



Arranging Solar Energy For Farming Life: Designing A Solar Power Generation System As A Solution For Rice Field Irrigation In Kemulan Village, Turen District, Malang Regency

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ABSTRACT

This research aims to design and test a solar power generation system (PLTS) as an alternative energy solution for agricultural irrigation in Kemulan Village, Turen District, Malang Regency. The method used is Research and Development (R&D) with the 4D model: Define, Design, Develop, and Disseminate. The define stage shows that farmers experience limited access to energy and high irrigation costs, with an average daily energy requirement of 1,500 Wh and operational costs of Rp 300,000-500,000 per season. Based on this data, a solar PV system was designed using two 100 Wp solar panels, a 12V DC pump, and an MPPT controller. Simulation through PVsyst showed an energy output of 1,620 Wh/day, while field testing produced 1,560 Wh/day with a water discharge of 70 liters/minute. Expert validation results show the system has high efficiency (86-88%), is easy to operate, and has the potential to be replicated. End-user evaluations showed positive scores on the aspects of convenience, usefulness, and re-adoption intention. The findings prove that a local needs-based approach and active involvement of farmers in the design to evaluation process can produce renewable technology systems that are applicable, efficient, and socially acceptable in the rural agricultural sector.

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1. INTRODUCTION

Kemulan Village, located in Turen Subdistrict, Malang Regency, is an agricultural area with great potential for agriculture. However, this potential is still hampered by structural issues, especially in the provision of energy for irrigation activities. Dependence on conventional electricity supply that has not reached all areas of the village, coupled with the use of inefficient and expensive fossil fuel water pumps, makes agricultural activities in this region unsustainable, especially during prolonged dry seasons as described by Prasetya in his article [1]. In the International Renewable Energy Agency's 2022 report, it is stated that the cost of energy for irrigation is one of the determining factors in the sustainability of agriculture in the Southeast Asia region, especially in areas that have not been integrated with the national electricity system [2]. This reality confirms that efforts to create efficient irrigation systems can no longer rely on old energy sources, but must turn to alternative solutions that are efficient, sustainable and suitable for local conditions. This challenge also provides a great opportunity to develop renewable energy-based approaches that can address agricultural energy needs in a more appropriate manner.

In this context, solar energy has emerged as one of the most promising options for meeting irrigation energy needs in rural areas. Indonesia, which is located on the equator, has a relatively stable intensity of solar radiation throughout the year. A study conducted by Apriani revealed that tropical regions have a competitive advantage in the utilization of small-scale photovoltaic systems, especially for the agricultural sector [3]. Correspondingly, Watto noted that solar-based irrigation systems can reduce energy consumption by almost half compared to fuel oil-based irrigation systems [4]. A field study conducted in Bangladesh by Amin also showed significant results in the form of increased agricultural production efficiency and decreased operational costs after the collective implementation of solar pumping systems [5]. Empirically, these data confirm that the application of solar energy is not only technically feasible, but also economically and environmentally promising. However, the success of this technology is largely determined by how the system is designed, implemented, and adapted to the specific needs of the local community [6]. Without a contextualized approach, a technology that is supposed to help may become an additional burden.

Despite the promising potential of solar energy, previous studies have shown that the development of solar PV-based irrigation systems still faces obstacles in terms of design relevance and social acceptability. Many of the existing studies are macro and generalist, assuming that one model can be applied to all contexts. For example, Pardo focuses only on technical dimensions such as panel and inverter capacity, without linking to variations in water demand based on crop type, growing season or land area [7]. In fact, these factors determine the effectiveness of irrigation in the field. Similarly, a study by Hoeck found that the failure of most solar PV projects in the agricultural sector is due to the mismatch of the technology with the socio-economic characteristics of farmers [8]. Kumar's study in India also highlighted the low adoption rate of solar technology due to the lack of community involvement in the planning stage [9]. This suggests that an approach that ignores the local context will result in low effectiveness and efficiency of system implementation. Therefore, it is imperative to integrate technical and social approaches in technology development, so that the designed system can be truly accepted and utilized by the community.

In response to these challenges, this study adopted a Research and Development (R&D) approach with a 4D model consisting of Define, Design, Develop, and Disseminate [10]. This model has proven effective in designing technology solutions oriented to the needs of local communities, as shown in a study by Narayanan [11]. In the define stage, researchers identified irrigation water needs based on direct observation, interviews with farmers, and measurement of the area and type of agricultural land. Furthermore, the design stage focused on calculating the capacity of solar panels, pump selection, inverter efficiency, and energy storage needs if needed. The system design refers to the modular principle proposed by Ali, which allows customization to the user's investment capabilities [12]. Following this, the develop phase involved the creation of a prototype system that is maintenance-friendly and resistant to tropical environmental conditions, as described in Rahmani's study [13]. Field trials were conducted to evaluate the water discharge produced, the stability of the electrical output, and the response of the system to weather fluctuations. In addition, social aspects were measured through surveys and in-depth interviews with farmers to determine their acceptance of the technology, based on the evaluation method developed by Mostafa [14].

This research is expected to make a real contribution to the development of solar irrigation systems that are not only technically efficient, but also socially and economically adaptive. Furthermore, the results of this study have the potential to be replicated in other areas with similar characteristics, such as agrarian villages in tropical areas that have limited access to energy. The findings of this study can also serve as a basis for formulating rural energy policies that are more responsive to community needs. In the regional context, this evidence-based approach has been applied in Vietnam and Thailand with positive results in the development of renewable energy policies [15][16]. On the other hand, from an academic perspective, this research also provides a theoretical contribution to the discourse on the integration of renewable energy technologies with local contexts. A participatory approach that places farmers as the main subject in the process of technology design and implementation is considered capable of significantly increasing the

success of technology adoption. This is as expressed by Martínez-López and reinforced by Kurniawan's study which shows that active community involvement can increase system acceptance by up to 72% [17][18]. Thus, through combining technical and social aspects in a structured R&D approach, this research offers a model of energy system development that is not only sustainable, but also firmly rooted in the needs and capacities of local communities.

2. RESEARCH METHOD

This study adopted the Research and Development (R&D) approach with the 4D [10] Define, Design, Develop, Disseminate) development model introduced by Thiagarajan because it is considered most suitable for developing educational technology solutions oriented to real needs in the field [19]. This model allows for systematic and structured development, from needs identification, design, prototyping, to product dissemination. In the context of this research, the 4D model was applied to design and develop a solar power generation system (PLTS) aimed at providing an independent energy solution for agricultural irrigation in Kemulan Village, Turen District, Malang Regency. This location was chosen because it still faces challenges in energy access for agriculture, so the implementation of PLTS is expected to improve the efficiency and sustainability of the irrigation system, as well as support energy independence based on local potential in a sustainable manner.

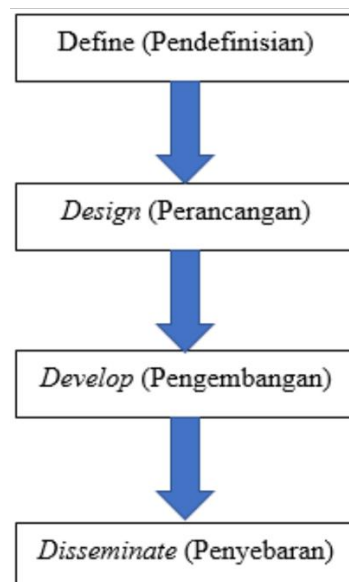


Figure 1. 4D development model

2.1. Research Stages

2.1.1. Define Stage (Problem Definition)

This stage is the first step that focuses on identifying real needs in the field, especially related to irrigation problems and limited energy access experienced by farmers in Kemulan Village. The main objective at this stage is to formulate the problems in depth and directed, so that the development of the PLTS system will be truly based on the real conditions and needs of end users. Data collection techniques were triangulated to ensure the validity and reliability of the information, namely through direct observation at the farm location, in-depth interviews with farmers and local community leaders, as well as documentation studies of agricultural reports, irrigation data, and previous energy usage records. The results of this stage provide an important foundation for designing a system that is responsive to actual and potential challenges on the ground, from technical, social and economic aspects. To gain a thorough understanding of the needs and actual conditions of farmers in irrigation management, an initial identification was conducted through the Define stage of the 4D development model. This stage aims to explore farmer profiles, irrigation needs, energy conditions, and the potential for adopting new technologies such as solar power generation systems. The instruments used were designed in the form of questionnaires and structured interviews, with a grid prepared based on relevant aspects in the field.

Table 1. Research Instruments in the Definition Stage of Identifying PLTS System Requirements

No.	Aspects	Specific Indicators	Problem Item / Measurement	Scale / Answer
1	Farmer Profile	Age, education, experience	Your age? Last education? Year you started farming?	Stuffing
2	Irrigation Needs	Watering frequency, water discharge, watering duration	How many times to water per week? How many liters per watering?	Stuffing
3	Crop Area	Active land area and crop type	Land size? What is the current main crop?	Fill-in / Choice
4	Energy Condition	Pump type, power source, electrical stability	Type of pump? Use PLN electricity or generator? Stable?	Fill-in/Yes-No
5	Operational Costs	Irrigation electricity/fuel costs	How much does it cost per growing season?	Stuffing (Rp)
6	New Solution Needs	Interest in solar PV	Are you interested in trying a solar system?	Likert Scale 1-4

2.1.2. Design Stage (System Design)

At this stage, the development process focuses on designing a Solar Power Plant (PLTS) system that is specifically tailored to the needs of agricultural irrigation in Kemulan Village. The design is carried out by considering the data on water demand and energy capacity that has been obtained from the Define stage, so that the system design is able to support irrigation operations optimally and sustainably. One of the main steps in this stage is to conduct technical simulations using PVsyst software, which serves to project the performance of the PLTS system based on local parameters such as solar radiation intensity, effective irradiation time, solar panel configuration, and storage battery capacity. Through this simulation, researchers were able to accurately determine system dimensions, select appropriate components, and quantitatively predict efficiency and energy output. This stage produces a complete technical design that is ready to be implemented in the next stage of development. In the Design stage of the 4D development model, the initial technical design of the Solar Power Plant (PLTS) system that will be used to support agricultural irrigation is carried out. Instruments were developed to estimate the energy requirements, water volume, and main components of the PLTS system based on field technical data and software simulations such as PVsyst. The aim is to ensure that the system design can meet the operational needs of irrigation in an efficient and sustainable manner.

Table 2. Design Stage Instrument Lattice for the Design of Agricultural Irrigation Solar System

No.	Aspects	Specific Technical Indicators	Problem Item / Estimation	Scale / Answer
1	Power and Duration	Daily pump requirements	What is the pump power and daily operational duration?	Stuffing (W, Hours)
2	Daily Water Estimation	Liter/m ³ water requirement for paddy fields	What is the total water requirement per day?	Fill (Liter)
3	System Specifications	Number of panels, inverters, batteries	System plan: number of panels, inverter power, batteries?	Technical content
4	PVsyst Simulation Results	System output per day	Simulation output? Enough for irrigation load?	Yes/No
5	Energy Efficiency	Output vs. daily requirement ratio	What is the system efficiency percent from the simulation?	Fill (%)

2.1.3. Develop Stage (Prototype Development and Expert Validation)

This stage is the initial implementation of the PLTS system design in the form of a small-scale prototype developed based on the results of the previous design. The prototype was built to test the extent to which the system can work in real field conditions, especially in supporting agricultural irrigation needs in Kemulan Village. After the construction was completed, field tests were conducted to observe system performance, energy utilization efficiency, and operational stability in various weather conditions. In addition, expert validation was also involved as an important part of this stage, involving experts in the fields of renewable energy, electrical engineering, and agriculture. This validation aims to assess the system's technical suitability, compatibility with user needs, and system feasibility from a technical and functional perspective. The results of this stage are taken into consideration for system improvement before the final stage of dissemination. In the system test stage, farmers are given instruments to measure the performance and effectiveness of the designed Solar Power Plant (PLTS) system. This system test aims to assess how well the system meets irrigation energy needs as well as the extent of operational ease and stability of the system in field conditions. Farmers were asked to provide data related to panel output, water discharge, operational stability, and ease of use and maintenance of the system. In the system test phase, farmers are given instruments to measure the performance and effectiveness of the designed Solar Power Plant (PLTS) system. This system test aims to assess how well the system meets irrigation energy needs and the extent of operational ease and stability of the system in field conditions. Farmers were asked to provide data related to panel output, water discharge, operational stability, and ease of use and maintenance of the system.

Table 3. Solar-Powered Irrigation System Testing Instrument for Farmers

No.	Technical Aspects	Indicator Details	Question Item	Scale / Answer
1	Panel Output	Power generated per day	What is the average electrical power generated by the panel?	Fill (Wh/day)
2	Pump Discharge	Volume of water pumped per hour	What is the average water discharge?	Fill (Liter/Hour)
3	Operation Stability	Voltage is stable or not	Was the system stable during the test?	Stable/Not
4	Operational Ease	Ease of use and maintenance	How easy is the system to use?	Likert Scale 1-4

The expert validation grid was used to assess the suitability, efficiency, operationality, cost feasibility, and replication potential of the developed irrigation solar PV system. This validation is conducted by experts to ensure that the system design meets the real needs of farmers, is efficient in energy use, and is easy to operate and maintain, without requiring specialized technicians. This efficiency aspect is very important so that the system can optimize the use of renewable energy in supporting irrigation needs in a sustainable manner. In addition, validation also includes an evaluation of cost feasibility to ensure that the system is affordable and provides significant economic benefits to farmers. The replication potential of the system is a key focus, with the aim that this solution can be widely applied to small-scale farmers in other villages, providing a greater positive impact in supporting food security and agricultural sustainability at the local level. This expert validation is an important step in ensuring that the irrigation solar PV system is accepted and benefits the farming community effectively and efficiently.

Table 4. Expert Validation Grid for Evaluation of Irrigation Solar System

No.	Validation Aspect	Technical/Contextual Indicators	Assessment Statement	Likert Scale 1-4
1	Design Appropriateness	System according to the needs of village farmers	Does the system match the irrigation needs of rice fields in the field?	1 = Very Unsuitable - 4 = Very Suitable
2	Energy Efficiency	Output vs. daily load	Is solar PV energy being used optimally?	1 = Very Unsuitable - 4 = Very Suitable
3	Operationality	Easy to assemble and maintain	Can the system be maintained without a specialized technician?	1 = Very Unsuitable - 4 = Very Suitable
4	Cost Feasibility	Affordable for smallholders	Is the system cost reasonable for small-scale farmers?	1 = Very Unsuitable - 4 = Very Suitable
5	Replication Potential	Can be applied in other villages	Is the system replicable in design and cost?	1 = Very Unsuitable - 4 = Very Suitable

2.1.4. Disseminate Stage (Evaluation and Limited Implementation)

At this stage, the main focus is the socialization and dissemination of the results of the PLTS system development to end users, namely farmers and communities in Kemulan Village. The socialization process is carried out through training and counseling, to ensure that users understand how the system works, its benefits, and how to care for and maintain the system independently. In addition, this stage also includes an evaluation of the acceptability of the system by farmers, which is conducted by collecting feedback through interviews and focus group discussions (FGDs). This evaluation aims to identify the level of understanding, comfort and response to the application of the new technology. Furthermore, it assesses the feasibility of adopting the system on a broader scale, including in terms of costs, economic benefits, and the ability of the community to sustain the system in the long term. The results of this evaluation form the basis for system improvement and further deployment planning. Farmer evaluation grids were designed to measure farmers' perceptions of the benefits, ease of operation, cost efficiency, and adoption intentions of irrigation solar PV systems. The evaluation aims to get direct feedback from farmers on how effective and efficient the system is in supporting their irrigation activities. In addition, farmers were also asked to provide their opinions on the potential of the system to be more widely implemented and recommended to other farmers, with a focus on the sustainability and economic attractiveness of the system.

Table 5. Farmer Evaluation Grid of the Irrigation Solar PV System

No.	Aspects	Detailed Evaluation Indicators	Question Item	Likert Scale 1-4
1	Perceived Benefits	System benefits to irrigation	Does the system help speed up irrigation and save energy?	1 = Very Unsuitable - 4 = Very Suitable
2	Operational Ease	System use and maintenance	Is the system easy to operate and maintain?	1 = Very Unsuitable - 4 = Very Suitable
3	Adoption Intention	Willingness to re-adopt the system	Do you want to continue using this system?	1 = Very Unsuitable - 4 = Very Suitable
4	Cost Efficiency	Comparison of old and new irrigation costs	Does the system provide irrigation savings?	1 = Very Unsuitable - 4 = Very Suitable
5	Recommendation	Willingness to recommend to other farmers	Would you recommend this system to other farmers?	1 = Very Unsuitable - 4 = Very Suitable

2.2. Data Analysis Technique

In this research, various data analysis techniques were used to obtain a comprehensive picture of the effectiveness and feasibility of the developed system. First, Qualitative Descriptive analysis was applied to interpret the data obtained through interviews and observations during the Define and Disseminate stages. This approach aims to understand the perceptions, challenges, as well as recommendations from stakeholders related to the implementation of the tested system. The collected data was analyzed in depth to identify emerging patterns and gain insights into potential improvements in the system. Furthermore, this analysis also serves to explore the factors that influence the success or failure of the system implementation, so as to provide a strong basis for further decision-making. Thus, Descriptive Qualitative analysis becomes an effective tool in understanding the existing dynamics and developing more relevant and applicable recommendations for system development.

2.2.1. Descriptive Qualitative

In this research, Qualitative Descriptive analysis was used to interpret the data from interviews and observations conducted during the Define and Disseminate stages. This approach aims to understand the perceptions, challenges, and recommendations provided by stakeholders related to the implementation of the tested system. By digging into the information in-depth, this analysis helped identify various factors affecting the effectiveness of the system, as well as revealing potential problems and obstacles that may not have been apparent at the initial development stage. In addition, insights gained from qualitative data also provide guidance in designing system improvements that are more in line with user needs and field conditions. Thus, Qualitative Descriptive analysis plays an important role in providing a clearer picture of how the system is received and implemented in the real context.

2.2.2. Technical Quantitative

Furthermore, for Technical Quantitative, data related to electricity output, water discharge, and system efficiency will be analyzed through graphs and simple calculations. This approach aims to provide a numerical overview of the system's technical performance, such as how efficiently energy is produced, as well as the level of success in optimizing the use of natural resources such as water. Through this analysis, more measurable data can be obtained on the operational effectiveness of the system, both in terms of energy consumption and water utilization as the main resource. Using graphs and technical calculations, it is expected to provide a clear understanding of the system's potential to achieve maximum efficiency, as well as detect areas that require further improvement. This quantitative approach provides a solid basis for objectively evaluating system performance and making data-driven decisions in further development.

2.2.3. Economic Analysis

Economic Analysis will be conducted using Cost-Benefit Analysis (CBA) and Payback Period approaches to assess the financial feasibility of the implemented system. CBA will be used to compare the total costs incurred with the benefits obtained from the system, so that it can be seen whether the investment made produces more value than the costs incurred. Meanwhile, the Payback Period will calculate how long it takes to return the initial investment in the system through operational cost savings and increased efficiency. By using these two approaches, economic analysis aims to provide a clear picture of the long-term profit potential of the system, as well as assist decision makers in assessing whether the implemented system is financially feasible and has a positive impact on the finances of the company or organization.

2.2.4. Expert Validation

Expert Validation will be conducted to ensure that the developed system design is in line with industry standards and expectations. This process includes calculating the average score for each indicator tested, followed by open feedback from experts in related fields. The feedback will be used as the basis for revision of the system design, in order to improve its accuracy and effectiveness in real applications. Through this validation, it is expected that the developed system not only meets the technical needs, but also aligns with industry best practices and end-user needs. By involving experts in this stage, the system design can be refined to be more optimal, as well as reduce potential errors or discrepancies that may occur when the system is applied in field conditions. Expert Validation is an important step in ensuring that the system developed is not only innovative, but also feasible and widely acceptable in the industrial world.

3. RESULTS AND DISCUSSION

3.1. Research Results

3.1.1. Define Stage

Observations of 10 farmers (P1-P10) showed a consistent pattern in watering practices on their farms. The average frequency of watering by farmers is in the range of 4 to 6 times per week, indicating that farmers tend to maintain soil moisture to keep plants growing optimally. This frequency of watering is driven by climatic factors and the types of crops cultivated, which require adequate water regulation to support good growth. In carrying out this activity, most farmers utilize water pumps to draw water from wells or other water sources, with the duration of pump operations ranging from 2 to 3 hours per day. This duration shows how important water use efficiency is, given the considerable water requirements to maintain soil fertility and crop sustainability.

Based on further observations, farmers' daily water needs reach an average of 3,000 to 5,000 liters per day. This large water requirement shows that water is one of the critical factors in agricultural production, which can directly affect crop yields. As such, farmers must ensure that they have sufficient access to a reliable water supply. The majority of farmers involved in this observation chose to use gasoline pumps as the main tool in the watering process. The use of gasoline pumps provides convenience and effectiveness in delivering water to their farm areas. However, the operational costs associated with using gasoline pumps are quite significant, with the average operational costs reaching between IDR 300,000 to IDR 500,000 per planting season. This cost includes the purchase of fuel and pump maintenance, which becomes an additional burden for farmers, especially in the long growing season.

Despite the high operational costs, the observation results also show that there is considerable interest from farmers in the implementation of Solar PV systems as an alternative to support agricultural activities, especially in terms of watering. The average score on the Likert scale for interest in solar PV systems is 3.6, indicating a high level of interest, although farmers have not yet fully switched to this technology. The high interest in solar PV is understandable given the potential benefits it offers, such as reduced operational costs related to fuel, as well as sustainability in the use of environmentally friendly energy sources. The use of solar PV can help reduce dependence on fossil fuels and provide a more efficient solution for energy supply, especially in areas that are hard to reach by conventional power grids. Thus, although initial and implementation costs are still a challenge, farmers' interest in solar PV shows the potential for developing this technology in the agricultural sector, which in turn can improve the efficiency and sustainability of agricultural production.

Table 6: Observational Findings on Irrigation Practices and Farmers' Interest in Solar PV Systems

Aspects	Details
Watering Frequency	4-6 times/week
Pump Operation Duration	2-3 hours/day
Water Requirements	3,000-5,000 liters/day
Type of Pump Used	Gasoline pump
Pump Operating Cost	IDR 300,000-500,000/planting season
Interest in solar power plant score	3.6 (Likert Scale)
Description	The majority of farmers are interested in solar PV systems, although implementation costs are still a constraint.

3.1.2. Design Stage

This solar energy system design was strategically developed to address the daily energy needs of an efficient and sustainable agricultural irrigation system, with a target consumption of approximately 1,500 Wh per day. The energy is used to operate a 12V DC water pump and various supporting components that function to optimally manage water distribution to the farmland. The system relies on two solar panels with a capacity of 100 Wp each, which were chosen for their optimal performance in capturing and converting solar radiation into electrical energy, especially in sunny weather conditions. In rural areas that generally experience limited access to electricity from the main grid, the use of solar panels is the right solution to overcome energy supply challenges. In addition to reducing dependence on expensive and environmentally unfriendly fossil fuels, the application of renewable energy also demonstrates a commitment to greener and more sustainable agricultural development.

To optimize the energy conversion performance of the solar panels, the system is equipped with Maximum Power Point Tracking (MPPT) technology, an intelligent power regulation device that automatically adjusts the output current and voltage of the solar panels to always be at the maximum power point. MPPT is a vital component in this system as it is able to maintain the efficiency of energy production,

even when the intensity of sunlight decreases due to cloudy weather or less-than-ideal sun positions. This ensures that the irrigation pump continues to receive a stable and sufficient supply of electricity, so that the crop watering process is not interrupted. Taking into account the operational dynamics in the field, the MPPT technology is proof that the system not only accommodates short-term energy needs, but is also designed to support long-term sustainability by minimizing the potential for energy loss due to unexpected changes in environmental conditions.

The results of technical simulations conducted through PVsyst software show that the system is capable of producing up to 1,620 Wh of energy per day from two 100 Wp panels, which means there is an excess energy production of about 120 Wh over daily demand. This excess creates an important safety margin for dealing with weather fluctuations or long-term degradation of equipment performance. The recorded system efficiency of 88% signifies the successful integration between the key components of the solar panels, the MPPT controller, and the precisely designed energy load. To further enhance flexibility and reliability, the system was also designed with the option of energy storage through batteries. These batteries allow energy to be stored during the day for use at night or during inclement weather, allowing irrigation to continue even when direct solar resources are not available. This approach shows that the system design is highly adaptive to real operational needs in the field, making it an appropriate, low-cost and environmentally friendly alternative energy solution in supporting sustainable agriculture in remote areas.



Figure 2. Single Line Diagram of Solar Powered Integrated Irrigation Pump

3.1.3. Develop Stage

The results of field tests of solar energy generation systems for agricultural irrigation provide a positive picture of their efficiency and effectiveness in meeting farmers' daily energy and water needs. Data shows that the average daily energy output reaches 1,560 Wh, which is sufficient to operate the irrigation system without relying on conventional energy sources that are expensive and not always available in rural areas. The stable energy output ensures the continuity of the system's operation, allowing the irrigation process to run without interruption. Furthermore, the system is capable of producing a water discharge of 70 liters per minute, which is sufficient to maintain soil moisture and meet crop needs, especially in the dry season. This water discharge capacity also allows for an even distribution of water to all plots of land, supporting optimal plant growth. With the combination of energy output and adequate water discharge, this system has the potential to be an innovative solution for sustainable agricultural practices, especially in areas that face constraints in access to electricity and irrigation water.

However, the evaluation results also show that in terms of ease of use and maintenance, the system still faces technical challenges. The ease of use score of 3.4 and ease of maintenance score of 3.2 (on a Likert scale of 1-4) indicate that farmers still experience difficulties in daily operation and maintenance, especially for those without a technical background. There is still a need to simplify the system interface and operational procedures to make its use more intuitive and easily understood by farmers of different education levels. In addition, capacity building of farmers through basic technical training is an important aspect to ensure the long-term sustainability of the system. With these improvements, the system is not only able to operate optimally but is also more likely to be widely adopted by the farming community. Therefore, the implementation of this technology should be accompanied by technical assistance and education strategies, so that the benefits can be maximized in supporting food security and sustainable agricultural efficiency in rural areas.

Table 7. Results of Field Testing by Farmers.

Criteria	Average
Energy Output (Wh/day)	1560.0
Water Discharge (liter/minute)	70.0
Ease of Use	3.4
Ease of Maintenance	3.2

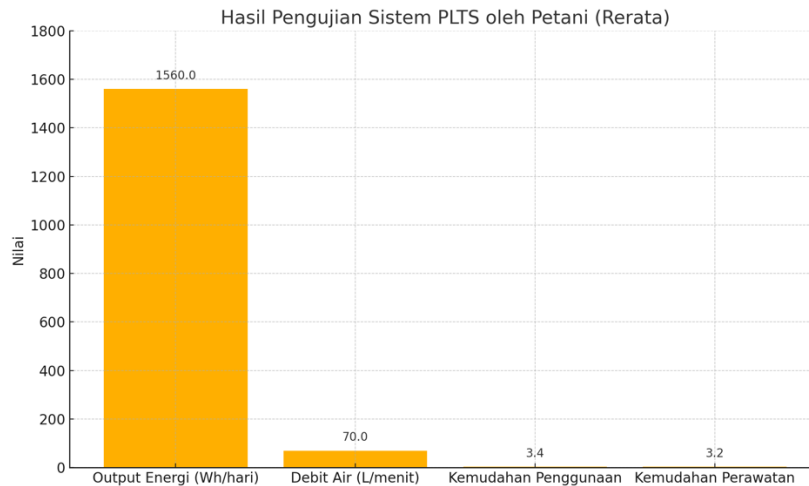


Figure 3. Visualization of Field Test Results

To evaluate the accuracy of the technical design and the effectiveness of the implementation of the Solar PV system for agricultural irrigation, a comparative analysis between simulation results and field realization data was conducted. This analysis includes four important aspects, namely daily energy output, water discharge, operational duration, and overall system efficiency. Simulation data was obtained from technical modeling using PVsyst software that considers ideal design parameters based on irrigation needs and potential solar radiation at the study site. Meanwhile, realization data was collected through actual measurements after the system was installed and operated in the target farmland. This comparison plays an important role in identifying gaps between the theoretically projected ideal conditions and the technical reality in the field, including the influence of environmental variables such as weather, installation conditions, and usage habits by farmers. The comparison results show that although there is a slight deviation between simulation and realization, the system performance generally shows good consistency. The energy output only differed by about 60 Wh/day, while the actual water discharge was slightly higher than the projection, indicating good hydraulic efficiency. The daily operational duration also increased, reflecting possible optimization in time management of system use by farmers. The overall system efficiency only decreased by 2%, which is still within the technical tolerance limit. Thus, this analysis provides a basis for continuous evaluation and development of a system that is more adaptive to real field conditions.

Table 8. Comparison of Simulated and Realized Efficiency

Aspects	Simulation	Realization
Energy Output (Wh/day)	1.620	1.560
Water Discharge (L/min)	70	72
Operational Duration (Hour/day)	2,5	2,8
System Efficiency (%)	88	86

As part of the development stage of renewable energy-based systems for agricultural irrigation, the expert validation process is a crucial step to ensure that the system design and implementation meet the standards of technical, economic and functional feasibility. Validation was conducted by three experts (A1-A3) with cross-cutting competencies, including solar power system engineering, energy efficiency, and sustainable agriculture development. The assessment was conducted on five main aspects: design suitability, energy efficiency, technical operation, cost feasibility, and replication potential. Scores were given on a Likert scale of 1-4, with a score of 4 indicating a very high level of suitability or feasibility. The validation results showed that the suitability of the design obtained the highest score (3.7), indicating that the system

has been well designed according to the end-user needs and field conditions. Replication potential also scored high (3.6), indicating that the system design has the flexibility to be applied to other locations with similar characteristics. Energy efficiency scored 3.5, confirming that the system is quite optimal in converting solar energy into electrical energy. However, technical operation and cost feasibility scored 3.3 and 3.0, respectively, indicating that although the system is feasible, there is still room for improvement, especially in terms of operational ease and efficiency of production costs. These validation results provide a strong basis for further development while strengthening the argument that the system has a high potential for implementation in the clean energy-based agriculture sector. Table 9 below summarizes the full results of the expert validation.

Table 9. Validation Results

Evaluation Aspect	Score (Scale 1-4)
Design Appropriateness	3,7
Energy Efficiency	3,5
Technical Operations	3,3
Cost Feasibility	3,0
Replication Potential	3,6



Figure 4. Installation of Solar Panels on Irrigation Systems

The installation stage of solar panels on a solar power generation system for agricultural irrigation, which is a crucial step in the implementation of renewable energy technologies in rural areas. In the picture, we can see the solar panel installation process being carried out with a calculated orientation and tilt to maximize the absorption of solar radiation. The installation was carried out by a technical team in collaboration with local farmers, illustrating the importance of collaboration between technology developers and user communities. The presence of these solar panels aims to fulfill energy needs that previously depended on conventional energy sources that are expensive and not always available in the area, thus providing an efficient and environmentally friendly solution for daily irrigation needs. The photo clearly shows the support structure that supports the solar panels, which are designed to withstand varying weather conditions and ensure optimal operation throughout the year. The installation process also reflects efforts to empower farmers through basic technical training, so that they can operate and maintain the system independently. With this system in place, farmers are expected to directly benefit in improving farming efficiency, especially in maintaining soil moisture and meeting crop needs during the dry season. The successful installation will play an important role in improving food security and supporting sustainable agriculture in rural areas, in line with the principles of clean energy and resource efficiency.



Figure 5. Photo of Irrigation Pump

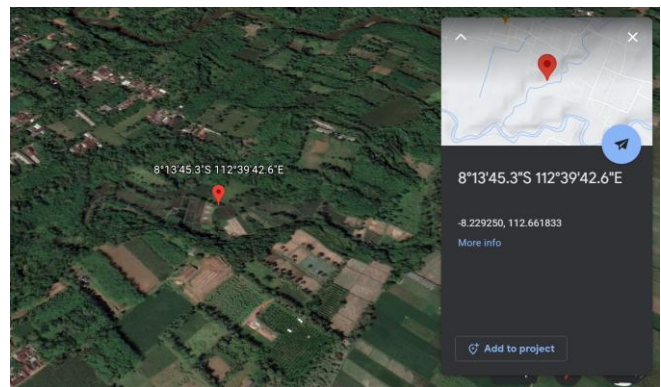


Figure 6. Location of Irrigation Pump and Solar Power Plant Installation



Figure 7. Placement of the Solar Power Plant and Control Room

3.1.4. Disseminate Stage Results: End User Evaluation

The results of the evaluation of farmers' perceptions of solar PV systems for irrigation showed that in general, they responded very positively to various functional aspects and usefulness of the system. Of the four main indicators measured using a 1-4 Likert scale, the highest mean score was found in the intention to reuse indicator at 3.8. This indicates a high level of enthusiasm from farmers to use the system again in the

long term. This indicator also reflects farmers' level of trust in the effectiveness of the system in supporting their agricultural activities. Meanwhile, perceived benefits obtained an average score of 3.6, indicating that the majority of farmers considered the system capable of making a significant contribution to the irrigation process, both in terms of labor efficiency and timeliness of crop watering.

In terms of ease of use, the average score of 3.4 indicates that although most farmers find the system quite easy to operate, there is still room for improvement especially in terms of user interface, operational guidelines, and hands-on training activities. Farmers with limited technological backgrounds reported that the initial assistance was very helpful in understanding the basic functions of the system. Meanwhile, cost efficiency received an average score of 3.3, which although lower than other aspects, is still in the good category. Some farmers noted that while the initial cost of procuring the system was relatively high, the much lower daily operational cost compared to diesel pumps was a major plus. This suggests that the system has the prospect of economic sustainability, provided it is supported by a financing or subsidy scheme in the early stages of adoption.

Interestingly, all respondents in this study expressed their willingness to adopt the system on an ongoing basis. However, they also emphasized that sustainability is highly dependent on two main supporting factors, namely technical training and the availability of start-up funds. Technical training is considered crucial so that farmers are not only able to operate but also maintain the system properly, thereby reducing the risk of damage due to misuse. Meanwhile, seed funding is a challenge for farmers with limited capital. Therefore, collaboration between the government, educational institutions, and microfinance institutions is crucial to encourage massive adoption of solar PV systems. With such support, this system is not only a technical solution, but also a strategy for sustainable agricultural transformation that is adaptive to climate change and future energy challenges.

Table 10. Assessment of User Perception and Experience of the System

Evaluation Aspect	Score (Scale 1-4)
Perceived Benefits	3,6
Ease of Use	3,4
Cost Efficiency	3,3
Reuse Intention	3,8

To determine the extent to which the small-scale solar PV system is accepted by users in the field, an evaluation of users' perceptions and experiences of the system's performance and benefits in supporting agricultural irrigation was conducted. The evaluation targeted farmers as direct users of the system, assessing four main aspects: perceived benefits, ease of use, cost efficiency, and reuse intention. Each aspect was assessed using a Likert scale of 1 to 4, where a score of 1 indicates high dissatisfaction and a score of 4 reflects very high satisfaction. The assessment results showed that reuse intention scored the highest (3.8), indicating that most respondents were willing to use the system sustainably in their farming practices. This indicates high system acceptability and potential for long-term adoption. Perceived benefits also scored positively (3.6), indicating that users perceived the system's direct impact on irrigation efficiency and energy savings. Meanwhile, ease of use scored 3.4, indicating that the system is fairly easy to operate although there is still room for improvement in technical aspects or training. Cost efficiency scored 3.3, indicating that users felt the system helped reduce operational costs compared to conventional irrigation methods. Overall, these evaluation results confirm that the solar PV system has a high level of user satisfaction and great potential for wider application in the agricultural sector. Table 10 below summarizes the details of the evaluation results.

3.2. Discussion

3.2.1. Identification of Farmers' Energy and Irrigation Needs

Field observations show that irrigation systems used by most farmers in rural Indonesia still rely heavily on gasoline-fueled pumps. Although this system has long been the main solution for irrigating fields, its existence now raises serious issues in terms of energy efficiency, economic burden and environmental impact. The use of gasoline pumps demands large amounts of energy and water consumption, and burdens farmers with high and fluctuating operational costs. According to Syed Ali, dependence on fossil energy in small-scale agriculture exacerbates energy inequality and creates economic inefficiencies, especially in remote agrarian areas [20]. Not only are gasoline-fueled pumps expensive, they also contribute to increased carbon emissions and enlarge the ecological footprint of the agricultural sector. On the other hand, the manual irrigation systems that are still widely used are not equipped with precision technology, so water is not optimally distributed. As reported by de Clercq, manual irrigation systems have the potential to cause water losses of up to 35% due to uneven distribution and are difficult to control [21]. This situation is

exacerbated by geographical conditions that are not entirely covered by the PLN electricity network, which makes alternative renewable energy-based technologies an increasingly urgent need for farmers.

Amidst these access limitations and operational challenges, new hope emerges from the increasing awareness and enthusiasm of farmers towards renewable energy technologies, particularly solar power plants (PLTS). Based on a local survey, farmers' level of interest in the use of solar power plants was recorded to be high, with an average score of 3.6 out of 4, indicating their mental readiness and openness to the adoption of new technologies. This finding is in line with the results of Chopra's study, which states that farmers in the ASEAN region generally support energy transition if they directly benefit from increased productivity and reduced operational costs [22]. Indonesia, which is geographically located in the tropics, has abundant sunlight intensity throughout the year, making it an ideal location for the development of photovoltaic energy systems. According to Maity, these climatic conditions provide a strategic advantage in the development of community-based solar power plants [23]. Moreover, farmers are increasingly recognizing the long-term benefits of solar PV, such as cost efficiency, reduced external energy dependence, and opportunities to increase the value of agricultural products through green certification. These trends show great potential for the transformation of national irrigation systems towards a more efficient, inclusive and sustainable direction, if supported by the right supporting policies and programs.

However, to realize the widespread adoption of solar PV, synergy between various parties is needed, ranging from the government, private sector, financial institutions, to educational institutions. Wang's study confirms that the integration of clean energy technologies in the agricultural sector is highly dependent on the availability of easily accessible microfinance and ongoing technical support from local authorities [24]. A number of pilot programs that have been conducted in villages have shown encouraging results. Yokamo revealed that pilot projects were able to increase farmers' confidence in new technologies by 70% in just three months [25]. In addition, *community-based* approaches such as *community-led solar irrigation* have been shown to increase farmers' ownership and active participation [26]. On the other hand, technical training is an important factor in ensuring the sustainability of technology use. Sunny stated that farmers who received comprehensive training had a retention rate of 1.5 times higher than those who only received installation assistance without further education [27]. With multi-stakeholder collaboration and an evidence-based approach, the transformation of irrigation systems through solar energy is not only feasible, but also a strategic step to strengthen national food security and push Indonesian agriculture towards a competitive and environmentally friendly future.

3.2.2. Design Stage: Designing a Solar System that is Responsive to Field Needs

The design of a Solar PV system as a renewable energy solution for agricultural irrigation begins with the identification of specific needs in the field. In the context of tropical agriculture, the daily energy requirement to operate a water pump in one irrigation cycle reaches around 1,500 Wh. This value is obtained based on direct observation of the type of pump, the volume of water required per cycle, and the frequency of irrigation adjusted to crop characteristics and soil conditions. This approach is in line with Emiralioglu's research, which emphasizes the importance of local data-based planning to make renewable energy systems truly applicable [28]. Moreover, Indonesia, which is located on the equator, has consistent exposure to solar radiation, with an average of 4.5-5.5 kWh/m² per day, as described by Suwadana [29]. This data makes the tropics an ideal candidate for the implementation of small-scale solar power systems in the agricultural sector. Therefore, before technical design begins, it is important to conduct an energy audit to ensure that each component in the developed system has a clear purpose and can contribute to overall energy efficiency.

In the technical design stage, two 100 Wp solar panels were installed with an optimal orientation towards the direction of sunlight. This combination of panels is supported by Maximum Power Point Tracking (MPPT) technology that keeps the panels working at their highest power point, despite fluctuations in light intensity. A number of studies have shown that the application of MPPT can increase system efficiency by up to 20%, as described by Salau [30]. In technical simulations using PVsyst software, the designed system showed a daily production capacity of 1,620 Wh. This figure not only exceeds basic needs, but also provides an energy buffer for emergency situations such as extreme weather. Girgis also mentioned that MPPT-based solar systems are more stable in the face of efficiency degradation due to high temperatures [31]. In addition, the integration of MPPT also improves system reliability when used in rural locations with high weather variability, as highlighted by Adamu [32]. Therefore, this design not only focuses on meeting energy demand, but also considers technical and environmental risk factors thoroughly.

Furthermore, the system is equipped with a lithium-ion battery component as energy storage, which plays an important role in maintaining operational continuity. In Liu's study, it was mentioned that the presence of batteries can increase the power availability rate to 95% in renewable energy hybrid systems [33]. With a storage capacity designed for two irrigation cycles, the battery not only meets operational needs at night, but also ensures continuity in the event of a main energy supply interruption. This strategy adopts

the principle of *resilience* in energy system design, which is the ability of the system to continue operating under unexpected conditions. This principle is also affirmed by Kosai, who emphasizes the importance of system resilience in the face of climate uncertainty [34]. In addition, the system is also *adaptable*, because it can be adjusted to changes in cropping patterns, crop types, and varying water needs. Yusriadi mentioned that the flexibility of the PLTS system in responding to farmers' operational dynamics determines the level of adoption in the field. With a modular and easily upgradable design, the system can be further developed according to the economic and technological capacity of local farmers [35].

The impact of the PLTS system implementation is not only technical, but also contributes greatly to local economic empowerment and the achievement of sustainable development targets. According to Yaya, the use of PLTS systems can reduce operational costs by up to 40% in one growing season. These savings open up opportunities for farmers to allocate resources to other productive sectors such as processing agricultural products or children's education. Not only that, the system also supports Sustainable Development Goals (SDGs) points 7 (clean energy) and 13 (climate change adaptation) by reducing carbon emissions and increasing water efficiency. Saraswat stated that solar-based community energy systems are highly effective in accelerating the green energy transition, especially in the global south [36]. Therefore, replication of this system model has the potential to be applied in regions with similar characteristics. In the policy context, regulatory support such as solar panel subsidies or technical training for farmers will accelerate the widespread adoption of this technology [37]. With a local needs-based development strategy, this solar PV technology is not only an energy solution, but also an instrument of sustainable social and ecological transformation.

3.2.3. Validation of System Effectiveness Through Field Tests and Expert Assessment

Field tests of the Solar PV system for irrigation in Kemulan Village showed very satisfactory performance in terms of technical efficiency and accuracy of design implementation. The system is capable of delivering 70 liters of water per minute and generating 1,560 Wh of daily energy. The energy deviation of 60 Wh from the initial simulation results indicates a high level of system accuracy, as stated by Nasir, that a deviation of less than 5% in photovoltaic systems is an indicator of the reliability of simulation-based design implementation [38]. The system's realized efficiency of 86% reinforces the results of a study by Hassan, who noted that efficiencies above 80% in agricultural solar power plants indicate optimal performance [39]. However, this technical success is not necessarily accompanied by the convenience of use by farmers. The ease of use score of only 3.4 and ease of maintenance of 3.2 indicate operational barriers, especially for farmers with limited technological literacy. A similar issue was highlighted by Durga, who mentioned that the lack of technical training is one of the main causes of the low adoption of renewable energy technologies at the grassroots level [40]. Marennya also added that hands-on training has a significant impact in increasing user confidence in operating new energy-based systems [41].

Expert validation of the irrigated solar PV system gave it high scores on three key indicators: system design (3.7), energy efficiency (3.5) and replication potential (3.6). This evaluation aligns with Yatnalli's analysis, which states that modular designs tailored to the local context increase efficiency and accelerate replication [42]. Gupta's research also emphasizes the importance of design adaptability to geographical and social conditions in determining the success of solar PV replication [43]. However, the score on the cost feasibility aspect only reached 3.0. This underscores the findings of Diop, who identified start-up costs as a major barrier to solar PV implementation in agrarian areas [44]. Therefore, innovative financing strategies need to be integrated, as suggested by Bhattarai, through microcredit schemes and private sector partnerships [45]. Fiscal policy support is also considered crucial, especially for regions with low purchasing power. This is also confirmed by Tamoor, who highlights the importance of institutional interventions and CSR support in supporting rural energy transition [46].

To ensure the sustainability of implementation and increase the adoption rate of the system, irrigation solar PV development needs to adopt a participatory and educative approach. Continuous training programs, as suggested by Sucipto, are crucial in building local capacity and shaping an inclusive technological culture [46]. System simplification, including the development of icon-based interfaces and multilingual instructions, can help reach users from different educational backgrounds. This recommendation is reinforced by Alabdali, who states that complex interfaces are one of the main barriers to the adoption of solar PV systems in rural communities [47]. In addition, institutional integration through farmer cooperatives or village-owned enterprises can strengthen the maintenance and benefit distribution aspects of the system in the long run. Studies by Rahmani show that collectively managed systems tend to be more resilient and inclusive [48]. In this context, policy support from central and local governments will be crucial, as Panda points out that regulation and technical training are simultaneously the main factors for successful implementation of local-scale solar energy [49]. Thus, this community-based irrigation solar PV system has the potential to become a renewable energy development model that is not only technically efficient, but also inclusive, adaptive and sustainable in the context of Indonesia's rural development.

3.2.4. Disseminate Stage: Evaluation of Farmer Perception and Acceptance

Positive end-user response is a key indicator reflecting the success of solar PV systems in the context of agricultural irrigation. In this study, the highest score was on the *reuse intention* indicator at 3.8, which confirms the high commitment of farmers to continue utilizing the system in a sustainable manner. This suggests that solar PV technology is not only technically acceptable, but also socially and culturally acceptable to the user community. Chanda stated that positive perceptions of technology are strongly influenced by the extent to which the technology is able to answer the basic needs of farmers, especially in terms of water and energy efficiency [50]. Ratings of *perceived usefulness* with a score of 3.6 and *ease of use* with a score of 3.4 reinforce this argument, suggesting that the system has met most users' expectations. However, these figures also reflect that there is room for improvement, especially in terms of interface simplification and improved technical training. In line with this, Okai emphasized the importance of visual-based education as a key medium in accelerating technological literacy for rural farmers [51]. In addition, de Almeida mentioned that active user engagement during the early stages of adoption can strengthen loyalty of use in the long run [52]. Therefore, locally-based mentoring and training strategies are crucial to support the continued use of these systems.

From an economic perspective, the solar PV system shows a significant contribution to irrigation cost efficiency. The score of 3.3 on the cost efficiency indicator shows that although the initial investment cost is high, the long-term operational cost savings are an added value that is felt directly by farmers. Govindarajan emphasized that in the context of *life-cycle cost analysis*, solar energy systems provide savings of more than 35% in the first five years compared to fossil fuel-based systems [53]. This efficiency has the effect of increasing farmers' purchasing power, while reducing the risk of dependence on fluctuations in conventional energy prices. Clausen even adds that clean energy systems such as solar PV allow farmers to shift energy budgets to other aspects of productivity such as improved seeds and organic fertilizers [54]. In a broader context, the OECD states that the application of renewable energy in the agricultural sector is an important strategy in realizing the transformation towards low-carbon agriculture and a circular economy [55]. However, the financial aspect remains a barrier, especially for smallholder farmers. Therefore, as Aziz argues, cooperative-based microfinance and subsidy schemes are relevant solutions that can increase the affordability of this technology in rural areas [56]. This cost-efficiency success also strengthens the attractiveness of solar PV systems as a far-reaching social and economic investment in farming communities.

Furthermore, the successful implementation of solar PV systems is measured not only by technical performance and cost efficiency, but also by social impact and long-term sustainability. Continuous technical support is needed, especially in the form of training, education, and mentoring at the local level. Ardiansyah explains that the sustainability of clean energy technologies is highly dependent on local capacity to manage, maintain and develop the system independently [57]. In practice, training not only improves technical skills, but also creates a sense of ownership of the technology, which results in a high retention rate. Negera showed that villages that implemented solar PV systems independently experienced an increase in productivity of up to 27%, as well as a decrease in dependence on diesel-based irrigation [58]. In addition, Tănăsie's study highlights the importance of integrating technical skills-based training to create new jobs in renewable energy [59]. Wagner also emphasized that local actors such as field extension officers play an important role in maintaining the sustainability of community energy projects [60]. In fact, Liu revealed that solar PV systems can reduce CO₂ emissions by up to 2.3 tons/ha/year on tropical farms, reinforcing their role in supporting the climate change mitigation agenda [61]. In the long term, as concluded by Meir, solar PV technology has the potential to become a key pillar of sustainable integration of the food, water and energy sectors [62]. As such, it is not just a technical innovation, but an instrument of social-ecological transformation towards a more self-reliant, green and resilient agriculture of the future.

4. CONCLUSION

This study aims to design and test a solar power plant (PLTS) system as an alternative energy solution for irrigated rice fields in Kemulan Village, Turen District, Malang Regency, using the 4D Research and Development (R&D) model approach consisting of define, design, develop, and disseminate stages. Initial identification results showed that farmers face limited access to efficient and affordable energy, with high dependence on gasoline-fueled pumps and unstable conventional electricity. Most farmers expressed high interest in solar-based renewable energy solutions. The designed solar PV system consisting of two 100 Wp panels, a 12V DC pump, and an MPPT controller generated 1,620 Wh/day in simulation and 1,560 Wh/day in field realization, with an average efficiency of 86-88%. The system is proven to be able to meet farmers' irrigation needs with stable water discharge (around 70 liters/minute) and operational duration of 2.8

hours/day. Expert validation showed high design suitability, efficiency, and replication potential, while field trials resulted in positive perceptions from farmers on ease of use, maintenance, and cost efficiency. All farmers expressed willingness to adopt and recommend the system to other farmers, with the condition of training and facilitation of initial financing. This study concludes that the development of renewable energy technologies based on local context and active end-user participation is an effective approach to support sustainable agriculture in rural areas.

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