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Review Article

Leveraging Solar Energy and IoT for Smart Irrigation: A Sustainable Solution for Indian Agriculture

Rahul kumar Vijaykumar Gupta[1], Vikash Ram Narayan Gupta[2]

[1,2]Research Scholar, Thakur Institute of Management Studies, Career Development and Research (TIMSCDR) Mumbai, India

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Corresponding Author:
Rahul kumar Vijaykumar Gupta, Thakur Institute of Management Studies, Career Development and Research (TIMSCDR) Mumbai, India
E-mail Id:
guptarahulvijay@gmail.com
Orcid Id:
https://orcid.org/0009-0000-4877-6762

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ABSTRACT

The agricultural sector in India is facing significant challenges, including inefficient irrigation practices, water scarcity, and increasing energy costs. Solar-powered IoT-based irrigation systems offer a potential solution to address these challenges. By utilizing solar energy to power irrigation pumps and leveraging IoT technologies to automate irrigation, water usage can be optimized, and energy consumption reduced. This research explores the feasibility of solar-powered smart irrigation systems for Indian agriculture, alongside proposing a digital platform to educate farmers and facilitate access to essential technologies. The paper reviews the current state of irrigation in India, highlights the benefits of solar-powered IoT systems, and identifies the challenges to their widespread adoption. Additionally, the research proposes a digital platform to bridge the gap between farmers' needs and access to technology, thereby enhancing productivity and promoting sustainable farming practices.

Keywords: Smart Irrigation systems, Solar Energy, Internet of Things (IoT), Water Conservation, Sustainable Agriculture

Introduction

India's agricultural sector is central to its economy, but it faces significant challenges, particularly in terms of irrigation. Over 60% of Indian agriculture depends on irrigation systems, yet traditional methods like flood irrigation often waste a considerable amount of water. Moreover, the rising costs of electricity, especially in rural areas, impose additional burdens on farmers. Traditional irrigation systems in Rajasthan can be both inefficient and costly for smallholders already facing unreliable power supplies.[1]

Solar-Powered IoT Smart Irrigation Systems offer a promising alternative: solar energy can drive pumps independently of the grid, and IoT sensors can monitor soil moisture and weather in real time to optimize water delivery. The integration of these technologies can reduce water and energy waste. This paper explores the technical feasibility of solar-powered IoT irrigation in India, and proposes a dedicated digital platform to educate farmers and streamline access to the necessary hardware for system deployment.[1]

Research Background

Solar-powered irrigation systems harness photovoltaic panels to generate the electricity needed for water pumps, eliminating reliance on diesel or unreliable grid connections. In regions with abundant sunlight—such as much of India—these systems can run autonomously, with battery storage providing power during non-sunlight hours. IoT devices (e.g., soil moisture sensors, temperature/humidity gauges, and weather stations) feed real-time data to a controller that activates pumps only when irrigation is required. This closed-loop automation delivers precise water volumes, reducing wastage and labor[2,3] (see Fig. 1).

Figure 1.Solar Drip Irrigation system

Integration pilots in Rajasthan and other states confirm the synergy of solar and IoT: they report water-use reductions up to 40% and energy savings of 25–30%.[1,4] A complementary online marketplace and training portal can further lower adoption barriers by offering equipment bundles, how-to guides, and remote technical support.

Problem Statement

India's agricultural sector faces persistent challenges due to outdated irrigation practices, increasing water scarcity, and reliance on non-renewable energy sources. Traditional irrigation methods often lead to inefficient water use, with significant losses. Approximately 40% of water used in irrigation is wasted, worsening water shortages in arid and semi-arid regions.[5]

In addition to water inefficiency, the energy required to operate irrigation systems—especially electric and diesel-powered pumps—places a financial strain on farmers. Rising energy costs have become one of the largest financial burdens for rural farmers in India, compounded by unreliable grid electricity.[6,7]

Although sustainable alternatives like solar-powered and IoT-based irrigation systems exist, their adoption remains limited. Barriers include high initial investment, lack of awareness, insufficient technical knowledge, and limited access to affordable solutions. The cost of solar panels and IoT infrastructure is a key deterrent, especially for small-scale farmers who form the majority of India's agricultural workforce.[8,9]

Beyond economic and technical hurdles, other factors such as intermittent solar supply during monsoons, inadequate energy storage solutions, data management and security concerns, and low digital literacy in rural areas further hinder adoption.

This research investigates how solar-powered IoT irrigation systems can address these interconnected issues. It also explores the development of a comprehensive digital platform integrating:

E-commerce for easy access to irrigation technologies

- E-learning modules to train farmers on usage and maintenance
- Remote diagnostics and monitoring tools for ongoing support
- The goal is to empower small-scale farmers with sustainable, affordable, and easy-to-use solutions to optimize water usage, reduce energy dependence, and enhance agricultural productivity.

Research Objectives

This paper aims to:

- Examine the role of solar energy and IoT technology in optimizing water usage for agricultural irrigation.
- Explore the potential of Information Technology in reducing energy consumption and operational costs for farmers.
- Evaluate the economic, environmental, and productivity impacts of solar-powered, IoT-based irrigation systems.
- Identify barriers to the adoption of these technologies and propose strategies to overcome these challenges, focusing on small-scale farmers in India.

This study adopts a qualitative research methodology to evaluate the effectiveness of solar-powered smart irrigation systems. The data will be sourced from field studies, government reports, and interviews with farmers, agricultural experts, and stakeholders involved in solar irrigation initiatives.

Data Collection

Analysing reports from government agencies like the Ministry of New and Renewable Energy (MNRE) and NABARD, which have funded and promoted solar irrigation systems Development of Digital Platform: The research also involves designing a conceptual model of a digital platform that will educate farmers about solar-powered irrigation systems and provide easy access to products such as solar panels, IoT sensors, and automation tools. Impact Analysis: Analyzing the potential impact of solar-powered IoT irrigation systems on water conservation, energy savings, and crop yield improvements. The research will also assess the financial feasibility of implementing such systems for small-scale farmers.

Literature Review

The integration of solar energy and IoT technologies in agriculture is gaining momentum as a sustainable solution to challenges such as water scarcity, rising energy costs, and inefficient irrigation practices. This section highlights key findings from recent studies.

Solar Energy in Irrigation

India's solar irrigation efforts have expanded significantly under the PM-KUSUM scheme, with thousands of solar-powered pumps deployed nationwide [10]. Such systems can reduce farmers' energy bills by up to 50% and cut CO_2 emissions by 30%, demonstrating both economic and environmental advantages (see Fig. 2).[11]

Figure 2.IoT in Agriculture

IOT in Agriculture

IoT technologies have transformed precision agriculture by enabling real-time monitoring and data-driven decision-making. Systems using soil moisture sensors and mobile alerts can increase yields by 15–20% while conserving water, particularly in regions with erratic rainfall patterns.[12]

Synergy of Solar and IoT in Agriculture

Combining solar power with IoT leads to smarter, sustainable irrigation systems. Integrating solar pumps with LoRaWAN-based IoT sensors resulted in a 35% decrease in water use and a 20% drop in pump runtime.[13] This model was further validated in off-grid Himalayan farms, proving that these systems are viable even in the most remote agricultural settings.[14]

Iot And Solar Integration In Irrigation

The fusion of solar energy and IoT in modern irrigation systems is revolutionizing agricultural practices. These systems comprise multiple interconnected components that enable autonomous, efficient, and sustainable water management

Solar Panels

Photovoltaic arrays ranging from 1–5 kW convert sunlight into electricity to power water pumps. This minimizes dependence on diesel or grid electricity, making them particularly valuable in off-grid or remote areas. Their environmental benefits also support India's renewable energy goals (see Fig. 3).

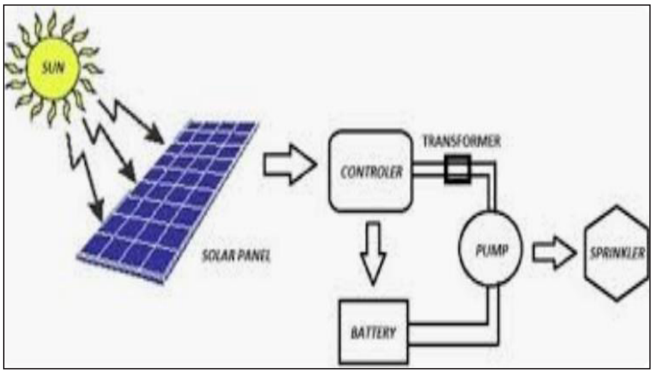

Figure 3.Solar powered water pumping system for Irrigation

Battery Storage Systems

To ensure continuous operation during nights or overcast conditions, solar irrigation setups incorporate lithium-ion or lead-acid batteries with a capacity of 10–20 kWh. These systems store surplus solar power generated during the day, allowing pumps to function consistently regardless of solar availability.

IoT Sensors

The system includes a network of sensors—such as soil moisture probes, ambient temperature and humidity sensors, and local weather monitors. These sensors gather and transmit real-time data to a central controller, enabling accurate irrigation decisions based on environmental conditions.

Automated Controllers

An embedded controller (CPU) interprets sensor data and triggers irrigation automatically. When soil moisture levels fall below a predefined threshold, the system activates the water pump, ensuring timely and precise irrigation without human intervention.

Cloud Computing and Data Analytics

Sensor data is transmitted to the cloud, where it is analyzed and visualized through dashboards accessible via mobile and web apps. These platforms enable:

- Predictive analytics for irrigation scheduling
- System diagnostics and alerts
- E-commerce functionalities for ordering replacement parts or equipment upgrades

This architecture empowers farmers to remotely monitor and manage their irrigation systems, enhancing both convenience and efficiency (see Fig. 1 and Fig. 2).

Benefits Of Solar – Powered Iot Smart Irrigation Systems For Indian Agriculture Water Conservation

By leveraging real-time data from IoT sensors, these systems ensure that irrigation is applied only when necessary, reducing water wastage. In regions suffering from water scarcity, this can lead to more efficient use of available water resources, benefiting both farmers and the environment.

Energy Saving

Solar-powered irrigation systems eliminate the need for grid electricity or diesel-powered pumps, significantly reducing energy costs for farmers. With solar energy being free and abundant, these systems provide a long-term, cost-effective solution for irrigation in rural areas.

Improve Crop Yield and Productivity

The precision offered by IoT-enabled irrigation systems ensures that crops receive the optimal amount of water at the right time, leading to improved crop health and higher yields. By automating irrigation, farmers can focus on other aspects of crop management, improving overall productivity.

Economic Sustainability

By reducing operational costs associated with energy consumption and water usage, these systems enhance the financial sustainability of farming operations. The initial investment in solar-powered, IoT-based systems can be offset over time through savings on energy and water costs.

Environmental Sustainability

The use of renewable solar energy and the reduction of water wastage contribute to the environmental sustainability of farming operations. By reducing the carbon footprint of agriculture, these technologies support India's broader environmental goals.

Studies Of Solar – Powered Iot Irrigation In India

The integration of solar-powered systems with IoT technologies is being successfully implemented in various Indian states, demonstrating the viability and benefits of smart irrigation solutions across diverse climatic and agricultural conditions.

Gujrat

Under the PM-KUSUM scheme, Gujarat has installed over 2,000 solar pumps equipped with IoT add-ons in regions like Saurashtra and Kutch. These systems enable automated irrigation based on real-time soil moisture data, resulting in 30% cost savings for farmers. Enhanced water efficiency and reduced dependence on diesel pumps have also led to improved crop yields and more sustainable farming practices.[15]

Maharashtra

Maharashtra has seen the successful implementation of solar-powered, IoT-based irrigation systems in the drought-prone Marathwada region. IoT sensors are used to monitor soil moisture levels, and irrigation is triggered only when necessary. This approach has significantly reduced water wastage and electricity costs, leading to higher crop productivity and better water management.

Rajasthan

In Rajasthan, solar-powered irrigation systems have been integrated with IoT technology to help farmers manage water usage in areas facing acute water scarcity. The system uses weather forecasting data and soil moisture sensors to predict irrigation needs and ensure water is applied only when needed. The system has helped farmers in Rajasthan achieve better water conservation and higher crop yields, especially in arid regions.

Tamil Nadu

Tamil Nadu has also been a leader in implementing solar-powered irrigation systems, especially in areas with unreliable power supply. The state has partnered with various IT companies to integrate IoT sensors into the solar irrigation systems. The IoT-based systems are able to send real-time data to farmers via mobile apps, allowing them to adjust irrigation schedules remotely. This has resulted in more efficient water usage and reduced energy costs.

Challenges And Barriers

Despite the promising benefits, the adoption of solar powered, IoT-based irrigation systems faces several challenges:

- **High Initial Costs:** The upfront cost of installing solar panels, IoT sensors, and automation systems can be a barrier, particularly for small-scale farmers. Financial subsidies, government support, and microfinance schemes can help mitigate these costs.
- **Technical Barriers:** The lack of technical expertise to operate and maintain solar-powered IoT systems is another challenge. Training programs and technical support services are essential for the successful implementation of these systems.
- **Intermittency of Solar Power:** Solar energy is dependent on sunlight, which can be inconsistent during cloudy days or the monsoon season. Hybrid systems that combine solar energy with battery storage can address this issue
- **Data Management and Security:** The reliance on IoT technology means that large amounts of data are generated and transmitted. Managing this data efficiently and ensuring its security is crucial, as any breach or system failure could lead to inaccurate water management or misuse of resources
- **Awareness and Adoption:** Farmers' lack of awareness about the potential benefits of these technologies can slow adoption. Awareness campaigns and demonstration projects can help increase adoption rates.

Conclusion

Solar – powered IoT-based irrigation systems present a viable solution to address water scarcity and high energy costs in Indian agriculture. The integration of solar energy with IoT technology not only improves water use efficiency but also offers significant savings in energy consumption. However, to ensure widespread adoption, there is a need for education and accessible platforms that provide farmers with the necessary tools and information. The creation of a digital platform dedicated to educating farmers and selling these products could be a key factor in overcoming the barriers to adoption and ensuring the sustainability of Indian agriculture.

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