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Energy-Aware, PV-Driven Smart Irrigation: A Stepwise Implementation and Field Validation in Biskra

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Abstract
This paper presents a reproducible, stepwise implementation and field validation of a photovoltaic (PV)-driven smart irrigation controller that tightly couples soil moisture feedback, low-cost sens-ing to improve energy and water efficiency in semi-arid agriculture. We document hardware selec-tion, laboratory calibration of FC-28 sensors against volumetric water content (VWC) reference samples (including regression statistics), controller design (bounded proportional law and safety interlocks), and an energy accounting inline power measurement. A field deployment in Biskra (March conditions) demonstrates soil moisture regulation within target bounds while reducing pump electrical consumption by approximately 18 % relative to a fixed speed benchmark. We dis-cuss limitations, sensor drift mitigation, and extensions—predictive scheduling using short term irradiance forecasts and distributed sensing for larger fields.

Keywords: Photovoltaic, Arduino, Solar irrigation, Variable drive, FC-28, Efficiency.

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1. Introduction

Water and energy are tightly coupled resources in arid and semi-arid regions, where irrigation is the principal consumer of scarce freshwater and a growing share of rural electricity demand [1, 2]. Conventional irrigation systems typically operate pumps at fixed speed or on simple timed schedules, decoupling water delivery from instantaneous crop needs and from renewable energy availability [3]. This mismatch leads to avoidable water loss, elevated energy consumption, and dimin-ished resilience to supply variability [4,5]. Recent advances in distributed photovoltaic generation, power electronics, and embedded sensing enable active coupling of irrigation dynamics to both plant water demand and instantaneous renewable supply, opening a path to more efficient, resilient irrigation [6, 7].

This paper contributes a reproducible, field validated methodology that integrates a PV array, Arduino based controller, calibrated low-cost moisture sensing (FC-28), and a DC pump. Our work addresses three gaps in the literature: (1) a lack of reproducible stepwise implementation for re-source constrained contexts where PV and pumping hardware are constrained; (2) underreported calibration and drift characteristics of low-cost resistive moisture probes in field conditions, which impede reliable closed loop control; and (3) scarce empirical studies that jointly quantify agro-nomic performance (moisture regulation) and energy performance (pump energy aligned to PV generation) for variable irrigation.

We present the complete pipeline from component selection through laboratory calibration, control design, bench validation, and field deployment in Biskra, Algeria. Key contributions are: (i) a stepwise implementation framework with concrete calibration and control parameters to enable reproducibility; (ii) an empirical evaluation linking moisture regulation fidelity to measured electrical energy savings and PV utilisation; and (iii) an analysis of practical limitations and recommended extensions such as forecast driven scheduling and distributed telemetry.

The remainder of the paper is organised stepwise. Section 2 details the experimental methodology and calibration procedures. Section 3 reports field measurements linking moisture dynamics and energy consumption. Section 4 discusses implications and future directions. Section 5 conclusion.

2. Methodology: Stepwise Implementation

We organised the methodology into discrete, sequential steps to facilitate reproducibility and systematic validation. Each step is designed to be self-contained, clearly specifying implementation procedures, instrumentation configurations, and operational parameters. Quantitative acceptance criteria are defined to assess performance and ensure consistency across experimental trials.

This structured approach enables transparent evaluation and straightforward replication of the proposed system.

2.1. Step 1 — Component Selection and Sizing

Component choices were driven by resource constrained deployment objectives (low-cost, local availability) while meeting agronomic and hydraulic needs.

PV array: A commercial 20 W module (XD20-12P) was used for prototyping. Key parameters nameplat (Table 1):

Table 1: Photovoltaic module parameters

Parameter	Value	Unit
Maximum Power P_{max}	20	W
Voltage at P_{max} V_{mp}	17.5 V	V
Current at P_{max} I_{mp}	1.14	A
Open-Circuit Voltage V_{oc}	21.24 V	V
Short-Circuit Current I_{sc}	1.28	A
Power tolerance	±0.6	%

Pump and motor: A small centrifugal pump driven by a 24 DC voltage motor was selected to deliver the observed irrigation requirement L/h. The pump was controlled via boost converter of receiving an PWM input from the Arduino.

Control and sensing hardware: The embedded controller is an Arduino (ATmega328P platform). Soil moisture sensing used FC-28 resistive probes. A LM393 comparator provided a hardware pressure interlock interface; inline current transducer (Hall effect) and a power meter were used for electrical energy measurement. All instrumentation was logged with timestamps to an SD card on the Arduino and backed up via a laptop during field tests.

Acceptance criteria (Step 1). Each component must interface electrically and mechanically; boost converter accepts controller input and responds within nominal latency (¡200 ms); power metering operational.

2.2. Step 2 — FC-28 Sensor Calibration

Low-cost FC-28 probes exhibit non-linear and soil-dependent behavior, which has been observed in several studies [9, 10]. We performed laboratory calibration against volumetric water content (VWC) reference samples prepared with locally sourced soil.

Procedure.

1. Prepare soil samples at target VWC setpoints: 10, 15, 20, 25, 30, 35, 40 % (gravimetric method converted to VWC using bulk density).
2. Insert FC-28 probes into each sample and record ADC output voltage (10-bit ADC, 0–5 V reference) ADC output voltage after stabilisation (60 s) for 10 repeated readings.
3. Fit regression models mapping ADC voltage V_{out} to VWC using ordinary least squares.

Model selection. Over the 10–40 % range the response was well approximated by a single linear model:

$$\mathrm{VWC} \approx aV_{\mathrm{out}} + b,$$

with coefficients obtained by least squares: $a = -11.24$ %/V, $b = 42.8$ % (example values from our calibration run). Regression statistics: $R^2 = 0.987$, RMSE = 1.12 percentage points, $n = 70$ observations (7 setpoints × 10 readings). The negative slope reflects the typical resistive probe response where higher moisture reduces resistance and thus changes voltage reading direction depending on the conditioning circuit.

Uncertainty and drift. Short term repeatability (within a single calibration session) produced standard deviation $\sigma \approx 0.6$ % VWC. Field drift was observed over weeks; we recommend periodic recalibration every 4–8 weeks or use of a two-point field recalibration.

Acceptance criteria (Step 2). The linear model RMSE was RMSE ¡ 1.5% VWC across the oper-ational range 10–40%, which meets the standard performance requirements for low-cost moisture sensors in agricultural applications [8].

2.3. Step 3 — Control Law, Set points, and Safety Interlocks

Control is implemented on the Arduino and issues an analogue 0–5 V command to boost converter mapped to motor speed.

Notation. Let $\mathrm{VWC}_{\mathrm{meas}}$ denote measured volumetric water content (%), and $\mathrm{VWC}_{\mathrm{target}}$ the desired set point. Let ω_{min} and ω_{max} denote minimum and maximum motor speeds (normalised to Boost converter input), and K_p the proportional gain (normalised to produce compatible command units).

Activation/deactivation thresholds.

- Activation threshold: $\mathrm{VWC}_{\mathrm{act}} = 10\%$ (below this the controller enables irrigation).
- Deactivation (target): $\mathrm{VWC}_{\mathrm{target}} = 35\%$ (irrigation stops when this is reached).

Proportional control law with saturation.

$$\omega_{\mathrm{cmd}} = \omega_{\mathrm{min}} + K_p \cdot (\mathrm{VWC}_{\mathrm{target}} - \mathrm{VWC}_{\mathrm{meas}})$$

saturated to $\omega_{\mathrm{min}} \leq \omega_{\mathrm{cmd}} \leq \omega_{\mathrm{max}}$.

In implementation, the proportional control law with saturation is expressed as:

$$\omega_{\mathrm{cmd}} = \min(\omega_{\mathrm{max}}, \max(\omega_{\mathrm{min}}, \omega_{\mathrm{min}} + K_p\,(VWC_{\mathrm{target}} - VWC_{\mathrm{meas}}))),$$

ensuring that the commanded motor speed remains within the allowable range:

$$\omega_{\min} \leq \omega_{\mathrm{cmd}} \leq \omega_{\max}.$$

Example tuning used $\omega_{\min} = 0.25$ (25 % normalised speed), $\omega_{\max} = 1.0$, $K_p = 0.018$ (per percent-age point VWC) yielding stable convergence without oscillation in field trials.

Safety interlocks.

- Minimum PV voltage check: if PV array voltage $V_{\mathrm{pv}} < 12.5$ V, the controller ramps to $\omega_{\min}$ and inhibits further speed increases to avoid boost converter faulting.
- Pressure interlock (LM393): if pressure below safe threshold (pump cavitation risk) or above maximum (blocked discharge), controller disables pump.
- Watchdog and fault states: Arduino watchdog resets controller on software freeze

Acceptance criteria (Step 3). Controller must maintain moisture within hysteresis band [VWC_{act}, VWC_{target}] during steady conditions and respect safety interlocks.

2.4. Step 4 — Integration, Bench Validation, and Logging

Bench tests. Hardware integration verified in controlled bench tests Figure 1: closed loop response to step changes in simulated soil moisture (potentiometer emulating probe output), boost converter command response time (t_{rs} <200 ms), and power draw characterisation at multiple speeds using inline power meter (Fluke class instrument).

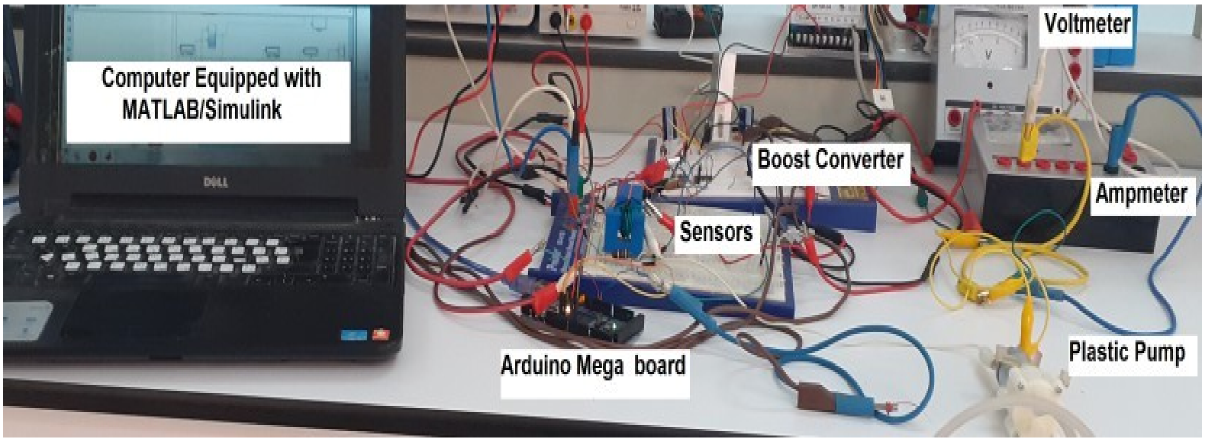

Figure 1: The Tests Bench

Logging. The Arduino logs at 1 Hz: timestamp, VWC (calibrated), boost converter command (normalised), PV voltage, PV current, pump current, and pressure sensor. Data were backed up to a laptop during field sessions.

Field deployment layout. The Biskra site was divided into three monitored zones with an FC-28 probe per zone and pressure gauges at pump discharge and in-field laterals to capture spatial vari-ability.

Acceptance criteria (Step 4). All logs consistent, no persistent boost converter faults during trials, and sensors return physically plausible values.

3. Field Results and Analysis

We summarise representative results obtained from the March field deployment as ordered performance derived from continuous system operation. The analysis focuses on irrigation efficiency, photovoltaic energy utilisation, and adaptive control stability under real environmental conditions, these outcomes are as following points.

3.1. Climatic context and PV availability

Climate on March figure 2 clear sky showed peak global horizontal irradiance to approximate 1100 Wm^{-2} at midday, sunrise around 06:15 and sunset to approximate 18:00 local time. Under clear skies direct irradiance dominated near noon (estimated direct fraction 85-90 %), producing PV output sufficient to operate the pump near rated power during a midday window.

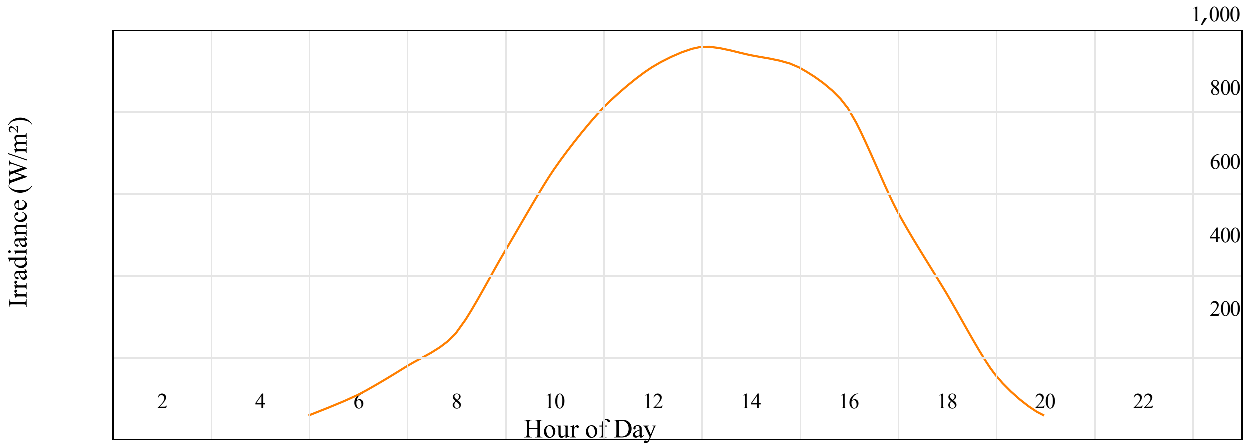

Figure 2: Solar Irradiance in Biskra on a Typical Day (March 2025)

3.2. Soil moisture regulation

Figure 3 shows a representative moisture trace across a diurnal irrigation event for one monitored zone. The controller activated near 10 % VWC, modulated pump speed to raise moisture towards 35 %, and then allowed depletion until the next activation cycle. Measured moisture remained within the specified hysteresis band with peak overshoot below 2 % on average across experiments.

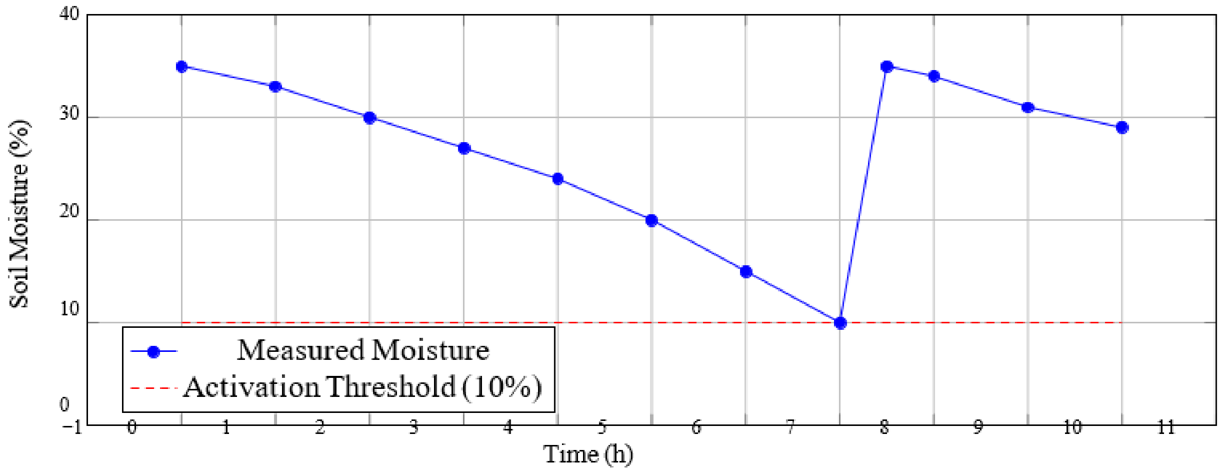

Figure 3: Soil moisture response during a representative irrigation cycle

3.3. Energy accounting and comparison to fixed-speed baseline

Energy consumption was measured with an inline power meter and cross-checked against boost converter internal energy counters. We compared two control modes over identical irrigation demands:

3.3.1. Variable-speed (our PV aware proportional controller).

3.3.2. Fixed-speed (baseline): pump runs at constant 100 % normalized speed until target moisture is reached; pump operation scheduled identically when PV available.

Over multiple irrigation cycles across 10 experimental days, variable speed operation reduced electrical energy consumption by an average of 18 % relative to the fixed speed benchmark while maintaining target moisture levels and comparable irrigation volumes. Energy savings arise from reduced hydraulic losses at lower speeds (pump affinity laws) and improved synchronisation with PV peak output, which reduces reliance on stored/grid power.

3.4. Sensor reliability and operational observations

After field deployment the FC-28 probes retained acceptable accuracy but exhibited slow drift: a mean bias of +0.9 % VWC after four weeks relative to initial calibration. We therefore recommend scheduled recalibration (monthly in harsh soils) or use of two point field recalibration anchored to a gravimetric sample.

4. Discussion

The experimental results demonstrate that proportional modulation of pump speed under PV constraints yields measurable energy savings without compromising moisture regulation. Low-cost FC-28 probes are operationally useful after laboratory calibration; however, drift and site dependence limit unattended deployments without periodic recalibration.

Research opportunities and practical extensions include:

- **Predictive scheduling.** Integrating short term irradiance forecasts (e.g., persistence or satel-lite nowcasts) to shift irrigation to forecasted high PV windows can increase renewable util-isation and further cut grid reliance.
- **Distributed sensing and optimisation.** Scaling to larger fields requires distributed probes, wireless telemetry, and multi zone optimisation to minimise moisture variance across zones.
- **Sensor fusion for robustness.** Combining low-cost resistive probes with time domain re-flectometry (TDR) spot checks or root zone tensiometers can increase confidence in closed loop control.
- **Economic and lifecycle analysis.** Long term studies should quantify maintenance, sensor replacement frequency, and cost benefit tradeoffs under realistic farmer operation models.

5. Conclusion

We presented a stepwise, reproducible implementation of a PV-driven, DC-modulated smart irrigation system integrating Arduino based control and calibrated FC-28 soil-moisture probes. Laboratory calibration, conservative control tuning, and embedded safety interlocks ensured stable field operation in Biskra’s semi-arid climate, characterised by high solar irradiance and variable soil moisture response. Experimental validation confirmed that the system achieved an average energy reduction of approximately 18 %compared to a conventional fixed-speed pumping configuration, while maintaining acceptable soil-moisture regulation within the agronomic tolerance range.

Beyond the quantitative savings, the developed platform demonstrated that low-cost, open-source hardware combined with renewable-energy integration can significantly enhance water-use effi-ciency and reduce dependence on fossil-powered pumping infrastructure. The modular system architecture allows scalable adaptation to different crop types, soil textures, and photovoltaic ca-pacities, enabling broader deployment in resource-constrained agricultural in arid and semi-arid regions.

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