a fixed solar panel in response to climate change. [2] has carried out a comparative study of several Maximum Power Point Tracker (MPPT) control techniques, including: the most widely used classical P&O (Perturbation and Observation) method; intelligent meta-heuristic methods; PSO (Particle Swarm Optimization) and GWO (Grey Wolf Optimization). Their simulation results show that the PSO technique gives the best performance compared with the other methods. Author [3] in his study develops a model based on the adaptive neuro-fuzzy inference system (ANFIS). This technique combines the advantages of P&O-MPPT to take account of slow and rapid variations in solar irradiation. [4]-[6] show the effect of tilting the solar panel to an optimum angle for optimizing the energy captured in Senegal, Ethiopia and Burundi. Researchers into the optimization of photovoltaic efficiency have launched research into solar tracking systems. Studies of [7]-[12] reveal that solar tracking systems generally offer an improvement of more than 15% to 40% in energy yield compared with fixed photovoltaic panels in USA, China, Ouargla, Vietnam, Colombia and Malasia. [13]-[16] show the gains of solar trackers. A gain of 40% of the solar tracker by double axis compared to the fixed panel is found in Türkiye, a gain of 22% to 56% of solar tracker in Romania and a gain of 24.7% compared to a fixed angle of inclination of 45˚ is found in Trabzon. Simulations of single-axis tracking systems are less accurate, however, with the 2D view factor and 3D ray tracing being approximately 2% and 1% of the bifacial gain measured in Denmark, respectively [17].

[18] shows the gain of a heliostat dual-axis sun tracking system in Dhahran. Results of [19] show an increase of 9.87% in the energy obtained with the solar tracker compared to a static solar panel oriented optimally. For [20] using solar

tracking systems is complex and expensive, but we can have the same amount of energy with fewer solar modules than with fixed systems in Iran. For [21], the rate of energy increase relative to the fixed PV module is 22.45% and 25.86% respectively for cloudy and sunny skies in Cameroon. For [22], the first applications of solar trackers began in 1750. He has developed a solar tracker using four LDR light sensors that can faithfully follow the position of the sun in Algeria. In regions with an equatorial climate, characterised by almost constant daylight throughout the year, high temperature and high humidity, the availability of sunshine is disrupted by heavy cloud cover and the daily variability of weather conditions. An in-depth simulation of a dual-axis tracking mechanism was carried out by [23], confirming the significant improvement in energy efficiency and the relevance of an equatorial/polar design. According to [24], the use of a bi-axial solar tracker in the equatorial region can increase solar energy capture with net gains of 31.8% and 37.0%, by ensuring optimal orientation of the panels throughout the day and year. Like these other authors who have already carried out research on solar trackers, we note a loss of energy from fixed panels when the sun's rays are not emitted perpendicular to the solar panel during the day. Compared with existing studies, we note a loss of energy due to motor consumption, as these systems reposition the solar panel at any time, even in the event of very low sunlight levels. Hypothesis 1: The integration of a dual-axis or single axis solar tracker significantly increases the energy yield of photovoltaic panels compared with an installation with a fixed solar panel. Hypothesis 2: The use of an intelligent control algorithm (Arduino, microcontroller) improves tracking accuracy and reduces losses due to shading and inappropriate orientation.

The aim of this project is to design and produce a system that can track the sun's rays perpendicular to the solar panel in order to optimize the photovoltaic efficiency of the Burundi. In our project, we will demonstrate our novelty in relation to studies already carried out by developing a control algorithm for the solar tracker, enabling the solar panel to be rotated at an angle of 3 degrees every 12 minutes. We will design and simulate the solar tracker control algorithm. We will study the energy gains of the solar tracker compared with the optimized fixed solar panel.

2. Method and Materials

In this section, we will develop the methodology. Several solar tracker techniques exist, including the single-axis solar tracker and the dual-axis tracker [22]. In this study, we will use the single-axis sun tracker and the two-axis sun tracker. We will determine the sun's trajectory in Burundi and in the region throughout the year. In this section, we will develop a solar tracking algorithm applicable to the region. For the rotation of the panel in azimuth, the method consists of developing a control algorithm for the solar tracker based on Light Dependent Resistor sensor (LDR) to rotate the panel from North to South and vice versa. This method is based on the difference in incident illuminance of Light-Dependent-Resistor

(LDR) light sensors separated by opaque walls and placed on the PV panel. These walls form a shaded angle of 3˚ on the light sensors, corresponding to a 12-minute displacement of the sun's rays. For the rotation of the panel in elevation, the technique also involves developing a control algorithm for the solar tracker based on the RTC3231 module, which will give the current time for the panel to be repositioned from East to West after 12 minutes. The Arduino UNO microcontroller is a control and command circuit, which compares the signals emitted by the LDR sensors by calculating their differences or reading the current time, then sends pulses to the two servomotors to reposition the solar panel at an angle of 3˚. The control circuit will be created using Proteus Professional 8.10.SP3 software, and the behaviour of the solar tracker will be designed using MATLAB 2020a software. MATLAB (Matrix Laboratory) is a matrix calculation program with a "simple" syntax (compared with advanced languages such as C and C++). It is used in scientific calculations and engineering problems because it allows complex numerical problems to be solved in less time [25]. To compare the energy gains of the solar tracker with a fixed solar panel, the method consists of optimizing a fixed solar panel by determining the optimal tilt angle of the fixed solar panel. [6] describes the method for optimizing the fixed solar panel and gives us the equation for the model used to determine the optimal angle of inclination of the fixed panel at Burundi:

$$\beta = 0.939\lambda + 11.079 \quad [6] \tag{1}$$

where, β is optimum yearly tilt of inclination (in ˚), λ is latitude of the site (in ˚S)

The trajectory of the sun will be obtained using the sunEarthtools software [26]. The mechanical design, 3D modelling and simulation of the solar tracker under study will be carried out using SolidWorks, a computer-aided design (CAD) software package developed by Dassault systems [27].

2.1. Control Algorithm for the Dual-Axis Solar Tracker

In this step, we will develop the control algorithm for the solar tracker. In this algorithm:

- V_LDR North designates the voltage of the light sensor in the North;
- V_LDR South refers to the light sensor voltage at South;
- Vs refers to the light sensor threshold voltage;
- Tol2 is the potential difference between the North and South light sensor voltages;
- Tol1 designates the potential difference between the voltage of the South light sensor and the North light sensor.

Figure 1 illustrates the control algorithm developed for the solar tracker.

2.2. Block Diagram

The system configuration diagram includes an Arduino UNO microcontroller, a real-time clock RTC 3231, two light sensors, two servomotors and a solar panel. **Figure 2** illustrates the configuration of the solar tracking system studied. It includes the main components for building the solar tracker.

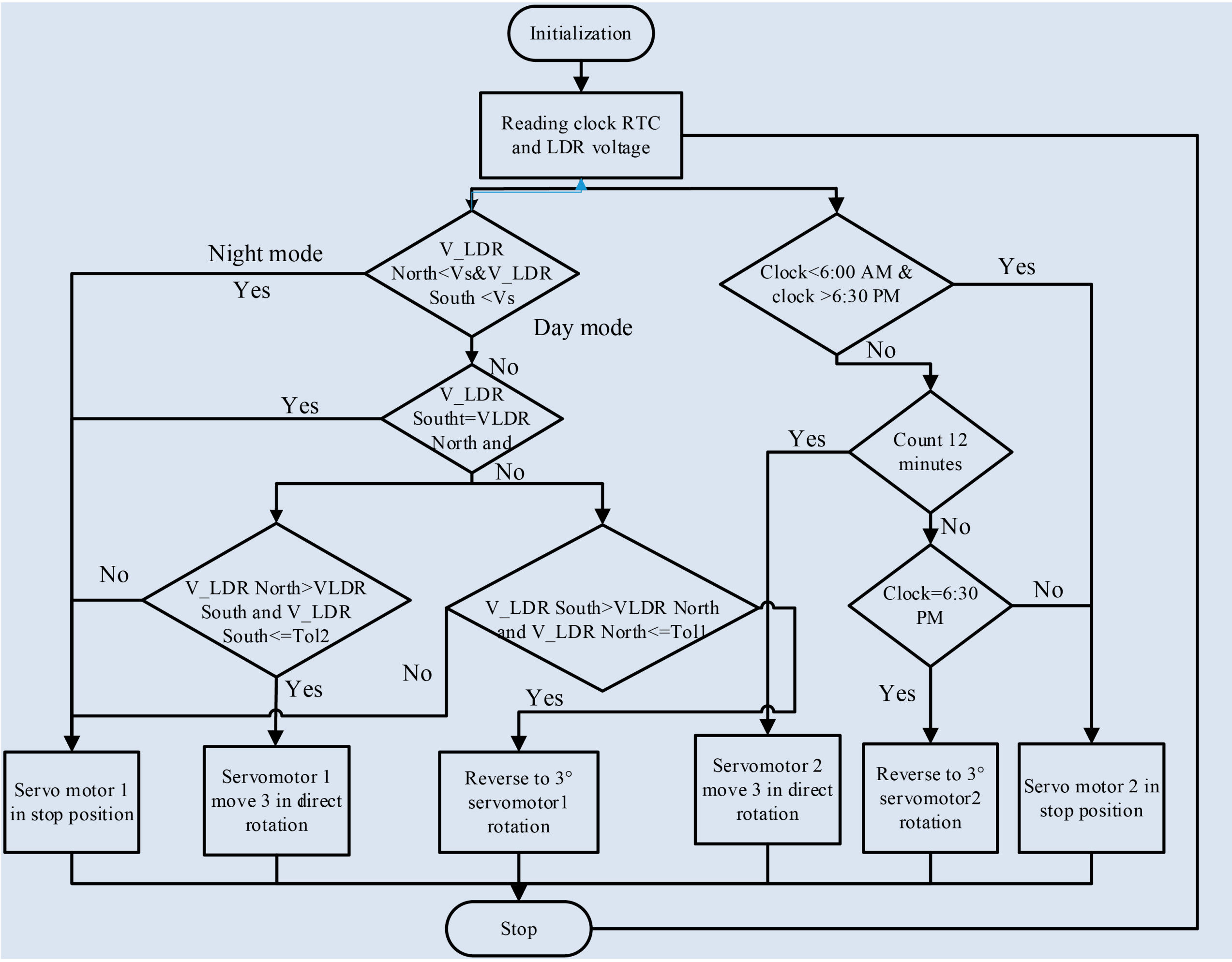


Figure 1. Control algorithm for the developed dual-axis solar tracker.

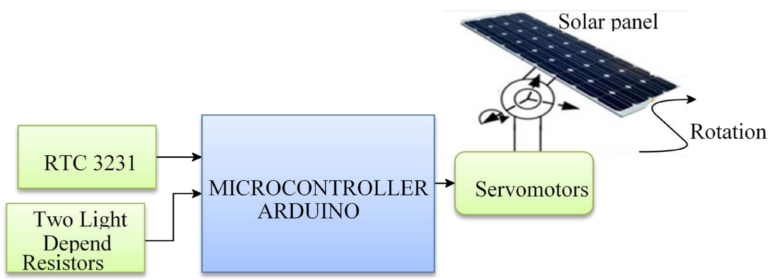


Figure 2. Block diagram of the configuration of the solar tracking system.

2.2.1. Solar Panel

A solar panel is a device that converts sunlight into electricity using photovoltaic (PV) cells. Photovoltaic cells are made of materials that produce excited electrons when exposed to light. The electrons circulate in a circuit, producing a direct current (DC) that can be used to power various devices or stored in batteries. Under the effect of the electric field, the electron goes to the N side and the hole to the P side. The holes behave, in different ways, like particles with a positive charge equal to that of the electron. The potential difference can be measured between the positive and negative terminals of the cell. The maximum cell voltage is approximately 0.6 V at zero current [28].

2.2.2. Light-Dependent Resistor Sensor

The Light Depend Resistor sensor is a variable-resistance component used to measure light intensity. It gives the intensity value as an electrical signal to the microcontroller to control servomotors to reposition the solar panel in relation to the sun's rays. LDRs are made of semiconductors, and this material is sensitive to light. The LDR's sensitivity depends on the light falling on its surface, and this will have an effect on the LDR's output signal sent to the microcontroller. Figure 3 shows how to measure the light sensor voltage.

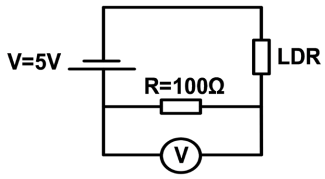


Figure 3. LDR voltage measurement method.

The voltage at the terminals of the LDR is obtained by the law of meshes,

$$U_{-LDR} = V - U_R \tag{2}$$

Figure 4 illustrates the layout of the LDR sensors. Here "ε" is the angle of the solar shadow. "ε" is a function of the height "H" of the wall and the distance "d" separating it from the collector; "ε" is the threshold angle or threshold of the solar shadow.

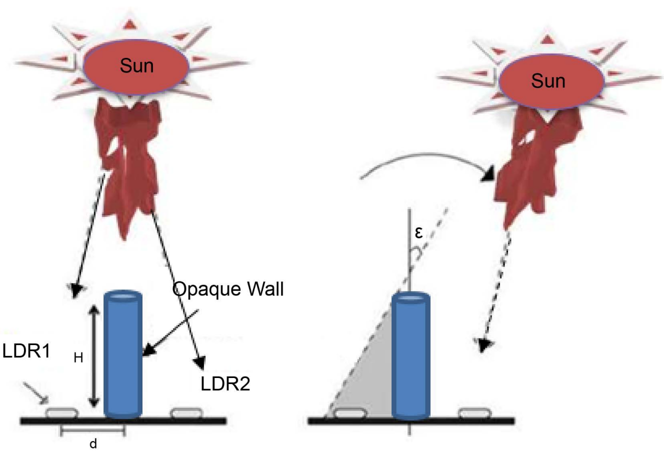


Figure 4. Layout of the LDR sensors.

2.2.3. Real Time Clock

Real Time Clock (RTC) is used to track the current time and date. It is generally used on computers, laptops, mobiles, embedded system applications devices, etc. In many embedded systems, we need to put a time stamp while logging data, *i.e.* sensor values, GPS coordinates, etc. It needs to be further programmed to track the path of the sun. In our study, we will use Real Time Clock RTC3231.

2.2.4. Arduino Uno

The microcontroller is a microprocessor-type information processing unit to which internal peripherals have been added to facilitate interfacing with the outside world without the need for external components. With the Arduino board, we can write programs, create interface circuits and develop algorithms to control switches, sensors and so on.

2.2.5. Servo Motor

A servomotor is a linear or rotary actuator that provides fast, precise position control for closed-loop control applications. Motor speed is proportional to the difference between actual and desired position. In digital control applications, a microcontroller is used to generate PWM pulses in terms of duty cycles to produce more precise control signals.

The servomotor's electrical equation is given by:

$$u(t) = k\omega(t) + Ri(t) + L\frac{di(t)}{dt} \quad [29] \tag{3}$$

where: k is the constant constriction of the servomotor, ω is the angular velocity (in rad/sec), R is the resistance in Ohm, i(t) is the armature current (in A), L is the inductance from the armature winding (in H).

The angle of rotation of the solar panel is found from the equation of motion given by the following expression:

$$J\frac{d\omega t}{dt} = T - T_r - f\omega(t) \quad [29]$$

where: T is the driving torque supplied by the rotor in N·m, Tr is the resistive torque in N·m, $f \cdot \omega(t)$ is the coefficient of viscous friction, J is the moment of inertia of the solar panel in kg·m^2. In our study, we will use MG996R servomotor with

- stall torque: 9.4 kgf·cm (4.8 V), 11 kgf·cm (6 V), weight: 55 g.
- Operation speed: 0.17 s/60˚ (4.8 V), 0.14 s/60˚ (6 V).
- Operating voltage: 4.8 V to 7.2 V.
- Running current: 500 Ma.
- Weight: 55 g.
- Dimension: 40.7 × 19.7 × 42.9 mm.

2.3. Charge Controller MPPT

Charge Controller MPPT prevents overcharging and excessive discharging of the battery. In the case of lead-acid batteries, overcharging is prevented by charging the batteries in three stages (bulk, absorption, or boost and float). It helps to optimize the solar energy produced by a fixed solar panel in response to climate change using MPPT technologies. In our study, as we used a small 1.2Wp solar panel with a 6 V voltage that can be rotated with a small MG996R servomotor, MPPT controller is not used in experimental prototype for the fixed solar panel and the solar tracker. We missed out a small controller MPPT 5 V/0.5 A.

2.4. Anemometer

The anemometer is a sensor that records the wind speed at the installation site in real time. This data is sent to the solar tracker controller (often via a microcontroller). In our study of the solar tracker system, in the event of strong winds, the anemometer plays an essential protection and safety role rather than a direct role in energy optimization.

2.5. Limitations of the Study

Like all applied scientific research, the study has its limitations:

2.5.1. Technical Limitations

The model studied is generally validated in simulation and on experimental prototype and may not reflect all real conditions (dust, rain, strong wind, corrosion).

2.5.2. Economic Limit

The study does not always take into account the real cost of the complete system (import, taxes, maintenance).

2.5.3. Energy Limitation

Optimization is studied solely in terms of energy efficiency, without considering storage, distribution and network losses.

3. Results and Discussion

In this section, a design and simulation using MATLAB, SolidWorks, Proteus Professional and Arduino IDE software will be carried out, together with an experimental realization. The results will be discussed in relation to other research, to show our contribution to existing studies.

3.1. Simulation Results

We have begun to determine the trajectory of the sun in Burundi. **Figure 5** shows the trajectory of the sun using the sunEarthtools software.

We see that in April, August, March, September, February and October, the sun's trajectory is from east to west.

Let's design and simulate Equations (1) and (2) of the servomotor assembly and the solar panel movement using MATLAB software.

Figure 6 illustrates the control of the solar tracker at an angle of 3˚ using MATLAB software.

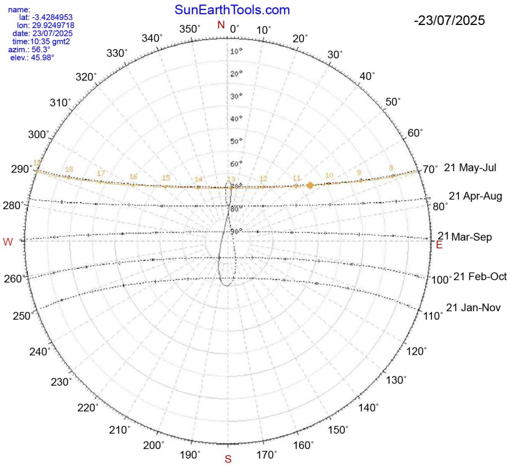


Figure 5. Trajectory of the sun in Burundi.

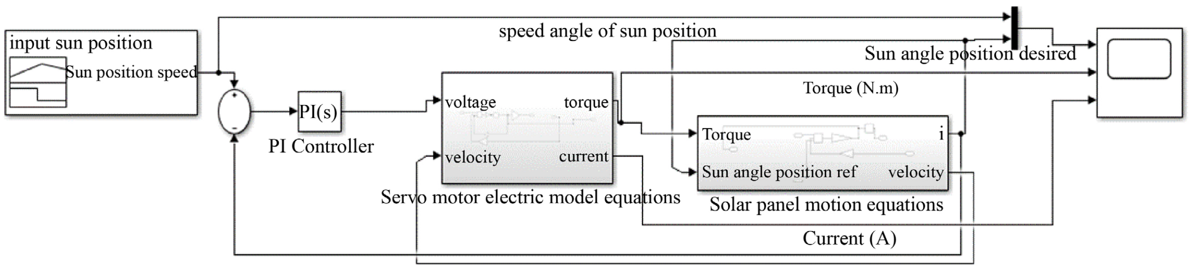


Figure 6. Control of the solar tracker at an angle of 3˚ using MATLAB software.

We entered three solar panel positioning angles at once: 3˚, 15˚ and −3˚ to evaluate the angles at which the solar panel could be positioned at the desired angle, and their effect on the servomotor's current consumption.

In Figure 7, the simulation results show that the angle at which the solar panel is repositioned follows the set value.

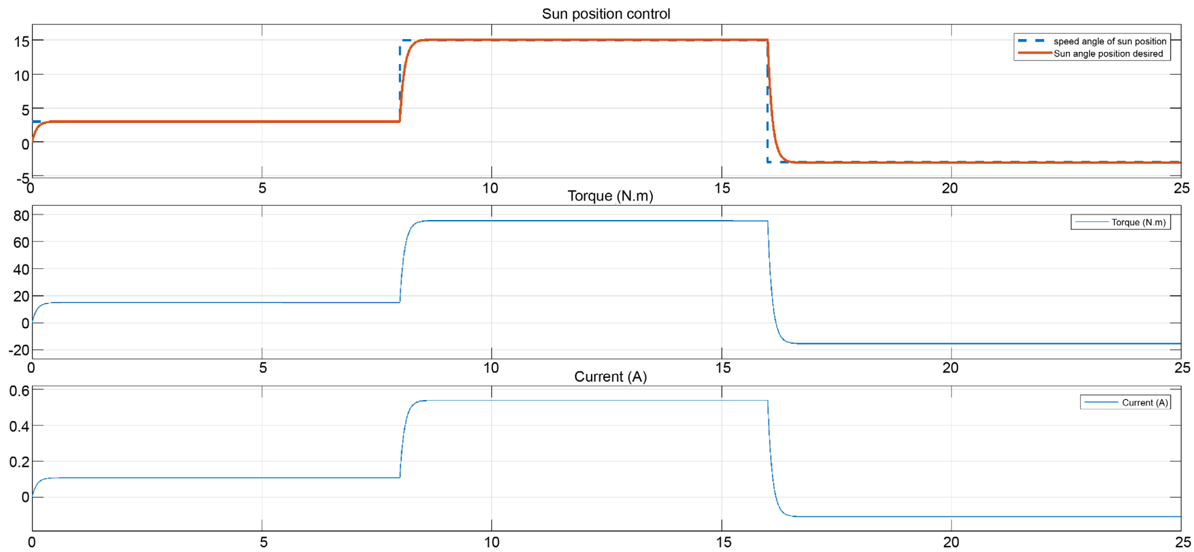


Figure 7. Tracking the solar panel at the desired angle.

In the interval [0, 8], for a positive input angle of 3˚, the solar panel is rotated by 3˚ in the direct direction of rotation of the servomotor. In the interval [16, 24], for a negative input angle of −3˚, the solar panel is also rotated by −3˚ in the opposite direction of rotation of the servomotor. We note that as the angle of rotation increases, so does the current and torque, demonstrating the energy savings in the consumption of the batteries powering the servomotors for our developed algorithm.

The developed dual-axis solar tracker algorithm using Proteus professional software and Arduino IDE software is designed and simulated. The schematic includes a power supply, two servomotors, the Real Time Clock RTC3231, an Arduino UNO board, two LDR light sensors and a display, are shown in Figure 8.

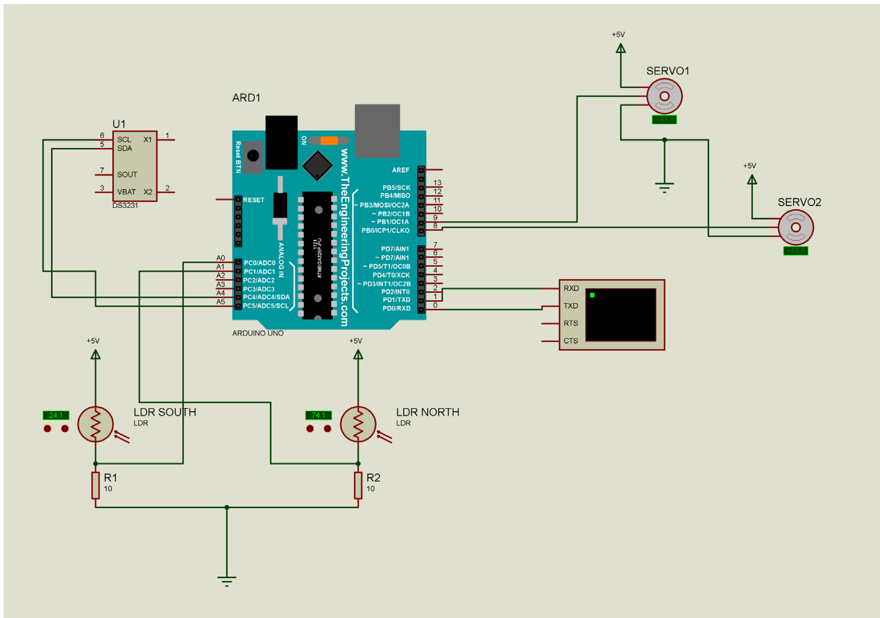


Figure 8. Schematic of the dual-axis solar tracker control circuit using Proteus Professional software.

According to the algorithm developed, the solar tracker changes the position of the solar panel every 12 minutes from 6:00 am to 6:00 pm. As this is a simulation that can last all day, we carried out a one-hour simulation test, *i.e.* positioning after 1 minute from 12:00 a.m. to 2:00 p.m. During the simulation, we took 1 minute because we did not want to wait the simulation since the moring (6:00 AM) until 6:30 PM. The simulation results are shown in Figure 9.

Figure 10 shows the messages from the algorithm developed, each time specifying the angle at which the solar panel is repositioned by 3˚ every 1 minute, and displaying the time and light sensor fluxes for each step.

In the first case, based on signals from the Real Time Clock RTC 3231 sensor, the simulation results obtained show that after 1 minute from 12 h (which in reality represents 6h in the morning), the Arduino microcontroller receives a signal from the Real Time Clock RTC3231 until 12h 58minutes. Through pin 9 of servo

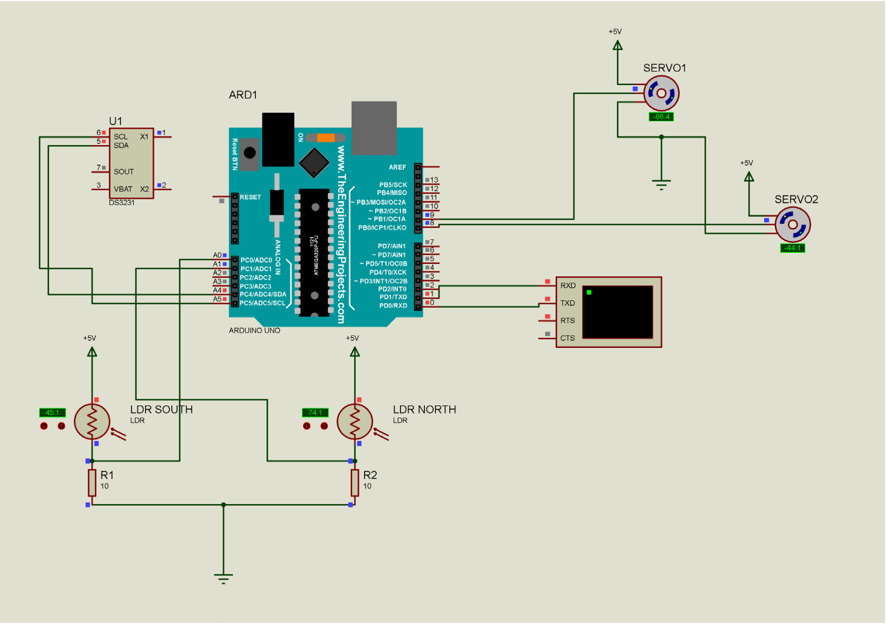


Figure 9. Servo motor1 in direct rotation from East to West and Servo motor2 in direct rotation from North to South.

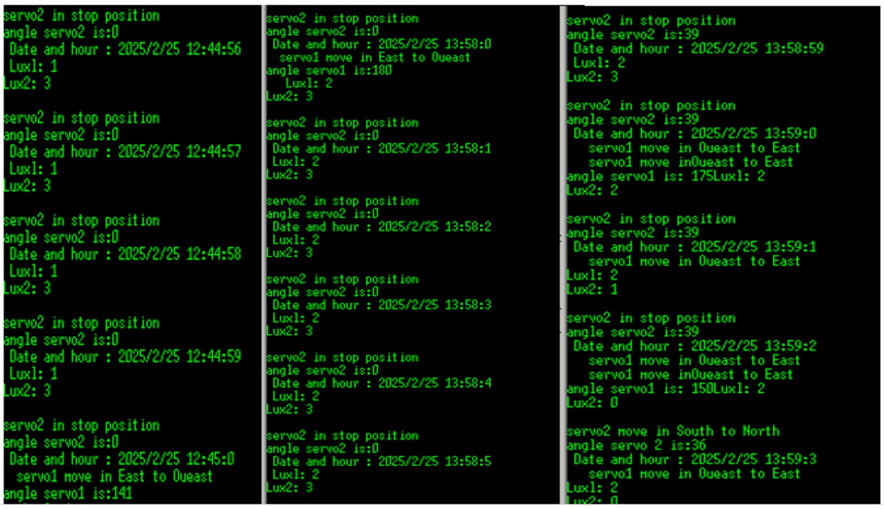


Figure 10. Display of the behaviour of the developed algorithm.

motor 1, the microcontroller sends a signal to servo motor 1 in elevation to reposition the solar panel at an angle of 3˚ from East to West after every 12 minutes. At 12 h 58 minutes (which is actually 18 h), servo motor1 completes 180˚ of rotation-rotation, corresponding to the 60 times the solar panel has been repositioned, and stops. At 12:59 (which is actually 18:30), the Arduino microcontroller receives a signal from the Real Time Clock RTC3231, which then sends a command to servo motor 1 to rotate the solar panel from West to East in the initial morning position.

Otherwise, servomotor 1 is in a fixed position. In the second case, based on the signals from the two light sensors (LDR), servomotor 2, which repositions the solar panel from north to south, is controlled according to the differences in illuminance from sensors LDR1 and LDR2. We note that if the voltage of one of the light sensors is greater than the voltage of the other light sensor, with tolerance, the Arduino microcontroller receives a signal from the LDR sensor via its analog inputs A0 and A1. The Arduino microcontroller converts the signal and then sends a command to pin 8 of servo motor 2 to reposition the solar panel from North to South if the voltage of the South light sensor is greater than the voltage of the North light sensor, and vice versa. We note that if the servo motor 2 remains in the off position, there is no great difference in illuminance. From the simulation results, we can see that the developed algorithm was able to track the sun's rays perpendicular to the solar panel at an angle of 3˚ every 12 minutes.

3.2. Mechanical Design and Modeling of the Solar Tracker

In this sub-section, the design and modelling using SolidWorks software is based on:

The main structure: this comprises a square frame fixed to the ground and a vertical support column that serves to pivot the azimuth rotation.

The solar panel

Azimuth axis

Two servomotors with internal gears that allow the solar panel to rotate horizontally or vertically to a desired angle.

Figure 11 shows the results of computer-aided design and modelling of the 3D model of the dual-axis solar tracker structure using SolidWorks software.

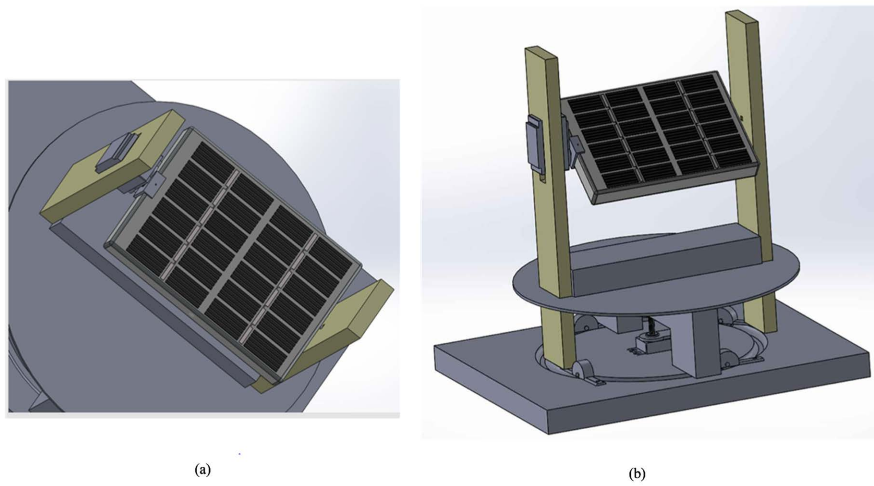


Figure 11. (a) Top view of the 3D dual-axis solar tracker structure and (b) General structure of the dual-axis solar tracker.

The general structure of the solar tracker comprises a solar panel, two servomotors, one for azimuth rotation and the other for elevation rotation, a solid base fixed to the ground with a hole above it through which freewheels pass to allow non-resistant rotation of the solar panel in azimuth, and a suitable solar panel support.

Figure 12 shows the results of the design and modelling of the 3D model of the servomotor assembly.

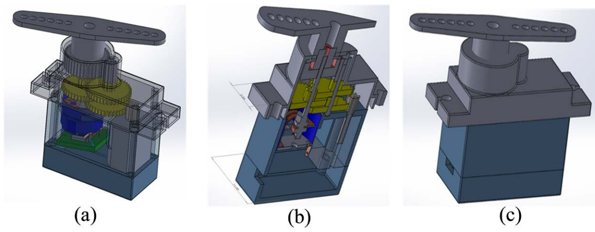


Figure 12. (a) Internal view of the servomotor design diagram, (b) Sectional view of the design diagram of the internal structure of the servomotor and (c) Design diagram of the general structure of the servomotor.

We have disassembled the MG996R servomotor. We designed and modelled all the measured internal parts of the servomotor. Finally, we carried out a simulation of the entire servomotor. This simulation enabled us to rotate the solar panel to a desired angle by acting on the rotation of the gearwheels. This shows us the efficiency of the system studied and verifies the other results.

3.3. Experimental Results

In this section, we will evaluate the experimental results of a fixed solar panel, single-axis solar tracker and a dual-axis solar tracker on the energy produced. The study was carried out in the center of Gitega province, in the site of Gitega, where the optimum angle of inclination for a fixed solar panel is 15˚ [6]. The coordinates of Gitega are latitude of 3˚25'42.583"S and longitude of 29˚55'29.898". In our study, the fixed solar panel is tilted at an optimum angle of 15˚. We used two 1.2Wp solar panels with the following characteristics: Solar polycrystalline panel, Maximum Power: 1.2 W, voltage at Pmax (Camp): 6 V, current at Pmax (Imp): 0.2 A measurement 84 * 130 * 10 mm. The other components used are shown in Figure 13.

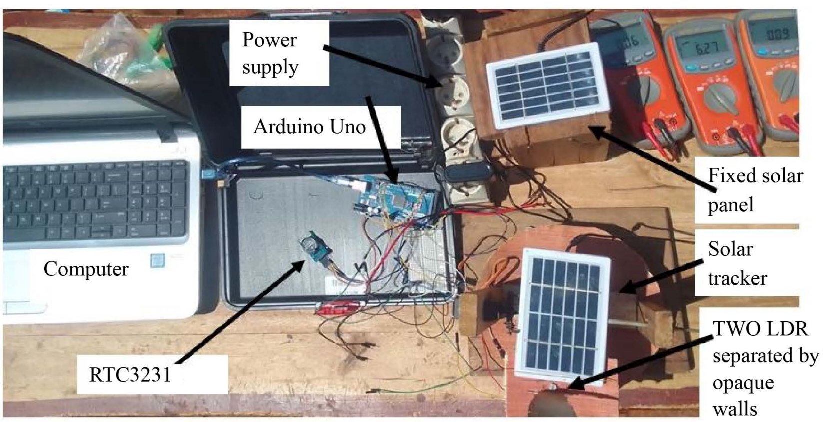


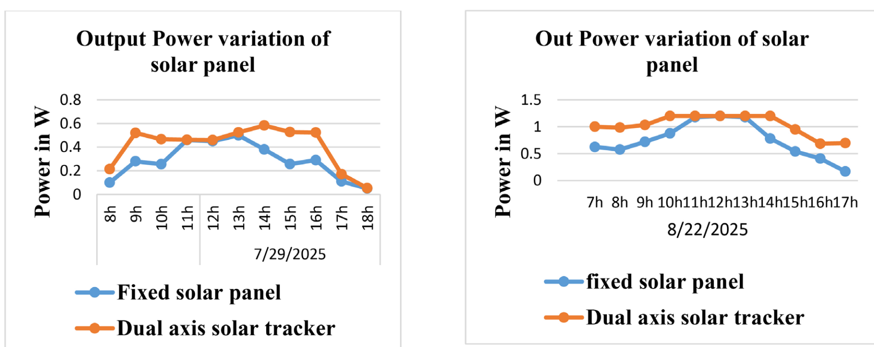
Figure 13. Diagram of the solar tracker experimental assembly.

We have visualized the operation of the solar tracking system using the computer. Figure 14 shows the message of serial monitor of Arduino IDE showing the operation of the solar tracking system.

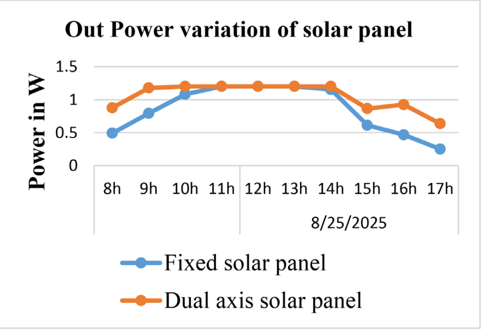
Figure 14. Results display diagram with serial monitor.

According to the experimental results obtained, which are displayed in the Serial Monitor, the solar tracking system starts from 6:00 AM to 6:30 PM. After every 12 minutes, an increment of 3˚ is observed, allowing the solar panel to be repositioned in elevation. We can see that at 12:00 AM the angle at which the solar panel is repositioned is 93˚ and the solar panel rotates from east to west. At 1:00 PM the angle at which the solar panel is repositioned is 105˚ and the program shows that the solar panel rotates also from east to west. At 6:30 PM the solar panel returns to the morning position by rotating from west to east using. We note that the results from model simulation and experimental results are matched.

Figures 15(a)-(c) illustrate the curves of the experimental results obtained for a fixed solar panel and a dual-axis solar tracker.



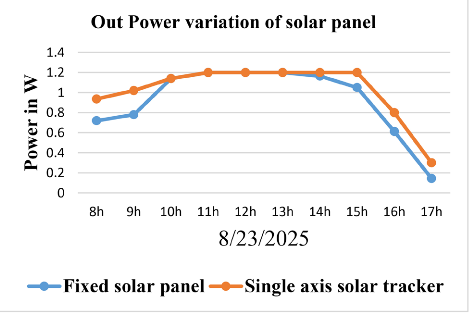
(a) (b)



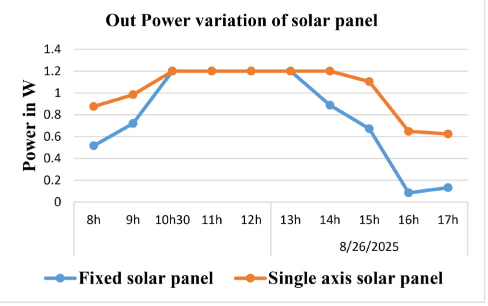
(c)

Figure 15. Diagram of experimental results of dual axis tracker solar (a) for 7/29/2025, (b) for date 8/22/2025 and (c) for date 8/25/2025.

According to the experimental results obtained, a large difference in solar energy production between the dual-axis solar tracker and the fixed solar panel is observed in the morning, and this difference decreases around 11 AM. From 11:00 AM to 1:00 PM, the energy production of the dual-axis solar tracker is close to the energy production of the fixed solar panel. From 2:00 PM onwards, the energy gain between the dual-axis solar tracker and the fixed solar panel increases. Based on the experimental results obtained, the energy gain of the dual-axis solar tracker compared with the fixed solar panel varies between 42% and 50%. 7/29/2025 was a day with low solar radiation. Figure 16(a) and Figure 16(b) illustrate the curves of the experimental results obtained for a fixed solar panel and a single-axis solar tracker.



(a)



(b)

Figure 16. Diagram of experimental results of dual axis tracker solar (a) for 8/23/2025, (b) for date 8/26/2025.

On date 8/23/2025 and 8/26/2025, we carried out experiments to study the energy gain of the single-axis solar tracker compared with the fixed solar panel. According to the experimental results obtained, a large difference in the energy gain of the single-axis solar tracker compared with the fixed solar panel was observed between 8:00 AM and 10.30 AM. This difference in energy decreases as 11 AM approaches. From 12:00 AM to 1:00 PM, the solar energy captured by the single-axis solar tracker corresponds to the solar energy captured by a fixed solar panel, and production reaches its maximum value. Based on the experimental results obtained, we note an energy gain of 29% to 41% for the single-axis solar tracker compared with the fixed solar panel. On the days 8/25/2025 and 8/26/2025, the sun's trajectory was in the East-West direction, while on the other days, the sun's path was East-North in the morning and West-North in the afternoon.

3.4. Discussions

We have noted that in the research work of [7]-[22], solar trackers allow rays at any time. We note that these systems studied consume a lot of energy since the panel is repositioned at every moment. We note that the authors should also address the study of the optimal angle of inclination of the solar panel for a proper comparison of energy gains between the fixed solar panel and the solar tracker. In relation to the novelty, we have developed a control algorithm for the solar tracker that allows the solar panel to be repositioned at an angle of 3˚ every 12 minutes using a microcontroller. We began by studying the effect of optimum tilt angle of fixed solar panel on the solar energy captured, in order to make comparison with solar tracker. This algorithm optimizes the solar energy captured and saves the energy consumed by the motors. Simulation and experimental results are similar. For [24], a dual-axial solar tracker in the equatorial region can increase solar energy capture with net gains of 31.8% and 37.0%. In this study, we obtained a gain of the single-axis solar tracker compared to the fixed solar panel of 29% to 41%. We obtained also a gain of the dual-axis solar tracker compared to the fixed solar panel of 42% to 50%. We found that from 12:00 AM to 1:00 PM, the electrical energy produced by a solar tracker is almost the same as that produced by a fixed solar panel. About daily energy saved by the servomotors, we know that the Earth completes a 360˚ rotation around its axis in 24 hours (average solar day), so the Sun's hour angle, defined as the angle between the local meridian and the Sun's position, changes by 15˚ every hour. If the solar panel is repositioned by an angle of 1˚ each time, there will be 15 repositionings during an hour corresponding to the 15˚. In our project, during one hour, the solar panel is repositioned 5 times. In this case, for a solar tracking system that changes by 1˚ each time there is a difference in the illuminance of the sensors, a consumption of the servomotor of 100% is observed for a repositioning of the actuator at one degree. In our case, the energy consumption of the actuator in one hour corresponds to:

$\frac{100\% \cdot 5^\circ}{15^\circ} = 33.33\%$. We note that a consumption of 33.33% of the servomotor is observed for a solar tracking system that is repositioned at an angle of 3˚ every 12 minutes, giving us an energy saving of around 70% in servomotor consumption. From an economic point of view, we note that in Burundi a single-axis tracking system is effective, taking into account the trajectory of the sun in the countries of the equatorial region. We have noticed that when the sun's trajectory is from east to west, the solar energy captured by the double-axis solar tracker is similar to the solar energy captured by a single-axis solar tracker. This can also be seen in **Figure 5** showing the sun's trajectory in Burundi. In terms of investment and maintenance costs, the single-axis solar tracker has a simpler structure, reduced motorisation, and lower installation and maintenance costs. The dual-axis solar tracker, on the other hand, has a more complex structure (double motorisation, precise sensors, more advanced control electronics). Initial and maintenance costs can be 30 to 50% higher than for a single-axis system. In terms of technical complexity and reliability, the single-axis solar tracker is more robust, with fewer moving parts and therefore less risk of breakdown. Whereas a dual-axis solar tracker needs more motors, more sensors and more components. There's a greater likelihood of mechanical or electronic failure with a solar tracker. Maintenance must be regular to avoid loss of yield.

We have also noted that a solar tracker in Burundi offers considerable energy savings compared with a fixed solar panel. Looking ahead, the local industrialization of these solar trackers could not only contribute to the energy autonomy of rural areas, but also stimulate economic development by creating jobs in design, manufacture and maintenance. However, the success of this transition depends on institutional support, appropriate technical training and targeted investment in research and development. So the solar tracker is not just a technological tool: it represents a strategic lever for sustainable development in Burundi, reconciling innovation, energy efficiency and social inclusion in the transition to renewable energies.

4. Conclusion

The development of a solar tracking system to optimize photovoltaic yields in Burundi meets a dual challenge: maximizing energy production and adapting technologies to local conditions. In a context where the electrification rate remains limited and dependence on fossil fuels is a major economic and environmental constraint, the integration of a solar tracking system is an innovative and sustainable solution. We showed that existing solar tracking systems consume a lot of stored energy, since they track the earth's movement around the sun at all times. In relation to the novelty, we developed an algorithm that allows the solar panel to be repositioned at an angle of 3˚ every 12 minutes since 6:00 AM until 6:00 PM. Design, simulation and programming software such as Matlab2020a, Proteus 8, Arduino IDE and SolidWorks were used. The simulation results were similar to the experimental results, demonstrating the effectiveness and validation of the system developed. We demonstrated our contribution, which consists of developing and implementing an intelligent mechanism that repositions the solar panel at an angle of 3˚ every 12 minutes so that the rays are perpendicular to the solar panel by using real time clock RTC3231 and light sensors photo-resistors. A dual-axial solar tracker in Burundi can increase solar energy capture with net gains of 42% and 50%. A single-axial solar tracker in Burundi can increase solar energy capture with net gains of 29% and 41%. This work has given a contribution in optimization of solar energy captured and reducing the energy consumption of motors. It also increases the service life of the motors. The development of an intelligent solar tracker adapted to the equatorial climate represents a promising solution for improving the profitability and efficiency of photovoltaic installations in this geographical area. Its large-scale adoption could make a significant contribution to the energy transition and to the electrical autonomy of local communities. The importance of this project lies in its ability to recover electrical energy. The system studied is a system that replaces the man-machine interface and awakens the world to the integration of artificial intelligence into systems all over the world, and especially in Africa, demonstrating the efficiency of the system studied. Several avenues could be explored to improve the performance and sustainability of the system studied: automatic cleaning of the solar panels, monitoring and predictive maintenance using Internet of Things sensors to anticipate breakdowns and extending the system's lifespan.

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Authors' Contributions

Bukuru Denis: Conceptualization, Methodology, Supervision, Project administration, Validation, Writing—review and editing;

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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