DESIGN OF AN IOT-BASED SOLAR PHOTOVOLTAIC IRRIGATION PUMPING SYSTEM FOR RAINFED FARMING IN KEMBANG SARI VILLAGE

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ABSTRACT
Rainfed agriculture is highly vulnerable to rainfall variability and limited irrigation infrastructure, resulting in unstable agricultural production, particularly during prolonged dry periods. This study aimed to develop a detailed engineering design for an integrated solar-powered irrigation system equipped with Internet of Things monitoring for rainfed farmland in Kembang Sari Village. The study employed a research-and-development approach focusing on electrical-load analysis, photovoltaic and battery sizing, pump and reservoir configuration, hydraulic-system design, and sensor-based monitoring architecture. The proposed system integrates photovoltaic modules, a solar charge controller, lithium iron phosphate batteries, an inverter, a 1.5-hp irrigation pump, a water reservoir, and sensors for soil moisture, water level, flow rate, battery condition, and pump status. The results showed a total connected load of 1,156 W and a daily energy requirement of approximately 6,019 Wh. Considering an overall system efficiency of 80% and five peak-sun hours per day, the required generation capacity was estimated at 7,523.75 Wh/day. The recommended configuration consists of seven 250-Wp photovoltaic modules with a total capacity of 1.75 kWp, a minimum 50-A charge controller, a 6-kW inverter, and two 48-V 100-Ah lithium iron phosphate batteries. The hydraulic subsystem uses a pump with an estimated 12-m head and a 36-m³ reservoir to support a target water supply of approximately 36 m³/day. The integrated monitoring system enables remote supervision, automatic protection, and data-informed irrigation management. The design provides a technically coherent basis for prototype construction, although field validation is required to assess actual solar generation, pump performance, water adequacy, sensor reliability, maintenance requirements, and economic feasibility.
Keywords: Internet of Things, Photovoltaic Irrigation, Rainfed Agriculture, Renewable Energy, Smart Farming

INTRODUCTION

Rainfed agriculture remains an important livelihood system in many rural areas of Indonesia, including Kembang Sari Village, where cropping decisions depend strongly on the timing and duration of rainfall. The absence of a reliable irrigation supply makes production sensitive to delayed monsoons, short dry spells, and prolonged drought. Farmers may postpone land preparation, reduce the cultivated area, or accept lower yields when water is unavailable during critical crop-growth stages. National agricultural statistics also show that the management of non-irrigated land continues to be a strategic issue because unstable water access constrains land productivity and the continuity of food production (Ministry of Agriculture of the Republic of Indonesia, 2022).

Climate variability intensifies these constraints. Changes in rainfall distribution make conventional planting calendars less dependable, while rising evapotranspiration during extended dry periods increases irrigation demand. The Food and Agriculture Organization (2021) emphasizes that resilient food systems require water-management technologies capable of maintaining production under climatic uncertainty. In the study area, farmers can use portable pumps when surface water or shallow groundwater is available, but fuel-powered pumping creates recurring expenses and exposes farmers to fuel-price fluctuations. Grid-connected electric pumps are not always feasible because agricultural plots may be distant from distribution lines and the available supply may be unstable.

Solar photovoltaic pumping offers an alternative because it converts locally available solar radiation into electricity for water lifting. Photovoltaic modules generate direct-current electricity, which can be used by a direct-current pump or converted through an inverter for an alternating-current motor. The required array capacity is determined by the daily energy demand, solar resource, conversion losses, and desired operating reserve. Pump selection must also account for discharge, total dynamic head, pipe losses, and the irrigation schedule. Properly sized systems can reduce fuel consumption, improve the predictability of pumping costs, and support decentralized irrigation where conventional energy infrastructure is limited (Messenger & Ventre, 2010; Sukhatme & Nayak, 2017).

Previous studies have demonstrated the potential of solar irrigation systems in agricultural applications. Hasanuzzaman et al. (2018) described the global development of solar pumping as a pathway toward more sustainable irrigation, while Nugroho and Kurniawan (2021) examined photovoltaic generation for rice-field water pumps. Santoso et al. (2022) showed that off-grid photovoltaic configurations can support agricultural pumping, and Atmaja et al. (2023) highlighted the importance of battery-storage efficiency when pump operation is extended beyond periods of strong solar radiation. These studies indicate that technical feasibility depends not only on module capacity but also on the coordination of the charge controller, battery, inverter, pump, and hydraulic system.

Digital monitoring can strengthen this coordination. The Internet of Things connects sensors, controllers, communication devices, and user interfaces so that operational data can be collected and transmitted in near real time (Rose et al., 2015). In agriculture, sensor-based systems can observe soil moisture, water level, flow rate, battery voltage, and equipment status. Such information enables farmers or system operators to identify low-water conditions, excessive pumping, battery depletion, or component failure without continuous physical inspection. Li et al. (2011) noted that connected monitoring is a central element of smart agriculture because it supports decisions based on field conditions rather than fixed schedules alone.

However, several gaps remain between the expected characteristics of smart irrigation and the practical condition of rainfed farming. Ideally, an irrigation system should provide sufficient water, use renewable energy efficiently, protect electrical components, and allow simple monitoring by local users. In practice, many designs address only one part of this requirement: some focus on photovoltaic sizing without sensor-based control, whereas others demonstrate Internet of Things monitoring without integrating the energy-storage and hydraulic calculations needed for off-grid operation. In addition, village-scale implementations often require a detailed engineering design that translates general concepts into component capacities, physical layouts, and operating logic that can be used during procurement and construction.

The novelty of this study lies in the integrated treatment of energy, hydraulics, storage, structural layout, and digital monitoring within one detailed design for rainfed agriculture. Rather than claiming field performance before installation, the study develops a technically consistent design basis and identifies the capacities required under the stated operating assumptions. The design combines a photovoltaic array, charge controller, lithium iron phosphate battery bank, inverter, 1.5-hp pump, water reservoir, irrigation outlet, and Internet of Things monitoring points. This integrated approach is intended to reduce dependence on diesel fuel, improve the continuity of irrigation, and provide operational information that supports preventive maintenance.

Accordingly, the objective of the study was to design and analyze an integrated solar-powered irrigation system with Internet of Things monitoring for rainfed farmland. The analysis specifically determined the electrical load, daily energy requirement, photovoltaic-array capacity, charge-controller rating, inverter capacity, battery requirement, pump and reservoir configuration, and monitoring architecture. The resulting detailed engineering design is expected to serve as a basis for prototype construction and subsequent field validation.

METHOD

Research Design and Design Object

The study used a research-and-development approach focused on engineering design. The output was not a mass-produced device or a completed impact evaluation, but a detailed engineering design that can be used as the technical reference for prototype assembly. The design object was an off-grid irrigation system for rainfed rice fields in Kembang Sari Village. Its main subsystems were the photovoltaic generator, solar charge controller, battery storage, inverter, pump, reservoir, pipe network, sensors, communication unit, and remote monitoring interface.

The system requirements were derived from the planned operating pattern and the physical irrigation concept. The pump was specified at 1.5 hp with an estimated connected power of 1,125 W, a total head of approximately 12 m, a 3-inch inlet, and a 2-inch outlet. Supporting loads consisted of lighting and Internet of Things equipment. The storage concept used a reservoir measuring 6 m × 6 m × 1 m, equivalent to a gross volume of 36 m^3. No human participants were involved in the electrical calculations; therefore, the unit of analysis was the technical system and its component specifications.

Instruments and Data Sources

The design instruments consisted of a system-needs worksheet, an electrical-load table, a component-sizing worksheet, manufacturers' nominal specifications, a hydraulic-design checklist, and a detailed engineering drawing checklist. The electrical-load worksheet recorded component quantity, connected power, operating duration, and daily energy use. The sizing worksheet was used to calculate system energy after conversion losses, photovoltaic-array capacity, charge-controller current, inverter capacity, nominal battery energy, and the required number of batteries.

The primary technical data were the planned power and operating hours of the pump and auxiliary equipment, the assumed average peak-sun duration of five hours per day, system efficiency of 80%, nominal battery voltage of 48 V, battery capacity of 100 Ah, and battery efficiency of 95%. The component ratings were treated as design inputs rather than measured field performance. The hydraulic data consisted of the target daily water volume, reservoir dimensions, pump head, and pipe sizes. These values were cross-checked for internal consistency before the detailed drawings were finalized.

Integrated System Architecture

The proposed architecture links the energy and irrigation subsystems. Solar modules supply the charge controller and battery bank; the inverter provides alternating-current power for the pump and auxiliary loads. Water is lifted from the source to the reservoir and distributed to the cultivated area. Sensors and the controller monitor soil moisture, reservoir level, water flow, battery condition, and pump status. Figure 1 presents the relationship among the principal components.

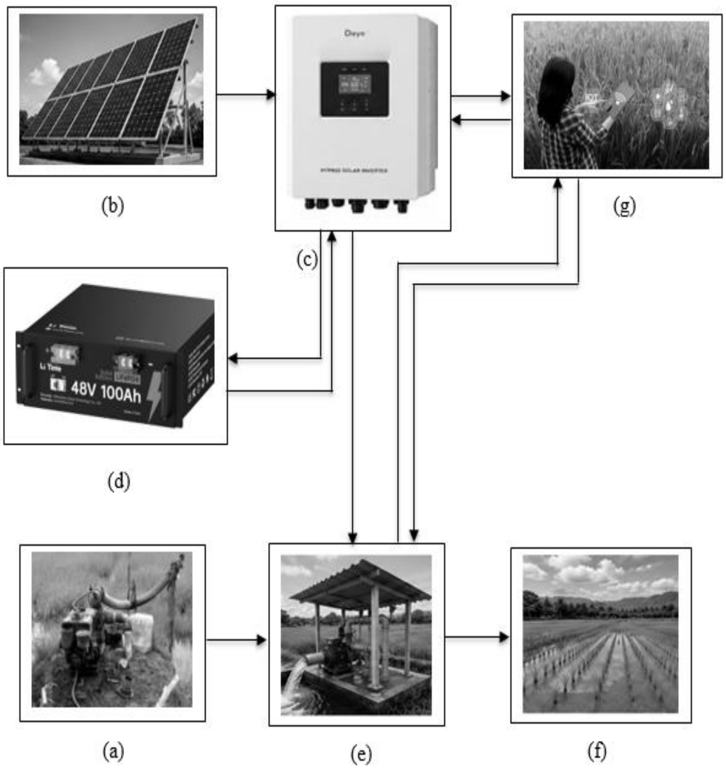

Figure 1. Integrated photovoltaic pumping and Internet of Things monitoring architecture

Design Procedure

The design procedure began with the identification of irrigation constraints and the amount of water required for the planned operating period. A literature review was then used to establish the principles of photovoltaic pumping, battery storage, inverter sizing, and connected agricultural monitoring. Electrical and hydraulic requirements were analyzed before selecting component capacities. The resulting configuration was translated into detailed engineering drawings and evaluated for consistency. When a calculated capacity was below the required demand or lacked an operating reserve, the design returned to the load-analysis stage for adjustment. Figure 2 summarizes this iterative procedure.

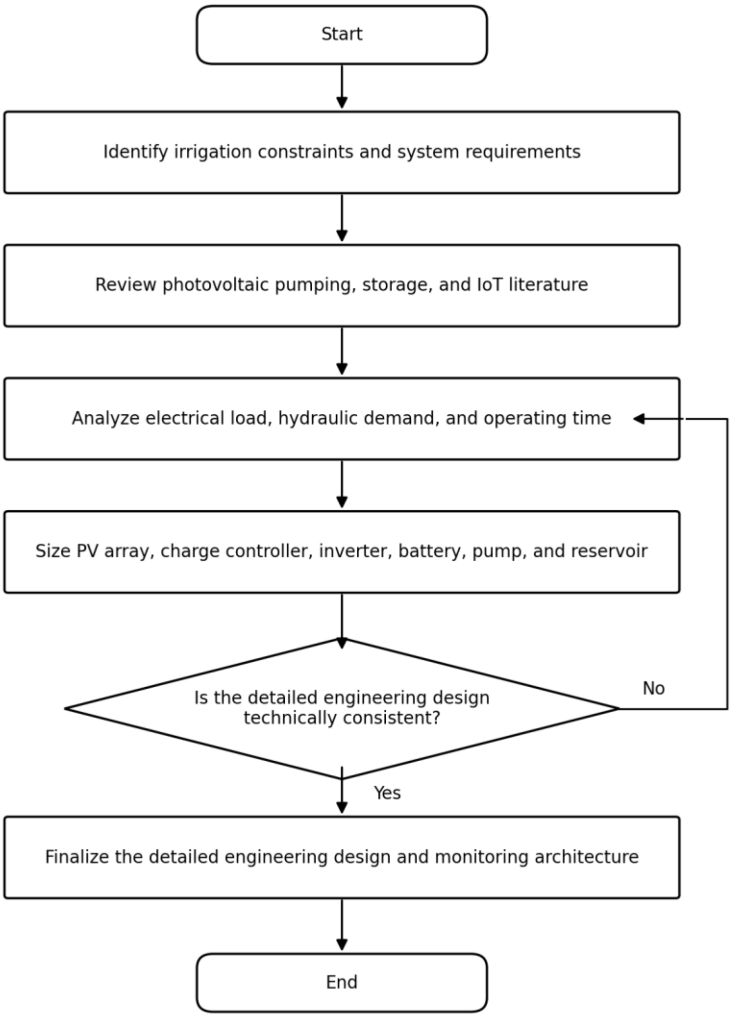

Figure 2. Research and detailed engineering design stages Energy and Component Sizing Analysis

Daily load energy was determined from the connected power and operating duration of each component. The load-energy equation was:

$$E_{beban} = \sum(P_i \times t_i)$$

where E_load is total daily load energy in watt-hours, P_i is the connected power of component i in watts, and t_i is its daily operating time in hours. The electrical loads were summed to obtain the total daily demand.

Because energy is lost in conductors, the charge controller, battery, and inverter, the energy that must be supplied by the photovoltaic subsystem was calculated as:

$$E_{total} = \frac{E_{beban}}{\eta_{sistem}}$$

where E_total is the design energy supplied by the generation subsystem and η_system is the assumed overall system efficiency. In this study, η_system was set at 0.80, consistent with the design assumption used in the original calculation framework (Ramadhan & Hidayat, 2020).

The daily energy generated by a photovoltaic array depends on its rated power and effective peak-sun duration:

$$E_{PV} = P_{PV} \times PSH$$

where E_PV is photovoltaic energy, P_PV is the total array rating in watt-peak, and PSH is peak-sun hours per day. The required number of modules was then obtained from:

$$N_{panel} = \frac{E_{total}}{P_{panel} \times PSH}$$

The result was rounded upward because a fractional module cannot be installed and because operating conditions may be less favorable than the nominal assumption.

The inverter had to carry the simultaneous connected load and tolerate the starting demand of the induction motor. The basic and starting-capacity relationships were:

$$P_{inverter} \geq P_{beban}$$
$$P_{inverter} = k \times P_{beban}$$

where P_inverter is the inverter rating, P_load is the connected load, and k is the motor starting factor. A factor of five was used for the pump motor. Auxiliary loads were added to the motor-starting requirement before the commercial inverter rating was selected.

Battery nominal and effective energy were calculated using:

$$E_{baterai} = V \times Ah$$
$$E_{efektif} = E_{baterai} \times \eta_{baterai}$$

where V is battery voltage, Ah is ampere-hour capacity, and η_battery is battery efficiency. The number of battery units was estimated by dividing the design energy by the effective energy per battery and rounding upward:

$$N_{baterai} = \frac{E_{total}}{E_{baterai}}$$

The analysis was descriptive and engineering-based. Calculated capacities were compared with the planned operating demand, and commercial ratings were selected at or above the calculated minimum. The design did not include long-term field measurements of solar irradiation, crop water requirement, pump efficiency, or financial return; these variables are identified as priorities for prototype testing.

RESULTS AND DISCUSSION

Electrical Load and Daily Energy Requirement

The connected load consists of the pump and two auxiliary categories. The pump dominates both instantaneous power and daily energy use, but lighting and the monitoring unit must be included because they operate during periods that do not necessarily coincide with full solar generation. Table 1 summarizes the design load. The connected powers shown for lighting and Internet of Things equipment are aggregate values for each category.

Table 1. Electrical Load of the Integrated Irrigation System

Component	Quantity	Connected Power (W)	Operating Time (h/day)	Energy (Wh/day)
Lighting	2	25	10	250
Internet of Things and control equipment	2	6	24	144
Irrigation pump	1	1125	5	5625
Total		**1156**		**6019**

The total connected load is 1,156 W, while the estimated daily energy demand is 6,019 Wh. The original pump-only calculation used 5,625 Wh as the dominant load, but the complete system must also supply 394 Wh/day for lighting and monitoring. Including the auxiliary loads prevents undersizing of the photovoltaic array and gives a more realistic basis for battery management. The pump accounts for approximately 93.5% of the daily energy demand, confirming that pump operating time is the principal variable controlling system size.

At an assumed overall efficiency of 80%, the generation subsystem must provide 7,523.75 Wh/day. This adjustment represents aggregate losses rather than the efficiency of a single device. In practice, losses vary with irradiance, battery state of charge, inverter loading, cable length, and motor efficiency. The 80% assumption is therefore suitable for preliminary sizing, but it should be replaced by measured component efficiencies during prototype commissioning.

Photovoltaic Array and Charge-Controller Capacity

Using 250-Wp modules and an assumed five peak-sun hours per day, one module can produce approximately 1,250 Wh/day before the aggregate system-loss adjustment. Dividing the required generation energy of 7,523.75 Wh by 1,250 Wh gives 6.02 modules. The result is rounded upward to seven modules, producing a nominal array capacity of 1.75 kWp. Six modules represent the theoretical minimum when only the dominant pump load is considered, but seven modules are technically preferable because they include the auxiliary demand and provide a modest reserve for non-ideal conditions.

The charge-controller current was calculated from the array rating and the 48-V system voltage. A seven-module array produces a nominal charging current of approximately 36.46 A. After applying a 1.25 protection factor, the minimum controller current is approximately 45.57 A; therefore, a 50-A controller is recommended. The controller should also be selected on the basis of maximum photovoltaic input voltage, temperature-adjusted open-circuit voltage, battery chemistry, and communication capability. A controller with data output can transmit charging current, battery voltage, fault status, and energy production to the monitoring platform.

The array configuration should be finalized only after the selected module voltage and controller input limits are known. Series connection raises voltage and reduces cable current, whereas parallel connection raises current and requires larger conductor and protection ratings. The detailed installation must include overcurrent protection, direct-current isolation, surge protection, grounding, weather-resistant connectors, and cable routing that limits voltage drop. These provisions are essential because agricultural environments expose equipment to moisture, dust, heat, and mechanical disturbance.

Inverter and Battery Configuration

The inverter must support normal operation and the transient starting demand of the pump motor. Applying a starting factor of five to the 1,125-W motor gives 5,625 W. Adding the 31 W of auxiliary connected power produces an estimated starting requirement of 5,656 W. A 6-kW inverter therefore meets the preliminary requirement. The preferred unit should provide a pure sine-wave output, sufficient short-duration surge capacity, motor-compatible protection, low-voltage shutdown, and fault communication. The selected inverter voltage must match the 48-V battery bank.

A 48-V, 100-Ah battery stores 4,800 Wh nominally. At 95% battery efficiency, the effective energy used in the preliminary calculation is 4,560 Wh. Dividing the required design energy of 7,523.75 Wh by 4,560 Wh gives 1.65 units, which is rounded upward to two batteries. The resulting nominal storage is 9.6 kWh, with 9.12 kWh after the stated efficiency adjustment. This capacity is adequate for the assumed daily demand under the simplified model, although actual usable energy will be lower when the manufacturer's depth-of-discharge limit, aging allowance, temperature, and reserve state of charge are considered.

The use of lithium iron phosphate batteries is appropriate for repeated cycling because the chemistry generally offers stable voltage, high cycle life, and integrated battery-management protection. Nevertheless, the battery bank should not be treated as maintenance-free. The enclosure requires ventilation appropriate to the product specification, protection from direct solar heating and flooding, secure terminals, appropriate fusing, and periodic inspection. Monitoring should include state of charge, voltage, current, temperature, and alarm conditions so that irrigation is automatically curtailed before damaging depletion occurs.

Physical and Hydraulic Design

The detailed engineering drawings translate the calculated component capacities into a physical arrangement. The structural frame supports the photovoltaic modules above the pumping and control area, allowing the roof surface to produce energy while providing partial protection for the electrical equipment. The reservoir is positioned adjacent to the pump and irrigation outlet. Figures 3 to 7 show the principal views of the proposed arrangement.

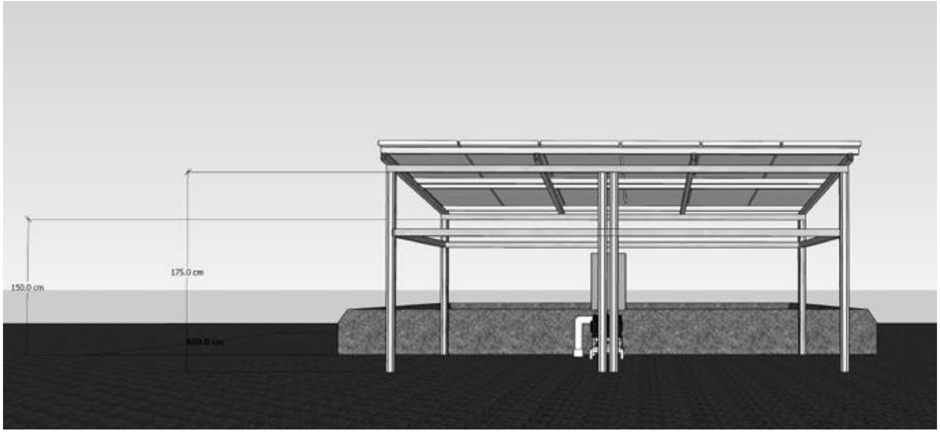

Figure 3. Front view of the integrated irrigation structure

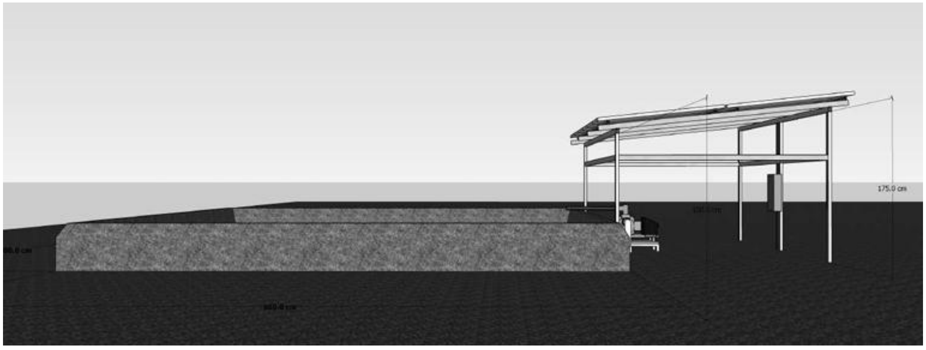

Figure 4. Side view of the photovoltaic support and reservoir

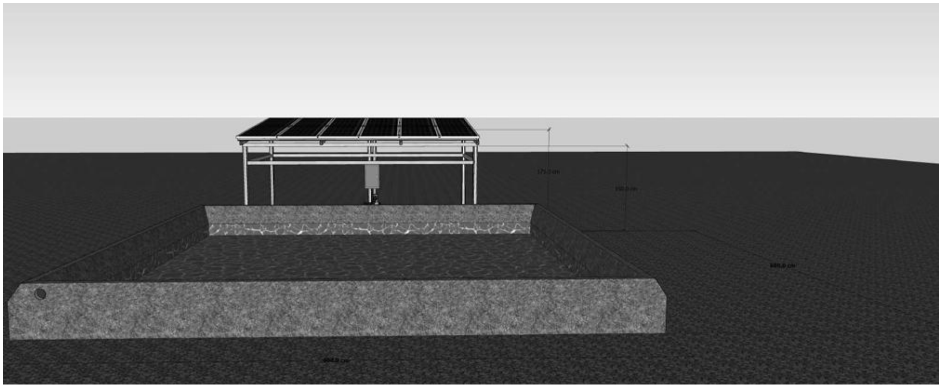

Figure 5. Rear view of the reservoir and photovoltaic structure

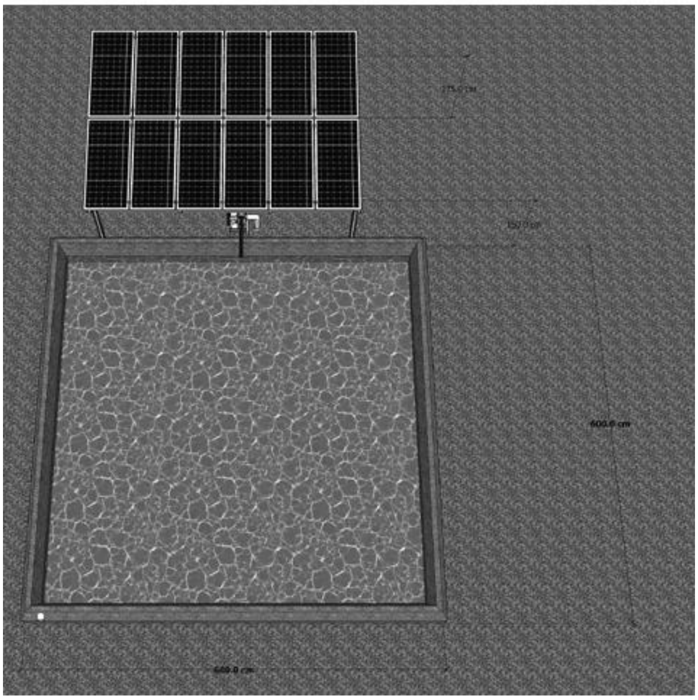

Figure 6. Top view of the reservoir and photovoltaic array

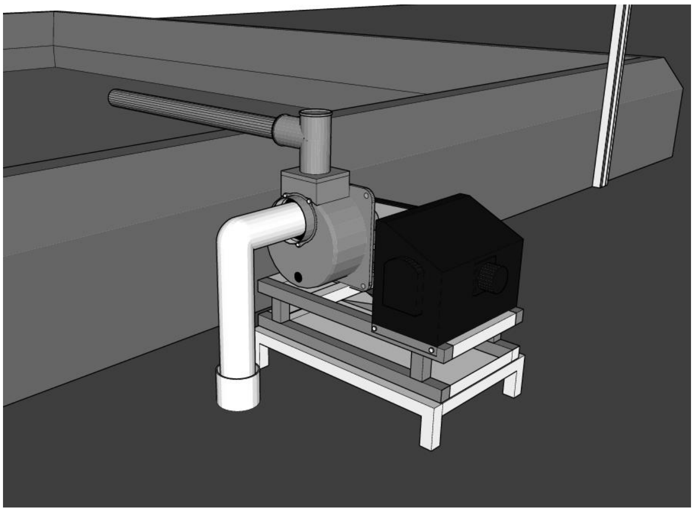

Figure 7. Pump inlet, motor, and support assembly

The reservoir dimensions of 6 m × 6 m × 1 m provide a gross storage volume of 36 m³. This volume is consistent with the stated target water delivery of approximately 36 m³/day and can decouple pumping time from field application time. Water can be pumped when solar energy is available and released according to crop demand, thereby reducing the need to operate the pump at the exact moment irrigation is required. The reservoir also provides a visible operational buffer that can be measured with a level sensor.

The pump specification of 1.5 hp and a design head of 12 m must be verified against the actual pump curve. A motor power rating alone does not guarantee the target discharge because flow depends on total dynamic head, pipe friction, suction conditions, and pump efficiency. The 3-inch inlet and 2-inch outlet shown in the design should therefore be checked against the final pipe length, number of bends, valve losses, and the elevation difference between the water source, reservoir, and field. A flow meter at the outlet will allow the prototype to compare measured discharge with the 36-m³/day design target.

The drawings indicate a compact arrangement, but field construction should include foundations, corrosion-resistant framing, secure module clamps, safe access for cleaning, and drainage around the electrical enclosure. The photovoltaic tilt and orientation must be adjusted to the local site rather than copied mechanically from the conceptual drawing. Shading from trees, buildings, or the reservoir structure should be avoided because partial shading can reduce array output and create mismatch among modules.

Internet of Things Monitoring and Control Logic

The monitoring subsystem is intended to convert the irrigation design from a manually observed installation into a data-informed system. Soil-moisture sensors indicate whether irrigation is needed, reservoir-level sensors prevent dry pumping and overflow, a flow sensor verifies water delivery, and electrical sensors provide battery and pump information. The controller can combine these inputs into operating rules. For example, pump operation can be permitted when the water source is available, the reservoir is below its upper limit, and the battery state is above the protective threshold. Pumping can be stopped when the reservoir reaches its maximum level, abnormal current is detected, or the battery reaches the minimum allowable state of charge.

Remote access through a smartphone or web interface can reduce routine travel to the installation, but local autonomous control remains essential. Agricultural sites may have intermittent mobile coverage, and the system must continue operating safely when the internet connection is unavailable. Data should be stored locally and synchronized when communication returns. Manual override should be provided for maintenance, but override events should be logged to preserve accountability and support troubleshooting.

Sensor accuracy and placement are critical. A soil-moisture reading from one location may not represent the entire field, and water-level sensors can be affected by sediment, condensation, or turbulence. Calibration, redundancy for critical protections, and scheduled inspection should therefore be included in the operating procedure. The proposed Internet of Things system is best understood as a decision-support and protection layer rather than a substitute for agronomic judgment. Irrigation thresholds must be adapted to crop stage, soil texture, rainfall, and local water-management practices.

Technical Contribution, Sustainability, and Limitations

The main technical contribution is the integration of photovoltaic sizing, storage, motor starting, hydraulic buffering, physical layout, and connected monitoring within one design. Previous work has established the value of solar pumping and smart-agriculture monitoring separately; the present design combines these functions for a rainfed setting and converts them into component ratings and drawings. The revised calculation also demonstrates the importance of including auxiliary loads. When lighting and monitoring are omitted, the array appears to require six modules, whereas the complete load profile requires seven under the stated assumptions.

From a sustainability perspective, replacing fuel-powered pumping with photovoltaic energy can reduce direct fuel use and local exhaust emissions. The reservoir allows energy to be harvested during sunny periods, and monitoring can limit unnecessary pumping or overflow. Economic benefits are plausible because recurring fuel purchases can be reduced, but this study does not calculate life-cycle cost, payback period, maintenance expenditure, or battery replacement. Those outcomes depend on local equipment prices, fuel costs, financing, crop value, and actual system utilization.

The design has several limitations. Peak-sun hours were represented by a single average value rather than a seasonal solar-resource dataset. Crop water demand was represented by a target daily volume rather than an evapotranspiration-based irrigation schedule. Pump efficiency and total dynamic head were not measured at the site, and no prototype data were available for flow, energy production, battery cycling, communication reliability, or sensor accuracy. Consequently, the results should be interpreted as a detailed preliminary design, not as evidence of realized productivity gains.

Prototype validation should measure photovoltaic energy, charge-controller efficiency, inverter losses, pump discharge, reservoir filling time, irrigation uniformity, sensor error, communication uptime, and battery state of charge across wet and dry seasons. The field test should also compare manual and automatic operating modes and document maintenance requirements. An economic analysis can then calculate the cost per cubic meter of water and compare the solar system with diesel pumping. These steps will determine whether the technical design is operationally robust and financially appropriate for farmer adoption.

CONCLUSION

The study produced a detailed design for an integrated solar-powered irrigation system with Internet of Things monitoring for rainfed agriculture. The complete load profile consists of 1,156 W connected power and approximately 6,019 Wh/day of energy demand. With an assumed 80% system efficiency and five peak-sun hours, the recommended configuration is seven 250-Wp photovoltaic modules, a minimum 50-A solar charge controller, a 6-kW inverter, and two 48-V 100-Ah lithium iron phosphate batteries. The hydraulic design uses a 1.5-hp pump, an estimated 12-m head, and a 36-m^3 reservoir to support a target discharge of approximately 36 m^3/day. Sensors for soil moisture, reservoir level, flow, battery condition, and pump status provide the basis for remote monitoring and protective control. The design is technically coherent under the stated assumptions and offers a pathway to reduce dependence on fuel-powered pumping; however, prototype testing is required to verify solar availability, pump performance, water adequacy, sensor reliability, maintenance needs, and economic feasibility under actual field conditions.

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