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Integrated Solar-Powered Irrigation System (ISIS)

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ABSTRACT

Hydroponic farming has become one of the solutions for urban food security, as it enables agricultural production on limited land with more efficient water use. However, most hydroponic systems still rely on conventional electricity to operate circulation pumps, sensors, and control devices, thereby increasing energy consumption and operational costs. Furthermore, the utilization of solar energy in hydroponics is generally limited to powering pumps, without considering the balance between the energy generated, stored, and consumed by the system. This research proposes ISIS (Integrated Solar-Powered Irrigation System) as a smart hydroponic innovation that integrates solar power generation, energy storage, and an adaptive control system within a single platform. The system employs a PV-MPPT-battery-DC load configuration combined with the Nutrient Film Technique (NFT) hydroponic method. Voltage, current, light intensity, water level, pH, and TDS/EC sensors are used to monitor energy conditions and plant nutrition in real time. Sensor data are then processed by the control system to regulate pump operation based on energy availability and hydroponic operational needs, thereby enabling automatic optimization of energy consumption. The main advantages of ISIS over conventional hydroponic systems lie in its adaptive energy management capability, the use of DC loads that reduce energy conversion losses, and battery integration that maintains operational continuity when solar intensity declines. This innovation has the potential to improve the efficiency of solar energy utilization, reduce dependence on the electricity grid, and support the development of more self-sufficient, economical, and environmentally friendly urban agriculture at both household and commercial scales.

1. Introduction

Increasing energy and food demands pose challenges to the development of efficient and sustainable production systems. In controlled-environment agriculture, the use of pumps, lighting, sensors, and control devices can result in high energy requirements [1]. Hydroponics is a suitable method for food production in urban areas because it can be implemented on limited land while

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using water relatively efficiently. The development of hydroponic systems also incorporates IoT technology and sensors to monitor and control cultivation conditions more systematically [2]. These considerations indicate that the development of hydroponic systems must account for both energy efficiency and the operational requirements of cultivation.

Hydroponic systems still require electrical energy, particularly to operate circulation pumps and other electronic devices. Several studies have utilized solar energy as an electricity source for hydroponic pumps and integrated it with IoT systems [3], [4], demonstrating the potential to improve energy efficiency and reduce environmental impacts compared with the use of grid electricity [5]. However, solar energy availability fluctuates, meaning that power generation does not always match the energy demands of hydroponic systems. Various studies have developed MPPT, solar tracking, and energy storage technologies to improve solar energy utilization [6], [7], while energy storage requirements in PV-based hydroponic systems depend on daily consumption and solar radiation availability [8]. In addition, State-of-Charge (SoC)-based adaptive control strategies have been used to adjust pump operations according to energy and environmental conditions [9].

Although PV, IoT, energy storage, and adaptive control technologies have been developed, previous studies have focused on different aspects, such as increasing PV energy generation, monitoring system conditions, and regulating pump operations based on battery conditions [9], [10]. Intelligent hydroponic systems have also incorporated plant parameter monitoring and IoT-based automation, but energy management has not always been a primary consideration in operational decision-making [11]. These findings indicate the need to integrate energy condition information with hydroponic operational requirements within a single adaptive control system. Therefore, this study developed the Integrated Solar-Powered Irrigation System (ISIS), which integrates solar PV, MPPT, batteries, DC loads, IoT, and adaptive control using the Nutrient Film Technique (NFT) hydroponic method. The system uses voltage, current, light intensity, water level, pH, and TDS/EC sensors to monitor energy and operational conditions in real time and adjust pump operations according to energy availability and hydroponic requirements.

Table 1

Summary of previous studies related to solar-powered hydroponic and energy management systems

Research	Key Feature	Method/Approach	Main Finding	Research Gap/Contribution of ISIS	Reference
Photovoltaic energy utilization	PV, solar pumping	Solar conversion pumping	Solar energy can be utilized for pumping and can reduce dependence on conventional electricity.	Does not address integrated adaptive energy management in hydroponic systems.	[12], [13]
PV power optimization	MPPT, converter	MPPT and power control	MPPT improves the utilization of available PV energy under changing operating conditions.	Power optimization is not directly integrated with hydroponic operational requirements.	[14], [15]
Solar energy storage	PV, battery, DC load	Generation-storage integration	Energy storage maintains energy availability when generation is insufficient.	Energy storage is not fully integrated with adaptive hydroponic operations.	[15], [16]
NFT hydroponics	NFT, circulation pump	Continuous solution circulation	NFT supports the continuous delivery of water and nutrients to plant roots.	Pump operation is generally treated as a fixed hydroponic load.	[17]

IoT-based hydroponics	Sensors, microcontroller, IoT	Real-time monitoring and control	IoT enables the monitoring automated control of hydroponic parameters.	the Energy conditions are not always included as control inputs. [18], [19]
Adaptive agricultural control	Sensor data, adaptive control	Data-based resource optimization	Operational data support resource management.	Integration of energy availability and hydroponic demand remains limited. [20]

Based on the identified research gap, this study developed ISIS (Integrated Solar-Powered Irrigation System), an intelligent hydroponic system that integrates solar PV, MPPT, batteries, DC loads, IoT, and adaptive control into a single system. The system employs the NFT method and incorporates voltage, current, light intensity, water level, pH, and TDS/EC sensors to monitor energy conditions and hydroponic operations in real time. The collected information is used to determine pump operation according to energy availability and hydroponic system requirements. This approach is expected to optimize solar energy utilization while maintaining continuous hydroponic operations under changing energy availability conditions. Thus, ISIS is designed to support the implementation of more efficient, independent, and sustainable hydroponic systems.

2. Methodology

The design methodology of the Integrated Solar-Powered Irrigation System (ISIS) was developed to integrate the Nutrient Film Technique (NFT) hydroponic system with solar energy generation, energy storage, monitoring, and adaptive control. The design process was carried out in three main stages: design specifications, tool specifications, and system specifications. These stages were established based on the operational and energy requirements necessary to operate the hydroponic system sustainably.

2.1 Hydroponic Design

The hydroponic system in ISIS was designed using the Nutrient Film Technique (NFT) method, with several planting channels arranged on a supporting frame, as shown in Figure 1. The system consists of NFT channels, distribution piping networks, nutrient solution reservoirs, and pumps that circulate nutrient solutions through the planting channels. The nutrient solution flows through the NFT channels as a thin film passing over the plant roots before returning to the reservoir through the return piping system. This circulation configuration allows the nutrient solution to be reused, supporting more efficient water utilization. The selection of the NFT hydroponic method is also consistent with the concept of hydroponics as a cultivation technique suitable for limited land areas and capable of incorporating sensor technology and IoT for more systematic monitoring of cultivation conditions [1], [2].

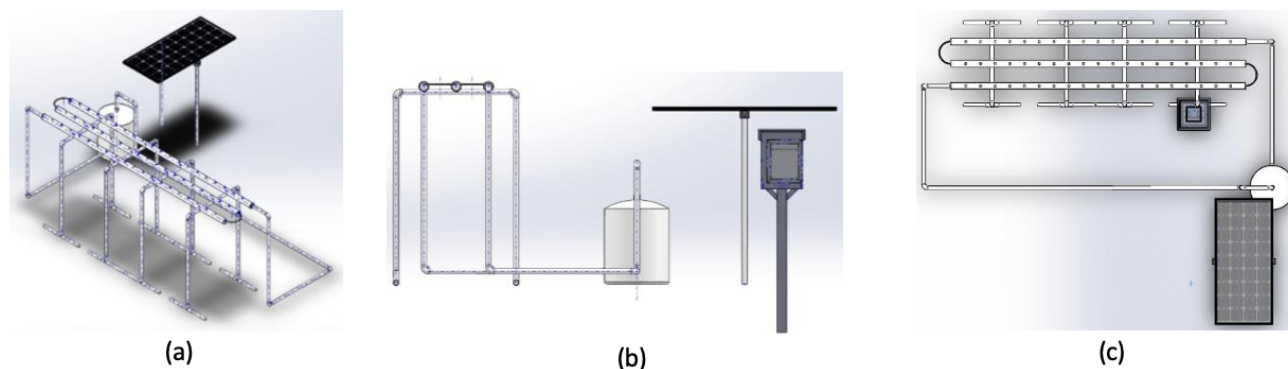


Fig. 1. Hydroponic design: (a) Top-southeast view, (b) Side view, and (c) Top view

In this design, the hydroponic system does not operate independently but is integrated with the solar energy generation and monitoring systems as part of ISIS. The solar panel serves as the electrical energy source supporting system operations, particularly the circulation pumps and electronic devices used for monitoring and control. The system is also equipped with sensors to monitor energy parameters and hydroponic operating conditions, including voltage, current, light intensity, water level, pH, and TDS/EC, in real time. The information collected by these sensors is then used as input for the control system to adjust pump operations according to energy availability and hydroponic requirements. The integration of the hydroponic system, solar energy generation, sensors, and adaptive control forms the basis of the ISIS design, which aims to increase solar energy utilization while maintaining continuous hydroponic system operations [3], [4], [9–11].

2.1.1 House of Quality

The ISIS system design applies the Quality Function Deployment (QFD) method using the House of Quality (HOQ) matrix. This approach systematically maps various operational requirements from the user's perspective. The primary requirements identified include efficient solar energy utilization, stable system operation, and reduced water consumption through closed-loop circulation. Through this matrix, these operational requirements can be translated into measurable priorities for the technical parameters of the final system design. This step ensures that each proposed hardware and software innovation addresses the energy efficiency challenges associated with conventional hydroponic systems.

Based on the HOQ matrix analysis presented in Figure 2, the design priorities were determined according to the parameters with the highest technical importance scores. The analysis identified three main technical aspects requiring priority during the design stage. The PLC-based adaptive control algorithm received the highest score of 119, making it the first priority. The NFT channel and frame configuration ranked second with a score of 112, followed by battery storage capacity with a score of 106. These scores provide a clear basis for the design team to prioritize critical technical components.

The priority rankings obtained from the HOQ matrix are closely related to the novelty proposed by the ISIS system. The adaptive control algorithm was identified as the most important element for maintaining system performance. This control logic actively aligns fluctuating solar energy availability with the real-time requirements of hydroponic nutrient circulation. In contrast, the solar PV array capacity received a relatively lower priority score of 78. This is because the proposed generation capacity of 30 kWp theoretically exceeds the total daily energy requirements of the system.

Therefore, the primary focus of innovation should be directed toward improving the reliability of the energy control system.

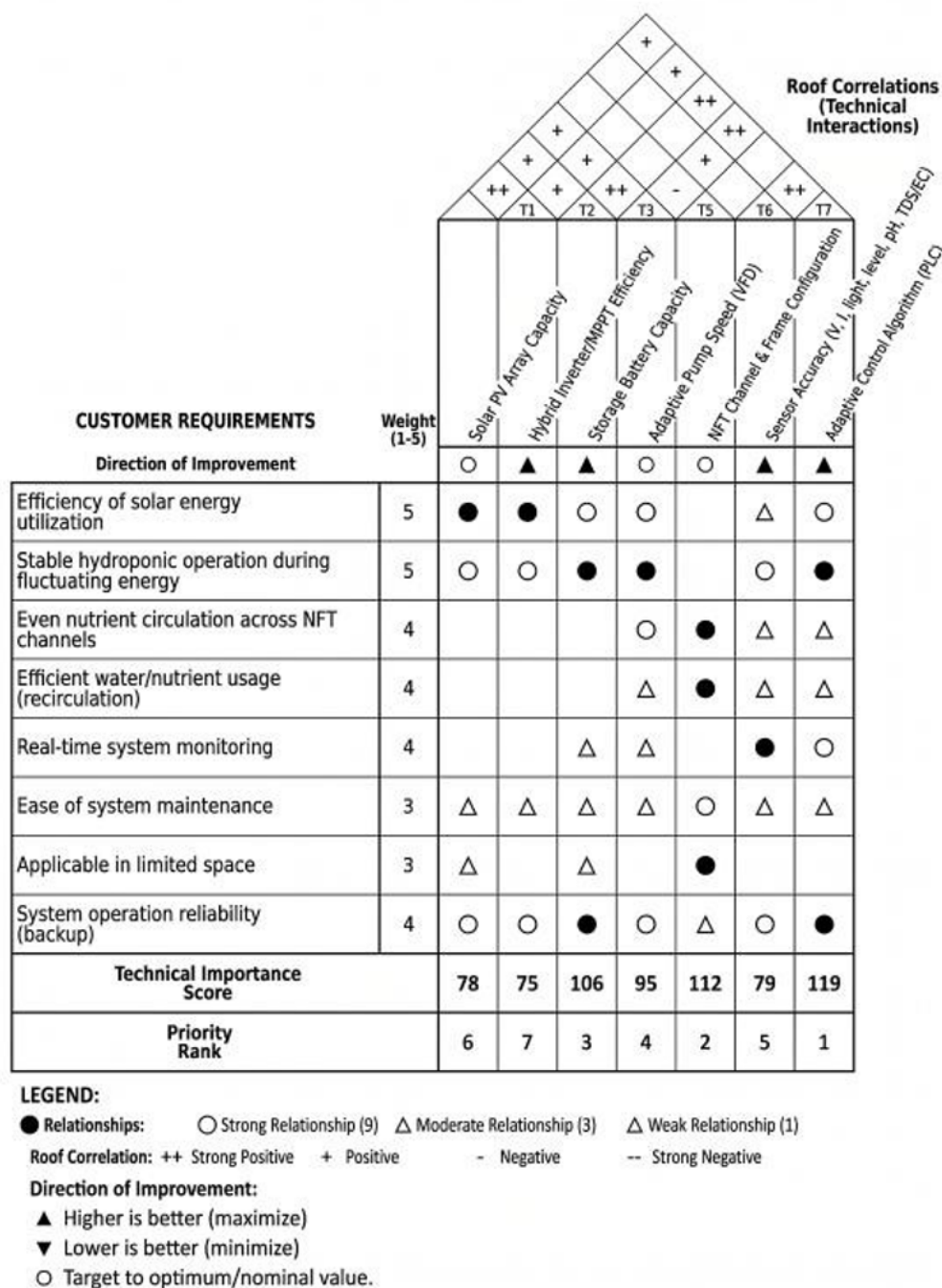


Fig. 2. House of Quality (HOQ) for the ISIS design

2.2 Tool Specifications

Based on the design specifications established in the previous stage, several components are required to implement the proposed solar-powered hydroponic system. The components were selected according to their functions in supporting energy generation, nutrient solution distribution, hydroponic system operation, and system monitoring and control. The energy subsystem consists of

a solar PV array, DC combiner box, hybrid inverter, distribution panel, and Variable Frequency Drive (VFD), which support energy generation, management, and distribution to the electrical loads. Meanwhile, the hydroponic subsystem includes a main pump, backup pump, filter, flow meter, nutrient reservoir, main pipe, header/manifold, NFT channels, return pipe, and dosing pump to support nutrient solution circulation and management. The system is also equipped with sensors and control devices, including pH sensors, EC sensors, level sensors, a PLC, and an HMI, to obtain system information and support monitoring and control operations.

Table 2

List of components and their functions

Components	Function
Solar PV Array	Generates DC electricity from solar energy.
DC Combiner Box	Combines PV string outputs and provides DC protection.
Hybrid Inverter	Converts DC electricity into AC electricity and manages energy distribution.
AC Distribution Panel	Distributes electricity and provides load protection.
Variable Frequency Drive (VFD)	Adjusts pump speed to improve energy efficiency.
Main Pump	Circulates nutrient solutions throughout the hydroponic system.
Backup Pump	Serves as a backup when the main pump malfunctions.
Filter	Removes impurities from water and nutrient solutions.
Flow Meter	Measures the flow rate in the main pipe.
Nutrient Reservoir	Stores hydroponic nutrient solutions.
Main Pipe	Delivers water and nutrient solutions to each zone.
Header/Manifold	Distributes the flow to different hydroponic zones.
NFT Channel	Provides a channel for nutrient solution flow and plant cultivation.
Return Pipe	Returns nutrient solutions to the reservoir.
Dosing Pump	Adds nutrient solutions with precision.
pH Sensor	Measures the acidity level of the nutrient solution.
EC Sensor	Measures the electrical conductivity of the nutrient solution to indicate nutrient concentration.
Level Sensor	Measures the water level in the reservoir.
PLC & HMI	Control and monitor the entire system.

Details of the components and their respective functions are presented in Table 2. The component grouping demonstrates that the system integrates the energy, hydroponic, and monitoring and control subsystems into a single operational unit. The energy subsystem supplies and manages the electrical energy required for operation, while the hydroponic subsystem distributes and circulates nutrient solutions to the plants. Sensors and control devices collect information on energy conditions and hydroponic operating parameters, enabling the system to operate according to actual conditions. Through this integration, each component performs an interconnected function that supports the overall operation of ISIS.

2.3 System Specifications

The system specification stage describes the integration of the energy generation, hydroponic, and monitoring and control subsystems established in the previous stage. The system uses solar PV as an energy source to generate DC electricity, which is then managed through a solar/MPPT

controller and converted into AC electricity using an inverter to meet the system's electrical load requirements. The electrical energy is subsequently used to operate the main pump, which transports the nutrient solution from the reservoir to the main pipe for distribution to each hydroponic zone. The nutrient solution flows through the NFT channels before returning to the reservoir through the return pipe, forming a closed-loop circulation system. The integration of energy flow and nutrient solution circulation is illustrated in Figure 3.

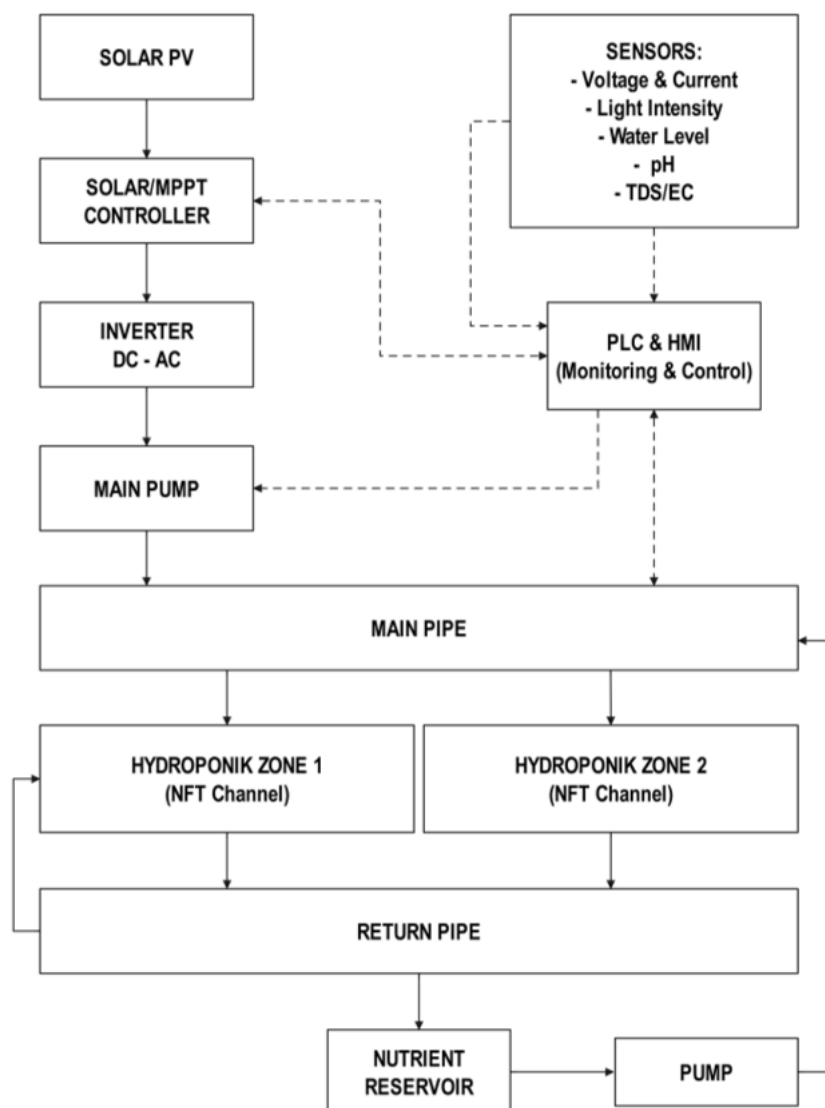


Fig. 3. Flowchart of the Integrated Solar-Powered Irrigation System

As shown in Figure 3, the system consists of three main flows: electrical energy flow, nutrient solution flow, and monitoring and control data flow. The energy flow begins at the solar PV array and passes through the solar/MPPT controller and inverter before supplying electricity to the pump, which serves as the system's main electrical load. The nutrient solution flows from the reservoir through the pump to the main pipe, where it is distributed to several hydroponic zones before returning to the reservoir through the return pipe. Meanwhile, sensors collect data on voltage, current, light intensity, water level, pH, and TDS/EC as indicators of energy and hydroponic operating

conditions. These data are transmitted to the PLC and HMI for monitoring and control, allowing system operations to be adjusted according to actual conditions.

2.4 Calculation Method

2.4.1 Calculation of Load Energy Requirements

Equation (1) is used to calculate the total electrical energy requirement based on the power consumption and operating time of each load [21]. The variable E_{load} represents the total electrical energy requirement (Wh/day), P_i represents the power of the i -th load, and t_i represents the operating time of the (h/day).

$$E_{load} = \sum_{i=1}^n (P_i \times t_i)$$

2.4.2 Calculation of Daily Solar Radiation Energy

Equation (2) is used to calculate the total solar irradiation based on the Global Horizontal Irradiation (GHI) value for each time interval. According to the Global Solar Atlas data presented in Figure 4, the research location in Malang has a GHI of 1,867.6 $kWh/m^2/year$. The GHI value is accumulated over the time interval (Δt) to obtain the total irradiation (H), which is subsequently used to calculate the potential PV energy generation [22].

$$H = \sum_{k=1}^n (GHI_k \times \Delta t)$$

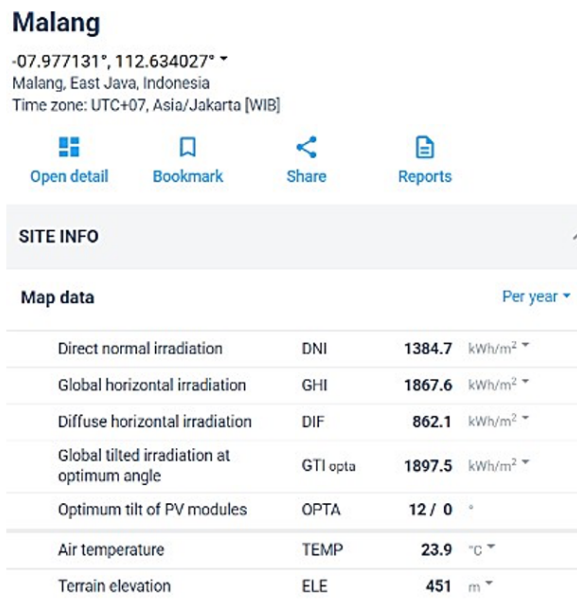


Fig. 4. Global Horizontal Irradiation (GHI) at the research site in Malang. Source: Global Solar Atlas

2.4.3 PV Power Calculation

Equation (3) is used to determine the required photovoltaic (PV) power capacity based on the load energy requirements, effective sunlight hours, and system efficiency [23].

$$P_{PV} = \frac{E_{load}}{H \times \eta_{sys}}$$

2.4.4 Comparison of Electrical Energy Consumption Between Conventional and PV Systems

Equation (4) is used to compare electrical energy consumption between a conventional system and a PV-integrated system. The comparison is performed by calculating the percentage reduction in electrical energy consumption achieved through PV integration [24].

$$SE = \frac{E_{grid,conv} - E_{grid,PV}}{E_{grid,conv}} \times 100\%$$

3. Results

3.1 Potential of Solar Energy

The solar energy potential of the system was determined based on the Global Horizontal Irradiation (GHI) value at the proposed installation site. According to Global Solar Atlas data, the annual GHI value used in this study was 1,867.6 kWh/m²/year. This annual GHI value was converted into average daily irradiation using Eq. (1) in the calculation method. The results indicate that the proposed installation site has an average daily solar irradiation potential of 5.12 kWh/m²/day. This value was subsequently used as the basis for determining the energy generation potential of a 30 kWp PV array.

Table 3

Solar energy potential of the PV system

Parameter	Value
Annual GHI	1,867.6 kWh/m ² /year
Daily GHI	5.12 kWh/m ² /day
PV Array Capacity	30 kWp
Gross PV Energy Potential	153.5 kWh/day
Annual Gross PV Energy Potential	56,028 kWh/year

Based on Table 3, the 30 kWp PV array has a theoretical gross energy generation potential of 153.5 kWh/day, equivalent to approximately 56,028 kWh/year. This result demonstrates the potential of photovoltaic energy to meet the system's electrical requirements. It is consistent with previous studies on photovoltaic energy utilization that have investigated solar energy conversion and pumping as alternatives to conventional electricity for pumping applications [12], [13]. However, the calculated value represents theoretical energy generation potential before accounting for losses associated with PV conversion, the inverter, cables, temperature, and other system components.

3.2 Characteristics of Electrical Load

Based on the system design, the main pump, rated at 7.5 kW, represents the primary electrical load because it circulates nutrient solutions from the reservoir to all hydroponic zones. The system is also equipped with a 5.5 kW backup pump, which operates as a standby unit and is therefore excluded from normal operating energy requirements. In addition to the main pump, the system includes several control and monitoring loads, consisting of a PLC, HMI, sensors, solenoid valves, and dosing pumps. Based on the specified power ranges, representative values of 17.5 W for the PLC, 10 W for the HMI, 5 W for the sensors, 7.5 W for the solenoid valves, and 37.5 W for the dosing pumps were used.

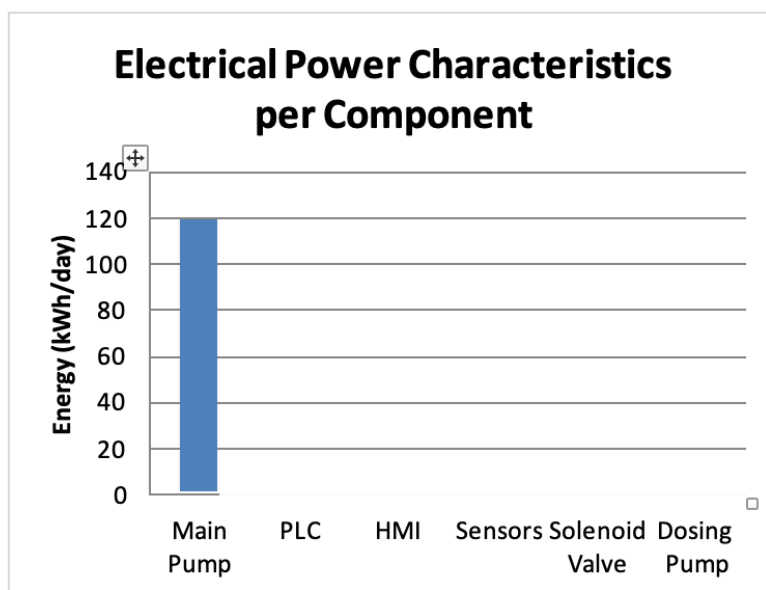


Fig. 5. Comparison of the representative power requirements of the main pump and the control and supporting components of the hydroponic system

As shown in Figure 5, the main pump has the highest power requirement at 7.5 kW, while the control and supporting components have a combined representative power requirement of 77.5 W. This indicates that the system's energy demand is primarily influenced by nutrient solution circulation. Therefore, regulating pump operation and power consumption is an important aspect of the energy management strategy. This consideration is consistent with previous studies on PV power optimization, in which MPPT and power control were employed to improve the utilization of available PV energy under changing operating conditions [14], [15].

3.3 Daily Energy Requirements and PV Energy Balance

Based on the calculated energy requirements, the system operates for 16 hours per day. During this operating period, the main pump consumes 120.00 kWh/day, while the control system and supporting devices consume 1.24 kWh/day. Therefore, the total electrical energy requirement of the system is 121.24 kWh/day. Meanwhile, the 30 kWp PV system has a theoretical daily energy generation potential of 153.50 kWh/day, based on an average solar irradiation of 5.12 kWh/m²/day. The difference between the theoretical PV energy potential and the total system energy requirement is 32.26 kWh/day. This value represents a theoretical energy margin rather than an actual electricity

surplus because losses associated with energy conversion, temperature effects, cables, the inverter, MPPT, and batteries have not yet been considered.

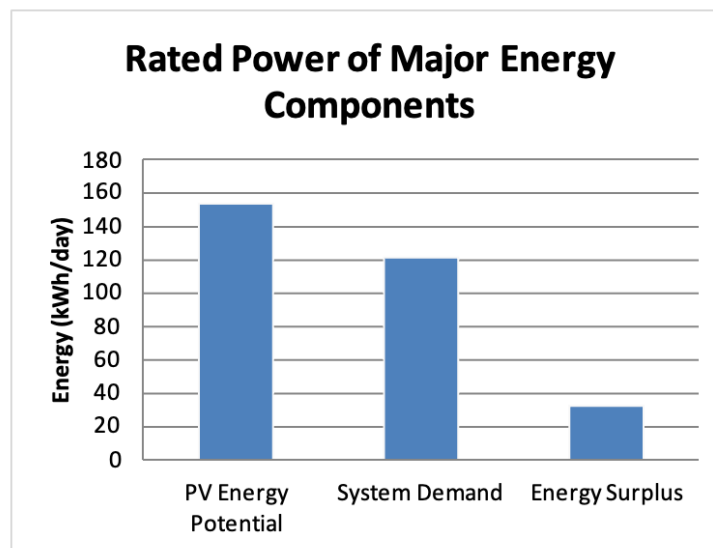


Fig. 6. Comparison of the theoretical PV energy potential and daily energy requirements of the hydroponic system

As shown in Figure 6, the total system energy requirement of 121.24 kWh/day is lower than the theoretical PV energy generation potential of 153.50 kWh/day. The main pump accounts for 120.00 kWh/day, while the control and supporting devices collectively account for 1.24 kWh/day. The resulting theoretical energy margin of 32.26 kWh/day indicates the potential energy available for management through energy storage and other operational requirements. The relationship between PV generation and daily energy demand highlights the importance of energy storage when PV generation is insufficient. This is consistent with previous studies integrating PV, batteries, and DC loads, which have demonstrated that energy storage can maintain energy availability when photovoltaic generation is inadequate [15], [16]. In the ISIS design, the battery is therefore incorporated as an integral component of the energy management system rather than as an independent storage device.

4. Conclusions

Based on the design results, the Integrated Solar-Powered Irrigation System (ISIS) successfully integrates solar power generation, energy storage, NFT hydroponics, and adaptive monitoring and control subsystems into a single platform. The analysis indicates that the system's operational energy requirement over 16 hours is 121.24 kWh/day. Meanwhile, a 30 kWp PV array has a theoretical energy generation potential of 153.50 kWh/day, based on the average solar irradiation conditions at the proposed installation site. This comparison yields a theoretical energy margin of 32.26 kWh/day, indicating that the proposed PV capacity has the potential to support the system's energy requirements. These findings suggest that integrating solar energy into hydroponic systems can reduce dependence on conventional power sources while supporting more independent and sustainable cultivation operations.

In addition to demonstrating theoretical energy adequacy, the study identifies the main pump as the component with the highest energy consumption, accounting for approximately 120.00 kWh/day, or nearly the entire system energy requirement. In contrast, control and monitoring

devices, including the PLC, HMI, sensors, solenoid valves, and dosing pumps, contribute relatively little to total energy consumption. This finding indicates that energy management strategies in hydroponic systems should focus on optimizing pump operation as the primary electrical load. The integration of sensors, PLCs, and HMI in the ISIS design enables real-time monitoring of energy conditions and hydroponic parameters to support operational decision-making. Thus, the proposed adaptive control concept has the potential to improve solar energy utilization efficiency under varying system operating conditions.

However, the findings of this study remain theoretical and are based on predetermined design parameters. The calculations do not comprehensively account for energy conversion losses, component efficiency, battery degradation, temperature variations, and fluctuating weather conditions, all of which may affect actual system performance. Therefore, future research should focus on prototype implementation and testing to verify system performance under real operating conditions. Further investigations should also evaluate SoC-based adaptive control strategies, optimize energy storage capacity, and regulate pump speed using a VFD to improve system energy efficiency. These developments are expected to provide a stronger foundation for implementing reliable, efficient, and sustainable solar-powered hydroponic systems.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes or conceptual design of the Integrated Solar-Powered Irrigation System (ISIS). The research and design processes were conducted without any commercial or financial relationships that could be construed as potential conflicts of interest.

Author Contributions Statement

Desriyanti Veronica Sitorus conceptualized the system methodology, developed the House of Quality (HOQ) matrix, created the graphical visualizations, and compiled the main manuscript. Firdaus Najwah Abdillah formulated the mathematical calculation methods and drafted the conclusion section. Fangky Faturrohman designed the 3D mechanical models of the hydroponic system and performed the data calculations for the results section concerning solar energy potential and electrical load characteristics. All authors read and approved the final manuscript.

Data Availability Statement

All data generated or analyzed during this study, including the energy consumption calculations and House of Quality (HOQ) matrix, are included in this article. No additional external datasets or links are associated with this work. The solar irradiation data used for the theoretical calculations were obtained from the publicly available Global Solar Atlas.

Ethics Statement

This study focuses exclusively on the conceptual design and engineering calculations of a renewable energy system, the Integrated Solar-Powered Irrigation System (ISIS). It does not involve human participants, animal subjects, or sensitive biological materials. Therefore, formal ethical approval from an institutional review board or national research committee was not required.

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