



## Energy-Aware IoT Control and Performance Evaluation of a Solar-Powered Smart Irrigation System

Kenjiro Balasingam

Department of Computer Science and Engineering, Angkor Mekong Technical University, Cambodia  
[kenjiro.balasingam@amtu-kh.edu](mailto:kenjiro.balasingam@amtu-kh.edu)

### Peer Review Information

Submission: 04 Jan 2021  
 Revision: 19 Feb 2021  
 Acceptance: 06 March 2021

### Keywords

Smart irrigation, Internet of Things (IoT), Solar photovoltaic, Soil moisture, Precision agriculture

### Abstract

Water scarcity, irregular grid supply, and inefficient irrigation scheduling continue to constrain agricultural productivity, particularly in remote and smallholder farming environments. This methodology paper proposes a solar-powered smart irrigation system in which photovoltaic energy, soil and environmental sensing, embedded control, and Internet of Things (IoT) connectivity are integrated into a closed-loop irrigation architecture. The system uses a solar photovoltaic panel, charge controller, battery, low-voltage pump, soil-moisture sensor, temperature-humidity sensor, water-level sensor, and an ESP8266-class controller connected to an IoT dashboard. Irrigation is initiated when calibrated soil moisture falls below a lower threshold and is stopped when an upper threshold is reached, while reservoir level and battery voltage operate as safety constraints. The proposed methodology combines hardware design, sensor calibration, threshold-based control, solar-energy sizing, IoT data transmission, and comparative performance analysis. For a representative 100 Wp photovoltaic module, 12 V-20 Ah battery, 60 W pump, and 3 W average electronics load, the energy-balance analysis indicates approximately 375 Wh/day of harvest under five peak-sun-hours and 75% system derating, compared with an estimated 150 Wh/day demand under smart scheduling. A scenario-based seven-day irrigation analysis indicates a potential water-use reduction of about 35% relative to fixed manual irrigation while maintaining soil moisture within a selected control band. The study provides a reproducible methodology for designing and evaluating off-grid IoT irrigation systems without overstating unverified field performance.

### Introduction

Agricultural irrigation is increasingly expected to deliver more crop production with less water and lower energy consumption. Conventional irrigation based on fixed schedules or manual observation often applies water without direct knowledge of root-zone moisture and may continue operating even when soil water is already adequate. Early wireless sensor network research demonstrated that distributed field measurements can support site-specific irrigation decisions and remote control, thereby improving the relationship between measured

crop conditions and applied water (Kim et al., 2008). Later automated systems combined soil-moisture and temperature sensors with wireless communication and pump control, establishing the practical basis for low-cost closed-loop irrigation (Gutiérrez et al., 2014).

Energy availability is an equally important design constraint. In off-grid agricultural locations, irrigation pumping may depend on diesel engines or intermittent electricity. Solar photovoltaic (PV) pumping provides a technically mature alternative because high solar

availability often coincides with periods of elevated irrigation demand. Reviews of photovoltaic water-pumping systems have identified pump selection, PV sizing, power-electronic efficiency, water-storage strategy, and local solar resource as major determinants of reliable operation (Chandel et al., 2015; Sontake & Kalamkar, 2016). When PV pumping is combined with sensor-based scheduling, the system can reduce both unnecessary pump runtime and dependence on conventional energy sources.

The Internet of Things extends this approach by enabling sensor readings, device status, alerts, historical data, and remote commands to be transmitted between the field and a web or mobile interface. IoT-based irrigation research has shown the value of integrating soil moisture, temperature, humidity, weather information, and intelligent scheduling into one decision framework (Goap et al., 2018). Reviews of precision-irrigation IoT platforms also emphasize that sensing accuracy, communication reliability, energy consumption, interoperability, and actuation logic must be evaluated together rather than as separate subsystems (García et al., 2020). Directly relevant work has further demonstrated the feasibility of combining solar power, embedded controllers, sensors, pumps, and remote monitoring in smart-farm irrigation architectures (Al-Ali et al., 2020; Devan et al., 2021).

Accordingly, the objective of this paper is to present a step-by-step methodology for the design and performance analysis of a solar-powered IoT smart irrigation system. The focus is not on claiming a completed agronomic field trial; instead, it establishes a technically defensible system architecture, sizing procedure, control strategy, test protocol, and analytical performance framework that can be implemented and validated in a greenhouse or field setting.

## Literature Review

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 monitoring for site-specific water application. Their work is important because it connected distributed sensing directly with irrigation control rather than treating sensing as a stand-alone monitoring function. Gutiérrez et al. (2014) subsequently developed an automated irrigation system using a wireless sensor network and

GPRS communication, in which soil-moisture and temperature measurements were used to automate water application. These studies provide the control-system foundation for the present design.

The energy subsystem has been studied extensively in the context of photovoltaic water pumping. Chandel et al. (2015) reviewed solar PV water-pumping technology for irrigation and community water supply and emphasized the economic and operational suitability of PV pumping in locations where grid electricity is unreliable or unavailable. Sontake and Kalamkar (2016) provided a broader technical review and highlighted interactions among PV rating, motor-pump characteristics, maximum power extraction, and system efficiency. These findings support the use of a separately sized PV-battery-pump subsystem rather than powering the pump directly from an undersized controller supply.

The transition from wireless monitoring to IoT-based decision making is reflected in the work of Goap et al. (2018), who combined sensor data, weather information, machine-learning-based soil-moisture prediction, cloud services, and closed-loop irrigation. García et al. (2020) synthesized trends in IoT irrigation and identified soil sensors, wireless communication, cloud platforms, and automated actuation as recurring components of modern precision-irrigation systems. Krishnan et al. (2020) proposed a fuzzy-logic IoT irrigation approach that used soil moisture, temperature, and humidity while also considering main and solar power conditions, illustrating how environmental variables and energy status can be included in the control logic.

Research specifically combining solar energy with smart irrigation has also matured. Bouzguenda et al. (2019) reported a solar-powered smart irrigation design using low-cost wireless networking, Arduino-class control, and environmental sensors. Al-Ali et al. (2020) designed an IoT-solar smart farm irrigation system that monitored soil moisture, humidity, temperature, and groundwater level and remotely controlled irrigation pumps. Devan et al. (2021) presented an IoT-based solar-powered irrigation system with field sensing and cloud visualization, while Sinugo and Longe (2021) evaluated a solar-powered smart irrigation prototype incorporating automatic and manual control modes and reported water and energy savings relative to conventional operation. Collectively, the literature supports an integrated architecture, but it also shows a persistent need for transparent design assumptions, energy-

budget calculations, calibration procedures, and clearly defined performance metrics. The methodology below addresses these requirements.

## Methodology

### 1. System architecture and component selection

The proposed system is divided into four interacting layers: the energy layer, sensing layer, control-actuation layer, and IoT application layer. The energy layer consists of a 100 Wp solar PV module, PWM/MPPT-capable charge controller, 12 V battery, and protected DC

distribution. The sensing layer consists of a capacitive soil-moisture sensor installed in the crop root zone, a digital temperature-humidity sensor positioned above the soil surface, and a reservoir or bore-well water-level sensor. The control layer uses an ESP8266-class Wi-Fi microcontroller, relay or MOSFET driver, and 12 V DC pump. The application layer uses an MQTT/HTTP-compatible cloud platform such as ThingSpeak, Adafruit IO, or an equivalent server to store data and display field status. This layered arrangement follows the sensing-control-cloud pattern observed in recent IoT irrigation systems (García et al., 2020; Al-Ali et al., 2020).

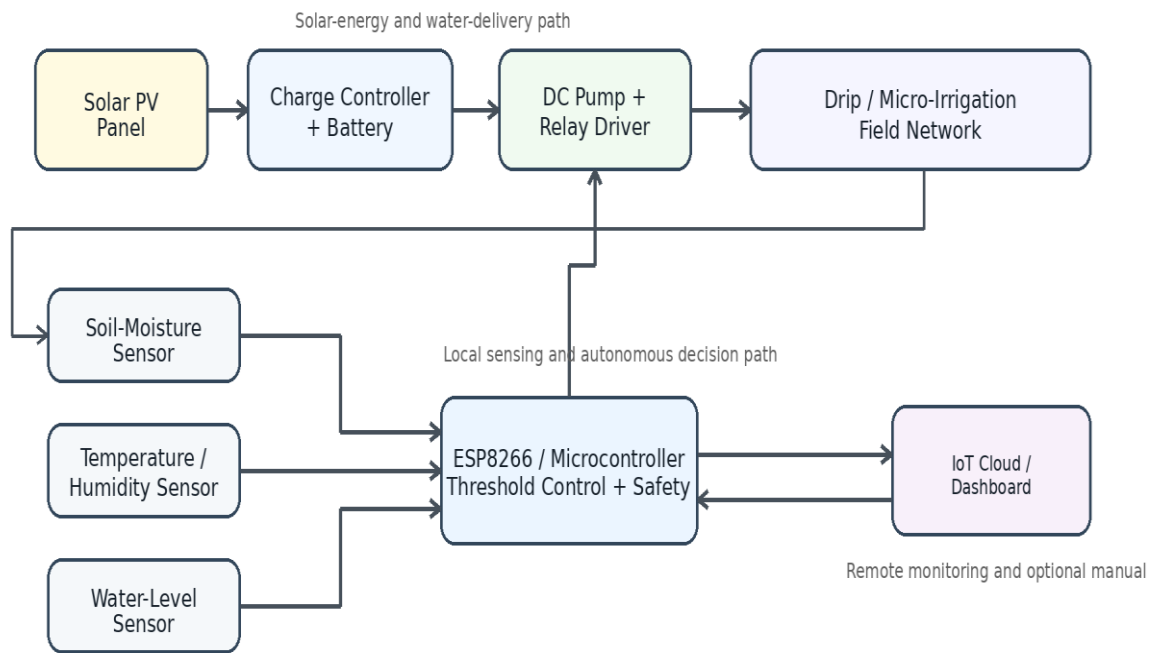


**Figure 1.** Proposed solar-powered IoT smart irrigation architecture.

### 2. Sensor calibration and irrigation control logic

Before deployment, each soil-moisture sensor is calibrated using dry and wet reference conditions for the selected soil. The raw analog-to-digital converter value is mapped to a normalized moisture percentage, and the calibration is checked at intermediate gravimetric moisture points when possible. To avoid rapid pump switching, two moisture thresholds are used. In the design scenario, irrigation starts when normalized soil moisture falls below 35% and stops when it reaches 55%. The exact thresholds must be adjusted to soil texture, crop type, rooting depth, and sensor placement. A hysteresis band is preferred to a single threshold because it prevents frequent relay cycling near one set point.

The controller samples the sensors at one-minute intervals and uploads a summarized reading every five minutes. The pump-enable decision is expressed as: Pump ON if  $M < M_{low}$ , reservoir level is safe, and battery voltage exceeds the minimum discharge limit; Pump OFF if  $M \geq M_{high}$ , reservoir level is unsafe, or battery voltage falls below the protection threshold. Manual override is permitted through the IoT dashboard, but safety interlocks remain active. This logic reflects the closed-loop principle used in sensor-driven irrigation systems while introducing explicit water-level and energy constraints (Gutiérrez et al., 2014; Al-Ali et al., 2020).

### 3. Design parameters and hardware specification

**Table 1.** Representative design specification used for methodology and sizing calculations.

| Subsystem       | Selected element              | Design value                  | Purpose               |
|-----------------|-------------------------------|-------------------------------|-----------------------|
| PV source       | Monocrystalline PV panel      | 100 Wp                        | Harvest solar energy  |
| Storage         | 12 V battery                  | 20 Ah; 70% usable DoD         | Night/cloud operation |
| Pump            | 12 V DC water pump            | 60 W nominal                  | Water delivery        |
| Controller      | ESP8266-class MCU             | Wi-Fi; 3.3/5 V logic          | Decision and IoT link |
| Soil sensing    | Capacitive moisture sensor    | 35–55% control band           | Root-zone feedback    |
| Climate sensing | Temp./humidity sensor         | 1-min sampling                | Context and logging   |
| Safety          | Water-level + battery sensing | Low-level/low-voltage cut-off | Protect pump/battery  |
| IoT             | MQTT/HTTP cloud dashboard     | 5-min upload                  | Remote visualization  |

#### 4. Solar-energy and battery sizing

The daily energy produced by the PV module is estimated using  $E_{PV} = P_{PV} \times H_{PS} \times \eta_d$ , where  $P_{PV}$  is the rated panel power,  $H_{PS}$  is the daily peak-sun-hours, and  $\eta_d$  is an overall derating factor accounting for temperature, wiring, charge-controller, and conversion losses. For a 100 Wp module, five peak-sun-hours, and a 0.75 derating factor, the expected usable harvest is 375 Wh/day. This conservative sizing method is consistent with the need to account for multiple loss mechanisms in PV water-pumping systems (Chandel et al., 2015; Sontake & Kalamkar, 2016).

The daily load is separated into pumping and control consumption. Assuming a 60 W pump operating for 1.3 h/day under demand-based scheduling, pump energy is 78 Wh/day. If sensing, control, communication, and relay electronics average 3 W continuously, their daily use is approximately 72 Wh/day. The estimated total is therefore 150 Wh/day. The energy margin is  $375 - 150 = 225$  Wh/day, and the generation-to-load ratio is 2.5. A 12 V, 20 Ah battery stores 240 Wh nominally; at a 70% usable depth of discharge, about 168 Wh is available, corresponding to approximately 1.12 days of autonomy at the assumed 150 Wh/day load. In real deployment, battery capacity should be increased where consecutive cloudy days are expected.

#### 5. IoT communication and data handling

Each uploaded data record contains timestamp, soil moisture, air temperature, relative humidity, water-level state, battery voltage, pump state, and operating mode. The dashboard displays current values and time-series plots and produces alerts for low water level, low battery, sensor failure, or excessive pump runtime. Local control continues even if the Internet connection fails; the cloud is therefore used for supervision rather than as the only control path. This edge-

first strategy reduces the risk that a temporary network outage will interrupt irrigation and is consistent with the reliability considerations identified in IoT-based precision agriculture (García et al., 2020).

#### 6. Performance evaluation protocol

Performance is evaluated over a seven-day test window under three irrigation strategies applied to an equivalent crop-water requirement: fixed manual irrigation, timer-based drip irrigation, and the proposed soil-moisture-controlled IoT method. The principal indicators are total water applied, pump runtime, electrical energy used by the pump, percentage water saving relative to manual irrigation, ability to maintain soil moisture within the selected band, renewable-energy coverage, and number of safety interruptions. Because this paper is methodology-focused and no raw field dataset was supplied, the Results section presents a transparent scenario-based analytical evaluation using the design values above; these figures should be replaced by measured values after prototype deployment.

#### Results

The energy-balance calculation shows that the 100 Wp PV module can theoretically supply considerably more daily energy than the representative smart-irrigation load. With 375 Wh/day available and 150 Wh/day required, the renewable-energy coverage is 250%, leaving a 225 Wh/day gross margin under the assumed solar resource. This margin is important because actual PV output varies with temperature, dust, shading, orientation, and cloud cover. The battery calculation indicates that the selected 12 V-20 Ah unit is adequate for short-duration buffering but provides only about 1.12 days of autonomy at the stated load, so longer autonomy requires either a larger battery, reduced

communications duty cycle, or additional PV capacity.

For water-use analysis, a seven-day manual baseline of 120 L/day is compared with a timer-based drip schedule of 95 L/day and a demand-based smart schedule averaging 78 L/day. The resulting totals are 840 L, 665 L, and 546 L, respectively. The proposed method therefore reduces water application by 294 L over seven

days, equivalent to 35.0% relative to the manual baseline and 17.9% relative to timer-based drip irrigation. This value is a design-scenario outcome rather than a claimed field measurement, but the direction of improvement agrees with the literature in which sensor-driven and solar-powered smart irrigation reduced unnecessary watering and pump operation (Goap et al., 2018; Sinugo & Longe, 2021).

**Table 2.** Scenario-based irrigation and pump-performance comparison for a seven-day evaluation period.

| Strategy                | Water/day (L) | 7-day water (L) | Pump time/day (h) | Pump energy/day (Wh) | Saving vs manual |
|-------------------------|---------------|-----------------|-------------------|----------------------|------------------|
| Manual fixed irrigation | 120           | 840             | 2.00              | 120                  | 0%               |
| Timer-based drip        | 95            | 665             | 1.58              | 95                   | 20.8%            |
| Proposed IoT control    | 78            | 546             | 1.30              | 78                   | 35.0%            |

The threshold strategy also changes how water is distributed in time. Manual irrigation tends to apply a large fixed amount independent of actual soil condition, whereas the IoT method applies water only after the lower threshold is crossed and stops at the upper threshold. This can reduce both over-irrigation and pump cycling when properly calibrated. The temperature-humidity channel is not used as the sole trigger in the basic method but provides contextual data that can later support evapotranspiration or fuzzy-logic control, as demonstrated by more advanced IoT approaches (Krishnan et al., 2020). Likewise, the water-level interlock prevents dry running, an important feature in solar-pumped systems where the controller may otherwise continue operating whenever energy is available (Al-Ali et al., 2020).

From a communications perspective, the architecture is designed so that irrigation remains autonomous at the field controller. A network outage therefore causes loss of remote visibility but not loss of threshold-based control. When connectivity returns, current sensor states and pump status can be synchronized with the dashboard. This division between local control and remote supervision improves robustness and is preferable to a cloud-only actuator path for agricultural systems where broadband coverage can be intermittent.

## Conclusion and Discussion

This paper developed a complete methodology for designing and evaluating a solar-powered smart irrigation system using IoT technology. The proposed architecture integrates photovoltaic generation, battery storage, soil and environmental sensing, local microcontroller-based decision making, water-level and battery

safety protection, pump actuation, and cloud monitoring. The method is grounded in prior wireless-sensor irrigation research, established PV water-pumping principles, and recent IoT smart-irrigation studies. The analytical sizing exercise indicates that a representative 100 Wp PV module can support the assumed 150 Wh/day smart-irrigation load under five peak-sun-hours, while a 12 V-20 Ah battery provides short-term buffering. The scenario-based water analysis indicates a 35% reduction relative to a fixed manual schedule when irrigation is controlled by a 35–55% soil-moisture hysteresis band. The main design advantage is the coordination of water and energy decisions: irrigation is permitted only when the crop requires water, the water source is safe, and electrical energy is available. However, the calculated results should not be interpreted as substitute evidence for field trials. Soil-specific calibration, crop-specific thresholds, emitter uniformity, actual pump head, PV temperature losses, battery aging, network quality, and seasonal weather can substantially alter performance. Future experimental work should therefore record volumetric soil moisture, measured flow, PV current-voltage data, battery state of charge, pump energy, communication uptime, and crop-response indicators over multiple irrigation cycles. Such validation would convert the proposed methodology into a fully empirical performance study while preserving the reproducible design framework presented here.

## References

Al-Ali, A. R., Al Nabulsi, A., Mukhopadhyay, S., Awal, M. S., Fernandes, S., & Ailabouni, K. (2020). IoT-solar energy powered smart farm irrigation system. *Journal of Electronic Science and*

Technology, 17(4), 100017.  
<https://doi.org/10.1016/j.jnlest.2020.100017>

Bouzguenda, M., Rajamohamed, S., Shwehdi, M. H., & Aldalbahi, A. (2019). Solar powered smart irrigation system based on low-cost wireless network: A senior design project experience. *The International Journal of Electrical Engineering & Education*. Advance online publication. <https://doi.org/10.1177/0020720919860414>

Chandel, S. S., Nagaraju Naik, M., & Chandel, R. (2015). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews*, 49, 1084–1099. <https://doi.org/10.1016/j.rser.2015.04.083>

Devan, P. K., Arun, K., Arvindkumar, N. H., Aravind, R., & Dinesh Kumar, R. (2021). IoT based solar powered smart irrigation system. *Journal of Physics: Conference Series*, 2054, 012074. <https://doi.org/10.1088/1742-6596/2054/1/012074>

García, L., Parra, L., Jimenez, J. M., Lloret, J., & Lorenz, P. (2020). IoT-based smart irrigation systems: An overview on the recent trends on sensors and IoT systems for irrigation in precision agriculture. *Sensors*, 20(4), 1042. <https://doi.org/10.3390/s20041042>

Goap, A., Sharma, D., Shukla, A. K., & Krishna, C. R. (2018). An IoT based smart irrigation management system using machine learning and open-source technologies. *Computers and Electronics in Agriculture*, 155, 41–49. <https://doi.org/10.1016/j.compag.2018.09.040>

Gutiérrez, J., Villa-Medina, J. F., Nieto-Garibay, A., & Porta-Gándara, M. A. (2014). Automated irrigation system using a wireless sensor network and GPRS module. *IEEE Transactions on Instrumentation and Measurement*, 63(1), 166–176.

<https://doi.org/10.1109/TIM.2013.2276487>

Kim, Y., Evans, R. G., & Iversen, W. M. (2008). Remote sensing and control of an irrigation system using a distributed wireless sensor network. *IEEE Transactions on Instrumentation and Measurement*, 57(7), 1379–1387. <https://doi.org/10.1109/TIM.2008.917198>

Krishnan, R. S., Julie, E. G., Robinson, Y. H., Raja, S., Kumar, R., Thong, P. H., & Son, L. H. (2020). Fuzzy logic based smart irrigation system using Internet of Things. *Journal of Cleaner Production*, 252, 119902. <https://doi.org/10.1016/j.jclepro.2019.119902>

Sinugo, R., & Longe, O. M. (2021). Solar-powered smart irrigation system. In *2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI)* (pp. 30–35). IEEE. <https://doi.org/10.1109/RTSI50628.2021.9597219>

Sontake, V. C., & Kalamkar, V. R. (2016). Solar photovoltaic water pumping system—A comprehensive review. *Renewable and Sustainable Energy Reviews*, 59, 1038–1067. <https://doi.org/10.1016/j.rser.2016.01.021>