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Optimal Electricity Consumption in the Agricultural Sector and Its Implications for Startups: An AI Enabled Photovoltaic Approach

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Abstract

This paper examines optimal electricity consumption in the agricultural sector, starting from the realities of remote areas where grid connection is weak or absent. Such constraints disrupt irrigation operations, hinder product cooling and cold chain storage, complicate the preservation of veterinary medicines and vaccines, and ultimately increase operating costs and production risks. In this context, photovoltaic (PV) solar systems have emerged as a practical and promising alternative. However, field performance is neither stable nor automatically efficient, it is shaped by multiple technical and operational factors dust accumulation, high temperatures, partial shading, installation and configuration issues, undetected faults, and poor storage management leading to energy losses and a higher effective cost per kilowatt hour actually delivered.The study aims to highlight the role that startups can play in rationalizing electricity use and improving PV system performance on farms through Artificial Intelligence (AI) and Internet of Things (IoT) solutions. These include generation forecasting, agricultural load scheduling (especially water pumping), maximum power point tracking, solar tracking, intelligent fault detection, and predictive maintenance, in addition to technical advisory services and user training. Using a descriptive–analytical approach based on recent literature and an analysis of Algeria's national regulatory framework for startups, the paper concludes that optimal energy use in agriculture cannot be achieved through hardware alone. Rather, it requires a smart service layer driven by startups within a supportive ecosystem that includes targeted financing, data governance, stronger university–farm linkages, and technical interoperability standards.

Keywords: *Optimal Consumption, Electricity, Agriculture, Startups, Artificial Intelligence, Photovoltaic Solar Energy.*

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Introduction

Electricity has become a decisive factor in agricultural productivity and stability. It is no longer a secondary input: in irrigated systems it enables water pumping, in postharvest operations it sustains cooling, cold storage, and primary processing, and in livestock production it supports ventilation, lighting, milking equipment, and the preservation of medicines and vaccines. As the cost of conventional energy rises and global fuel markets remain volatile, improving efficiency and rationalizing consumption has become increasingly important particularly in sectors with strong socioeconomic sensitivity such as agriculture.

At the national level, large areas especially remote, border, and Saharan zones still face limited access to electricity or unreliable supply. As a result, farmers and livestock breeders have increasingly turned to alternative solutions, foremost among them PV solar systems. These systems have reduced isolation for many agricultural perimeters, yet they have also exposed new operational challenges. Field performance is not determined by installed panel capacity alone, it depends on the entire operating chain, including system sizing and design, orientation, cleanliness, battery management, fault monitoring, and critically the alignment of farm loads with solar production hours.

Within this transition, Artificial Intelligence offers a concrete opportunity to recalibrate the relationship between generation and consumption. AI enables solar generation forecasting using weather data, distinguishes early between "normal" and "abnormal" performance drops, and supports decisions about when to run pumps or cooling units in ways that reduce losses and improve the economic return per unit of energy. However, turning these capabilities into solutions that can be used in everyday farming practice

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requires an economic and innovative intermediary capable of design, piloting, and rapid deployment. This places startups at the center of the discussion.

Research Problem, Significance, and Objectives

Research Problem

This paper addresses the following question:

Do startups contribute to achieving optimal electricity consumption in agriculture by leveraging AI, particularly for operating and improving photovoltaic solar systems?

Sub questions include:

1. How can AI be used to improve the electricity output of solar PV systems in agricultural environments?

2. What is the value of AI models in reducing faults, shortening downtime, and lowering maintenance costs?

3. What institutional, financial, and technical requirements are needed to scale startup solutions in Algeria?

Significance of the Study

The topic is significant for three interrelated reasons:

- **Economic significance:** electricity in agriculture is no longer marginal, it strongly affects irrigation profitability, storage costs, and continuity of production. Efficiency improvements reduce costs and strengthen competitiveness.

- **Socio developmental significance:** improving energy services in remote areas supports local stability and reduces fragility in food supply chains.

- **Innovation significance:** startups are a practical channel for translating knowledge and technology into field solutions especially as AI/IoT tools are increasingly scalable and the costs of sensing and computing continue to decline.

Study Objectives

The paper seeks to:

1. Ground the concept of optimal electricity consumption in agriculture and link it to operational indicators.

2. Analyze the role of startups in delivering smart solutions for solar energy management and agricultural loads.

3. Present key AI applications that can improve PV performance and reduce failures.

4. Propose an applied framework for a startupled service model in remote farms.

5. Derive policy recommendations to strengthen the enabling ecosystem (finance, data, regulation, partnerships).

Methodology and Scope

The paper adopts a **descriptive–analytical approach**, drawing on:

- Recent literature on AI in agriculture and AIoT (AI + IoT) for PV monitoring and control (European Commission HLEG AI, 2018, Hadi, 2023, Boucif et al., 2025, IEA, 2024, IPCC, 2023).

- Analysis of Algeria's regulatory framework for startup labeling (Executive Decree No. 20254) and national studies on the startup landscape (Baroudi, 2020, Bougtaya et al., 2021).

- A conceptual framework linking agricultural load characteristics, PV system behavior, AI tools, and startup business models.

Scope limitation: the paper does not report original field measurements on a farm sample. Its conclusions are based on literature and institutional analysis, with illustrative examples used for clarification rather than statistical generalization.

Optimal Electricity Consumption in Agriculture: Concept and Measurement Pathways

From "Reducing Consumption" to "Improving Efficiency"

Energy rationalization is often misunderstood as merely reducing demand. Agriculture follows a different logic: the objective is to **deliver the required productive service** timely irrigation, adequate cooling to preserve quality, continuous operation of essential equipmentat the lowest possible energy cost. Accordingly, optimal electricity consumption in agriculture can be defined as:

Managing demand, scheduling loads, and operating equipment according to efficiency and reliability criteria, in order to maximize the productive/economic return per kWh.

Determinants of Optimal Consumption in Solar Dependent Contexts

In off grid or weak grid farms, optimal consumption is shaped by three constraints:

1. **Variability of solar generation:** production changes throughout the day, across seasons, and with clouds, dust, and heat.

2. **Flexibility of agricultural loads:** some loads can be shifted (part of pumping), while others are relatively inflexible (basic cooling, critical lighting, medical storage).

3. **Storage availability and cost:** batteries are not "free reservoirs", they degrade and require careful management to reduce depth of discharge and unnecessary cycling.

Practical Indicators at Farm Level

To operationalize efficiency, farms can rely on indicators such as:

- **kWh/m³:** energy intensity of water pumping, reflecting pump efficiency, piping, leakage, and operating practices.

- **kWh/ton or kWh/ha:** energy intensity of production.

- **kWh/kWp:** PV specific yield, indicating system quality and maintenance.

- **Downtime** and number of faults per year: reliability indicators.

- **Effective energy cost:** assessed not by panel price alone, but by delivered energy after losses, maintenance, and component replacements.

Startups: Conceptual Foundations and Economic Role in "EnergySmart" Agriculture

Startup Concept and Key Features

The literature converges on the idea that a startup is not merely a newly established firm, it is an organization searching for a scalable business model, relying on innovation within high uncertainty (Noui & Dehan, 2020). Local studies similarly emphasize growth potential, innovation, and uncertainty as core attributes (Bougtaya et al., 2021).

Algeria's Regulatory Framework

Executive Decree No. 20254 (2020) introduced a formal startup labeling mechanism and eligibility criteria (age limit, innovative product/service or business model, growth potential, employment and revenue thresholds), providing institutional recognition and potential access to support mechanisms (Baroudi, 2020).

Why SolarBased Agricultural Energy is Attractive to Startups

This market exhibits three innovation friendly characteristics:

1. **Urgent and concrete demand:** electricity is essential for continuity of production in many areas.

2. **Measurable solutions:** improvements in kWh/kWp or reduced downtime are quickly observable, enabling performance based business models.

3. **Scalability:** digital layers (monitoring, alerts, forecasting) can expand geographically at relatively low marginal cost compared with purely hardware intensive expansion.

Artificial Intelligence in Agriculture: From Decision Support to Energy Management

Definition and Relevant Features

AI is commonly defined as the development of systems capable of perceiving their environment, analyzing data, and taking actions to achieve specified goals (European Commission HLEG AI, 2018, Hadi, 2023). Its relevance to agriculture lies in learning from experience, supporting decision making, reducing human error, and providing timely, actionable information (Guettaf, 2024).

AI Applications in Agriculture Connected to Energy Use

Recent work highlights expanding AI use in smart irrigation, yield prediction, fertilizer optimization, livestock management, and drone based sensing (Hassan, 2025). These applications intersect with energy efficiency by:

- Reducing unnecessary pumping through better estimation of crop water needs.

- Aligning operational timing with solar availability.

- Lowering cold chain losses via intelligent temperature and energy monitoring.

Photovoltaic Solar Systems and AI: Technical Tools to Raise Output and Reduce Losses

PV Systems in Real Farm Conditions: Where Losses Occur

In practice, weak performance is often not due to insufficient sunlight. Daily operational factors dust buildup, inadequate cleaning, partial shading, high module temperatures, wiring issues, inverter degradation, and battery mismanagement create cumulative losses. Without monitoring, a small performance drop can persist unnoticed, eventually becoming a costly fault or prolonged outage.

Intelligent Fault Detection and Diagnosis (FDD)

FDD is fundamental to improving reliability and reducing energy losses. The recent literature identifies two principal pathways (Boucif et al., 2025):

- **Visual/thermal pathway:** using thermal or RGB imaging (including UAV inspections) and deep learning to detect micro cracks, hotspots, dust accumulation, and discoloration.

- **Electrical–environmental pathway:** using sensors for voltage/current plus irradiance and temperature, then comparing expected versus actual output to detect anomalies, employing classifiers (e.g., Random Forest) or temporal models (e.g., LSTM) to characterize fault patterns.

In agricultural contexts, the value is not purely technical. Reduced faults mean fewer missed irrigation cycles during critical periods, fewer losses in stored products, and lower emergency maintenance and travel costs.

Predictive Maintenance: From Post Failure Repair to Pre Failure Intervention

Predictive maintenance relies on performance and environmental data to anticipate failures before they occur, improving system availability and lowering operating expenditures (Boucif et al., 2025). This is particularly valuable in remote areas where the economic cost of downtime is amplified by the lack of alternatives, prevention is often cheaper than corrective interventions.

Generation Forecasting and Better Energy Management

Forecasting needs vary by time horizon:

- **Very short term (minutes–hours):** adjusting pump schedules or battery charge/discharge in response to sudden variability.

- **Day ahead:** planning irrigation, cooling, and load distribution under limited storage constraints. Temporal models such as LSTM and RNN are well suited to these data structures and frequently outperform traditional approaches in volatile weather conditions (Boucif et al., 2025).

Improving Energy Harvest: MPPT and Solar Tracking

AI assisted control can enhance energy extraction through improved maximum power point tracking (MPPT) and solar tracking especially when integrated with IoT for remote monitoring and tuning. The literature reports notable gains in output when advanced tracking and measurement schemes are deployed under suitable conditions (Boucif et al., 2025).

How Startups Translate These Tools into "Optimal Consumption" on Farms: A Proposed Applied Framework

Field experience suggests that technology generates impact only when it becomes an accessible service that changes daily operating behavior. This paper proposes a five stage roadmap for startup intervention at farm level:

Energy–Water Audit (Diagnostic Phase)

The service begins by identifying:

- Critical and noncritical loads and their time flexibility.
- Waste points (mismatched pumps, excessive pressure, leaks, operation during low solar hours).
- Baseline values for indicators such as kWh/m³ and kWh/kWp.

This transforms general perceptions into measurable baselines.

Instrumentation and Digitization

Installing sensors (current/voltage/power, module temperature, irradiance, ambient temperature) and connecting them to a data platform. Here, startup value becomes clear: generating continuous local data rather than relying on rough estimates.

Forecasting and Scheduling

Using machine learning to forecast solar generation and expected demand (e.g., pumping linked to irrigation plans), then recommending an operating schedule that reduces deep battery discharge and avoids unnecessary backup generator use.

Prevention and Predictive Maintenance

Tracking performance deviations enables early alerts: abnormal production drops at module level, hotspot risks, inverter efficiency decline, or battery capacity fade. These services reduce sudden failures and extend asset life.

Impact Measurement and Performance Based Business Models

To be economically compelling for farmers and financiers, results should be reported in clear metrics:

- Reduced kWh/m³ after scheduling or pump optimization.
- Increased kWh/kWp after targeted cleaning, better orientation, or early fault repair.
- Lower downtime hours per year.

This supports “pay for performance” models or subscription based monitoring and maintenance services.

Economic Discussion: Efficiency Gains and Their Effects on Agriculture and Startup Sustainability

Farm Level Impacts: Lower Cost and Reduced Risk

Efficiency improvements translate into:

- **Lower operating costs:** less unnecessary operation, longer battery lifespan, fewer emergency repairs.
- **Lower production risk:** irrigation continuity during critical water stress periods and protection of cooling systems from outages.
- **Higher value added:** more stable production improves quality, marketability, and reduces supply chain losses.

Startup Level Impacts: From Selling Equipment to Delivering Scalable Services

Service based models (monitoring, diagnosis, predictive maintenance) are typically more scalable than one off hardware sales because they:

- Create recurring revenue that funds continuous development.
- Strengthen customer relationships through measurable results.
- Build a data asset that improves models and enhances competitive advantage.

Policy Level Impacts: Food Security and Energy Transition

International assessments emphasize that climate adaptation and resource efficiency are prerequisites for sustainable food systems (IPCC, 2023), while renewable deployment is central to the energy transition (IEA, 2024). In Algeria, improving electricity services in remote agricultural areas supports food security and local stability, can reduce certain pressures on the grid, and limits reliance on fuel based generators.

Challenges in Algeria and Prospects for Improvement

National studies note persistent constraints affecting startups: limited applied research, financing difficulties, and insufficient data infrastructure (Bougtaya et al., 2021). In solar based agricultural energy, additional challenges include:

1. **Financing:** many farms cannot afford upfront costs, while startups may lack suitable financing instruments for digital services.

2. **Data scarcity:** limited local datasets on performance, faults, and agro meteorology constrain model accuracy and learning.

3. **Human capital:** demand for hybrid skills (energy + data + agriculture) exceeds current supply.

4. **Interoperability:** equipment diversity without standards may produce “closed” solutions that are hard to maintain and scale.

5. **Trust and adoption:** farmers adopt solutions when benefits are understandable and reliability is proven, which raises the importance of field based guidance and training.

Conclusion

This paper concludes that optimal electricity consumption in agriculture articularly in remote areas requires moving beyond a purely hardware centered approach that equates solution with the installation of PV systems. Instead, it calls for a “smart service” approach that improves operation, reduces waste, and increases reliability. Integrating AI and IoT into PV monitoring and optimization is a viable pathway to higher output, fewer failures, and a lower effective cost of electricity. Startups are well positioned to drive this shift due to their flexibility, their capacity to tailor solutions to specific needs, and their ability to develop performance based service models. Yet success in Algeria depends on activating the broader ecosystem: targeted finance, stronger university–sector linkages, data governance, and updated technical and regulatory standards.

Recommendations

1. **Launch pilot farms** combining PV systems with smart metering and forecasting/predictive maintenance models to build local datasets and demonstrate economic impact.

2. **Establish targeted financing mechanisms** for projects that improve efficiency indicators (kWh/m³, kWh/kWp, reduced downtime), potentially involving agricultural development banking instruments and risk guarantees.

3. **Build a national database** of PV performance and common faults in agricultural contexts, differentiated by climate zones, enabling AI models adapted to Algerian conditions.

4. **Strengthen university–farm–startup partnerships** through applied labs, capstone projects, and field based research on dust, heat, storage management, and pumping optimization.

5. **Develop interoperability standards** for sensors, inverters, and platforms to encourage scalable, maintainable solutions rather than closed systems.

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