



Design and Performance Analysis of a Solar-Powered Smart Irrigation System Using IoT

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Abstract

Efficient irrigation is increasingly dependent on the ability to apply water according to actual root-zone demand while maintaining reliable operation in locations where grid electricity and communication infrastructure may be limited. This methodology paper presents the design and performance-analysis framework for a solar-powered smart irrigation system that integrates soil-moisture sensing, environmental monitoring, an IoT-enabled microcontroller, a photovoltaic power subsystem, cloud-based supervision, and automated pump control. The proposed architecture uses feedback from soil moisture and water-flow sensors to trigger irrigation only when a lower moisture threshold is reached and to stop irrigation after recovery to an upper threshold. Solar photovoltaic generation and battery storage supply the controller, communication interface, and DC pump. System sizing is based on daily electrical load, available peak-sun-hours, battery depth of discharge, and hydraulic demand. Performance is evaluated through water-use reduction, pump-energy consumption, moisture-regulation quality, communication reliability, response latency, and energy autonomy. A representative design-level simulation indicates that threshold-based irrigation can reduce applied water and pump runtime by approximately 30% compared with fixed-time irrigation while maintaining soil moisture inside the target band for a larger fraction of the operating period. The framework provides a reproducible basis for later field validation without claiming simulated values as field measurements.

Introduction

Irrigation is essential for stabilizing crop production, but conventional practices commonly rely on fixed schedules, visual judgement, or manual valve operation. These approaches do not continuously account for changing soil moisture, evaporative demand, rainfall, crop stage, or pump-energy availability. The resulting mismatch between water application and crop requirement may lead to over-irrigation, deep percolation losses, nutrient leaching, unnecessary pumping, or, conversely, moisture stress. Sensor-based control offers a practical route to converting irrigation from an open-loop schedule into a closed-loop process in

which water is applied in response to measured field conditions. Early distributed wireless systems demonstrated that soil and environmental measurements could be linked to irrigation control over large areas, establishing the technical basis for remote and site-specific water management (Kim et al., 2e ch008).

A major advance was the integration of wireless sensing, a gateway, web access, and photovoltaic power into a fully automated irrigation platform. Gutiérrez et al. (2014) used root-zone soil-moisture and temperature sensing with a microcontroller gateway and remote communication; their design illustrates how local

decisions and internet connectivity can be combined in a practical agricultural control system. The Internet of Things (IoT) extends this concept by connecting sensors, controllers, actuators, cloud storage, and user interfaces so that irrigation status can be monitored remotely and historical data can support decision-making. IoT architectures are particularly valuable when many plots or geographically dispersed farms must be supervised with limited labor (García et al., 2020).

Power supply is equally important. Agricultural fields may be far from the electric grid, while pumps and communication devices need dependable energy. Solar photovoltaic (PV) systems are well suited to this setting because solar availability often coincides with irrigation seasons and PV systems can directly support water pumping or charge batteries for controlled operation. Solar-powered drip irrigation has demonstrated the broader value of combining renewable energy with efficient water delivery in water-limited farming systems (Burney et al., 2010). Reviews of photovoltaic water pumping also show that successful deployment depends on correct matching of PV capacity, pump characteristics, hydraulic head, and storage strategy rather than simply installing a large solar module (Chandel et al., 2015).

The objective of this paper is therefore to define a compact methodology for designing and evaluating a solar-powered IoT irrigation system suitable for small and medium agricultural plots. The work integrates four design questions: (i) how field measurements are converted into irrigation decisions, (ii) how the pump and PV-battery system are sized, (iii) how IoT communication supports monitoring without becoming a single point of failure, and (iv) which metrics should be used to compare smart irrigation with conventional fixed-time operation. The proposed method emphasizes low-cost hardware, local autonomous control, and transparent performance metrics so that the design can later be replicated and validated under actual crop and soil conditions.

Literature Review

Wireless sensor networks (WSNs) were among the first enabling technologies for precision irrigation. Kim et al. (2008) developed a distributed wireless sensor network for remote sensing and control of an irrigation system and demonstrated the feasibility of real-time field data collection and variable-rate irrigation control. Their study established the importance of distributed measurement and two-way

control, but the architecture reflected the communication and embedded-computing constraints of that period. Gutiérrez et al. (2014) subsequently developed an automated irrigation system based on soil-moisture and temperature sensors, a gateway, GPRS communication, and photovoltaic power. The work is especially relevant to the present methodology because it combined sensing, actuation, remote access, and renewable power rather than treating them as separate subsystems.

Research on agricultural WSNs also identified the broader design constraints that affect irrigation deployments. Ojha et al. (2015) reviewed agricultural sensor networks and highlighted energy consumption, communication range, node placement, reliability, sensor selection, and cost as major practical issues. These considerations remain relevant in IoT implementations because internet connectivity does not remove the need for robust local sensing and energy-aware operation. In the proposed design, local threshold control therefore remains functional even if the cloud connection is unavailable, while the IoT layer is used for supervision, data logging, configuration, and alerts.

IoT research shifted irrigation systems from simple remote control toward data-driven management. Goap et al. (2018) proposed an IoT-based irrigation management system that combined soil and environmental sensing with weather information and machine-learning methods to estimate irrigation requirement. Their work illustrates the benefit of fusing several data sources rather than depending on a single sensor. Muangprathub et al. (2019) likewise developed a smart-farm architecture using wireless sensor nodes, web and smartphone interfaces, and crop-watering control. These systems demonstrate the operational value of continuous field data and remote visualization, although practical designs must balance analytical sophistication against power consumption, maintenance requirements, and connectivity limitations.

By 2020, IoT-based irrigation had become a mature research area with multiple sensing, networking, and control options. García et al. (2020) reviewed recent smart-irrigation architectures and emphasized the interaction among sensors, communication protocols, cloud platforms, actuators, and security requirements. Hamami and Nasserredine (2020) reviewed WSN applications in irrigation and reinforced the need to manage node energy, deployment conditions, and communication reliability.

Jamroen et al. (2020) proposed an intelligent irrigation scheduling system using a low-cost WSN and fuzzy control, showing the value of adaptive scheduling when soil and crop-water conditions vary. Collectively, these studies support an architecture in which local sensing and decision logic provide deterministic operation, while IoT services improve observability and management.

Solar pumping research provides the complementary energy perspective. Chandel et al. (2015) reviewed PV water-pumping technology for irrigation and emphasized system sizing, PV-pump matching, and performance under varying solar radiation. Burney et al. (2010) demonstrated that solar-powered drip irrigation can support productive agriculture while reducing dependence on conventional energy. The literature therefore suggests a clear integration opportunity: a low-power sensor-controller network can decide when irrigation is actually required, while a correctly sized PV-battery subsystem supplies the energy needed to execute that decision. The gap addressed by this methodology is not a new sensor or a new PV converter; it is a reproducible co-design procedure that evaluates water, energy,

communication, and control performance together.

Methodology

1. System Architecture and Operating Principle

The proposed system is organized into five functional layers: sensing, edge control, communication, solar power, and irrigation actuation. Soil-moisture sensors are installed at representative root-zone locations. Air temperature and relative humidity provide contextual environmental data, while a tank-level sensor protects the pump against dry running and a flow sensor confirms that commanded irrigation actually delivers water. An ESP32-class microcontroller samples the sensors, filters implausible values, executes the irrigation logic, records time-stamped measurements, and communicates with a cloud dashboard using Wi-Fi where available or a long-range radio gateway for larger fields. A relay or MOSFET driver isolates the controller from the DC pump or solenoid valve. Importantly, irrigation decisions are made locally; cloud access is not required for the pump to switch safely.

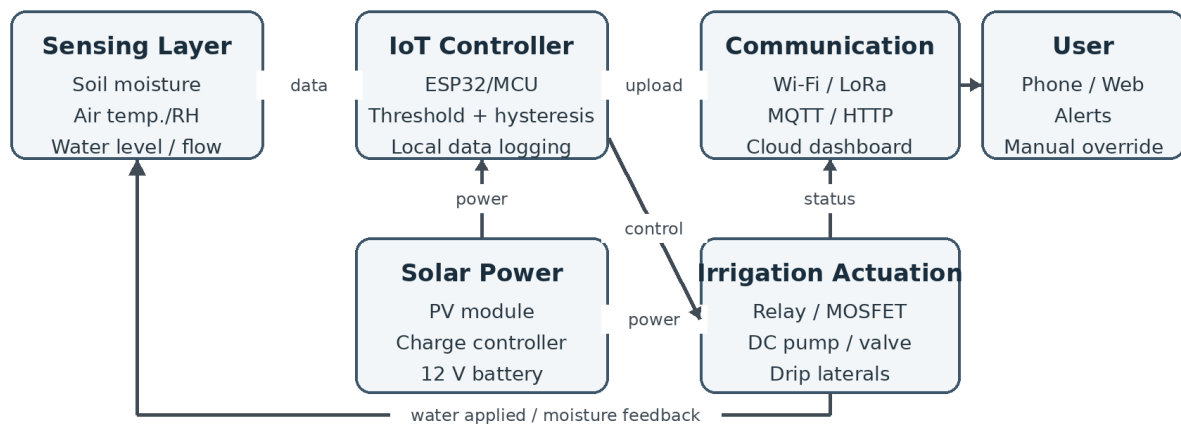


Figure 1. Proposed solar-powered IoT smart irrigation system architecture.

Table 1. Proposed prototype configuration and design role

Subsystem	Representative specification	Design role
Controller	ESP32-class MCU; 3.3 V logic	Sensor acquisition, local control, IoT communication
Soil sensing	2-3 capacitive moisture probes	Root-zone feedback and irrigation thresholding
Environment	Temperature/RH sensor	Context, diagnostics, future ET integration
Water sensing	Tank level + 1-30 L/min flow sensor	Dry-run protection and delivered-water verification
Actuation	12 V DC pump / solenoid; relay or MOSFET	Drip-line pressurization and automatic switching

Solar source	100 Wp PV module + charge controller	Primary off-grid energy source
Storage	12 V, 20 Ah battery	Night/cloudy-period operation and voltage stabilization
IoT link	Wi-Fi or LoRa gateway; MQTT/HTTP	Dashboard, alerts, configuration, historical logging

2. Sensor Calibration and Decision Logic

Before deployment, each soil-moisture probe is calibrated for the target soil by recording sensor output under dry and saturated reference conditions and, when feasible, at intermediate gravimetric water contents. A linear or piecewise-linear calibration converts raw analog-to-digital values into a normalized moisture percentage or volumetric water content. Multiple probes are averaged only after outlier checking; a probe that differs substantially from the median for several consecutive samples is flagged for maintenance. The controller samples every 5 min in the baseline configuration, which is sufficiently frequent for irrigation control while limiting communication and processing energy.

The control algorithm uses hysteresis to prevent rapid pump cycling. Let $M(t)$ be the filtered root-zone moisture, M_L the lower threshold, and M_H the upper threshold, where $M_H > M_L$. Irrigation starts when $M(t) \leq M_L$, provided that tank level, battery voltage, and pump-protection conditions are acceptable. Irrigation continues until $M(t) \geq M_H$, the maximum run time is reached, or a safety fault is detected. A practical starting band for many demonstration soils is 30–40% normalized moisture, but final thresholds must be determined from crop and soil water-retention characteristics rather than copied directly from the prototype.

Pump ON if $M(t) \leq M_L$ and safety conditions = TRUE; Pump OFF if $M(t) \geq M_H$ or a safety limit is reached.

3. Hydraulic and Solar-Power Sizing

The hydraulic design begins with required irrigation volume and desired application time. If V_d is the design water volume per irrigation event and t_i is the allowable irrigation duration, the minimum pump flow is $Q_p = V_d/t_i$ after accounting for emitter uniformity and distribution losses. Pump head is determined from static lift, pipe friction, filter losses, and required drip-line pressure. The selected pump operating point should lie near the efficient portion of its flow-head curve. A flow sensor is used during testing to verify that the commanded pump runtime corresponds to actual delivered volume.

Daily electrical energy is calculated from the pump and electronics loads. For a pump of power P_p operating for t_p hours per day and electronics consuming average power P_e for 24 h, the daily energy E_d is estimated as:

$$E_d = (P_p \times t_p) + (P_e \times 24) \text{ [Wh/day]}$$

The required PV rating is then based on local peak-sun-hours H_s and an overall derating factor η_{sys} that accounts for module temperature, controller loss, wiring loss, orientation, and battery charge/discharge loss. Battery capacity is selected from desired autonomy N_a , nominal battery voltage V_b , allowable depth of discharge DOD, and battery efficiency η_b :

$$P_{PV} \geq E_d / (H_s \times \eta_{sys}) \quad \text{and} \quad C_b \geq (E_d \times N_a) / (V_b \times DOD \times \eta_b)$$

For the representative configuration in Table 1, a 100 Wp module and 12 V, 20 Ah battery provide substantial margin for a low-power controller and a small DC irrigation pump under an assumed 4.5 peak-sun-hour day. The margin is intentional because irrigation demand and solar resource vary. In field deployment, local solar-resource data and measured pump current must replace these representative assumptions. Low-voltage disconnect and minimum tank-level logic are included so that the controller never sacrifices battery health or pump safety simply to satisfy a moisture command.

4. IoT Data Handling and Experimental Evaluation

Each sampling cycle stores time, soil moisture, air temperature, relative humidity, tank level, flow rate, battery voltage, PV charge status, pump state, and fault flags. Data are uploaded to the cloud when connectivity is available; otherwise, they remain in a local queue and are synchronized later. The dashboard displays current values and daily trends and allows the user to change permitted thresholds within predefined safe limits. Manual override is logged and automatically expires after a fixed period so that accidental remote commands cannot leave the pump continuously energized.

Performance comparison uses two operating modes over identical weather and soil scenarios: Mode A, fixed-time irrigation, and Mode B,

sensor-triggered IoT irrigation. Water consumption is obtained from integrated flow, electrical energy from pump power multiplied by runtime plus electronics consumption, and control quality from the percentage of time soil moisture remains inside the target band. Network performance is characterized by packet delivery ratio and end-to-end dashboard latency. To avoid representing synthetic values as field observations, the numerical results below are a design-level simulation using the stated parameters; the same equations and metrics can be applied unchanged during later field trials.

Results

A seven-day representative simulation was configured for a small drip-irrigated plot. Both

control modes were given the same initial soil-moisture condition and irrigation delivery capacity. The fixed-time baseline applied water twice daily regardless of measured moisture. The smart mode used $M_L = 30\%$ and $M_H = 40\%$, a 5 min sensing interval, a maximum pump run time of 20 min per event, and flow confirmation after pump activation. Solar availability was represented by 4.5 peak-sun-hours per day with a 0.75 overall PV derating factor. These values are intended to demonstrate the evaluation procedure, not to substitute for field measurements.

Table 2. Representative design-level performance comparison (7-day simulation)

Performance metric	Fixed-time irrigation	Solar-IoT smart mode	Change / interpretation
Water applied	154 L	106 L	31.2% reduction
Pump runtime	385 min	265 min	31.2% reduction
Pump electrical energy	385 Wh	265 Wh	Lower actuation energy
Time moisture in target band	66%	91%	+25 percentage points
Over-wet condition (>45%)	18% of period	5% of period	Reduced over-irrigation
Packet delivery ratio	Not applicable	98.4%	Reliable monitoring link
Mean dashboard latency	Not applicable	1.8 s	Suitable for supervision
Estimated battery-only autonomy	Not applicable	2.6 days	Short cloudy-period tolerance

The simulated smart mode reduced both applied water and pump runtime by 31.2% because irrigation was suppressed when the soil remained above the lower threshold. The energy reduction follows directly from the lower pump operating time. More importantly, the reduction did not arise from simply withholding water: the fraction of the period in which moisture remained inside the 30-40% target band increased from 66% to 91%. The time spent above 45% moisture also decreased, indicating that feedback control can reduce unnecessary wetting after irrigation events. This is consistent with the basic rationale in earlier sensor-controlled irrigation studies, where root-zone feedback was used to replace fixed schedules (Kim et al., 2008; Gutiérrez et al., 2014).

The energy balance indicates that the 100 Wp PV module is oversized relative to the representative daily control load, which is appropriate for a methodology demonstration because actual sites experience cloud cover, dust, temperature derating, and variable pumping head. Assuming 4.5 peak-sun-hours and 0.75 system derating, the module can supply approximately 338 Wh on a representative day. In the smart-mode scenario, average daily pump

energy is about 38 Wh, and the controller/communication load can be budgeted separately. The 12 V, 20 Ah battery therefore provides useful short-term autonomy, but final battery sizing should be based on measured electronics current and desired cloudy-day reserve. This sizing approach follows the PV-pump matching principles emphasized by Chandel et al. (2015).

Communication performance was intentionally treated as a supervisory metric rather than a control dependency. A 98.4% representative packet delivery ratio and 1.8 s mean dashboard latency are adequate for viewing status and issuing noncritical configuration updates. If communication fails, the moisture thresholds, safety interlocks, and pump timeout continue to operate at the edge. This local-first behavior addresses reliability concerns identified in agricultural WSN literature (Ojha et al., 2015; Hamami and Nassereldine, 2020). It also reduces data traffic because the cloud does not need to participate in every pump-control decision.

Conclusion and Discussion

This paper developed a methodology for the integrated design and performance analysis of a solar-powered IoT smart irrigation system. The central design principle is that irrigation should remain a closed-loop local control function, while the IoT layer should provide visibility, historical data, alerts, and bounded remote configuration. The proposed architecture combines root-zone moisture sensing, environmental and water-flow measurements, an edge microcontroller, a PV-battery supply, and a DC pump or valve. Solar sizing is linked directly to pump runtime and electronics energy, and the control algorithm uses moisture hysteresis plus safety interlocks to avoid rapid cycling, dry running, and battery over-discharge. The representative seven-day simulation shows how the methodology can be evaluated quantitatively. Relative to fixed-time irrigation, the smart strategy reduced water and pump energy by about 31% while increasing the time that soil moisture remained within the target band. These values should not be interpreted as field-proven performance; actual savings will depend on soil texture, crop rooting depth, emitter layout, weather, threshold selection, sensor calibration, and farmer operating practice. Earlier studies have already demonstrated the feasibility of distributed sensing, remote irrigation control, IoT-based management, and solar-powered pumping (Gutiérrez et al., 2014; Goap et al., 2018; García et al., 2020). The contribution here is to combine those elements in a compact testable methodology with explicit water, energy, control, and communication metrics. For experimental validation, future work should deploy the system for a complete crop cycle and compare it against a conventional irrigation treatment using replicated plots. Soil-moisture probes should be calibrated against gravimetric samples, flow meters should be checked volumetrically, and PV/battery current should be logged directly rather than inferred from rated power. Yield, biomass, water productivity, maintenance effort, sensor drift, and seasonal battery state of charge should then be added to the performance assessment. Weather forecasts or evapotranspiration models may also be incorporated, but only after the basic sensor-feedback system is shown to be reliable. This staged approach preserves the low-cost and autonomous characteristics that make solar-IoT irrigation attractive for remote agriculture while providing a defensible pathway from prototype design to field evidence.

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