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Solar energy applications in agriculture: Design, implementation, and performance of a solar-powered irrigation system

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Abstract
The increasing demand for sustainable energy solutions in agriculture has intensified interest in solar photovoltaic (PV) systems, particularly for irrigation and rural electrification. Agriculture in developing countries faces persistent challenges such as unreliable grid supply, high diesel costs, and environmental degradation. This study presents the design, working principle, and practical implementation of a solar-powered agricultural system, with emphasis on solar water pumping, battery charging, and auxiliary loads such as water level indicators and lighting. The proposed system integrates photovoltaic panels, charge controllers, energy storage, and DC motors to deliver an efficient and environmentally friendly solution for irrigation. Performance analysis indicates that solar-powered irrigation systems significantly reduce dependency on fossil fuels, operating costs, and carbon emissions while ensuring reliable water supply. The study highlights technical feasibility, economic viability, and environmental benefits, making solar energy a promising alternative for sustainable agricultural development.

Keywords: Solar photovoltaic systems, agriculture, irrigation, renewable energy, solar water pumping

1. Introduction

Energy availability plays a pivotal role in agricultural productivity, particularly in irrigation, mechanization, and post-harvest processing. In many rural and semi-urban regions, conventional electricity supply remains unreliable, while diesel-based pumping systems impose high operational costs and environmental burdens. Solar energy, owing to its abundance, renewability, and declining technology costs, has emerged as a viable alternative for agricultural applications (Syam & Arafa, 2023; Wamalwa *et al*., 2024) [13, 16].

India and other sun-rich countries receive an average solar radiation of 4-7 kWh/m²/day with more than 250 sunny days annually, making solar energy especially suitable for decentralized agricultural power generation (Khan *et al*., 2024; Yadav *et al*., 2024) [7, 17]. Solar-powered irrigation systems convert sunlight directly into electrical energy to drive water pumps, ensuring uninterrupted water supply during critical cropping periods. Unlike fossil-fuel-based systems, solar irrigation operates with minimal maintenance and zero fuel cost, thereby improving farm-level energy security. (Gupta *et al*., 2023; Liang *et al*., 2023; "The Use of Solar Energy in Irrigated Agriculture," 2022; Wamalwa *et al*., 2024) [5, 9, 4, 16]. The present study restructures the work into a scholarly format, expands the theoretical context, and situates the system within contemporary research on renewable energy in agriculture.

This shift towards sustainable energy solutions in agriculture is driven by the imperative to enhance water use efficiency and reduce the carbon footprint associated with traditional farming practices (Daraz *et al*., 2025) [2]. Globally, agriculture accounts for approximately 70% of freshwater withdrawals, exacerbating issues of water wastage and energy overuse through traditional irrigation methods (Daraz *et al*., 2025) [2]. Moreover, the escalating global population necessitates increased food production, placing immense pressure on existing agricultural systems and underscoring the urgency for innovative, sustainable irrigation solutions (Abdelhamid *et al*., 2025) [1]. The economic and environmental benefits of photovoltaic-powered pumping for crop irrigation are substantial, offering a sustainable alternative to fossil fuels that contribute to climate change and air pollution (Ugbodaga, 2020) [15]. Such systems not only mitigate greenhouse gas emissions but also reduce operational expenses for farmers, enhancing agricultural resilience against fluctuating energy markets (Gorjian *et al*., 2022; Okomba *et al*., 2023) [3, 12]. Furthermore, the widespread adoption of solar photovoltaic pumps has been significantly propelled by decreasing panel costs since the 2000s, positioning them as a critical component in the transition away from conventional diesel or grid-connected pumps due to their cost-effectiveness, energy security benefits, and reduced environmental impact (Jadhav *et al*., 2020) [6].

This paradigm shift in agricultural practices not only addresses water and food security challenges intensified by climate change but also aligns with broader goals of sustainable development by reducing reliance on conventional energy sources (Mghouchi & Udriştioiu, 2025; Michael *et al*., 2021) [10, 11]. This is particularly relevant for small-scale farmers in developing countries, who often lack access to reliable grid electricity and rely on expensive and polluting diesel pumps for irrigation (Guno & Agaton, 2022; Okomba *et al*., 2023) [4, 12].

1.1 The Solar Resource Potential

Solar energy represents a virtually infinite, non-polluting, and inexhaustible energy source capable of meeting the escalating demands of the agricultural sector. India, situated in the favorable "Sun Belt," receives a solar energy equivalent of approximately 5,000 trillion kWh/year, with a daily average solar incidence ranging between 4 and 7 kWh/m². Most regions experience 250 to 300 sunny days annually, making solar photovoltaic (PV) technology not merely a viable option but a strategic necessity for rural energy security.

Recent market analysis indicates a robust growth trajectory for solar water pump systems. The global market size reached $1.69 billion in 2024 and is projected to expand to $2.93 billion by 2029 at a Compound Annual Growth Rate (CAGR) of 11.9%.[3] This growth is propelled by government incentives, the declining cost of PV modules, and the increasing recognition of "Agrivoltaics" the synergistic use of land for both solar energy generation and agriculture as a solution to land constraints.

2. Solar Energy in Agricultural Applications

Solar photovoltaic technology has been widely adopted in agriculture for irrigation pumping, greenhouse climate control, crop drying, fencing, lighting, and remote sensing. Among these, solar water pumping systems represent the most mature and impactful application.

2.1 Solar Water Pumping Systems

A solar water pumping system typically consists of PV panels, a charge controller, an optional battery bank, and a DC or AC motor-driven pump. During daylight hours, the PV array converts solar radiation into DC electricity, which either directly powers the pump or charges batteries for later use. Such systems are particularly beneficial in off-grid regions where extending transmission infrastructure is economically unfeasible.

Studies indicate that solar irrigation systems can reduce diesel consumption by up to 100% and operational costs by over 60% across their lifetime. Additionally, solar-powered pumps align with climate-resilient agricultural practices by minimizing greenhouse gas emissions.

3. System Architecture and Working Principle

The developed solar agricultural system is composed of the following major subsystems

- Solar photovoltaic panel
- Battery and charge controller
- DC water pump
- Water level indicator
- Auxiliary loads (lighting)

System Architecture

$$P_{PV} = V_{PV} \times I_{PV}$$

Where

- P_{PV} = Power generated by solar panel (W)
- V_{PV} = Panel voltage (V)
- I_{PV} = Panel current (A)

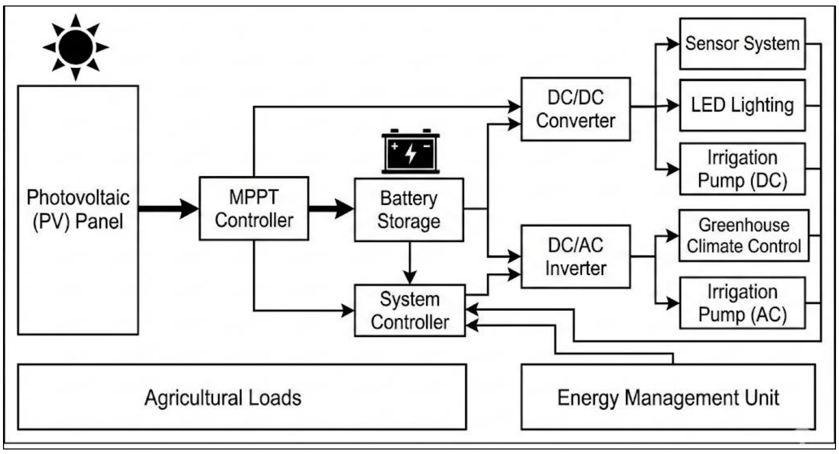

Fig 1: Block diagram of the solar-powered agricultural system

3.1 Block Diagram Description

The block diagram illustrates energy flow from the solar panel to various agricultural loads. Solar panels generate DC electricity, which is regulated by a charge controller before charging the battery. Stored energy is then supplied to the water pump, water level indicator, and lighting system as required.

3.2 Working Principle
When sunlight falls on the PV panel, semiconductor materials such as silicon absorb photons and generate electron-hole pairs, producing DC electricity. This energy is either used directly or stored in a battery via a regulated charging circuit. The DC motor pump converts electrical energy into mechanical energy to lift water for irrigation. The water level indicator monitors tank levels to prevent overflow and dry running, enhancing system reliability. The operating mechanism of the solar water pumping system is shown in Figure 2

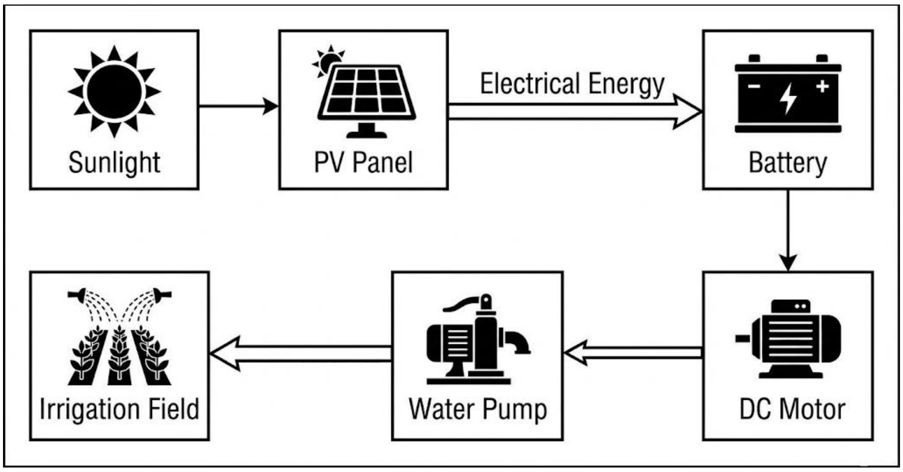

Fig 2: Working principle of the solar-powered irrigation system

4. Hardware Components
The system integrates widely used and cost-effective electronic components

- **Solar Cell:** Converts solar radiation into electrical energy.
- **Battery:** Stores excess energy for use during low irradiance.
- **Charge Controller (LM317-based):** Regulates voltage and current to prevent overcharging.
- **DC Motor Pump:** Provides water for irrigation.
- **Water Level Indicator:** Uses priority encoder and BCD decoder ICs to display tank levels.
- **Protection Devices:** Diodes and Zener diodes ensure safe operation.

The choice of DC components enhances system efficiency by eliminating inverter losses, making the system suitable for small to medium-scale farms.

5. Advantages and Limitations
5.1 Advantages
- Zero fuel cost and low maintenance
- Environmentally friendly with no emissions
- Suitable for remote and off-grid locations
- Long operational life and high reliability

5.2 Limitations
- Initial installation cost
- Reduced performance during cloudy or rainy conditions
- Seasonal variability in solar radiation

Despite these limitations, lifecycle cost analysis demonstrates that solar irrigation systems become economically favorable within a few years of operation.

6. Performance and Economic Considerations
Field implementation of the system demonstrates consistent water delivery during daylight hours. The absence of fuel expenses significantly reduces operational costs. Government subsidies and declining PV prices further enhance economic feasibility. Compared to diesel pumps, solar systems offer higher long-term returns and energy independence for farmers.

Performance Analysis

$$E = P_{PV} \times t$$

Where

- E = Energy generated (Wh)
- t = Time of operation (h)

7. Environmental Impact
Solar-powered agricultural systems contribute directly to sustainable development goals by reducing carbon emissions, conserving fossil fuels, and promoting clean energy adoption. Each solar irrigation system can offset several tons of CO_2 emissions annually when replacing diesel-based pumping.

8. Comparative Analysis and Future Outlook
8.1 Logic Control vs. Microcontrollers
While the industry trend is toward microcontrollers (MCUs) like the Arduino or ESP32, this research validates the discrete logic approach (74HC147/CD4511) for specific contexts.

- **Advantages of Discrete Logic:** Instant start-up (no bootloader), zero software vulnerability, high ESD/noise tolerance, and repairability by technicians with basic soldering skills (no coding required).
- **Advantages of MCUs:** Flexibility, IoT connectivity, and data logging. Future iterations could integrate an MCU to log water usage data for long-term aquifer analysis.

8.2 Motor Technology Evolution

The current design uses Brushed DC motors. The future lies in Brushless DC (BLDC) motors, which offer 10-15% higher efficiency and longer lifespans due to the absence of brushes. However, BLDC motors require complex electronic speed controllers (ESCs), which would increase the system cost and complexity.

8.3 Battery Technology Transition

The move from Lead-Acid to Lithium Iron Phosphate ($LiFePO_4$) batteries would offer a longer lifecycle (2000+ cycles vs. 300-500 for lead-acid) and better thermal stability. However, this would necessitate upgrading the simple LM317 charger to a dedicated Lithium charge controller to manage cell balancing and strict voltage cut-offs.

9. Conclusion

The research presented in this paper confirms that the integration of Solar Photovoltaic systems in agriculture is a technically feasible and economically transformative strategy. The detailed analysis of the discrete-component design featuring the 74HC147/CD4511 water level indicator and the LM317 charging circuit demonstrates that high-tech solutions are not always required to solve fundamental problems. "Appropriate technology," characterized by low cost, high repairability, and robustness, often provides the optimal solution for rural electrification.

The system addresses the "Water-Energy-Food" nexus by utilizing abundant solar energy to secure water resources, thereby enhancing food productivity. The high Benefit-Cost Ratios observed in case studies validate the economic model, while the logic-based automation ensures resource efficiency. As solar panel costs continue to decline, such decentralized, automated irrigation systems will become increasingly pivotal in ensuring global food security and climate resilience for the developing world. The transition from fossil-fuel dependency to solar autonomy is not just an engineering upgrade; it is a foundational shift toward sustainable agricultural development.

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