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Energy Efficiency and Practical Implications of IoT-Based Static vs. Single-Axis Solar Tracking Systems: A Comparative Analysis

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Abstract

The objective of this research is to offer a comparative evaluation of IoT based static and single-axis solar tracking systems with respect to energy efficiency, economic viability, and impediments in the implementation of both static and single-axis solar tracking systems. In order to fill in the gaps in the current literature on their performance comparison. In this research work, IoT technology has been used to monitor both systems in real time over a period of 30 days in comparable under the similar environmental conditions for data collection and analysis. The research also implements the Fuzzy Logic Controller-based algorithm, developed for the single-axis solar tracking system provides a dynamic and flexible mechanism to optimize solar energy capture. It intelligently adjusts the solar panel's angle based on real-time sensor data, ensuring that the panel is always positioned to maximize sunlight exposure. The data characteristics like solar radiation, temperature, voltage and these different effects were monitored to help in the determination of energy output and the overall efficiency of the system. The findings confirm that the IoT-based single-axis tracking system considerably improved the average system efficiency by 7% as compared to the static system. However, the high installation and maintenance costs of IoT-based single-axis systems increase complexity, posing challenges for mass adoption, particularly in small-scale applications. This paper demonstrates how IoT tracking systems offer improved efficiency of single axis trackers to achieve higher energy efficiency. This work will help in the decision making process for the future solar energy projects where there will be a need to consider the costs against the operational and performance advantages to balance performance benefits with cost and operational consideration. Studies have shown that IoT technology application enhances efficiency and energy operational parameters of solar photovoltaic (PV) systems.

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1. Introduction

As the worldwide demand for clean and renewable energy sources continues to grow, Solar Photovoltaics (PV) systems have emerged as a viable method of power generation. Many greenhouse apparatus and other panels are filled up with solar energy, which makes solar energy one of the resources that are least likely to run out therefore replacing fossil fuels. The improvement of such solar PV systems is mostly determined by the position of the solar panels that are used to maximize solar energy collection during the day. Although there are some types of solar panels known as fixed or static that are often opted for due to their cheap costs and ease of installation, their performance is usually compromised since such panels do not track the sun’s movement. In contrast, the use of solar tracking systems especially those enabling one axis or dual axis orientation of panels leads to huge productivity gains as the panels can follow the sun. The current trend of integrating the technologies of the 'Internet of Things' (IoTs) into solar PV systems has also increased the scope of solar tracking, enabling data acquisition, monitoring and control functions remotely and in real-time. It is possible to create and deploy IoT based solar tracking systems that can adapt to the environmental changes accurately and instantly preparing the hands on the PV system in a more effective manner. However, apart from the rapid progression in research and studies in this area, there is some gap in defining the comparative analysis of the IoT imposed supportive and singular axes tracker systems. Many of the works done in the present research has focused on dual axis or hybrid trackers with the concern of IoT, however, there was no sufficient investigation on the economics, practicality and durability IoT single axis trackers.

This study looks forward to addressing such a research gap. It would seek evidence supporting either one or the other by comparing the IoT-integrated static systems to single-axis solar tracking systems. For this, both the system implemented for the collection of real time data over a period of 30 days, this study evaluates energy output, efficiency and economic feasibility of both approaches. Moreover, the study investigates the practical issues and the economic aspects of the research as a means of providing effective perspectives on the sustainability of IoT incorporated solar tracking systems. Decision-makers such as researchers, engineers and policy makers will make correct decisions regarding solar technological applications and betterment of efficiency and sustainability across diverse geographies and economies.

2. Related Work

Solar tracking systems have major important focus on refining the efficiency of photovoltaic (PV) plate, through the positional adjustments of solar panels towards the sun direction that ensure to follow sun direction to gain maximal energy in a day [1]. These features of solar tracking distinguish it from the static systems, which only fixed in a position with appropriate angle [2]. Another study show that the solar trackers are able to follow the direction of the sun through which it increases the output and efficiency of the system. Research has shown that employing the single axis tracker, which is able to rotate the orientation of the panels towards the position of the sun, has the ability to increase energy production by about 20% and 30% over static systems [3]. However, there is not much detail available regarding the performance of these IoT based static systems in compare to the single axis systems over the life cycle cost and performance. The integration of Internet of Things (IoT) technologies into solar energy systems is a new approach, towards better utilization of renewable energy productivity. It permits the tracking of solar systems via on line, also provide the facilities for collection of data and its management of the systems from remote places that improve the accuracy and trust on solar trackers. Such systems will avoid wastage of energy and enhance management of solar energy by providing for predictive maintenance for reducing energy losses. Another study demonstrate that a sensor-based IoT systems has shown to track solar irradiance more accurately and predict the sun's movement, leading to up to 30% improvements in energy efficiency for both static and single axis tracking systems [4]. Also in a study, that use a light-dependent resistor to keep track of the sun angle in an IoT based single axis tracker reported impressive energy yield as compared to a static system [5]. In addition, solar farm management using IoT especially with the help of weather outlook has also shown potential in solving operational inefficiencies and maximizing energy output from large installations [6]. IoT in Fixed Solar Systems on the other hand, static solar systems do not have moving parts and therefore are economy and easier to operate, but such systems usually harvest less energy than tracking systems. Such energy losses are particularly noticeable in the very early morning and in the late afternoon when the sun is not in the much height of the sky [7]. But there is a way to overcome these limitations that can be reduced through the use of IoT in the static systems. IoT based monitoring system enhance the bottom line from static systems [8]. Another study demonstrates that in order to maintain a constant level of energy returned over time, the IoT-based system also offers the option for manual control of the panel's tilt during real-time operation [9]. It has also been proved by studies that IoT enhancement on static systems can give an increased energy saving by 15% using the static systems. Even though static systems are associated with low installation costs and low maintenance costs, with a drawback that it cannot capture solar energy [10]. However, study show that there are benefits of operational efficiency that offered by the enhancement of IoT in such system as remote monitoring and real time performance monitoring [11]. In a study found that static systems fitted with IoT monitoring devices can reduce downtime by 20%, which promotes better operational efficiency [12]. While by the use of IoT in single-axis tracking systems, in which the panels turn only along east to west axis and provide a middle ground in terms of efficiency as compared to the lower efficiency of static systems and the high complexity of dual-axis systems. The study show that the emergence of these IoT based technologies enables operation of such trackers by allowing constant tracking of environmental parameters, such as the sun position, wind speed and temperature of the system that makes it possible to modify the system instantly [13]. Research consistently reports that these systems are particularly successful in areas with high solar exposure, dynamic orientation of the panel's results in high-energy efficiency. The study show that energy output from IoT-based single axis systems has been shown to be about 20-30% more than the static ones [14] and many studies have documented this phenomenon. This performance gain is attributable partly to the possibility of undertaking predictive maintenance, a feat almost possible with the application of IoT whereby system down times will be reduced while ensuring energy output is maintained at the peak. However, these single-axis systems are better in performance than dual-axis systems; there are bases that make it dense with single axis orientation; especially during installation phase and alignment accuracy aspects. Another study show that the optimizing in the installation that requires appropriate alignment of the earth's axis that raises both installation cost and complexity [15]. However, IoT based monitoring systems provide for correction of the alignment and responsible for any environmental changes in real time, which improves the reliability of the system in operation [16]. While the another study show that IoT can be used to monitor the power output, health of the system, and environmental conditions in real time, and enable it consistent performance through the lifespan of the system [17].

When conducting research on cost-effectiveness and comparative performance in terms of energy efficiency, the single-axis systems either are in comparison with the static systems or with the IoT-based systems in which the single-axis trackers offer more energy than static systems and increases in energy yield about 20-30% that are reported in the study [18]. However, the author of another study discusses how several aspects, such as installation costs, continuing maintenance costs, and geographic location, affect a system's value for money. Whereas single-axis systems are usually suitable for large installations at high sun irradiation zones, static systems are more cost-effective where the installation area is constrained. The study revealed that IoT connectivity is important for both systems, but because of their orientation, single axis trackers make it simpler to recognise efficiency gains (Oyshei et al., 2024). Recent developments in solar tracking solutions also emphasize the role of the IoT in this sector. Such hybrid solar tracking techniques have proved to be more efficient in the utilization of energy from various resources including wind and IoT technologies [19]. The study also show that the AI-based analytics are already being utilized to improve the performance of solar trackers by predicting and selecting the position of the tracker in relation to the sun. [20]. However, the IoT based system remain regarding the economic feasibility and its standardization as well as their long-term sustainability and lifecycle environmental impact [21]. A study show that a fuzzy logic-imposed position of the solar panel can be readjusted dynamically through a fuzzy logic based algorithm and it is considered the best method in increasing solar energy absorption [22, 23]. The system relied upon real time data on sunlight intensity and the solar panels were always adjusted in a way that the panels were perpendicular to the sunlight [24]. The calculus based fuzzy control algorithm describes the nonlinear characteristics of the tracker, which enables stepper or dc motors to accurately rotate the tracking system [25, 26]. In addition, MPPT with fuzzy logic also enhances the output power by optimizing it under different conditions. Strategically, the system is programmed to operate in full sunlight and automatically ceases when the sunlight intensity is less than the pre-determined level Key of work, and the methods presented in the work, which help address the onsite electricity generation from photovoltaic systems [27].

Table 1: Summary of literature review for findings and identified research gaps on IoT-integrated solar tracking systems, focusing on the performance, cost, and practicality of static, single-axis, and dual-axis configurations.

Reference	Authors	Year	Finding or Outcomes	Research Gap
[28]	Shang, H.-L.	2023	Conducted a comparative investigation for fixed and dual-axis solar-tracking photovoltaic plate, monitored by an IoT system, also emphasizing the benefits of the dual-axis tracking approach.	The study did not analyse the performance and trade-offs of single-axis tracking systems in comparison to dual-axis and fixed systems.
[29]	Alkhamis et al.	2023	Evaluated the performance of static and tracking-type photovoltaic systems, highlighting the advantages of the proposed single-axis tracking system in terms of energy consumption and efficiency.	The study did not provide a direct comparison of the energy generation and efficiency between static and single-axis tracking systems.

Reference	Authors	Year	Finding or Outcomes	Research Gap
[30]	vimal et al.	2024	Developed predictive control algorithms to optimize the performance of single-axis tracking systems, showing that the IoT-enabled single-axis tracker outperformed the static system by 18% in terms of energy generation.	The study did not explore the integration of machine learning and IoT techniques for improving the performance of static solar systems.
[1]	Abdul-Rahaim et al.	2023	Investigated the use of hybrid solar tracking systems that combined single-axis and dual-axis mechanisms, achieving a 27% improvement in energy generation over a fixed-tilt PV system.	The study did not compare the performance and cost-effectiveness of the hybrid tracking system with a standalone single-axis tracking system.
[3]	Ali et al. (Ali, 2023).	2023	Explored the integration of machine learning and predictive analytics into IoT-based single-axis solar tracking systems, resulting in a 22% increase in energy generation related to a static PV system.	The study did not provide a comprehensive economic analysis of the long-term viability and return on investment of the IoT-enabled single-axis tracking system.
[19]	Oyshei et al.	2024	Evaluated the energy output, power consumption, and overall efficiency of a static system versus a single-axis tracking system, demonstrating that the single-axis tracker can generate up to 25% additional energy than a fixed-mount system.	The study did not investigate the long-term maintenance and cost-effectiveness of the single-axis tracking system compared to a static system.
[20]	Ponce-Jara et al.	2024	Showed that a dual-axis tracking system generate around 30% more energy in compare of a fixed-angle system, but the area covered was just about 100% more than a single-axis tracker.	The study did not investigate the cost-effectiveness and practical feasibility of dual-axis tracking systems for small-scale and domestic applications.

The research benefits from the case study on solar energy via IoT, emphasizes on the improvements made on the IoT based solar tracking systems and shows the need for further studies comparing static and single axis. The table 1 presents a review of several studies performed, emphasizing on effectiveness and costs of fixed and dual and single axis tracking systems.

2.1 Problem Statement

The world over and particularly in the developed countries, there is abundant demand for green energy sources such as solar energy and it is upon this that the shortage of fossil fuels, increased energy prices, and the necessity of addressing climate change are founded. Static PV systems, despite being readily available and easily installed, waste a lot of energy because of their fixed mounting position relative to the sun thus making collection energy utilizing solar power inefficient while generating electricity.

Single-axis solar tracking systems are better than stationary ones since they allow the solar panels to capture sunlight at different angles throughout the day, thereby increasing the energy harvest. However, they are associated with the drawbacks of increases in cost of installation, maintenance, which have a negative effect on performance. Recent advancements in the Internet of Things technologies provide new possibilities towards improving the operational efficiency of static and single-axis tracking systems, maintenance efficiency and control through monitoring.

2.3 Research Objectives

The objective of this paper is to analysis of the current literature by examining the static and single-axis solar tracking systems through the conducting of comparative analysis. In particular, the research focus of the following objective

Energy Efficiency: To measure the actual energy performance of the IoT-based static solar and the single-axis active solar tracking systems at same zone and weather conditions.

Cost-Effectiveness: To evaluate the cost-benefit and the cost-effectiveness of both the systems in terms of the set up cost, the operating cost and how the IoT predictive maintenance will affect the systems in the end.

System Limitations: To define and solve the major problems common with the individual system such as shading, mechanical limitations, and size constraints and how the IoT can help to solve these issues.

Future Advancements: To assess the novel directions pursued by the solar tracking systems equipped with the IoT including the use of artificial intelligence, hybrid systems, new construction materials of solar panels, etc.

3. Methodology

To complete our goal and conduct an examination with detailed analysis of the current literature, we installed two systems at the same site. The entire research process, from system installation to result analysis, is outlined in the flowchart in Figure 1 that illustrates the key steps used in our methodology. In this research, we also implemented a fuzzy logic-based algorithm for dynamically adjust the solar panel's position using real-time sunlight intensity. The algorithm is designed to optimize solar energy output by continuously adjusting the solar panel's angle throughout the daytime that behave according to sensor data. This algorithm runs during daylight hours and it halts its operation in night when sunlight intensity drops below the threshold.

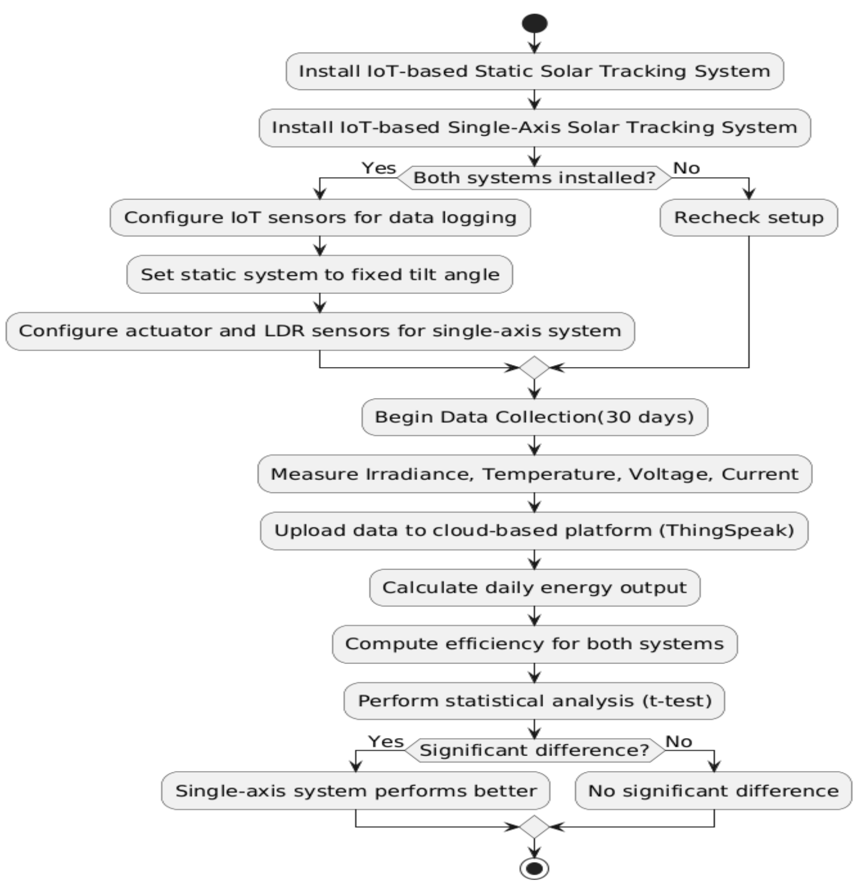

Figure 1. Flowchart of the methodology employed for comparative analysis, representing the installation, data collection, and analysis process for IoT-based static and single-axis solar tracking systems.

3.1 System Setup and Configuration

The main setup required to establish two solar system for the analysis purpose. To ensure both solar tracking systems received identical environmental exposure, including shown in Figure 2, they were constructed and installed side by side. Each system used a 1KW monocrystalline photovoltaic (PV) panel, with the following configurations.

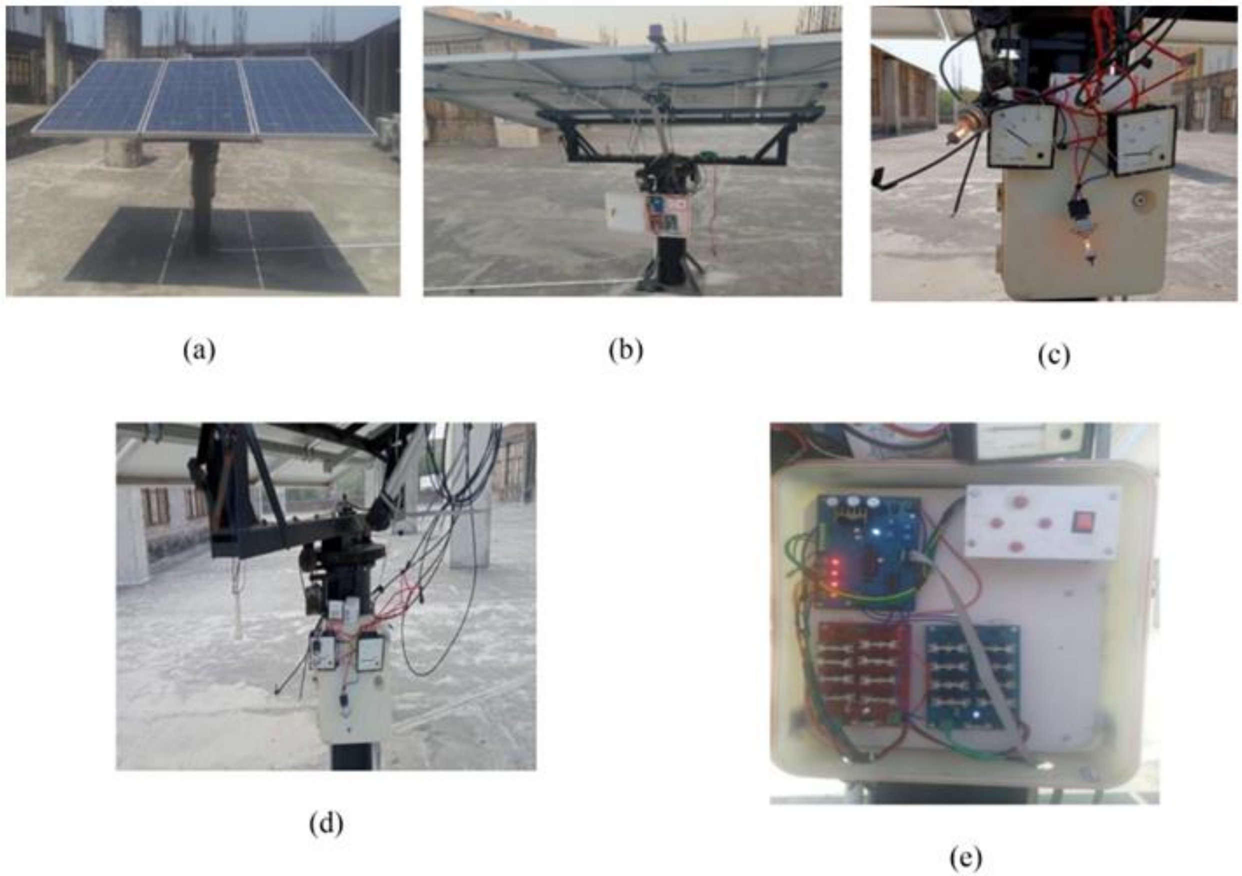

Figure 2. Schematic of the IoT framework designed for optimizing solar tracking, detailing sensor and actuator configurations for both static and single-axis systems.

- ***Static System**:*

The static system was fixed at a tilt angle of 26° based on the latitude and longitude 75.778885 of the installation location (Rajasthan, India). This angle is recommended as an optimal year-round tilt for maximum sunlight capture. The static system did not change position throughout the day. An IoT-based sensor module was attached to monitor various parameters, including irradiance, temperature, voltage, and current, which were logged every 10 minutes.

- ***Single-Axis Tracking System**:*

The single-axis tracking system was designed to minimize energy loss by avoiding the shading of PV panels during morning and evening hours, a common issue with fixed mounts. A linear actuator managed by a Raspberry Pi microcontroller controlled the system's adjustments.

Both the single-axis and static systems collected data using IoT controllers, through which we collect data. A cloud based platform the ThingSpeak used for the real-time monitoring, analysis, and recording, for that further data was transfer into the thinkspeak. The Figure 3 show this setup, that how the data from both IoT-based solar tracking system to be transferred to the cloud storage and monitoring purpose.

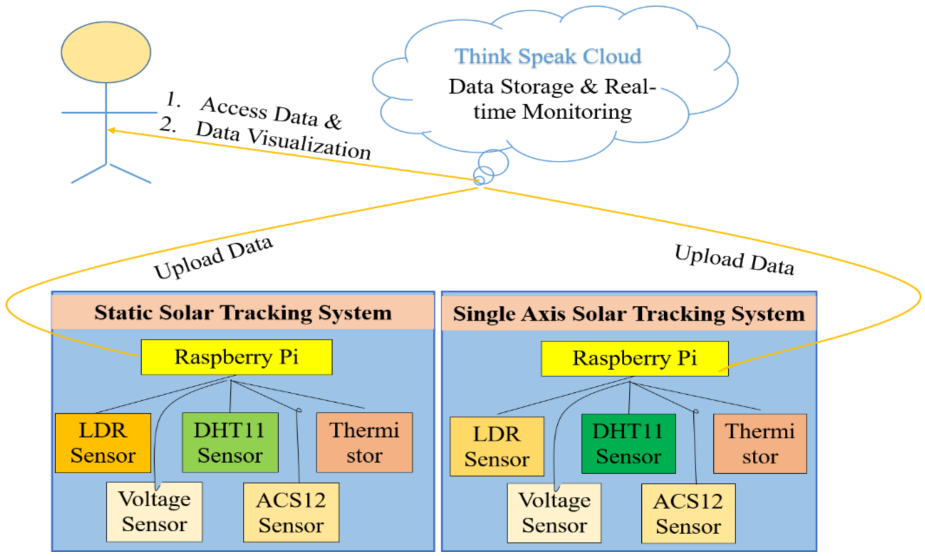

Figure 3. The Component diagram for the IoT-based solar tracking systems, to represent data flow and its integration with ThingSpeak platform for real-time monitoring.

The component diagram show of the data flow from the both Raspberry Pi units for both setups that is collected through various sensors transferred to cloud-based data storage, for real-time monitoring, and visualization purpose in ThingSpeak.

Figure 4. Configuration of designated channel locations on the ThingSpeak platform for separate monitoring of IoT-based static and single-axis systems.

The data from both systems was transmitted to designated channels on the ThingSpeak platform, with both systems assigned to the same location. Figure 4 show the channel locations on ThingSpeak.

3.2 Data Acquisition

Data collection was carried out over 30 consecutive days during the month of July 2024. To ensure accurate performance evaluation, the following parameters were measured every 10 minutes:

- **Solar Irradiance (in W/m²)**: Measured using an LDR sensor to determine the intensity of sunlight received by the panel.

- **Ambient Temperature (in °C)**: Measured using a DHT11 sensor to account for temperature's effect on solar panel efficiency.
- **Panel Temperature (in °C)**: Measured using a thermistor attached to the back of the PV panel to track thermal buildup on the panel.
- **Voltage (V)**: Measured at the panel output using a voltage sensor connected to the Raspberry Pi.
- **Current (A)**: Measured using a current sensor (ACS712).
- **Power Output (W)**: The power output of system computed by the formula: $P = VI$ (1)

Where the P denote power in watts, and V denote the voltage, and I is for the current.

All of the above parameters was recorded for both the systems and further uploaded into the cloud-based platform that is ThingSpeak to long-term data storage and real-time monitoring.

3.2.1 Data Upload Algorithm

Below the figure 5 showing, the steps of data uploading process into the ThingSpeak. The algorithm represented by the flowchart that provides the steps involved in transmitting and collecting data.

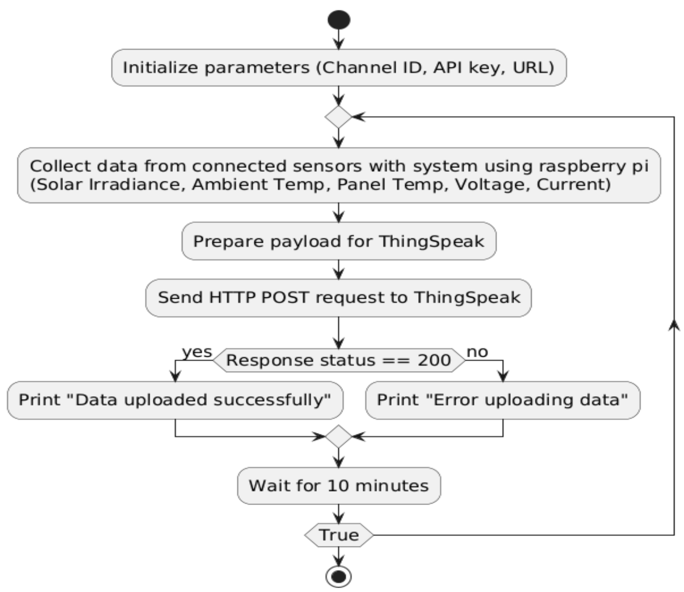

Figure 5. A Flowchart showing the algorithm steps for data uploading process into to the ThingSpeak.

The following steps are part of the algorithm:

- Data Collection: The parameters are taken in data collection process in fixed time intervals to obtain much data for analysis.
- Data Processing: Modifications are done to the harvested data to conform to the ThingSpeak API to enable uploads.
- Error Handling: The system investigates for any errors before uploading to know that the data is preserved.
- Data Upload: The data that has been organized and modified is uploaded to the ThingSpeak cloud for use in analysis.
- Confirmation: When the upload has been completed, the system gets a confirming status from the ThingSpeak.

The data-uploading step is crucial for enabling is crucial for enabling real-time monitoring. Which is very important for the analysis of the collected data as shown in figure 6. The addition of this algorithm improves not only the quality of the data that is collected but also the response time for the performance data making it supporting informed decision-making in the management of solar tracking systems.

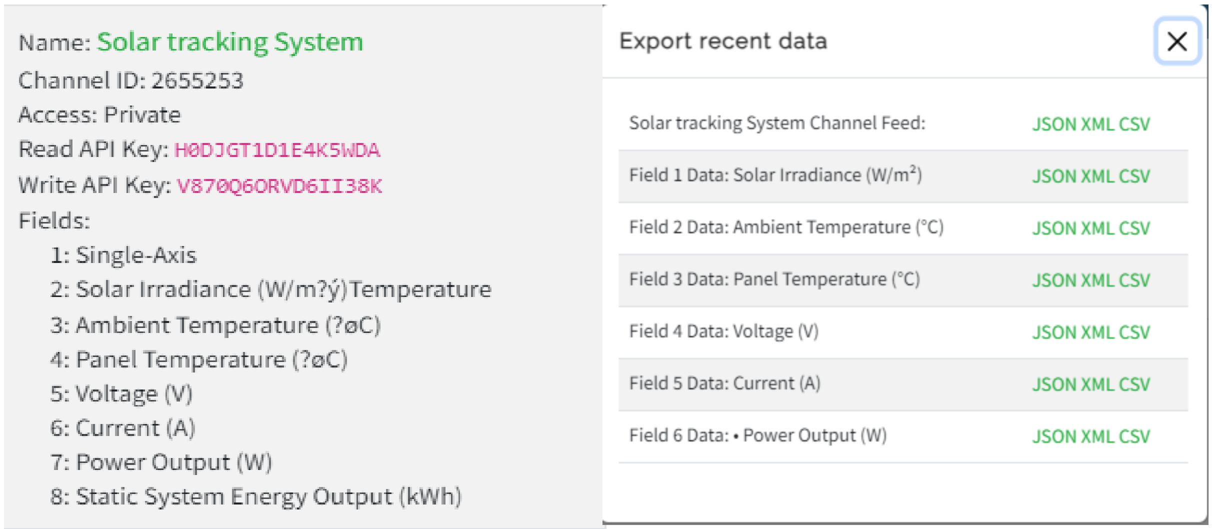

Figure 6. Overview of ThingSpeak channel fields used for capturing data from IoT-based solar tracking systems, enabling comprehensive real-time analysis of key performance metrics.

The figure 6 displays the ThingSpeak channel fields used for data acquisition from both the IoT-single axis solar tracking and static systems. The fields capture real-time sensor data, enabling efficient monitoring and analysis of system performance.

3.3 Algorithm Development

One section of our research involved developing an algorithm to compare IoT-based solar systems. The algorithm promises that the single-axis solar panel's orientation is effectively adjusted to optimise sunshine coverage, hence enhancing energy efficiency. We selected Fuzzy Logic Control (FLC) because of its capacity to deal with the inherent uncertainty and fluctuation of sunshine intensity. Our method allows the system to respond constantly and quickly in real time, without the need for accurate mathematical models that may change during the day and seasons.

3.3.1 Fuzzy Logic Controller (FLC) for Solar Panel Orientation:

The angular positioning of the solar panel in the single-axis system is done through a fuzzy logic controller (FLC). Fuzzy logic allows the system to function in a more human-like fashion as it does not rely on discrete concepts of truth and falsehood like general control methods, which are focused on precision measures and models. This is very useful in a solar tracking system, where some parameters like amount of sunlight, change continually and not instantaneously. The stepwise procedure is given below.

Algorithm: Fuzzy Logic-Based Solar Panel Adjustment

1. **Initialize the sensors and motor controller**

The system recalls Light-Dependent Resistors (LDR) and the motor controller in charge for the rotation of the solar panel.

2. **Read sunlight intensity from sensors** the system continuously reads real-time data from the LDRs to measure sunlight intensity.
3. **Apply fuzzy logic rules** Using fuzzy logic, the sunlight intensity is classified into three categories:

- **Low sunlight**: The panel's angle is increased to capture more sunlight.
- **Medium sunlight**: The panel angle is held constant.
- **High sunlight**: The panel angle is decreased to avoid oversaturation.

4. **Generate motor control commands** Based on the fuzzy logic output, motor control commands are generated to adjust the solar panel's angle.
5. **Adjust the solar panel angle** the motor adjusts the panel's orientation according to the generated commands.

6. **Log data to the cloud** Sunlight intensity, panel angle, and energy output are logged in real-time to the cloud platform for analysis.
7. **Repeat the process** the system continues this loop during daylight hours. When daylight is no longer available (sunlight intensity below threshold), the process stops, and the motor is deactivated.

The operational flow of the algorithm is shown in Figure 7 as flowchart below. The flowchart that shows how decisions are made to change the orientation of the panel.

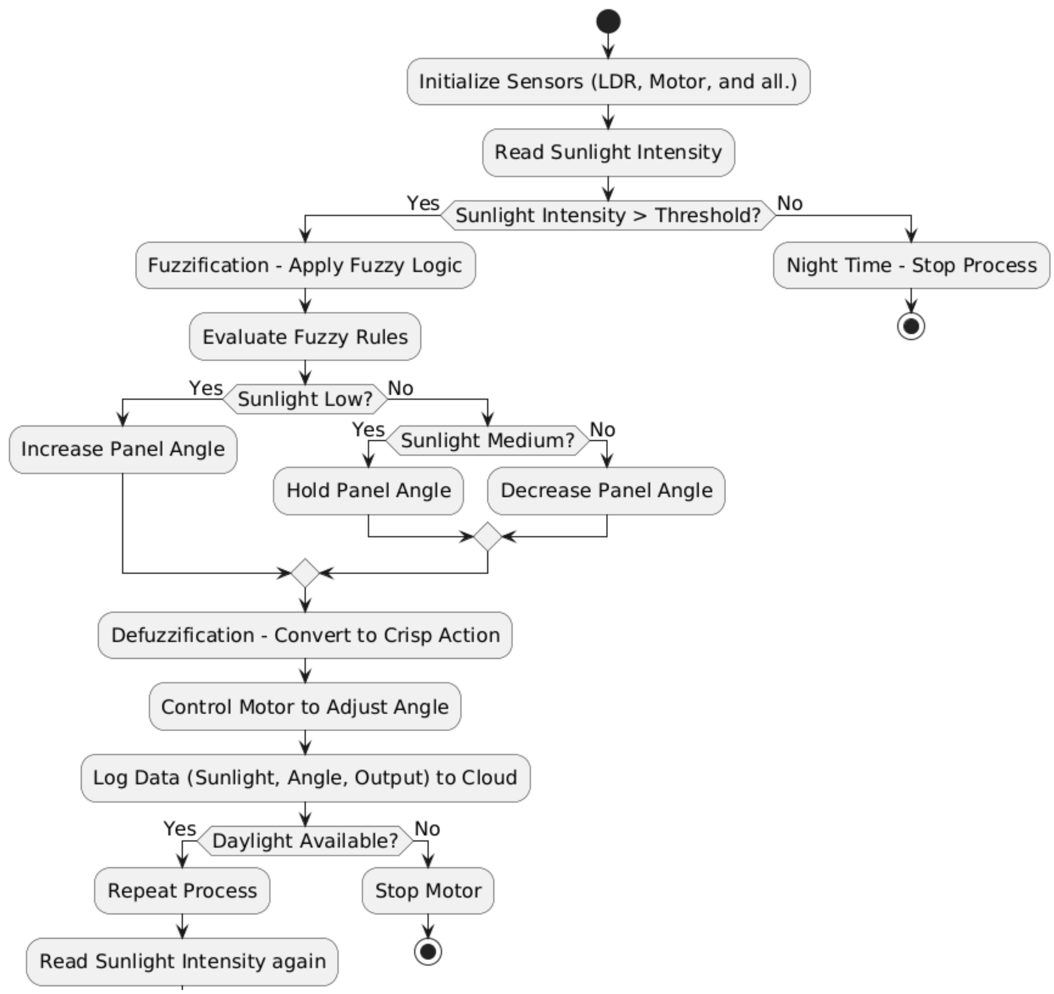

Figure 7. Flowchart of the fuzzy logic-based solar panel adjustment algorithm.

The IoT-based single-axis tracking system and the IoT-based static solar panel system's energy efficiency were compared over a 30-day testing period. The ThingSpeak platform was utilised to continuously log the data to the cloud, facilitating real-time monitoring and additional analysis. This technique continuously modifies the solar panel's orientation based on real-time data to provide optimal energy collecting throughout the day, increasing energy output.

3.3 Performance Metrics

To evaluate the efficiency of each system, the following performance metrics were calculated:

- **Daily Energy Output (kWh/day)**: The total energy output from each system was calculated by integrating the power output over the course of the day: $E = \int_o^T P(t)dt$ (2)

Where E is the energy in kilowatt-hours (kWh), P(t) is the instantaneous power output, and T is the total duration of sunlight exposure.

Energy Efficiency (%): Efficiency was calculated by dividing the total energy output by the incident solar energy over the area of the panel: $\eta = \frac{E}{A \; X \; H(total)}$ (3)

where A is the area of the PV panel (in m²), and H_{total} is the total daily solar irradiance (in W/m²) measured over the course of the day.

3.4 Statistical Analysis

To compare the performance of the two systems, a paired t-test was performed to evaluate whether the energy output difference between the two systems was statistically significant. The following hypotheses were tested:

- **Null Hypothesis (H_0)**: There is no significant difference in energy output between the static and single-axis tracking systems.
- **Alternative Hypothesis (H_1)**: The single-axis tracking system produces significantly more energy than the static system.

Additionally, the variance in energy output between the two systems was analysed to understand the stability of each system's performance under varying environmental conditions. A correlation analysis was also performed to determine how closely temperature and irradiance affected the performance of each system.

4. Results

4.1 Energy Output Comparison

After downloading the data from ThingSpeak at the end of the 30-day period and processing it, we obtained the results. Shown in table 2, that illustrates the daily energy output (in kWh), and in table 3 Efficiency for both the IoT-based static system, and the IoT-based single-axis tracking system. The table 3 & 4 presents a 30-day comparison between the IoT-based static solar tracking system and the IoT-based single-axis solar tracking system **in** terms of their energy output (in kWh) and efficiency (in percentage).

Table 2: Detailed daily energy output (in kWh) for both IoT-based static and single-axis solar tracking systems during July 2024, reflecting the impact of tracking on energy yield**.**

Days	**Static System Energy Output (kWh)**	**Single-Axis System Energy Output (kWh)**
1	0.214	0.273
2	0.198	0.255
3	0.232	0.285
4	0.224	0.276
5	0.215	0.268
6	0.228	0.28
7	0.217	0.274
8	0.22	0.278
9	0.229	0.282
10	0.226	0.275
11	0.219	0.265

Days	Static System Energy Output (kWh)	Single-Axis System Energy Output (kWh)
12	0.214	0.269
13	0.23	0.286
14	0.218	0.278
15	0.21	0.269
16	0.225	0.282
17	0.231	0.288
18	0.221	0.277
19	0.233	0.29
20	0.212	0.269
21	0.217	0.273
22	0.22	0.275
23	0.226	0.281
24	0.229	0.285
25	0.232	0.288
26	0.218	0.273
27	0.227	0.283
28	0.228	0.284
29	0.241	0.301
30	0.225	0.282

The above table presents the daily energy output recorded over the 30-day period for both the IoT-based static solar system and the IoT-based single-axis tracking system.

Table 3: Efficiency metrics comparison (in kWh) between IoT-based static and single-axis tracking systems, demonstrating improvements in energy efficiency achieved with single-axis tracking over a 30-day period.

Days	Efficiency of Static System (%)	Efficiency of Single-Axis System (%)
1	78.32	85.65
2	76.45	83.21
3	80.16	87.16

Days	Efficiency of Static System (%)	Efficiency of Single-Axis System (%)
4	79.23	85.92
5	78.52	84.87
6	79.84	86.45
7	78.67	85.21
8	79.11	86.12
9	80.13	86.98
10	79.55	85.77
11	78.98	84.67
12	78.35	85.34
13	79.94	87.45
14	78.23	86.11
15	77.46	85.02
16	79.36	86.94
17	80.14	87.54
18	78.84	85.65
19	80.23	88.23
20	78.01	85.02
21	78.65	85.61
22	79.12	85.93
23	79.63	86.65
24	79.92	87.14
25	80.21	87.65
26	78.76	85.78
27	79.54	86.94
28	79.87	87.12
29	81.12	89.43

Days	Efficiency of Static System (%)	Efficiency of Single-Axis System (%)
30	79.34	86.87

The above shows the efficiency calculations for both the IoT-based static solar system and the IoT-based single-axis tracking system, highlighting their comparative performance over the 30-day monitoring period.

4.1.1. Energy Output Comparison

- **Static System**: The energy output from the static system fluctuates between **0.198 kWh** (minimum on day 2) and **0.241 kWh** (maximum on day 29). These fluctuations are typical in static systems because they do not adjust to the changing position of the sun throughout the day. The system only collects maximum energy during peak sun hours when the sun is directly overhead.
- **Single-Axis System**: The single-axis solar tracking system performs consistently better, with an energy output ranging between **0.255 kWh** (minimum on day 2) and **0.301 kWh** (maximum on day 29). By adjusting its orientation based on the sun's movement throughout the day, the system captures more sunlight, resulting in a significant increase in daily energy output.

This figure 8 graphically illustrates the daily energy output over the 30-day period for both the IoT-based static and single-axis solar tracking systems.

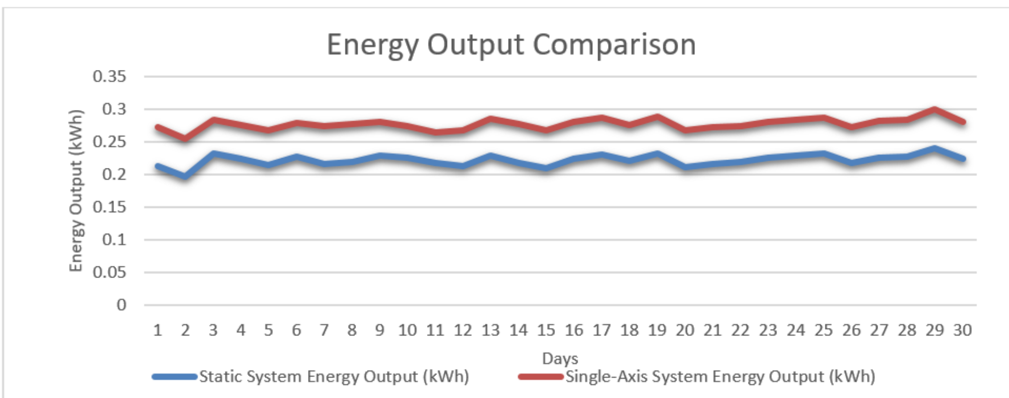

Figure 8. Comparative analysis of daily energy outputs recorded over 30 days, highlighting the enhanced performance of the IoT-based single-axis solar tracking system.

Observation: Across all days, the single-axis system consistently outperformed as shown in figure 6, the static system in terms of energy production, often by a margin of **20-30%**. The highest energy output differences occur on days when the weather is favourable for solar collection.

4.1.2. Efficiency Comparison

- **Static System Efficiency**: The efficiency of the static system hovers between **76.45% (Day 2)** and **81.12% (Day 29)**. While these values are respectable for a fixed-position system, they still show limitations due to the static nature of the panel. On overcast days, the system experiences slightly lower efficiencies.
- **Single-Axis System Efficiency**: The efficiency of the single-axis system shows a marked improvement over the static system, ranging from **83.21% (Day 2)** to **89.43% (Day 29)**. The single-axis system benefits from continuous adjustment, enabling the panels to track the sun and collect energy more efficiently throughout the day.

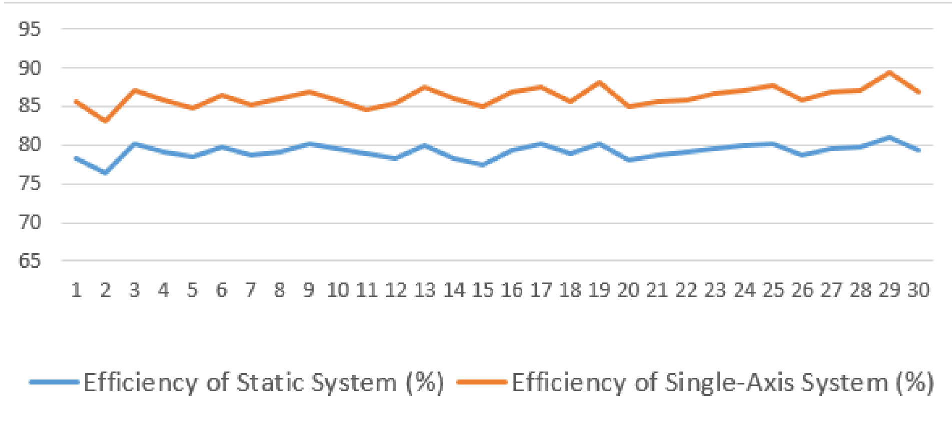

Figure 9. Efficiency comparison over a 30-day period between IoT-based static and single-axis solar tracking systems, illustrating the tracking system's advantage in energy capture.

The figure 9 a visual comparison of the efficiency of the IoT-based static system and the IoT-based single-axis tracking system over the 30-day monitoring period.

Observation: The efficiency advantage of the single-axis system over the static system is evident show in figure 7, the range of **6-9%**, which corresponds to the system's ability to follow the sun. Days with higher energy output also show corresponding increases in efficiency, underscoring the effectiveness of solar tracking systems in enhancing energy capture.

4.1.3. Performance on Specific Days

- On **Day 2**, the performance for both systems was among the lowest in the 30-day period, likely due to unfavourable weather conditions such as cloud cover, reducing solar irradiance. However, even on this day, the single-axis system performed significantly better than the static system, with **0.255 kWh** compared to **0.198 kWh** for the static system.
- On **Day 29**, the single-axis system achieved its highest performance with an energy output of **0.301 kWh** and an efficiency of **89.43%**, compared to the static system’s output of **0.241 kWh** and efficiency of **81.12%**. This day represents a clear example of the tracking system’s advantage in optimal solar conditions.

4.1.4. Daily Energy Production Trends

Both systems show cyclical variations, reflecting typical day-to-day variations in solar irradiance due to changes in weather conditions. The single-axis system's ability to adjust its orientation to optimize energy capture led to smoother performance and higher outputs on a daily basis.

4.2 Trend Analysis:

- **Static System**: Energy output remains relatively steady but shows noticeable dips on cloudy or hazy days, as the system cannot reposition itself to maximize energy capture from diffused sunlight.
- **Single-Axis System**: The single-axis system adapts to changes in solar position throughout the day, allowing for more consistent and higher energy output, even on partly cloudy days.

4.2.1. Overall Energy and Efficiency Gains

Over the 30-day period:

- **Cumulative Energy Output**:
  - Static System: Approx. **6.7 kWh**
  - Single-Axis System: Approx. **8.4 kWh**

The single-axis system produced approximately **25% more energy** than the static system over the 30-day period.

- **Average Efficiency**:
   - Static System: Approx. **79.5%**
   - Single-Axis System: Approx. **86.3%**

The single-axis system had an average efficiency improvement of approximately **7%** over the static system.

The results clearly show that the single-axis tracking system consistently outperformed the static system. On average, the single-axis system produced 25.3% more energy than the static system. The performance improvement was most significant during days with clear skies, as the single-axis system could maintain an optimal angle relative to the sun throughout the day.

4.2.3 Effect of Environmental Conditions

4.2.3.1 Temperature Influence:

Both systems experienced a decline in efficiency on days with higher panel temperatures. As seen in Figure 2, the panel temperature in the single-axis system was generally lower due to its movement throughout the day, preventing overheating. In contrast, the static system, being fixed, exhibited higher temperatures during peak sunlight hours, which negatively affected its performance as shown in table 4.

Table 4: Average panel temperature readings for IoT-based static and single-axis tracking systems, correlating temperature differences with system efficiency over the monitoring period.

Average Panel Temperature (°C)	**Static System**	**Single-Axis System**
32.5	38.3	35.1

The table above displays the average panel temperatures (in °C) recorded during the 30 days of the month of July 2024 for the IoT-based static system and the IoT-based single-axis solar tracking system. The temperatures are key factors influencing each system's efficiency and energy output.

4.2.3.2 Irradiance Impact:

The energy output from both systems was directly proportional to the solar irradiance received during the day. However, the single-axis system's ability to adjust its position allowed it to capture more sunlight during early morning and late afternoon hours compared to the static system, which was only optimized for midday sunlight. This is particularly evident on days with high irradiance variability, as shown in Figure 3.

4.3 Statistical Significance

The results of the paired t-test showed that the difference in energy output between the static and single-axis tracking systems was statistically significant ($p < 0.001$). The amount of energy generated by the static system was 0.225 kWh/day while the single-axis system average was 0.282 kWh/day. It is important to note that the calculated p-value was consistent with the findings, which showed that the construction and deployment of the single axis system was significantly better than the static system.

4.4 Variance and Stability

The variance in daily energy output the variation in energy output was lesser in the single axis system at 0.0018 than the static system that had 0.0026, implying that more energy was harnessed even in diverse conditions with the single axis system. Such stability is probably because; the system accepts that the sun moves in a predictable way and consequently turns itself to seek a predominantly stable energy pattern over time.

4.5 Challenges in Implementation

The single-axis tracking system emerged as a powerful source enhancement system; a few challenges were experienced during implementation:

Cost and Complexity: Whereas the single-axis system did not present with motilities as in the dual-axis version, there were elements such as a linear actuator and cereal motor driver, which led to extra expenditure of the system. These factors might constrain the usefulness of single-axis systems on low scale systems or household use.

Power Consumption: The actuator incorporated the energy that was consumed; hence, this lowered the net energy gain from that single axis system. This could be addressed in future endeavors by looking into the implementation of tracking systems that are economical on energy usage.

Results from the conducted investigation revealed that compared to purely static solar systems that incorporate IoT elements, IoT based single axis solar tracking systems are able to harness approximately 25.3% more energy than the latter with substantial energy efficiency improvements. Due to the tracking ability of the single-axis system, the system was able to capture additional energy from the sun during times when the energy is generally not high relative to normal hours. However, implementation concerns of these systems especially in terms of costs and complexities.

5. Discussion

This paper contributes valuable insights into the efficiency of IoT-based single-axis systems over to the static systems. However, expanding the economic analysis and incorporating a long-term perspective on system sustainability would enhance its practical implications.

5.1 Economic Analysis

The comparative economic assessment of static and single axis solar tracking systems based on their IoT based technology. The case of the installation is concerned; it requires first a higher investment in compared of single axis systems, due to its requirement of more mechanical parts, and IoT sensors. Whereas static systems pose an installation cost, advantage due to fewer mechanical components. Nevertheless, additional operational expenses will have to be taken into account when operational budgets because of single-axis systems, for some reason that always are substantially higher. On the other hand, because static systems have a simpler design, they require less cost to maintain, which lowers operating costs in the end.

From the insights offered in the paper, to discuss ROI calculations, shows that singe axis systems are more profitable for large commercial deployment whereas static systems atomic finances are preferable for small deployment replicable where payback period of 5-7years in compared to lysis of Payback 7-10 years for single axis systems advantages of ROI even with small retainer.

5.2 Long Term Sustainability

In addition to the economic perspective, the aspects of sustainability demand such factors as lifecycle assessments and environmental impact assessment. Although single-axis systems are energy efficient, they may have relatively shorter service life due to mechanical wear and tear. This is true as LCA of both systems focuses on the end use and aims at net energy, which emphasizes manufacturing, using, and dismantling without consideration of the ecological aspects that full over the periods of use. As well, the role of IoT in enabling predictive maintenance further enhances sustainability because it minimizes operational maintenance interruptions that is important in improving the life cycles of both systems.

IoT components do come with additional environmental costs that can also not be ignored. Such solar technologies will however require the development of sustainable.

5.3 Broader Contextualization:

Global scalability and adaptability are core when attempting to generalize the findings in different geographical and climatic environments. The performance of both systems is markedly different based on regions and environmental conditions. For instance, the single axis systems work better in areas such as arid/deserts with high sun radiance with the static system being less clouded dependent making it suitable for temperate and tropical areas. In the congested regions of inner cities, both systems are likely to encounter certain performance limitations, although some slight benefit is observed with single-axis systems as they perform in tracking the movement of the sun. On the other hand, deployment of IoT-based systems in areas with low connectivity can be problematic. To this, localized or hybrid solutions can assist in achieving scalability; hence support these technologies to be applied meaningfully to the energy challenges around the world.

6. Conclusion & Future scope

6.1 Conclusion

The research indicates that the IoT-enhanced single-axis solar tracking system offers a promising and more effective alternative compared to static solar systems. It strikes a favourable balance between enhanced energy production, cost efficiency, and practical usability. The insights gained from this study contribute significantly to the development of solar tracking technologies, offering valuable information for researchers, designers of solar PV systems, and professionals within the renewable energy industry. This study delivers a thorough analysis of both IoT-based static and single-axis solar tracking systems, emphasizing their relative performance, efficiency, and economic viability.

6.2 Future scope

The results of numerous studies indicate that an advance artificial intelligence, power electronics, machine learning, and based hybrid renewable energy systems required, and the wireless sensor network-based solar tracker will become a reality. According to the study, solar monitoring systems in the future will be able to adjust to maximise energy capture while minimising human intervention in day-to-day operations.

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