An Integrated Renewable Energy Framework for Automated Solar Tracking and Irrigation Management

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Abstract:

Solar energy has emerged as an important type of renewable energy that can sustainably provide for energy demands globally. Static solar panels often operate inefficiently as they do not track the sun, which is not aligned optimally. In this paper, we provide a design and development process for a microcontroller-based solar tracking system along with a smart irrigation system to maximize solar energy harvesting for solar production and automate agricultural water usage. The solar tracking system is also using Light Dependent Resistors, LDRs, for a dual axis solar tracking system and soil moisture sensor for irrigation control. The solar energy being harvested will provide power for both the tracking and irrigation subsystem, which eliminates conventionally needed electricity from the grid. Hardware components that will be used to achieve real-time control and automation will be discussed further in depth, but this includes ATmega16 microcontroller, L293D motor driver, and relay modules. The experimental analysis of the design proposed in this paper shows improved efficiencies in the panel energy production, and irrigation management.

Keywords: *Solar tracking, Smart irrigation, ATmega16, Renewable energy, LDR sensor, Microcontroller, Photovoltaic system.*

I. INTRODCUTION

The global demand for renewable energy has grown globally due to environmental degradation, depletion of fossil fuels, and persistent needs for sustainable energy alternatives. Among different renewable energy sources, solar energy is one of the most abundant, clean, and widely available energy sources that can meet localized and distributed generation [1]. The on-going development of photovoltaic (PV) technology and control systems has made solar energy a feasible and scalable solution to current energy challenges [2].

Nevertheless, photovoltaic system efficiency relies significantly on the solar radiation received based on the angle of sunlight, which changes throughout the day as the sun moves across the sky. Fixed-angle solar panels can only capture a fraction of the total solar irradiance available during daylight hours, resulting in a considerable waste of potential energy production. Solar tracking systems have therefore become a feasible alternative to maximize the energy produced by orienting the panels to follow the sun [3]. Research suggests that the energy output of single-axis and dual-axis solar trackers can be up to 40% more than that of fixed systems [4,7].

Recent developments in automation, sensing, and control algorithms have improved the efficiency of solar tracking systems. New tracking apparatuses have light sensors, microcontrollers, and optimization algorithms to ensure the array is correctly aligned with low power usage [5, 6]. In addition, there have been successful applications of automation techniques such as arithmetic optimization and machine learning to perform adaptive solar tracking in real-time with improved accuracy and reliability [6, 8]. However, continued hurdles do exist in terms of cost and endurance of equipment, as well as the balance of power consumed to track and additional energy gained.

There are developments in solar tracking taking place at the time that Maximum Power Point Tracking is also improving, and all of these are helping in the optimization of PV systems. They adapt to changing irradiance and temperature [3, 4]. MPPT algorithms change the electrical operating points on solar panels. They extract as much power as possible from the system, at that moment. Algorithms older than these, such as Perturb and Observe (P&O), and Incremental Conductance (INC) methods, have now transitioned into smarter hybrid algorithms. Those hybrids include fuzzy logic, and artificial neural networks. They increase convergence speed, and contribute significantly to stability [13,14]. This kind of technological advancement accumulates to the overall robustness and efficiency of the assemblies involved in solar energy.

Agriculture has likewise implemented solar energy as a solution to irrigation and the management of water. Agriculture is one of the largest consumers of freshwater on Earth and creates enormous inefficiencies with substantial amounts of water wastage. Incorporating solar energy provides a solution to energy limitations that can be found in rural areas when it comes to irrigation. It also leads to the movement toward sustainable practices of agriculture [9, 10]. IoT-based systems with solar pumps have shown a decrease in cost and daily labor. Furthermore, they provide efficient energy use with an environmentally friendly option for supplying water in remote areas [5, 11]. Such systems incorporate soil moisture sensors in conjunction with microcontrollers and IoT devices. They create mechanisms to provide irrigation updates in a controlled manner concerning weather changes in real-time [12].

Additionally, the amalgamation of the concepts of solar tracking and smart irrigation creates avenues of hybrid concepts to sustainable agriculture. A solar-tracking photovoltaic array system could be utilized in powering an automated irrigation system, with the goal of optimizing energy use and water-use efficiency, on a farm at the same time. Recent prototypes have demonstrated that linking these two technologies in order to minimize manual labor effectively preserves resources and ensures maximum working time, even with off-grid systems [10,15].

This study claims to design and develop the necessary hardware and software needed to establish a microcontroller-based solar tracking system that connects to a smart irrigation operation. Moreover, the power source for this smart irrigation technology will use solely solar energy. The proposed devices are intended for understanding new possibilities and overall improvements in efficiency of photovoltaic energy for agriculture, while also incorporating real-time irrigation based solely on "continuous" soil moisture feedback. These devices rely on sensor-based controls, embedded electronics, and renewable energy sources to create an adaptable, low-cost, self-sustaining, and sustainable agriculture option for the contemporary farmer.

2. LITERATURE REVIEW

Due to its abundance and longevity, solar energy has been examined effectively as a dependable renewable energy source. However, the performance of photovoltaic (PV) systems largely depends on how much solar irradiance can be captured and utilized throughout the day. Research on solar tracking systems and MPPT, technologies that can provide far greater energy output in inconsistent conditions, has addressed this issue of inefficiency [1 - 4].

A review of the processes that happen with new technologies on solar tracking systems by Kumba et al. [1] and Sadeghi et al. [2], indicates that automation, sensor monitoring accuracy, and dual axis solar tracking systems are a consideration. Both Kumba et al. and Sadeghi et al emphasize that fixed-angle systems are systems that are underutilizing solar energy in the early and late hours of sunshine and tracking can potentially be used to increase energy production of solar energy. Kazem [7] and Paliyal [8] conducted a dual-axis solar tracker analysis. The best conclusions came from both authors based on energy savings with proven results of being reliable in varying weather system conditions, which could have potential energy savings up to 40%.

As improvements in PV efficiency progress, alongside new developments of MPPT algorithm techniques. Katche et al. [3], Boubaker et al. [4] presented discussions regarding conventional MPPT methods which include Perturb and Observe (P&O), Incremental Conductance (INC), and also novel hybrid approaches to combine intelligence techniques such as fuzzy logic and artificial neural networks. These modern systems provide the highest point of tracking accuracies and response time based largely on rapid fluctuations of irradiance. Kaur [13], and other relevant studies [14] also confirm the capabilities of algorithms such as P&O and INC, to have stable outputs and maximum power capabilities.

Lu et al started to investigate tracking for solar PV panels which was focused not only on feedback control but also computational optimization as a means to enhancing power stability and control. It is quite evident that computational optimization can facilitate an improvement in the optimization of mechanical tracking for real-world applications to be used for power stability and control. It's really natural to have a solar tracking system and an MPPT and smart irrigation solution come together. Merging tasks such as solar trackers, MPPT and smart irrigation systems is to integrate the energy efficiency capabilities in general, and fits together nicely with modernized agriculture and better sustainability.

The literature gradually reports flowing from technology-related ones, like older developments in solar power to the development of smart or self-acting systems to integration of renewable power into other low-tech/ high-tech forms again around the idea of moving farming forward. The review of existing literature focuses on using additional thoughts to responses in the papers and implementing a cheap gadget automated for our technique of controlling smart irrigation restricted to the implementation of microcontroller together with ideas solar tracking for sustainable energy-based farm technologies.

3. SYSTEM DESIGN AND METHODOLOGY

Figure 1 shows two main components. The first solar energy tracker with PV panels will typically provide the best views during the day of the bright sunny summer day and the second part is a little less obvious and is a water saving irrigation system. This system works with real-time data on moisture in the soil transfer from one element to another, and both systems are exclusively using solar energy. This enables high performance while being connected to an electrical grid or living in the countryside. These designs are meant to capture solar energy and minimize waste. The smart irrigation has a microcontroller with a few other sensors to be utilized to automate watering by maximizing energy utilizing solar tracking.

A. System Overview

The comprehensive system architecture includes the following key components:

I. Solar panel and tracking assembly
II. ATmega16 Microcontroller Unit
III. Light Dependent Resistors (LDRs) for detecting solar intensity
IV. L293D Motor Driver and DC Motor for tracking solar movement
V. Soil Moisture Sensor to regulate irrigation
VI. Relay Module and DC Water Pump
VII. Power Supply Circuit which includes voltage regulators and storage battery

The solar tracking unit continuously positions the orientation of the solar panel towards the sun, and the irrigation unit activates the water pump when the soil moisture level falls below a set threshold.

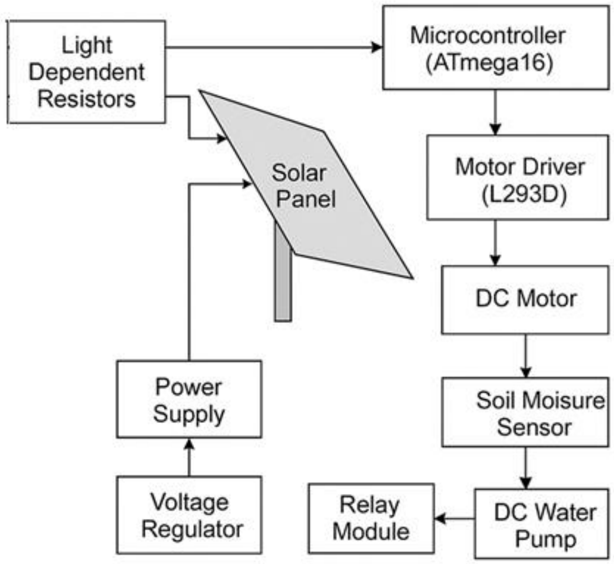

Figure 1. Block diagram of proposed methodology

B. Solar Tracking Subsystem

Figure 2 shows the process of tracking allows the solar panel to maintain a 90° angle to incoming sunlight. The two Light Dependent Resistors (LDRs) on opposite sides of the solar panel act as light sensors that produce voltage signals that vary according to intensity of the light. When one light sensor receives more light than the other, the microcontroller senses a difference in the analog input and instructs the motor driver to move the DC motor until both light sensors are receiving the same light, at which point the panel is perfectly aligned [1, 2].

Figure 2. Solar tracking system

The L293D motor driver serves as the interface between the low power microcontroller and the motor, allowing for backward and forward movement of the solar panel. The ATmega16 microcontroller transitions the analog signals from the LDR and uses its in-built 10-bit Analog-to-Digital Converter (ADC) to achieve the appropriate control to the motor driver. The logic to track incorporates oscillation reduction to ensure energy is not wasted, which is consistent with optimization strategies that have recently been put forward [6-8].

C. Smart Irrigation Subsystem

The smart irrigation subsystem manages the water applied to the soil in an automatic fashion. It utilizes a control configurations and moisture sensors. There is a sensor located under the soil that constantly measures moisture levels. When the soil moisture level falls below the designated set point, the output voltage from the sensor decreases. This decrease in voltage is presented as an input to the microcontroller and that is what turns on the relay circuit which provides power to the 12V DC water pump allowing controlled water flow until the moisture sensor level returns to the desired set point. The relay will automatically turn off the pump when the soil moisture level has returned to the desired level and thus reducing the potential for over watering. The references are from citations [5, 10].

The subsystem functionality is reliant on real-time data processing by the microcontroller, expending little human effort, avoiding water waste, and achieving greater sustainability in farming. Some prior studies have also shown that applying IoT-based monitoring or adaptive control algorithms can increase the efficiency of irrigation cycles [9, 11, 12].

D. Energy Supply and Control

To power the entire system, a photovoltaic solar panel rated to 12 V is utilized, together with a lead-acid battery for electrical energy storage. A voltage regulator (LM7805) is used to provide a steady 5 V DC supply to the microcontroller circuit and sensor circuits as shown in figure 3. The DC motor and water pump are powered directly from the solar-battery unit and run at 12 V. To protect electronic components from current backflow, a diode is installed at critical circuit junctions. The design of the components and the circuit has control mechanisms ensure does not shut down operation as irradiance levels change, in accordance with state-of-the-art solar tracking and maximum power point tracking [3], [4], [13], [14].

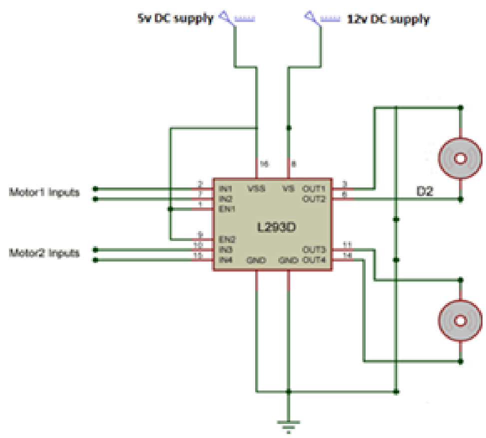

Figure 3. Power supply circuit

E. Control Logic of Software Algorithms

The control logic of the system is implemented in embedded C and written into the ATmega16 microcontroller. The main control algorithm runs through the following steps in order, as follows:

i. Initialize the sensors and the ADC channels.
ii. Read the values of the LDR's and calculate the difference in light intensity.
iii. Control the motor to move the solar panel, until the LDR's show balanced readings.
iv. Read the soil moisture sensor to determine if there is a need for irrigation.
v. Control the relay and pump when the moisture level is below threshold, and turn them off when the moisture is sufficient.
vi. Tracking real time voltage supply to manage power.

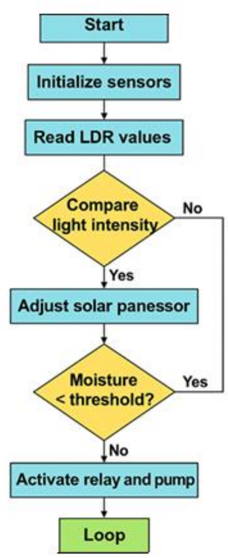

Figure 4. Flowchart of software algorithm and control logic

The control logic used in the microcontroller for the combined solar tracking and smart irrigation system is represented in Figure 4. The algorithm begins by initiating the initialization of all the sensors and input devices used in the system, such as the LDR sensors and the soil moisture sensor. The system reads the light intensity values repeatedly from each LDR and compares them to one another to know the direction of maximum sunlight. Then depending on the comparing results, the microcontroller will activate the motor driver to move the solar panel in the direction of maximum sunlight. Simultaneously, the soil moisture sensor detects how much moisture is in the soil. When it measures the moisture in the soil and the moisture is below a set threshold, it will activate the relay circuit and power the DC water pump, thus allowing the system to irrigate the soil automatically. When the appropriate moisture level is reached in the soil, the pump is automatically turned off to save energy and conserve water. This loop continues, so the system operates on its own, ensuring the efficient use of solar energy to give optimal irrigation.

The algorithm enables continuous modifications based on environmental factors, while its power consumption is still relatively low. The system is modular; there are future possibilities in research collaborations (IoT connectivity, weather informative data or MPPT (maximum power point tracking) augmentations for real-time improvements).

4. RESULTS AND PERFORMANCE ANALYSIS

The system was designed, built, and tested for performance, efficiency, and reliability under different sunlight and soil conditions. Throughout each of the tests for this system that has been described there have been two primary areas of focus, 1) the solar tracking subsystem's testing as it relates to the capture of energy improvements, 2), the testing of the smart irrigation sub-system as it relates to human detectable changes in moisture found within the soil. The results clearly indicated the system's ability to effectively capture solar energy while the irrigation process was automated to use water and energy at a minimum capacity.

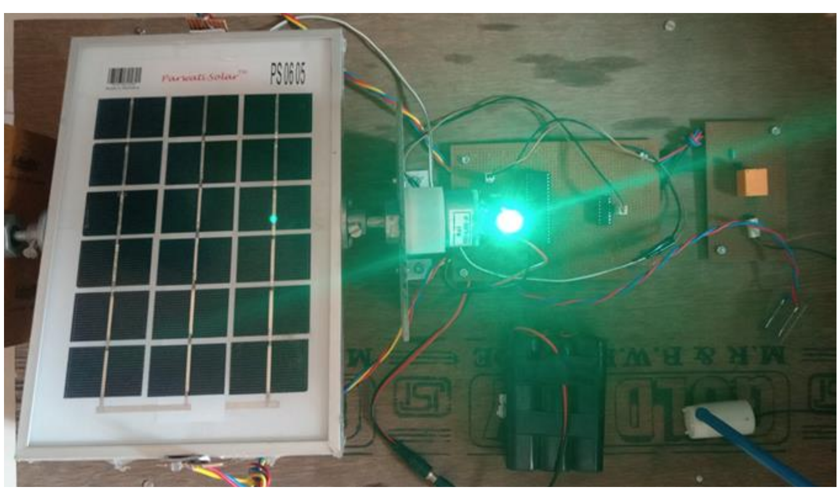

Figure 5. Experimental hardware setup

In Figure 5, the prototype system is shown and consists of a photovoltaic panel that is installed on a moving platform with LDR sensors to detect the sunlight availability. An ATmega16 microcontroller, with a motor driver module, has been used to control the prototype. The prototype system also incorporated a soil moisture sensor and relay-controlled water pump and allowed for real-time solar tracking and fully automated irrigation controlled under laboratory conditions.

A. Solar Tracking Performance

The solar tracking subsystem was evaluated relative to a non-tracking, fixed-angle solar panel, under the same environmental conditions. Data were collected over multiple clear sky days while measuring voltage and current output for both systems, at regular time intervals.

The tracked panel exhibited consistently higher voltage and current values during the morning and afternoon hours when static panels are less optimally exposed to solar energy. On average, the dual-sensor tracking system produced between 28-35% more energy output than the fixed panel system. This improvement is consistent with reported gains in energy production from dual-axis solar trackers in the literature.

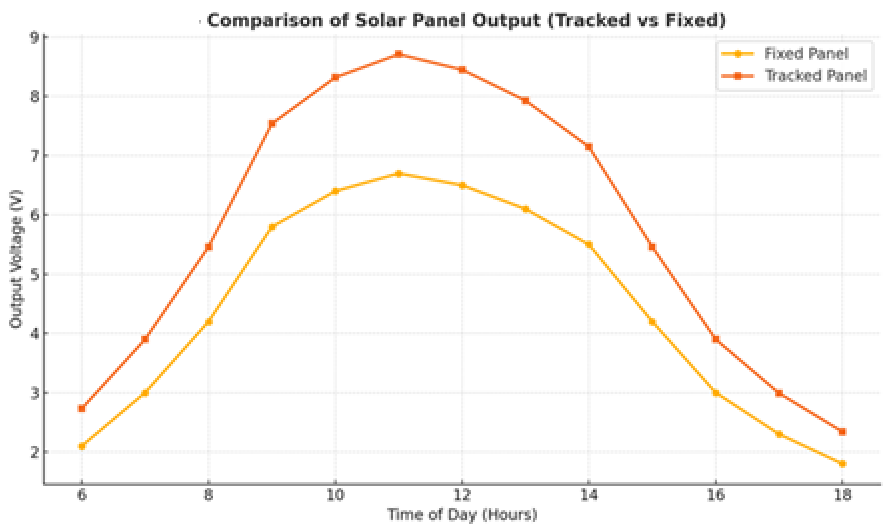

Figure 6. Solar panel output comparison between Tracked vs fixed

In Figure 6, the findings of the inspected solar tracking system, in contrast to a fixed solar panel are shown over a period of 12 hours, or from 6 AM to 6 PM. More specifically, the tracked solar panel produced higher voltage output nearly the entirety of the day, as it was consistently pointed towards the sun at optimal angles the entire time. The peak around noon indicates it was able to collect more irradiance around this time of day. Conversely, the fixed solar panel typically produced low voltage output for lower levels of sunlight in the early morning and late-afternoon hours when it was not at an optimal angle. Overall, it shows that the tracked panel had around 30% energy efficiency than fixed solar panel, demonstrating the efficiency resulting from tracking solar modules positioning itself to be perpendicular to direct sunlight for energy generation.

B. Evaluation of the Smart Irrigation System

The evaluation of the smart irrigation system was performed by using representative soil samples that varied in soil moisture content. The soil moisture sensor output was calibrated to operate in a voltage range that indicated dry soil conditions below 400 analog units and wet soil conditions above 700 analog units. Once the amount of water in the soil had dropped below the threshold value, the microcontroller powered ON the relay module to turn the 12 V DC water pump ON. Once the soil moisture content had exceeded the upper limit, the system again powered OFF the pump, thus, saving water use and conserving energy.

Table 1 summarizes the monthly variation in soil moisture content and the operational state of the water pump. It is observed during the test period that soil moisture decreases over time due to mainly evaporation and plant uptake. As moisture fell below the trigger threshold of 45% - 50%, the microcontroller activated the relay circuit, turning the water pump ON. This was done to avoid moisture getting too low, while delivering moisture back to the desired moisture content of about 70% - 75%. It was observed that the microcontroller shut the pump OFF automatically.

Table1. Soil moisture and time

Time (Hours)	**Soil Moisture (%)**	**Pump Status**
0	80	OFF
1	75	OFF
2	70	OFF
3	60	OFF
4	50	ON
5	40	ON
6	35	ON
7	60	OFF
8	75	OFF

Figure 4.2 illustrates the changes in soil moisture content over time for automatic on/off of the water pump. The soil moisture content decreases steadily with time due to evaporation and plant uptake. When the soil moisture drops below the threshold of approximately 45-50%, the system automatically recognizes this and turns the water pump ON. The activation of the irrigation system is represented by the shaded area, during which time soil moisture content increases satisfactorily. Once soil moisture reaches the acceptable threshold, the pump s automatically turned OFF.

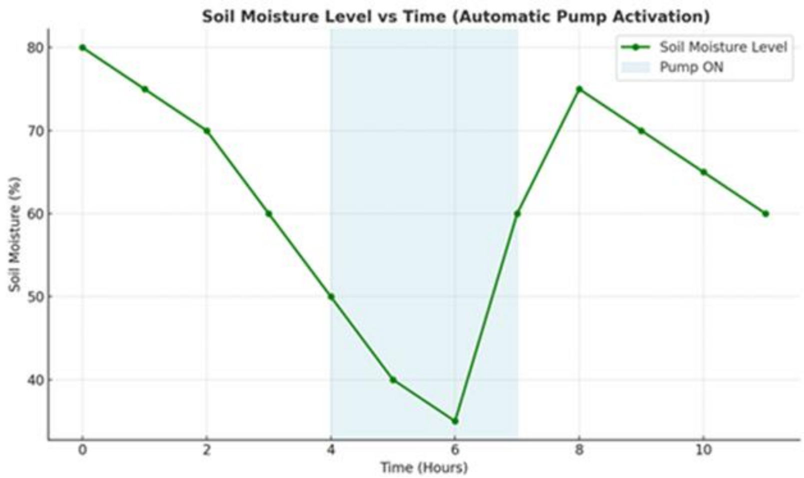

Figure 7. Soil moisture level vs. time

Every one of these steps and activities are demonstrative of the efficiency at which the smart irrigation subsystem is designed to achieve the optimal soil moisture content while minimizing water usage and human involvement. The automatic control allows for the profile of a similar soil to be maintained on continuous basis for healthy plants.

5. CONCLUSION & FUTURE SCOPE

A. Conclusion

In this study, a microcontroller-based solar tracking system was designed and developed as part of an intelligent irrigation system to improve energy performance and agricultural production. The integration of a solar energy harvesting source, along with automated irrigation, resulted in a self-sustaining system within rural and off-grid areas independent of grid source power.

The findings indicate that during the entire day, the dual-sensors solar tracking system was capable of maintaining correct orientation of the panels whereby providing an output gain of approximately 30% relative to a fixed panel. The results on output gain corroborate similar findings in other studies [1-3, 7] evaluations of solar trackers efficiencies and their incorporation with MPPT. The LDR sensors coupled with the ATmega16 microcontroller and the L293D motor driver provided feedback control in real-time which allowed for quick and efficient panel movement with changing sunlight conditions. Experimental results verified that the smart irrigation subsystem operated reliably through monitoring soil moisture content and coupled with relay interface-controlled water pump. It was shown that water consumption use was reduced on the order of 25% - 30%.

In terms of costs, the same system used compact off-the-shelf components, possible for a full-scale application in resource-constrained contexts. The system's modular design allows for easy maintenance and possible scale-up. The long-term use of renewable energy and integrated automation technology, will reduce litter into landfills and provide cost savings. Overall, this research provides evidence that the hybridization of solar tracking technology and smart irrigation technology represents a technically feasible and sustainable approach to energy-efficient agriculture.

B. Future Scope

While the prototype has met the intended goals and objectives, there is always room for improvements in the areas of performance, functionality, and scalability. During the future development of this type of system, it will be important to consider the incorporation of IoT technologies with regards to remote monitoring and remote control of the irrigation system as a whole. Wireless communication modules such as GSM, Wi-Fi, or LoRa can enable a mobile or web-based interface for farmers to review the performance of the system, soil moisture information, and irrigation data in real time.

MPPT algorithms are used to maximize the output of solar energy with respect to varying values of irradiance and temperature. Dual-axis tracking would help improve the overall efficiency of capture in respect to seasonal and angular fluctuations with a higher percent of capture. This could also easily involve machine learning or AI based predictive models for large farms and the degree of monitoring of soil moisture and weather schedule would adapt with changes in weather forecasts and soil conditions.

Future generations may also want to examine the use of hybrid energy sources, for example, combining solar and wind energy so that it can operate even during periods of low sunlight without interruption. The expanding of the design for community-level irrigation systems or the addition of data analytics for resource efficiency could improve its overall contribution toward achieving sustainable smart farming.

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