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Design And Development of a Rotational Solar Collector Panel Array for Effective Trapping of Sunlight Radiation to Optimize Power Generation in Solar Energy Systems

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ABSTRACT
Zambia's electricity sources include, hydro power, solar energy and small produce from coal and biomass. The country is basically self-sufficient in all the other electricity resources, as it has substantial unexploited reserves of these forms of energy, Mabvuto Mwanza (2012). According to Gauri Singi, SofiatouAlzoumaNouhou, MohamaedYoubaSokana, (2013) IRENA report, the Sun, Wind, Waves and geothermal heat are renewable energy sources that will never run out. Therefore, the purpose of this project is to design and develop a rotational Solar Collector Panel for effective trapping of sunlight radiations in order to optimize power generation in solar energy systems. To maximize the power output from solar panels, we need to keep the panels aligned with the sun. In this paper, the design of an efficient solar tracking system based on Real Time Clock (RTC) using microcontroller is described. The proposed tracking system is a low cost, high accurate, more efficient, with low power consumption.

I. INTRODUCTION

As the non-renewable energy resources are decreasing worldwide, use of renewable resources for producing electricity is increasing. Solar panels are becoming more popular day by day. Solar panel absorbs the energy from the Sun, converts it into electrical energy and stores the energy in a battery. This energy can be utilized when required or can be used as a direct alternative to the grid supply. Utilization of the energy stored in batteries is mentioned in below given applications. The position of the Sun with respect to the solar panel is not fixed due to the rotation of the Earth. For an efficient usage of the solar energy, Mwanza et al (2017), the Solar panels should absorb energy to a maximum extent. This can be done only if the panels are continuously placed towards the direction of the Sun. So, solar panel should continuously rotate in the direction of Sun. This article describes about circuits that rotates solar panel.

Scope of Study

This study was limited geographically to Zambia and it concentrated on how a solar collector panel can effectively utilize the sun light radiation for maximum optimization of power generation, with regard to system components, design and operation by developing a prototype of the system.

Main Objective Specific Objectives

- To assemble the circuit which will contain the microcontroller.
- To write a code that will control the microcontroller.
- To erect a stand for the solar collector panel and to connect the motor to the microcontroller.

Background to Solar Trackers

In reference to M. J. Clifford and D. Eastwood, Solar tracker has already passed fifty years since its beginning. The first successful solar tracker was built in 1968. However, it was a passive solar tracker. It was a non-motorized pole-top tracker that uses refrigerant and aluminium channel reflectors to shift PV panels toward the sun. Though, it was expected that to bring in the commercial market within 1970, the idea had not come into reality. Within a decade, the development in the field of photosensitive elements gave rise to the concept of active solar tracker. According to Mwansa Kaoma et al. (2015) in his publication state of renewable Energy Technologies in southern Africa, in 1977, ARCO Solar began manufacturing solar panels in response to the oil and energy crisis. The first large-scale solar trackers were built in 1983 on the Carrizo Plains in California. ARCO leased land on the Carrizo Plains and assembled two intricately designed and controlled dual axis tracker

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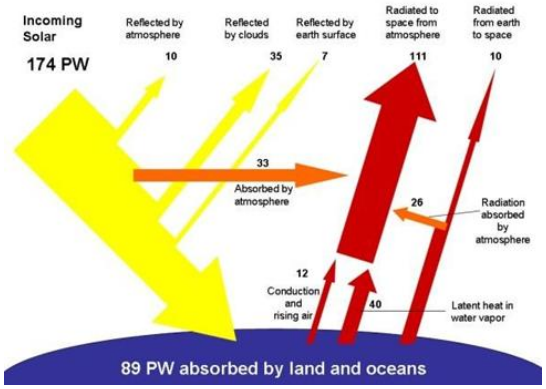
PV power plants, totalling 5.2 MW. However, power from these plants was sold to the grid at a mere $0.04 per kilowatt-hour. Since the plants were not economically viable, they were eventually sold off and disassembled. Within 1980s

Solar Energy

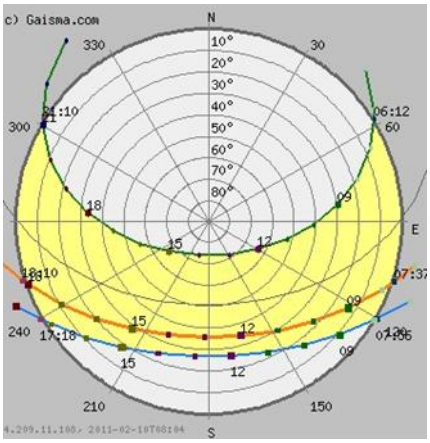
Solar energy is referred to the energy harnessed from sunlight. The energy from sun is considered unlimited and hence energy acquisition from sun is considered the leading energy source for futureIshii, T., Otani, K., Takashima, T., & Ikeda, K. (2013). Radiant light and heat from the sun, is harnessed using a different type of technologies such as solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis. It is calculated that earth receives at about 1000 Watts per square meter at noon and hence direct conversion from photon energy to electricity has already been done and solar power plants are now setting up on large scale.

According to Michel Boxiwell. (2017) in his Solar Electricity Handbook, Solar energy is a reliable source of energy in the hilly regions and isolated lands where transmission through cable is costly or impossible. Photovoltaic panels are used in rural areas for electrification. Also, urban electrification by street lighting by photovoltaic panel is becoming popular. Modern electric devices also have the facility to run with solar power. Recently electric vehicles, building integrated solar system and smart grid system have started adopting solar energy widely. Space shuttles and satellites that are sent to space for long time have no other alternative energy then solar. So, this research has been made extensively in this regard.



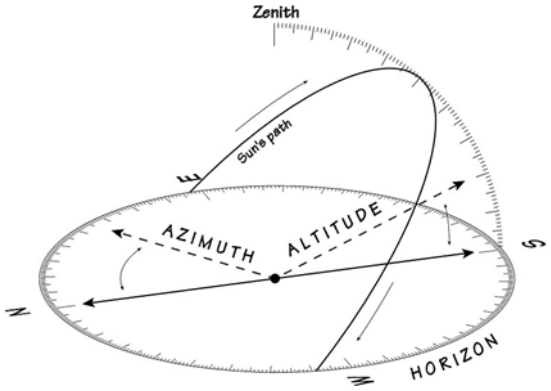
Sun Path, Azimuth & Altitude Angle

The position of the sun varies from time to time and season to season due to earth's continuous and periodic rotation and revolution. As a result, it has become necessary to locate the position of sun for a particular moment. The locations are placed on a special type of chart named Sun Path Diagram. A Sun Path Diagram shows the azimuth angle, elevation angle, sun paths throughout the years, sunrise and sunset time etc.



Solar azimuth, ψ, is the direction of sun from the Figure: Sun path diagram observer, expressed as the angular distance from the north point of the horizon to the point at which a vertical circle passing through the sun intersects the horizon.

Solar altitude, α, is the angular height of the sun measured from the Horizon. Above the horizon is positive, below is negative. The sun directly in the centre of the sky has a Solar Altitude of 90 degrees.



The declination angle, δ, is the angle of deviation of the sun from directly above the equator.

Solar Irradiance

Solar irradiance is a parameter directly related to solar energy received by solar panel and maximum when rays are perpendicular to panel plane. To achieve maximum solar energy, it is necessary to rotate the panel face towards the sun. The device that is used for this purpose is called Solar Tracker.

Solar Tracker

A Solar tracker is a device that keeps track of the sun. It follows the path of the sun throughout

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daytime with the help of sensors. Since the sun's position in the sky changes with time and the altitude angle and azimuth angle varies continuously,S. R. Nayak and C. R. Pradhan, (2012, v2 p1278), solar trackers are used to align the energy collecting system. Solar trackers are used for solar panels in solar power plants where energy generation is desirable up to maximum limit. So, in solar tracking systems, solar panels are mounted on a structure which moves to track the movement of the sun throughout the day. Concentration of heat energy by optical devices (mirror, prism and lens) also requires solar tracking.

Types of Solar Tracker

Solar tracking system is classified by its degrees of rotation. According to degrees of rotation trackers can be grouped into two primary categories-

Single Axis Solar Tracker

Dual Axis Solar Tracker

Single Axis Solar Tracker

A single axis solar tracker follows the movement of sun either horizontally or vertically, M. I. Hossain, S. A. Khan and M. Shafiullah, (2012, volume 7, p. 900-903). As the name suggests, this type of tracker has only one axis for rotation. The horizontal type solar tracker is used in tropical regions where the sun gets very high at noon, but the days are short. On the other hand, the vertical type solar tracker is used in areas with high latitudes where the sun does not get very high, but summer days can be very long. In concentrated solar power applications, single axis trackers are used with parabolic and linear Fresnel mirror designs.

Dual Axis Solar Tracker

According to N. Barsoum, (vol. 2, pp. 49-56, June 2011.) a dual axis solar tracker has two degrees of rotation. It can track sun both horizontally and vertically. This type of tracker can be used anywhere in the world and ensures maximum efficiency in gaining solar energy. Concentrated Solar Power (CSP) applications using dual axis tracking include solar power towers and dish systems. Dual axis tracking is extremely important in solar power tower applications because the angle error is crucial for longer distances between the mirror and the central receiver located in the tower structure. Design for dual axis tracking system is complex than single axis tracking and operation is more energy consuming. However, for large scale solar energy production dual axis tracking is more economic**.**

Methods of Solar Tracking

There are three methods of solar tracking.

- Active Tracking
- Passive Tracking
- Chronological Tracking

Active Tracking

The position of the sun is continuously determined by the sensors during the day. The sensor triggers the motion of motor or actuator in such a way so that the solar panel will always face the sun throughout the day. Active tracking is accurate with the help of sensors. But the main problem occurs when the sensors fail to discriminate between the measurements and give false trigger or miss original trigger during cloudy days.

Passive Tracking

Passive tracking method does not use sensors like active tracking. Instead of using sensors, a passive tracker moves in response to imbalance in pressure between two points at the ends of the tracker. This pressure imbalance is caused by heat from sun that creates gas pressure from compressed gas of low boiling point. The pressure moves the structure. This method does not have to rely on electrical sensors and requires negligible amount of power to operate. However, the mechanical design has to be very crucial to maintain accuracy.

Chronological Tracking

A chronological tracker is a timer-based tracking system. The structure is moved at a fixed rate throughout the day since the sun moves across the sky at a fixed rate of about 15 degree per hour. This method is better suitable for single axis tracking without sensors. For dual axis tracking a modified version can be implemented.

The position of sun throughout the day can be calculated and set by the program implemented on the controller module. The solar tracker rotates according to data sent from control unit's memory of pre-stored data or calculated from given formula. This method of sun-tracking is accurate and reliable. However, data storage, calculation continuous data transmission is power consuming and unnecessary rotation when sun light is too low can never be avoided.

All the three methods are applicable with single axis and dual axis tracking system. Which method is best suitable, is determined by the location of installation, purpose of generation and demand of solar power. Modern trackers combine both the sensor-controlled method and sensor less control method at the same time to increase efficiency.

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Basic Components of Solar Tracking System
A Solar tracker has several basic components. The major components are described here-

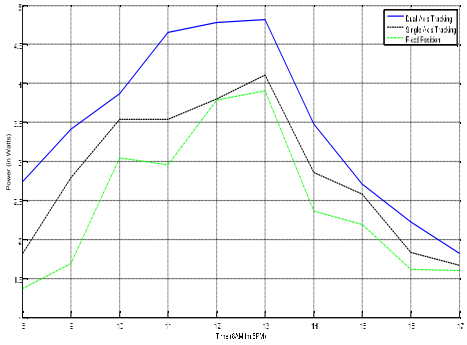
Sun Tracking Algorithm:
Solar tracking can have open-loop control algorithm or closed-loop control algorithm. Open-loop control algorithm involves calculation of azimuth and altitude angle of sun on a purely mathematical platform based on astronomical references. The open-loop component is needed because the sun can be obscured by clouds, eliminating or distorting the feedback signals. Closed-loop control algorithm includes detection of the position of sun by real-time light-sensing method and is needed to eliminate errors due to variability in installation, assembly, calibration, and encoder mounting. These two methods can be combined together to keep balance between economic design and increased efficiency.

Tracker Control Unit:
The control unit executes the sun tracking algorithm and necessary calculations. It can also coordinate the movement of the positioning system.A. H. Yamin, M. N. Ibrahim, M. Idoras and A. R. Zin(2013, volume 7, p. 223-227). A microprocessor or a computer can be used as the Centre of control unit. It normally has command input and data output mechanism for interfacing. For the trackers placed in remote region automatic tracking control mechanism is best suitable.

Positioning System and Drive Mechanism:
Positioning system moves the solar tracker according to the preference of control unit. It can be either electronic or hydraulic. Electrical systems utilize encoders and variable frequency drives or linear actuators to monitor the current position of the panel and move to desired positions. The drive mechanism includes mechanical devices- rotary motors, linear actuators, linear drives, hydraulic cylinders, swivel drives, worm gears, planetary gears, and threaded spindles. These drives can be of different types according to design method.

Sensors:
Sensors are used to detect position of sun accuratelyE. Ritchie, A. Argeseanu and K. Leban (2009). For open-loop system light sensors are implemented to correct calculation and mechanical errors. Closed-loop system solely depends on several light sensing devices. Light intensity detecting device includes photo-resistor, photo-transistor, solar cell etc. Solar power-based stations also use temperature, pressure, humidity, wind velocity, solar irradiance and other necessary parameters monitoring systems with trackers.

Advantages of Solar Tracker
The main advantage of using solar tracker is that it increases the availability of solar power from a location. A feasibility study was performed through an experiment prior to the design of solar tracker and it is found that power generation increased distinctively, Gaisma. (2013)
A 5-Watt solar panel was used for the experiment. Open circuit voltage, close circuit current, voltage at different load were measured and maximum power points were determined throughout the daytime of a regular sunny day and the values were plotted for comparison. The following figure shows the difference of power that can be obtained among the solar panel at foxed position, solar panel with single axis solar tracker and solar panel with dual axis solar tracker.



It is found that the fixed 5Watts solar panel has generated 23.051 Watt-hour of energy. The energy with single axis tracking was 26.794 Watt-hour and dual axis tracking was 32.213 Watt-hour

II. METHODOLOGY

HARDWARE SPECIFICATION
Solar panel
ATmega328 Micro Controller
Light Dependent Resistor (LDR) x 2
10KΩ x 3 Resistor
Servo Motor
16MHz Crystal
22pF Ceramic Capacitors x 2
Push Button
Breadboard
Cardboard

System design
The solar tracker designed here has one degree of rotation. The solar tracker can track the sun only in horizontal direction (that is, from east to west). The algorithm is based on the difference of solar irradiance at different position. Voltage detected by

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the solar panel at different position will be compared and the optimum position will be found. The motion of this tracker panel is controlled. The tracker sensor is a 5 Watts solar panel. For large scale power plant project, an individual tracker, placed on a high tower can be used to detect the position of sun and then the data can be used to rotate a set of solar panels to that specific direction according to signal. The design has three main units-

Position Sensor Unit
Motor Unit
Controller Unit

The sensor unit performs the detection of difference of solar irradiance due to change in position of sun. The control unit decides on the motion of tracker analysing the input detected by sensors and sends necessary signals to track the sun. The motor unit performs the tracking operation physically. Hence the control unit is a connection between the other two units.

Position Sensor Unit

The sensor unit consists of a 5 Watts monocrystalline photo voltaic panel. The panel generate voltage as light is incident on it. A small portion of the generated voltage can be measured by a microcontroller. Using these measurements and running the analysis tracking of sun is possible.

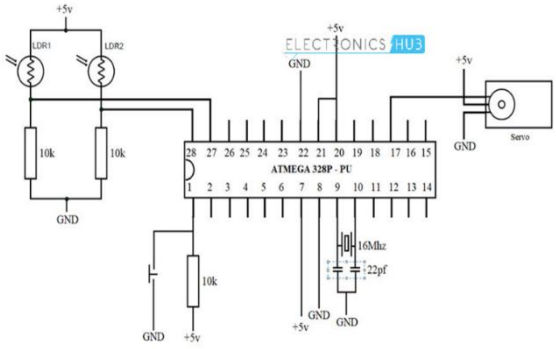
Mono Crystalline

This type of sensor can be used with the solar tracker can be used in solar based power plant, where the tracker, placed at a position, tracks the sun and conveys the data of required rotation to the solar panels of the plant and then all the panels are oriented to the specified direction. For a single solar panel, the sensor panel can be attached to the main panel along with tracking mechanism.

Motor Unit

To track the sun in horizontal direction variable reluctance servo motor is selected. With reference toKazungu I. Moshi J. &Mchopa A. (2014). A variable reluctance servo motor is constructed from ferromagnetic material with salient poles. The stator is made from a stack of steel lamination. The rotor is either solid or laminated. When there is no current in any coil the rotor is completely free to rotate. There are three independent stator phases 1, 2 and 3 and each one can be energized by DC signal from the drive circuit

Energizing one or more stator coils causes the rotor to step forward or backward to a position that forms a path with least reluctance with the magnetized teeth. It has a very high torque/inertia ratio giving high rate of acceleration and fast response.



The variable reluctance stepper motor is preferred for solar tracker design due to its micro-stepping facility. The solar tracker designed here can rotate by 7.5° per step if

pulses for half stepping are applied. The pulse sequence for CCW rotation is 1, 1-2, 2, 2-3, 3 and 3-1. Repetition of the same sequence continues the rotation. Reversion is also possible by reversing the controller pulse sequence.

The motor must deliver sufficient torque to withstand the maximum wind speed and the weight of the structure. Hence torque calculation for the motor is performed. To calculate the torque required to withstand the wind velocity a maximum velocity of 49.71Mph (80km/h) is considered. The weight of the panel is 1.3 kg and the structure supporting the panel weighs about 4.7 kg. Hence, Motor used in design the proposed model weighs 6kg.

Surface area of the panel, A = 0.0621m2

Wind pressure, P = 0.00256 × 49.712 Psf =30.865kg/m2

Drag coefficient, Cd = 2.0 for flat panel

Force due to wind, Fw = A × P × Cd = 37.57N

Gravitational force Fg = 6 × 9.8N = 58.8N

The radius of the base structure is, r = 0.0127m

Torque required, T= (Fw + Fg) × r = 12.5 kg-cm

The variable reluctance servo motor selected for horizontal tracking. It has a holding torque of 20 kg-cm. Its phases are energized by 12 Volt, 2 Ampere DC adapter.

Controller Unit

The operation of the solar tracker is controlled by the controller unit. The microprocessor, being the brain of this unit, gives necessary instructions for operation. However, it is not capable of supplying necessary current for operating the motor. It requires assistance of relays or switches to control the motor. The unit has three voltage-controlled switches to operate the motor. The designed controller unit has the following elements-

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ATmega328 Microcontroller

The ATmega328 microcontroller functions as the brain of the system"ATmega32 datasheet". ATmega328 is a high performance, low power consuming 8bit microcontroller with built-in timer, counters, ADC (analog to digital converter) and internal memory. It has 40 pins with their distinctive features.

Code.

The microcontroller is programmed by code developed on AVR GCC platform in C programming language."7805 datasheet", AVR Studio is used to compile the code. AVR Studio converts the code written in C for ATmega32 to hex file. This is a type of hexadecimal file that the microcontroller can understand. This is also known as machine language. It is then burned into the microcontroller with the help of the software named Extreme Burner. A serial programmer is used to transfer the code from Serial programmer for microcontroller computer to microcontroller.

5 Volt Relay

LM7805 Voltage Regulator Solar PanelJonGerberg (2015).The solar cell (photovoltaic cell) converts sunlight to electrical energy. A solar panel consists of several solar modules which further are comprised by many solar cells. Together do several solar panels make up a so-called solar array? The cell is of semi-conductive material, often silicon Si, and aggregates a mass of p-n junction in the module. The process of how the electricity is generated follows in different steps. First a photon (radiation) is absorbed by the semi electric apparatus conductive material. Then the material emits an electron making the electron free to either dispatch into heat, return to its initial state in the material or travel down the module until it reaches a conductive electrode. When the latest process is realized, in mass, a direct current is generated. The direct current is then directed straight to either a battery or through an inverter which converts the DC to AC so it can be consumed. Depending on the nominal voltage of the battery or the inverter the array might need to be constructed with the modules being connected in parallel or series. This is in order to achieve system voltage of the inverter which often times is 12V, 24V or 48V depending on the system size. Michael Boxwell. (2017). 22pF

Ceramic Capacitor

According to Kumar R. & Rosen M. (2011), a capacitor is a device that stores electrical energy in an electric field. It is a passive electronic component with two terminals. The effect of a capacitor is known as capacitance. While some capacitance exists between any two electrical conductors in proximity in a circuit, a capacitor is a component designed to add capacitance to a circuit. The capacitor was originally known as a condenser or condensator. This name and its cognates are still widely used in many languages, but rarely in English, one notable exception being condenser microphones, also called capacitor microphones.

Resistors

A resistor is a passive two-terminal electrical component that implements electrical resistance as a circuit element. In electronic circuits, resistors are used to reduce current flow, adjust signal levels, to divide voltages, bias active elements, and terminate transmission lines, among other uses. The electrical function of a resistor is specified by its resistance, B. L. Theraja and A. K. Theraja, (2005.) common commercial resistors are manufactured over a range of more than nine orders of magnitude. The nominal value of the resistance falls within the manufacturing tolerance, indicated on the component.

LDR

According to J.Mahere, (2010) Light Dependent Resistors or LDRs are the resistors whose resistance values depend on intensity of the light. As the intensity of light falling on the LDR increases, resistance value decreases. In dark, LDR will have maximum resistance. LDR will output an analog value which should be converted to digital. This can be done using analog to digital converter.

ATmega328 has analog to digital converter internally. It has six ADC channels from ADC0 to ADC5 (Pins 23 – 28). The two LDRs are connected to ADC pins i.e. 27 and 28 in a voltage divider fashion with the help of individual 10KΩ Resistors. ADC conversion is done using successive approximation method.

Servo Motor

Servo motor is used to rotate the panel. To drive the servo motor, a PWM Signal must be provided to its control pin and hence Pin 17 (which has PWM) is connected to the control pin of the servo motor. By connecting a battery to the solar panel, you can store the energy generated by the solar cells and this energy can be used when required. There are separate charge controller circuits dedicated to efficiently control the charge acquired from solar panels and charge the batteries.

The Battery, Controller, Inverter AndStep-up Transformer

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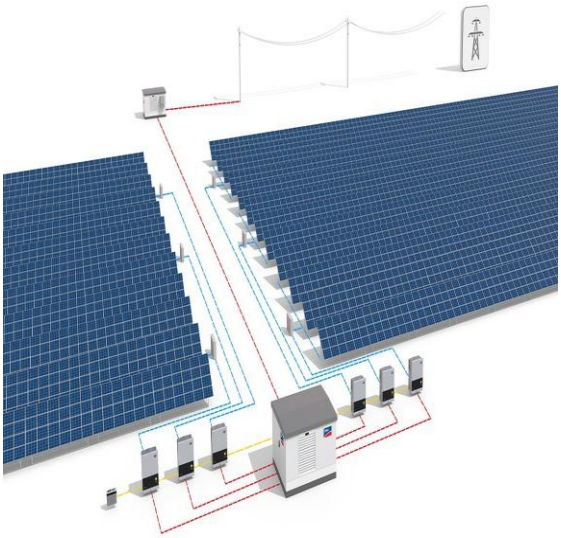

III. RESULTS

Introduction

This section outlines the results observed from the implementation and testing of the rotational solar collector panel array designed to optimize sunlight trapping and increase power generation in solar energy systems.

Efficiency Improvement

- **Increased Energy Output**: The dual-axis tracking system demonstrated a significant increase in energy output compared to fixed solar panels. On average, the tracking array achieved a **25% to 50% increase** in energy production throughout various seasons.
- **Angle Optimization**: The system was able to maintain an optimal angle of incidence with the sun throughout the day, leading to higher solar irradiance absorption. Measurements indicated that the tracking array consistently operated at angles closer to 90 degrees relative to the sunlight.

Performance Metrics

- **Daily Energy Generation**: The average daily energy generation was recorded, with results showing:
  - **Fixed Panels**: Approximately 5 kWh/day.
  - **Rotational Panels**: Approximately 7 kWh/day (in optimal conditions), demonstrating improved performance during peak sunlight hours.
- **Energy Generation Across Seasons**:
  - **Spring/Summer**: The tracking array particularly excelled during these seasons, increasing output by up to **50%** due to longer daylight hours and stronger sun angles.
  - **Autumn/Winter**: The improvement was slightly lower, but the tracking system still achieved around **20% to 30%** more energy compared to static panels.

System Reliability and Maintenance

- **Operational Stability**: The use of robust materials and quality components resulted in high reliability, with minimal maintenance required over the testing period. The system operated successfully through various weather conditions, including cloudy days, wind, and rain.
- **Sensor Accuracy**: The light sensors performed effectively, accurately detecting sunlight intensity changes and adjusting the panel's position in real-time, contributing to sustained energy production regardless of fluctuations in weather.

Cost-Effectiveness Analysis

- **Return on Investment (ROI)**: The initial investment in the tracking technology showed a payback period of approximately **3 to 5 years**, depending on local energy prices and conditions. Given the increased energy production, the system proved to be cost-effective compared to traditional fixed installations.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 8, Issue 1 Jan. 2026, pp: 215-223 www.ijaem.net ISSN: 2395-5252

- **Energy Payback Time**: The energy necessary to manufacture, install, and operate the rotational solar collector system was estimated to be recouped in **1.5 years**, significantly less than conventional solar technologies without tracking.

Environmental Impact

- **Carbon Footprint Reduction**: The enhanced energy generation correlated with a reduction in carbon emissions by approximately **1.5 to 3 tons** per year, depending on the local energy mix being offset by solar production.

User Engagement and Monitoring

- **User Interface Usability**: The developed monitoring system provided real-time feedback, increasing user engagement through accessible performance data, including energy output, operational status, and historical performance trends.
- **Remote Monitoring Capabilities**: Remote access features facilitated proactive system management, resulting in quicker issue resolution and optimizing overall performance.

Advantages of Sun Tracking Solar Panel

The solar energy can be reused as it is non-renewable resource.

This also saves money as there is no need to pay for energy used (excluding the initial setup cost)

Helps in maximizing the solar energy absorption by continuously tracking the sun.

Sun Tracking Solar Panel Applications

These panels can be used to power the traffic lights and streetlights

These can be used in home to power the appliances using solar power.

These can be used in industries as more energy can be saved by rotating the panel.

Use of Technology

Implementation of this project on national scale will significantly help to reduce over reliance of hydropower which depends on water and as the result it is affected by poor rainfall season resulting into power deficit. Optimizing the generation of solar energy has tremendous projection scope in Zambia. This is due to the geographical loc

Development of the System as a Solution

Zambia is slowly turning into the use of renewable energy and among those forms of renewable energies, it has been seen that solar energy is one the country is utilizing as a backup plan from hydro power M. R. Patel (2006). Due to that it has been seen that most of the solar panels are mounted in one fixed position therefore as the sun moves part of the radiations is not utilized. Therefore, the development of a solar tracking system is a specific device intended to move the photovoltaic modules in such a way that they continuously face the sun with the aim of maximizing the irradiation received by the PV array.

Conclusion

Solar energy is an unlimited source of energy. Solar tracker is used to harness this energy with more efficiency. This paper has demonstrated the implementation of solar tracking system in a cost-effective way. Direct use of output data from solar panel makes the system independent of light sensor that requires external biasing circuit. The use of stepper motor ensures more accurate tracking with minimum error. Thus, the proposed design offers a better solution to the implementation of solar energy. In order to solve the power crisis and meet the future increasing need, solar power must be extracted as much as is possible. Maximum cultivation of solar power can be performed by using solar tracker modules. The tracker designed here is much reliable and less power consuming then traditional trackers. Hence, it can be a better solution to maximum solar power extraction.

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