Smart Solar Irrigation System

Autonomous Solar-Powered Irrigation with Intelligent Water and Energy Management
Productive Use of Energy – Agriculture

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1. Project Description

1.1 Development Objective

The proposed project aims to increase agricultural productivity, water-use efficiency, and climate resilience by deploying autonomous, solar-powered irrigation systems in off-grid and weak-grid agricultural areas.

The intervention enables the productive use of electricity (PUE) through renewable energy–driven irrigation infrastructure combined with automation, sensing, and digital supervision, ensuring sustainable operation under real farm conditions.

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2. Technical Design Principles

The system is designed in accordance with the following principles:

- **Local autonomy is mandatory**

Irrigation and safety functions must operate independently of connectivity.

- **Fail-safe operation**

Hardware and software protections prevent flooding, over-irrigation, and pump damage.

- **Separation of control and supervision**

Critical decisions occur locally; remote systems supervise and configure only.

- **Scalability and replicability**

Architecture supports farms from 1 hectare to multi-hectare commercial operations.

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3. Structural System Architecture

3.1 Layered Control Structure

The system is composed of three structurally independent layers, each with clearly defined authority and interfaces.

Layer 1 – Field Control Layer (ESP32)

Role: Primary and authoritative controller for irrigation and safety: esp32

Responsibilities:

- Executes irrigation schedules
- Reads all field sensors
- Controls pumps and valves
- Enforces safety logic
- Operates continuously without internet or gateway

Structural Rule: No external system can bypass esp32 safety decisions.

Layer 2 – Farm Gateway Layer (NanoPi M4 V2)

Role: Data aggregation, configuration, monitoring, and reporting.

Responsibilities:

- Receives telemetry from esp32
- Stores operational data
- Hosts APIs and dashboards
- Sends configuration updates to esp32
- Supports monitoring & evaluation (M&E)

Structural Rule: Gateway cannot directly actuate pumps or valves.

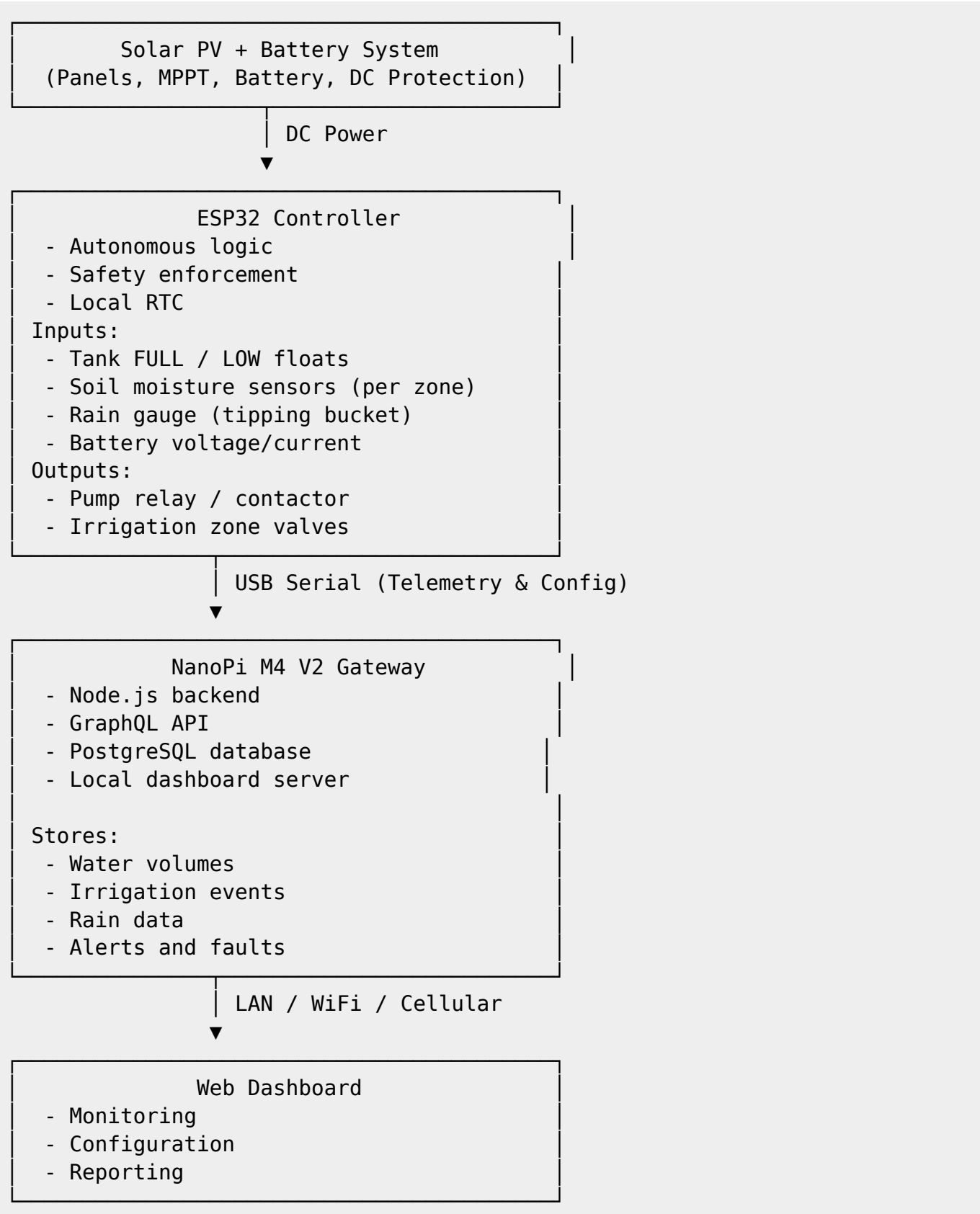
Layer 3 – Human Interaction Layer

Role: Supervised operational oversight.

Responsibilities:

- Monitor performance
- Adjust schedules and thresholds
- Generate reports
- Trigger manual requests (subject to validation)

4. End-to-End Structural Connection Diagram



5. Hydraulic & Water System Structure

5.1 Structural Hydraulic Diagram

```
[Water Source]
    │
    ├── Foot Valve + Strainer
    │
    ├── Pump (Solar-powered)
    │
    ├── Check Valve
    │
    ├── Flow Meter
    │
    ├── Filter (Screen / Sand)
    │
    ├── Storage Tank
    │      ├── FULL Float Switch
    │      ├── LOW Float Switch
    │      └── Overflow Line (gravity safety)
    │
    ├── Pressure Regulator
    │
    ├── Distribution Manifold
    │      ├── Zone Valve 1 → Drip / Sprinkler
    │      ├── Zone Valve 2 → Drip / Sprinkler
    │      └── Zone Valve N → Drip / Sprinkler
    │
```

6. Electrical & Control Structural Connections

6.1 Power and Control Topology

```
Solar Panels
   ↓
MPPT Charge Controller
   ↓
Battery Bank
   ↓
DC Protection (Fuse / Breaker)
   ↓
DC Bus (12V / 24V)
   ├── Pump (via Contactor + Float Switch)
   ├── Irrigation Valves
```

```
    ├── DC-DC Converter → ESP32 (5V)
    └── DC-DC Converter → NanoPi (5V)
```

6.2 Hardware Fail-Safe Connections

- Tank FULL float switch wired in series with pump coil
- LOW tank float blocks pump and irrigation
- Overflow pipe provides passive hydraulic protection
- Battery low-voltage cut-off prevents deep discharge

These safeguards operate even if software fails.

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7. Operational Logic

7.1 Decision Hierarchy

The system follows a strict decision hierarchy:

- **Hard safety**
  - Battery below minimum → system shutdown
  - Tank FULL → pump disabled
  - Tank LOW → irrigation disabled
- **Rain protection**
  - Rain detected → irrigation suspended
  - Rain lockout active → irrigation blocked
- **Soil moisture control**
  - Moisture ≥ threshold → skip irrigation
- **Schedule execution**
  - Irrigation only within authorized time windows
- **Manual requests**
  - Executed only if all above conditions are satisfied

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8. Farm-Scale Structural Adaptability

Farm Size	Structural Adaptation
1 ha	Single pump, 1–2 zones
5 ha	Higher-capacity pump, 4–6 zones
20 ha	Multiple pumps, staged tanks, zoned manifolds

The control architecture remains unchanged, enabling replication at scale.

9. Implementation Readiness

The system:

- Uses commercially available components
- Supports results-based verification
- Enables private-sector participation
- Reduces greenhouse gas emissions
- Improves water-use efficiency
- Is suitable for national or regional scale programs

10. Conclusion

This Smart Solar Irrigation System constitutes a production-ready PUE solution aligned with World Bank operational requirements. The architecture separates critical control from supervision, integrates layered safety mechanisms, and supports scalable agricultural deployment under real-world conditions.