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Optimization of an Off-Grid Solar Photovoltaic System for Agricultural Irrigation in Bogoran Village, Trenggalek

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ABSTRACT

Agricultural irrigation requires a reliable energy supply to maintain consistent water availability, particularly in rural areas where renewable energy resources remain underutilized. This study aims to optimize an off-grid solar photovoltaic system to support agricultural irrigation in Bogoran Village, Trenggalek, Indonesia. The study was conducted by modeling the irrigation energy demand of a 550 W water pump and evaluating the local solar energy potential. System configuration was optimized using HOMER Pro by considering photovoltaic generation, battery storage, and a power converter. The resulting configuration was further evaluated through MATLAB simulations under solar irradiance conditions of 1000 W/m², 600 W/m², and 400 W/m², with pump operating durations of 4, 6, and 8 hours per day. The optimization results indicate that the most suitable configuration consists of a 1.50 kW photovoltaic array, nine 1 kWh lead-acid battery units with a total nominal capacity of 9.01 kWh, and a 0.611 kW converter. The system produces 2,371 kWh of photovoltaic energy annually to supply an electrical load of 1,204 kWh/year, achieving a renewable fraction of 100% and an excess electricity fraction of 45.0%. The total net present cost is Rp53,810,930 with a levelized cost of energy of Rp3,456.29/kWh. MATLAB simulations show that longer pump operation increases battery utilization and results in a greater reduction in state of charge, particularly under low irradiance conditions. For 8 hour operation, the minimum battery state of charge is approximately 65%, while shorter operating durations maintain a higher state of charge. These results demonstrate that the optimized off-grid photovoltaic system has the potential to provide a reliable and renewable energy supply for agricultural irrigation while reducing dependence on conventional electricity sources.

1. Introduction

Irrigation is one of the most energy-intensive activities in agricultural production, as operating water pumps to lift and distribute water requires a continuous and reliable power supply [1], [2]. In many rural farming areas, this energy demand is still met through grid electricity or diesel-fuelled pumps, both of which impose recurring operational costs on farmers and expose irrigation activities to fuel-price volatility and unstable power supply [3]. Because agricultural land is frequently located

far from the main electricity grid, farming communities require an irrigation energy system capable of operating independently, without full reliance on centralized infrastructure [4]. Renewable energy, particularly solar photovoltaic (PV) technology, offers a promising alternative for powering irrigation pumps, as it converts freely available sunlight into electricity with low operating costs, minimal maintenance requirements, and no fuel-related emissions making it well suited to remote and off-grid agricultural settings [1], [5].

Bogoran Village, located in Kampak Sub-district, Trenggalek Regency, East Java, is one of the areas where agriculture forms an important part of the local economy, with farmland that still relies largely on conventional irrigation methods. Indonesia's geographical position along the equator provides consistently high solar irradiance throughout the year, making the country one of the regions with substantial technical potential for solar energy utilization [6]. To assess the solar resource available at the study site, this study uses long-term solar radiation data obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database, a satellite- and reanalysis-based dataset widely used for renewable-energy resource assessment (NASA Langley Research Center, n.d.). Based on this dataset, the average solar radiation at the Bogoran site is 5.37 kWh/m²/day, indicating that the location has adequate solar potential to support an off-grid photovoltaic system for agricultural irrigation [7].

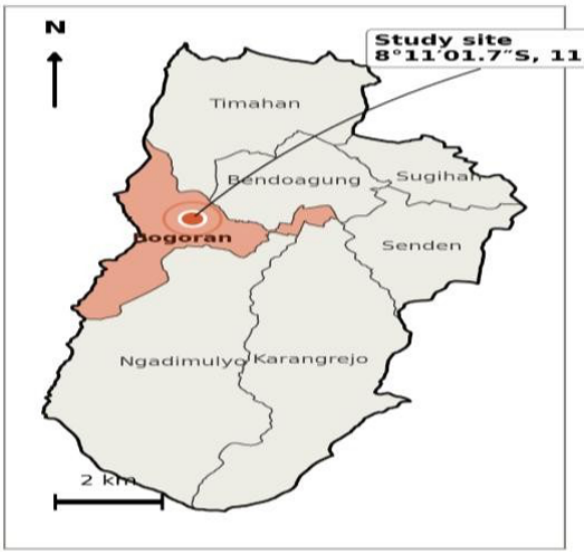


Fig. 1. Location of Bogoran Village within Kampak Sub-district, Trenggalek Regency, East Java, Indonesia



Fig. 2. Location of Kampak Sub-district within Trenggalek Regency, East Java, Indonesia

This research uses a 550 W water pump as the representation of a small-scale agricultural irrigation load. The selected pump operates with a single-phase AC supply at 220 V and 50 Hz, with a maximum pumping head of 10 m and a maximum flow rate of 10 m³/h. Pump capacity selection is an important aspect in photovoltaic water pumping systems because electrical power requirements are strongly influenced by pumping head, flow rate, and irrigation demand [8]. Previous research on solar water pumping applications has also investigated motor capacities around 0.55 kW, demonstrating that this power range is suitable for small-scale irrigation systems supplied by photovoltaic energy [9]. Therefore, the 550 W pump used in this study represents a realistic irrigation load for evaluating the performance of an off-grid PV-battery system.

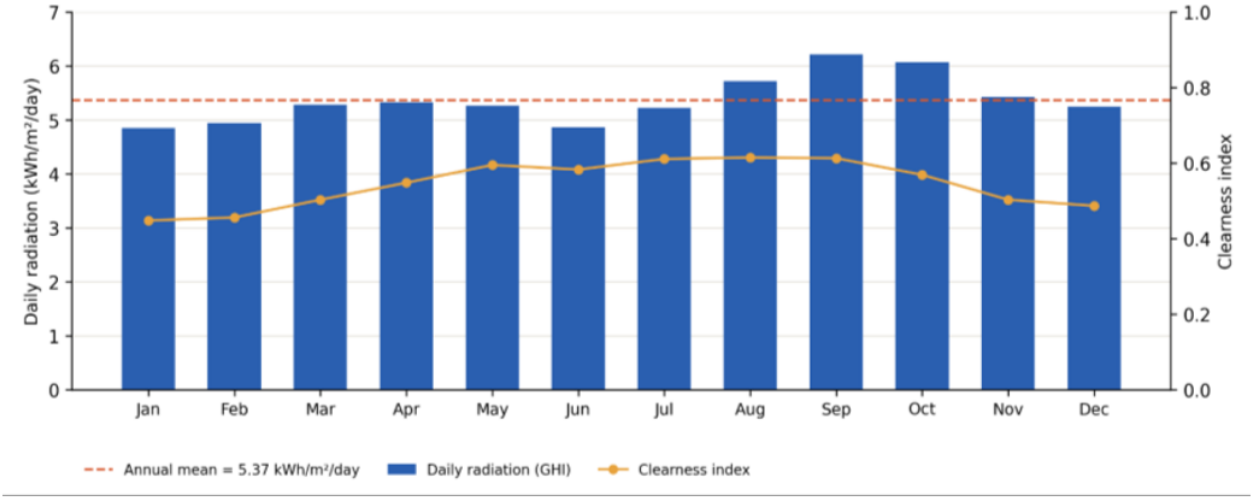


Fig. 3. Monthly average solar radiation at the Bogoran study site based on NASA POWER data, with annual mean of 5.37 kWh/m²/day

Previous studies have extensively investigated photovoltaic water pumping systems for agricultural applications, including system sizing, feasibility analysis, and energy performance evaluation [3], [9]. However, many studies mainly focus on determining system configuration without deeply analyzing the dynamic interaction between optimized PV-battery systems, pump operating duration, and changing solar irradiance conditions. Battery behavior, particularly charging and discharging patterns under different irrigation operating scenarios, remains an important aspect because variations in solar availability directly affect system reliability [10]. Therefore, a comprehensive analysis combining PV-battery optimization, techno-economic evaluation, and battery performance assessment under different operating conditions is still required for small-scale agricultural irrigation applications.

This study aims to optimize an off-grid solar photovoltaic system for agricultural irrigation in Bogoran Village, Trenggalek, and evaluate its performance under different pump operating durations and solar irradiance conditions. The system configuration is optimised using HOMER Pro by considering photovoltaic generation, battery storage, and converter capacity based on technical and economic parameters. Furthermore, MATLAB simulations are conducted to evaluate battery state of charge (SOC), charging and discharging behavior, and PV-load interaction under different pump operating durations of 4, 6, and 8 hours per day with solar irradiance levels of 1000 W/m², 600 W/m², and 400 W/m². The main contribution of this study is the integration of HOMER Pro-based techno-economic optimization with MATLAB-based dynamic performance analysis to evaluate an optimized off-grid PV-battery system under different irrigation operating durations and solar irradiance conditions.

2. Methodology

2.1 Study Area and Irrigation Load

The study area is located in Bogoran Village, Kampak District, Trenggalek Regency, East Java, Indonesia, at approximately 8°11′01.7″S and 111°38′21.3″E, as shown in Fig. 4. An agricultural area of 1 ha (10,000 m²) was considered as the design area. The geographical coordinates were used as the reference location for obtaining solar resource data required for the photovoltaic system simulation.

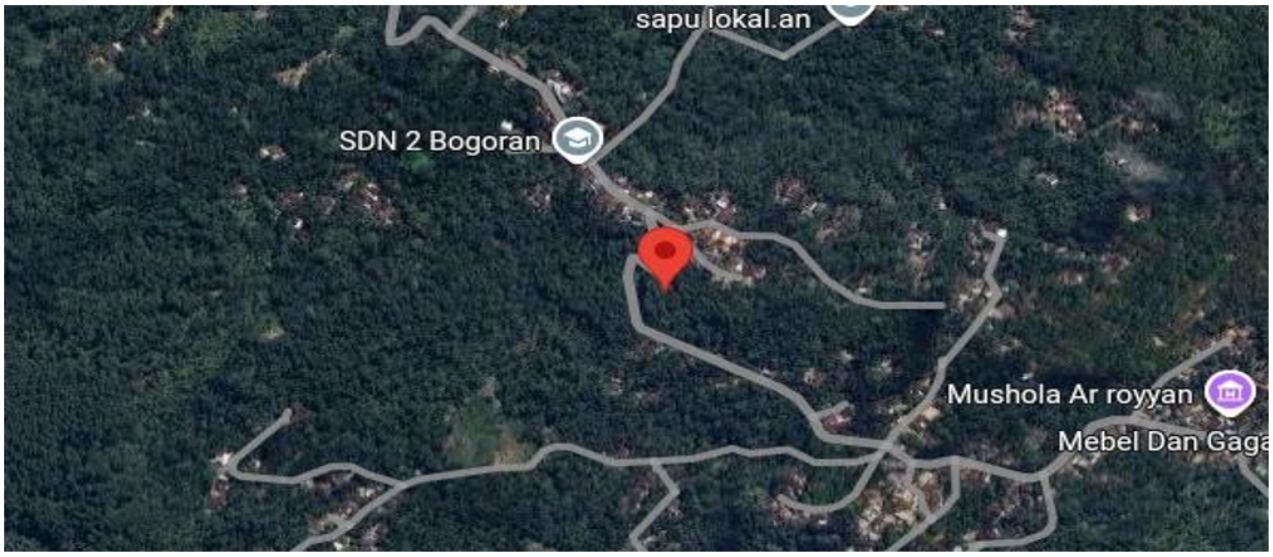


Fig. 4. Study area location in Bogoran Village, Kampak District, Trenggalek Regency, East Java, Indonesia (8°11'01.7"S, 111°38'21.3"E)

The irrigation load consists of a 550 W single-phase AC water pump operating at 220 V and 50 Hz, with a maximum head of 10 m and a maximum flow rate of 10 m³/h. Flow rate, pumping head, water demand, and operating duration are important parameters in determining the energy requirements of photovoltaic water pumping systems [4], [8], [9]. Three operating durations of 4, 6, and 8 h/day were considered to represent different irrigation load scenarios.

The daily electrical demand was calculated using:

$$E_{load} = P_{pump} \times t_{operation}. \quad (1)$$

where E_{load} is the daily energy demand (kWh/day), P_{pump} is the pump power (kW), and $t_{operation}$ is the operating duration (h/day). Based on a pump power of 0.55 kW, the 4, 6, and 8 h scenarios require 2.20, 3.30, and 4.40 kWh/day, respectively. The use of different operating durations is relevant because irrigation operating time directly affects water delivery and the energy required by the pumping system [4], [8].

2.2 Off-Grid PV System Configuration

The initial system model was developed to simulate an off-grid photovoltaic (PV) system designed to meet the energy requirements of agricultural irrigation. The proposed configuration comprises a PV array, battery energy storage system, power converter, and irrigation water pump. The PV array functions as the primary renewable energy source, converting solar irradiation into electrical energy to operate the irrigation system. Meanwhile, the battery storage system stores surplus electricity generated during periods of high solar availability and supplies additional power when PV generation is insufficient to meet the irrigation demand. The integration of PV generation with battery energy storage has been widely investigated in off-grid irrigation applications to enhance energy supply reliability and maintain system operation under fluctuating solar irradiation conditions [10].

The irrigation load was represented by a 550 W water pump operating at a rated voltage of 220 V and a frequency of 50 Hz. According to the pump specifications adopted in this study, the maximum pumping head and flow rate are 10 m and 10 m³/h, respectively. These specifications were used to define the electrical power requirements and hydraulic operating characteristics of the proposed irrigation system. In solar-powered irrigation applications, pump selection and energy consumption

are primarily influenced by the required water discharge and pumping head, which determine the hydraulic power demand and overall pumping performance [11]. Previous research has also examined the application of a 0.55 kW motor in small-scale solar PV water-pumping systems, demonstrating the suitability of this power rating for small-scale agricultural irrigation applications [12].

The baseline irrigation energy demand was established by assuming a daily pump operating duration of 6 hours. With a rated electrical power consumption of 550 W, the corresponding daily energy requirement was calculated to be 3.30 kWh/day, as described in Section 2.1. This energy demand was adopted as the reference operating condition for the HOMER Pro simulation model. Within the proposed system configuration, the irrigation pump was represented as the primary alternating current (AC) load, while the PV array and battery energy storage system were integrated on the direct current (DC) side through a power converter. This configuration provides the basis for evaluating the system's energy balance, component sizing, and ability to satisfy the specified irrigation load under off-grid operating conditions.

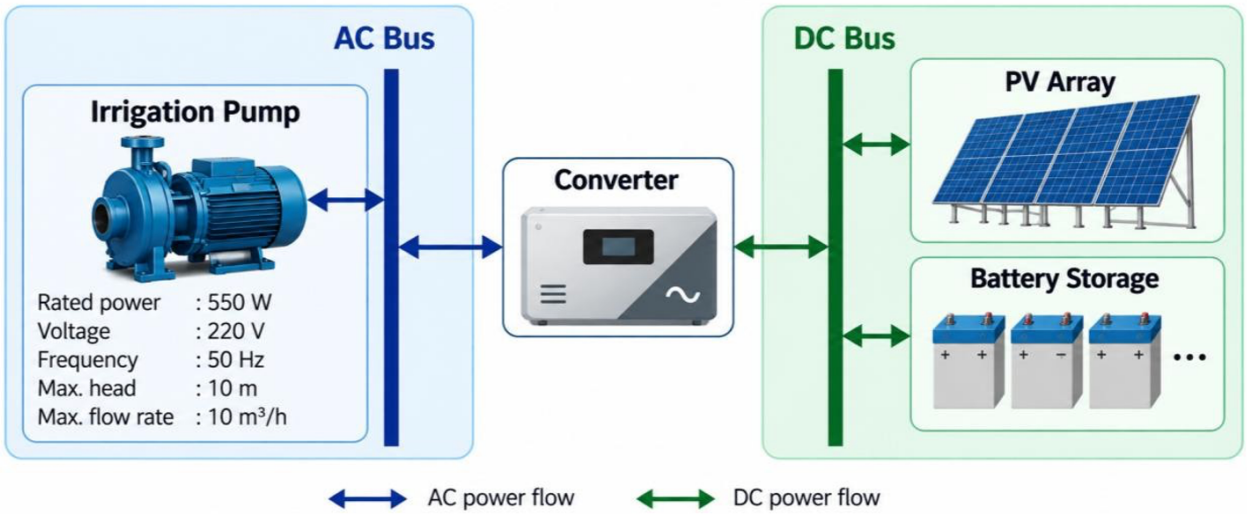


Fig. 5. Initial configuration of the proposed off-grid photovoltaic irrigation system

As illustrated in Fig. 5, the irrigation water pump serves as the primary alternating current (AC) load, while the photovoltaic (PV) array and battery energy storage system are connected to the direct current (DC) side of the system. The power converter acts as an interface between the DC components and the AC irrigation pump, facilitating the conversion of electrical energy to meet the pump's operating requirements. Under sufficient solar irradiance conditions, the PV array generates electricity to supply the irrigation pump, while surplus energy can be utilised to charge the battery storage system. Conversely, when PV power generation is insufficient to satisfy the instantaneous electrical demand of the pump, the battery provides supplementary energy through the power converter. This integrated configuration enables the irrigation system to operate independently of the conventional electricity grid while maximising the utilisation of solar energy as its primary power source.

The system configuration presented in Fig. 5 represents the preliminary design established before the optimisation process. Accordingly, the figure illustrates the general arrangement and interconnection of the system components without specifying the final PV array capacity, number of battery units, or power converter rating. These parameters were subsequently determined through the HOMER Pro optimisation process based on the defined technical and economic constraints. The resulting optimised configuration was then adopted as the reference system for further dynamic

performance evaluation using MATLAB, particularly under varying solar irradiance conditions and irrigation pump operating durations.

2.3 HOMER-Based System Optimization

HOMER Pro software was employed to optimise the configuration of the proposed off-grid PV irrigation system using the solar resource characteristics and electrical load requirements established in the preceding sections. The optimisation process involved evaluating multiple combinations of PV generation capacity, battery energy storage, and power converter ratings to identify technically feasible and economically viable system configurations. The evaluation was conducted according to the specified operating conditions, component characteristics, and economic assumptions. In HOMER Pro, the total net present cost (NPC) serves as the principal economic objective function for comparing alternative system configurations and identifying the most cost-effective solution over the project lifetime [13].

The primary components considered in the optimisation process were the PV array, lead-acid battery storage system, and power converter. The installed capacities and quantities of these components were specified as decision variables within the predefined optimisation search space. HOMER Pro systematically simulated different combinations of component sizes and evaluated their technical feasibility and associated life-cycle costs. This approach enables the determination of an appropriate system configuration through a structured optimisation procedure rather than relying on predetermined component capacities. Consequently, the optimisation variables provide the flexibility to identify suitable combinations of PV generation, energy storage, and power conversion capacity that satisfy the specified irrigation energy requirements [13].

The optimisation was conducted using the total NPC as the primary economic evaluation criterion. NPC represents the overall life-cycle cost of the proposed system, incorporating relevant expenditures and revenues throughout the project period, with future cash flows converted into their present values using the specified discount rate. This indicator provides a consistent basis for evaluating and comparing the long-term economic performance of alternative system configurations [13]. In addition to NPC, several technical and economic performance indicators were examined, including the levelised cost of energy (COE), renewable energy fraction, annual PV electricity generation, excess electricity production, unmet electrical load, capacity shortage, and battery autonomy. These indicators were used to assess the energy performance, operational reliability, and economic characteristics of the optimised system.

The Cycle Charging (CC) dispatch strategy was selected to represent the operational management of the available power sources and battery energy storage system. Under this strategy, when a dispatchable power source is operating, any available surplus electrical energy may be directed towards charging the battery. HOMER Pro determines the operation of generation and storage components according to the selected dispatch strategy, available energy resources, and the economic cost of meeting the electrical load [13]. For the proposed off-grid PV-battery irrigation system, the CC strategy was adopted to simulate battery charging and discharging behaviour throughout the operating period and to evaluate the interaction between solar power generation, energy storage, and irrigation electricity demand.

The HOMER Pro optimisation procedure was implemented through five main stages. First, the solar resource data and irrigation electrical load profile were incorporated into the simulation model. Second, the candidate PV capacities, battery quantities, and power converter ratings were defined within the optimisation search space. Third, HOMER Pro simulated the feasible system configurations using the specified technical, operational, and economic parameters over the project lifetime.

Fourth, the technical performance indicators and corresponding economic costs were calculated for each feasible configuration. Finally, the system configuration with the lowest calculated NPC, while satisfying the defined electrical load and operational constraints, was selected as the optimised design. The selected configuration was subsequently employed as the reference system for the MATLAB-based dynamic performance analysis presented in Section 2.4.

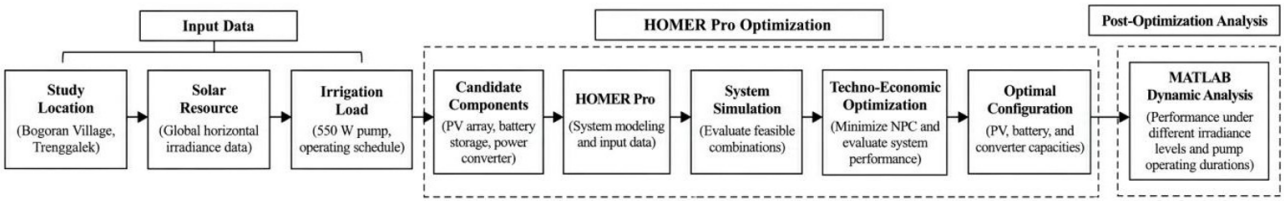


Fig. 6. Workflow of the HOMER-based system optimization and subsequent dynamic performance analysis

As shown in Fig. 6, the optimization process begins with the definition of the study location, solar resource, and irrigation load. These inputs are combined with the technical and economic characteristics of the candidate system components. HOMER Pro then evaluates the feasible system configurations and provides the corresponding technical and economic results. The optimized configuration obtained from this process is subsequently transferred to the MATLAB model to evaluate system behavior under different solar irradiance levels and pump operating durations.

2.4 MATLAB Dynamic Performance Analysis

The optimized configuration obtained from HOMER Pro, based on the baseline irrigation load of 6 h/day, was subsequently evaluated in MATLAB under different pump operating durations of 4, 6, and 8 h/day. The MATLAB model was used to examine the interaction between photovoltaic power generation, irrigation load, and battery storage under different solar irradiance conditions. Simulation-based analyses of PV-battery water pumping systems have been applied to evaluate system operation, energy management, and battery-supported pumping performance under changing operating conditions [14].

The optimized PV array, battery storage, and converter configuration obtained from HOMER Pro were maintained as the reference system for all MATLAB simulations. The irrigation pump was modeled as a constant 0.55 kW electrical load, while the operating duration was varied between 4, 6, and 8 hours per day. The corresponding daily energy demands were 2.20, 3.30, and 4.40 kWh/day, respectively. Pump operation was scheduled to begin at 08:00, resulting in operating periods of 08:00–12:00, 08:00–14:00, and 08:00–16:00.

To evaluate the effect of solar availability, three irradiance levels of 1000 W/m², 600 W/m², and 400 W/m² were applied to represent high, moderate, and low solar energy conditions, respectively. The simulations were conducted for each pump operating duration of 4, 6, and 8 hours per day, resulting in a total of nine simulation scenarios. The main simulation outputs included PV power, irrigation load, battery state of charge (SOC), and battery charging/discharging power. PV power was observed to determine the available energy generated by the PV array under each irradiance condition, while the irrigation load represented the energy required by the 0.55 kW pump during its operating period. Battery SOC was monitored to evaluate the remaining stored energy throughout the simulation, while the charging and discharging power indicated the energy exchanged between the battery and the system. The simulation results were subsequently compared across the different irradiance levels and pump operating durations to determine their effects on battery utilization and overall system performance.

2.5 Simulation Scenarios

The simulation scenarios were designed to evaluate the performance of the optimized photovoltaic irrigation system under different irrigation operating durations and solar irradiance conditions. The optimized system configuration obtained from HOMER Pro was maintained throughout all MATLAB simulations, while the pump operating duration and solar irradiance were varied. This approach was used to evaluate the response of the same system configuration to changes in daily irrigation energy requirements and solar energy availability.

Three irrigation operating durations were considered, namely 4, 6, and 8 hours per day. The irrigation pump was scheduled to operate from 08:00, resulting in operating periods of 08:00–12:00, 08:00–14:00, and 08:00–16:00, respectively. With a constant pump rating of 0.55 kW, the corresponding daily electrical energy requirements were 2.20, 3.30, and 4.40 kWh/day. These operating durations were selected to represent different levels of daily irrigation demand while maintaining the same pump rating and optimized system configuration.

The effect of solar energy availability was evaluated using three irradiance levels of 1000 W/m², 600 W/m², and 400 W/m². The three irradiance conditions represent different levels of solar availability during system operation, allowing the response of the PV array and battery storage to be examined under changing energy input conditions. By combining the three pump operating durations with the three irradiance levels, a total of nine simulation scenarios were obtained, as presented in Table 1.

Table 1
MATLAB simulation scenarios

Scenario	Pump Operating Duration	Operating Time	Daily Energy Demand	Solar Irradiance
1	4 h/day	08:00–12:00	2.20 kWh/day	1000 W/m²
2	4 h/day	08:00–12:00	2.20 kWh/day	600 W/m²
3	4 h/day	08:00–12:00	2.20 kWh/day	400 W/m²
4	6 h/day	08:00–14:00	3.30 kWh/day	1000 W/m²
5	6 h/day	08:00–14:00	3.30 kWh/day	600 W/m²
6	6 h/day	08:00–14:00	3.30 kWh/day	400 W/m²
7	8 h/day	08:00–16:00	4.40 kWh/day	1000 W/m²
8	8 h/day	08:00–16:00	4.40 kWh/day	600 W/m²
9	8 h/day	08:00–16:00	4.40 kWh/day	400 W/m²

The nine scenarios were evaluated by monitoring the PV power, irrigation load, battery state of charge (SOC), and battery charging/discharging power. The comparison was performed to identify how increasing the pump operating duration affects battery utilization and how decreasing solar irradiance affects the ability of the PV array to supply the irrigation load. Particular attention was given to the change in battery SOC during pump operation because longer operating durations and lower irradiance conditions increase the dependence on stored energy. The simulation results were subsequently used to discuss the dynamic behavior and operating performance of the optimized system under different irrigation and solar energy conditions.

3. Results

3.1 Optimal System Configuration

The HOMER Pro optimization resulted in an optimal configuration consisting of a 1.50 kW PV array, nine 1-kWh lead-acid batteries, and a 0.611 kW converter, as summarized in Table 2. The system produces 2,371 kWh/year to supply an annual electrical load of 1,204 kWh/year, with a battery autonomy of 39.3 h. In an off-grid PV-battery system, battery storage balances the mismatch between variable PV generation and load demand by storing surplus energy and supplying energy when PV generation is insufficient [15].

Table 2
HOMER optimization results

Parameter	Result
PV	1.50 kW
Battery	9 × 1 kWh
Converter	0.611 kW
PV production	2,371 kWh/year
Electrical load	1,204 kWh/year
Renewable fraction	100%
Excess electricity	45.0%
NPC	IDR 53,810,930
COE	IDR 3,456.29/kWh
Autonomy	39.3 h

The PV capacity and battery storage were selected by HOMER based on the configuration that satisfies the electrical demand while minimizing the total net present cost under the defined technical and economic constraints. HOMER uses NPC as the primary economic criterion for comparing feasible system configurations [16]. The resulting 1.50 kW PV capacity provides annual electricity generation that exceeds the irrigation load demand, while the nine-battery configuration provides sufficient energy storage to support the load during periods of insufficient PV generation.

The system produces 45.0% excess electricity. Excess electricity occurs when the available electrical power generation exceeds the load demand and the surplus energy cannot be absorbed by the storage system [17]. The system also achieves a renewable fraction of 100%, indicating that the modeled irrigation load is supplied entirely by renewable energy within the simulated system [18].

The optimized configuration results in an NPC of IDR 53,810,930 and a COE of IDR 3,456.29/kWh. NPC represents the life-cycle cost of the system expressed in present-value terms, while COE represents the average cost of supplying each unit of electrical energy to the load [16]. These economic indicators therefore describe the costs associated with operating the proposed off-grid PV-battery irrigation system over the project lifetime.

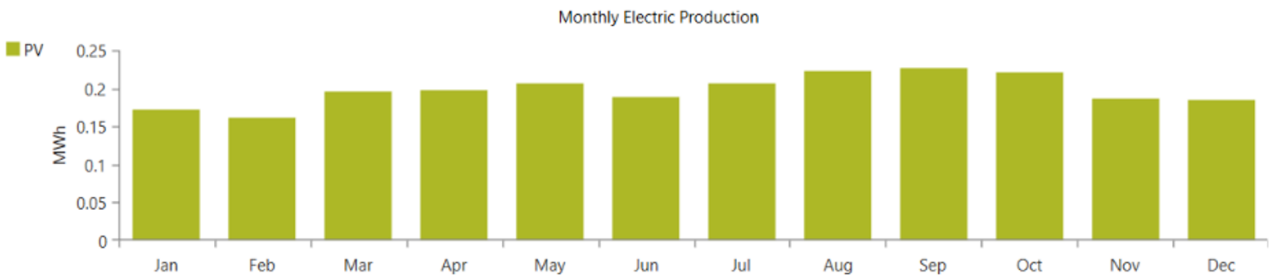


Fig. 7. Monthly photovoltaic electricity production of the optimized system

The monthly PV production in Fig. 7 varies according to the available solar resource. PV energy production is strongly influenced by the solar radiation received by the PV array [15]. Higher electricity production is observed around August–October, corresponding to the period of higher solar radiation at the study location. The NASA POWER data show that solar radiation ranges from 4.85 kWh/m²/day in January to 6.22 kWh/m²/day in September, with an annual average of approximately 5.37 kWh/m²/day.

3.2 PV Power and Irrigation Load

The dynamic performance of the optimized system was evaluated under solar irradiance levels of 1000, 600, and 400 W/m², as shown in Fig. 8(a)–(c). Solar irradiance directly influences the available power from a PV array, where higher irradiance generally results in higher PV power generation [4], [19]. Therefore, the 1000 W/m² condition produced the highest PV power, followed by 600 W/m², while the lowest PV power was observed at 400 W/m².

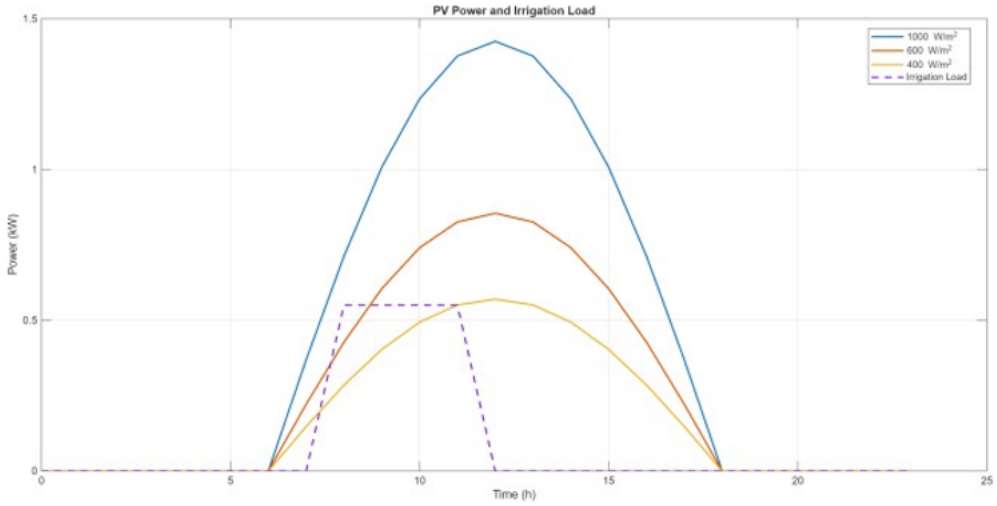


Fig. 8(a). PV power and irrigation load for 4 h/day pump operation under different solar irradiance conditions

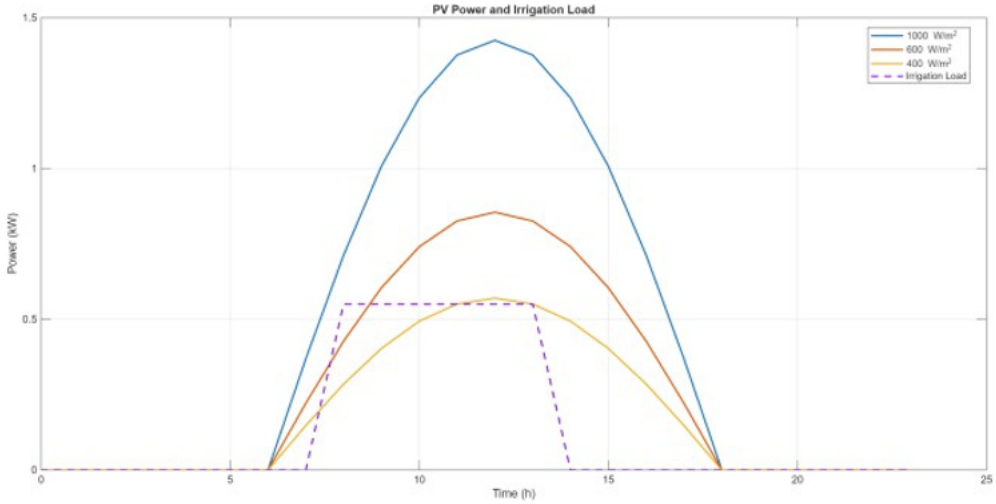


Fig. 8(b). PV power and irrigation load for 6 h/day pump operation under different solar irradiance conditions solar irradiance conditions

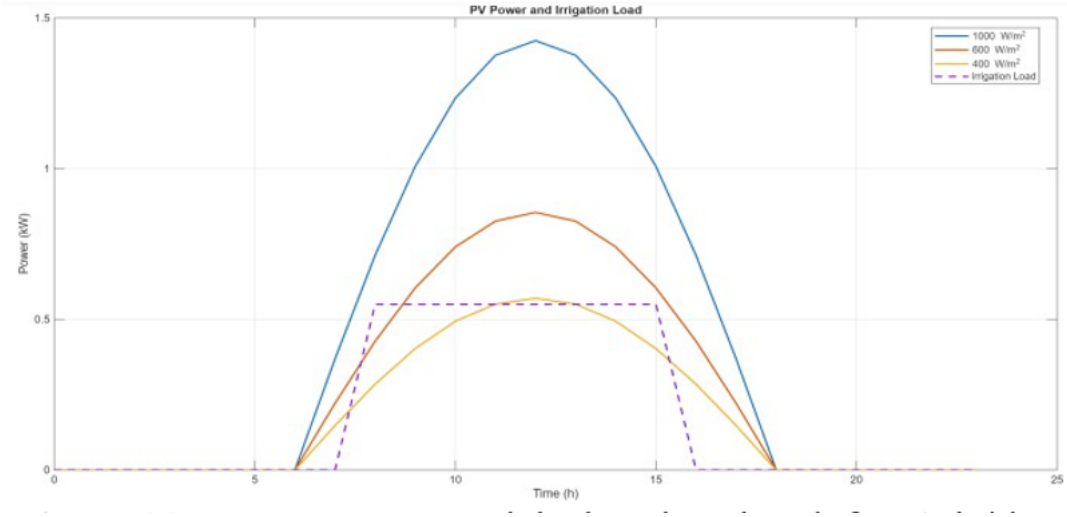


Fig. 8(c). PV power and irrigation load for 8 h/day pump operation under different solar irradiance conditions

The irrigation pump operated as a constant load of approximately 0.55 kW during its scheduled operating period. When the available PV power exceeded the pump demand, the surplus power could be directed to battery charging, whereas the battery supplied additional energy when PV generation was insufficient to meet the pumping demand [15].Consequently, decreasing solar irradiance increased the dependence of the irrigation system on battery storage. This PV–load power balance determines the charging and discharging behavior that is further analyzed through battery SOC and battery power in Sections 3.3 and 3.4.

3.3 Battery State of Charge

The battery state of charge (SOC) was analyzed to evaluate the effect of solar irradiance and pump operating duration on battery utilization. The simulation was conducted using three irradiance levels of 1000 W/m², 600 W/m², and 400 W/m² for pump operating durations of 4, 6, and 8 hours per day. The SOC profiles for each operating duration are presented in Fig. 9(a)–(c).

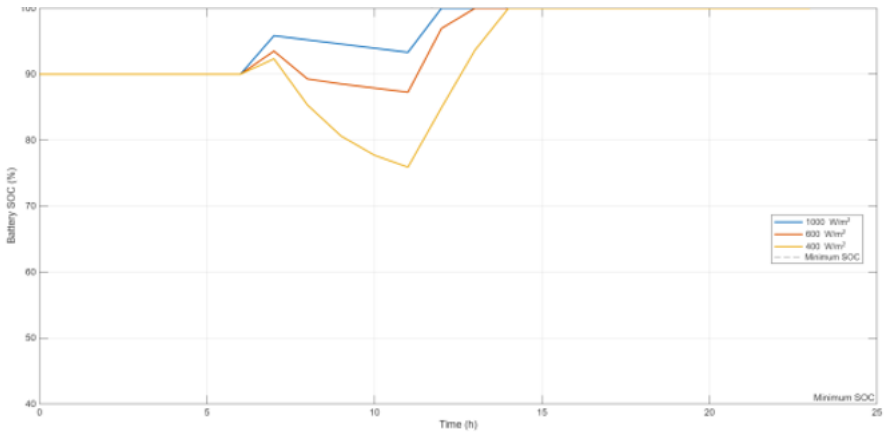


Fig. 9(a). Battery state of charge for 4 h/day pump operation under different solar irradiance conditions

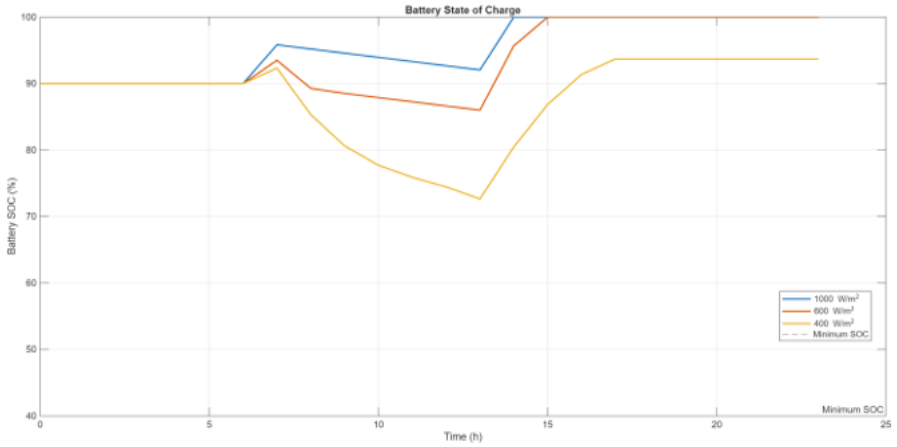


Fig. 9(b). Battery state of charge for 6 h/day pump operation under different solar irradiance conditions

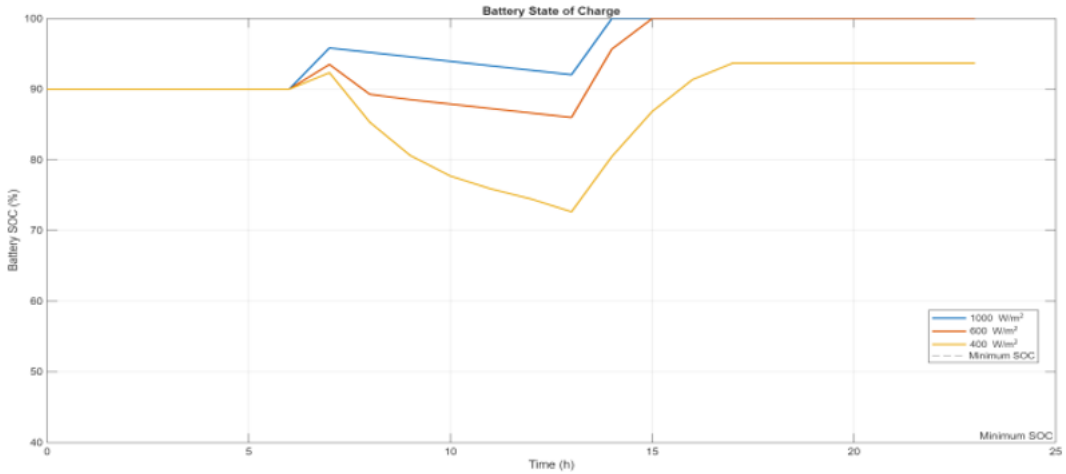


Fig. 9(c). Battery state of charge for 8 h/day pump operation under different solar irradiance conditions

The results show that the battery SOC decreases during pump operation, with the reduction becoming more pronounced under lower solar irradiance. At 1000 W/m², the SOC remains relatively high because the PV array provides greater power to support the irrigation load. In contrast, the 400 W/m² condition produces the largest SOC reduction, particularly during the 8 h/day operating scenario, where the minimum SOC reaches approximately 65%.

Increasing the pump operating duration also increases battery utilization because the daily electrical demand increases from 2.20 kWh/day for 4 hours to 4.40 kWh/day for 8 hours. After the pump stops operating, the battery SOC increases as the available PV energy is used for charging. These results indicate that longer irrigation operation combined with lower solar irradiance increases the dependence of the system on battery storage.

3.4 Battery Charging and Discharging

The battery charging and discharging profiles under different solar irradiance conditions are presented in Fig. 10(a)–(c). In the MATLAB model, positive battery power represents charging, whereas negative battery power represents discharging. Battery charging occurs when the available

PV power exceeds the irrigation load, allowing surplus PV energy to be stored, while battery discharging occurs when PV generation is insufficient to meet the required load [15], [20].

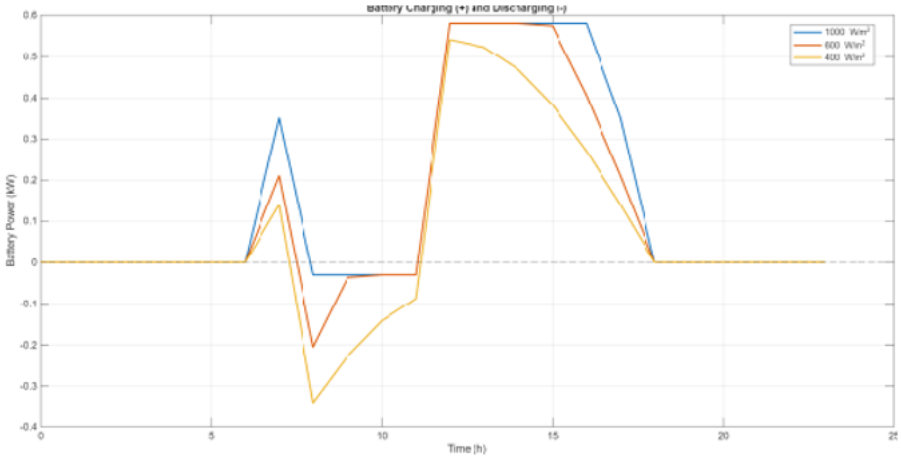


Fig. 10(a). Battery charging and discharging profiles for 4 h/day pump operation under different solar irradiance conditions

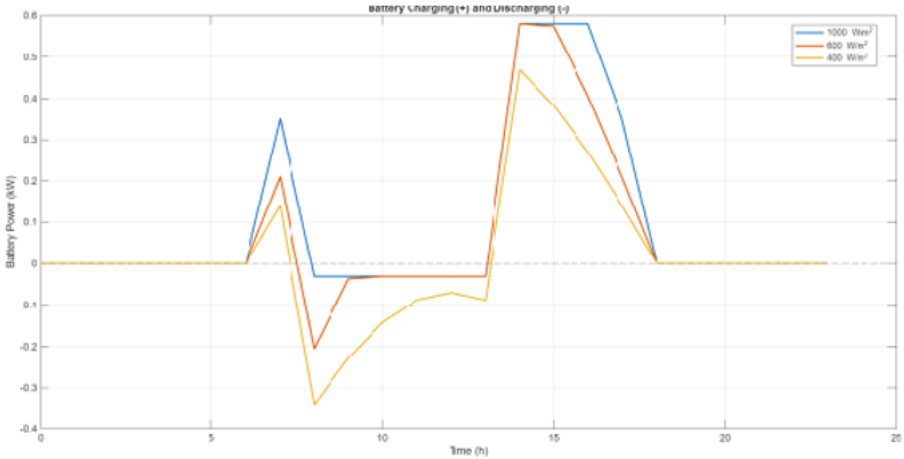


Fig. 10(b). Battery charging and discharging profiles for 6 h/day pump operation under different solar irradiance conditions

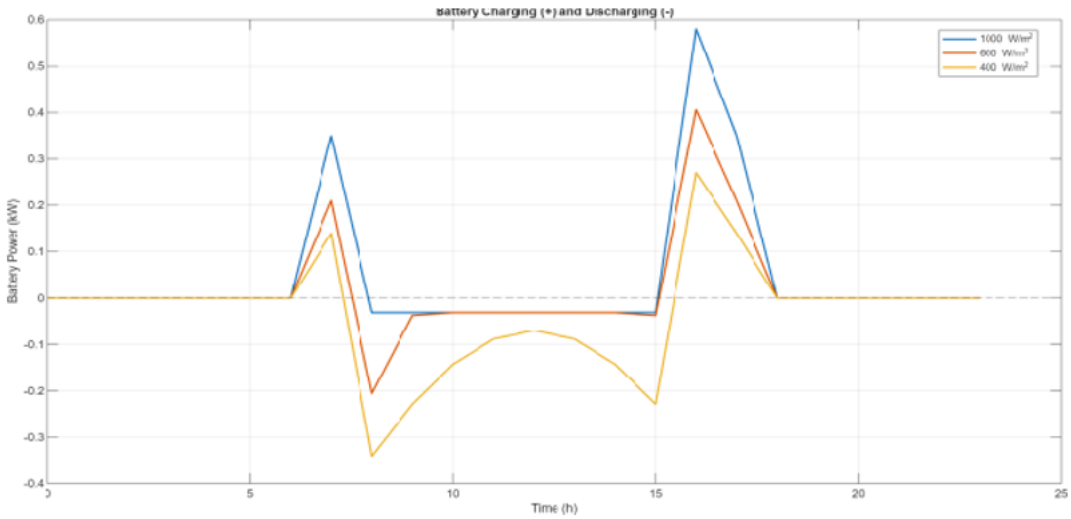


Fig. 10(c). Battery charging and discharging profiles for 8 h/day pump operation under different solar irradiance conditions

At 1000 W/m², the higher PV generation allows the pump load to be supplied predominantly by the PV array while providing greater opportunity for battery charging. As the irradiance decreases to 600 W/m² and 400 W/m², PV generation decreases and the battery provides a greater contribution to maintaining the irrigation load. Battery-supported photovoltaic water-pumping systems are particularly useful under low or variable solar conditions because stored energy can compensate for insufficient instantaneous PV generation [20], [21]. Consequently, the 400 W/m² condition results in greater battery discharge than the higher-irradiance conditions, which is consistent with the lower SOC observed in Section 3.3.

3.5 Effect of Pump Operating Duration

The effect of pump operating duration was evaluated for 4, 6, and 8 h/day, corresponding to daily electrical energy demands of 2.20, 3.30, and 4.40 kWh/day, respectively, as summarized in Table 3. For a constant pump power, increasing the operating duration increases the daily electrical energy demand and consequently the energy that must be supplied by the PV-battery system [22].

Table 3
Effect of pump operating duration on daily energy demand

Operating duration	Operating time	Daily energy demand
4 h/day	08:00–12:00	2.20 kWh/day
6 h/day	08:00–14:00	3.30 kWh/day
8 h/day	08:00–16:00	4.40 kWh/day

The simulation results show that increasing the pump operating duration increases battery utilization, particularly under lower solar irradiance conditions. Battery storage supplies the pumping load when instantaneous PV generation is insufficient, causing battery SOC to decrease during periods of energy deficit [15]. At 400 W/m², the minimum SOC decreased from approximately 76% for the 4-h scenario to 72–73% for the 6-h scenario and approximately 65% for the 8-h scenario. This indicates that the combination of longer pump operation and lower irradiance results in the highest dependence on stored battery energy.

In contrast, under 1000 W/m², the minimum SOC remained around 90–91% for all operating durations because higher PV generation was available during the daytime pumping period. The relationship between PV generation, load demand, and battery SOC determines whether the battery stores surplus PV energy or supplies energy during a deficit [15, 23]. Therefore, the 8-h operation at 400 W/m² represents the most demanding scenario evaluated in this study, with a daily energy requirement of 4.40 kWh/day and a minimum battery SOC of approximately 65%.

3.6 Techno-Economic Discussion

The techno-economic performance of the optimized system was evaluated based on the net present cost (NPC), cost of energy (COE), renewable fraction, PV production, and excess electricity. NPC represents the life-cycle cost of the energy system in present-value terms, while COE represents the average cost of useful electrical energy supplied by the system [24, 25]. The optimized configuration consists of a 1.50 kW PV array, nine 1-kWh lead-acid batteries, and a 0.611 kW converter, with an NPC of IDR 53,810,930 and a COE of IDR 3,456.29/kWh.

The system produces 2,371 kWh/year of PV energy to supply an annual electrical load of 1,204 kWh/year, resulting in a renewable fraction of 100%. A renewable fraction of 100% indicates that the

modeled electrical load is supplied entirely by renewable energy within the simulated system. The system also produces 45.0% excess electricity. In off-grid renewable energy systems, excess electricity occurs when generated power exceeds the load demand and the surplus cannot be fully utilized or absorbed by the battery storage system [17]. This condition is associated with the mismatch between daytime PV generation and the irrigation load profile, particularly when solar availability is high. The excess electricity therefore indicates that the optimized system has additional PV generation beyond the instantaneous irrigation demand and battery charging capacity during certain operating periods. Battery storage helps balance the temporal mismatch between renewable energy generation and electrical demand by storing available surplus energy and supplying the load when PV generation is insufficient [26].

These results indicate that the optimized system can supply the modeled irrigation load entirely from renewable energy, while battery storage supports operation under varying solar conditions. The NPC and COE describe the economic characteristics of the system, whereas the renewable fraction and excess electricity provide indicators of renewable energy contribution and energy utilization within the system [17, 24].

4. Conclusions

This study optimized and evaluated an off-grid solar photovoltaic system for agricultural irrigation in Bogoran Village, Trenggalek, by integrating HOMER Pro optimization with MATLAB-based dynamic performance analysis. Based on the baseline irrigation load, the HOMER Pro optimization resulted in a configuration consisting of a 1.50 kW PV array, nine 1-kWh lead-acid batteries with a total nominal capacity of approximately 9.01 kWh, and a 0.611 kW converter. The optimized system produced 2,371 kWh/year of photovoltaic electricity to supply an annual electrical load of 1,204 kWh/year, with a renewable fraction of 100%, battery autonomy of 39.3 h, and excess electricity of 45.0%. The resulting net present cost (NPC) was IDR 53,810,930, while the cost of energy (COE) was IDR 3,456.29/kWh.

The MATLAB simulations demonstrated the dynamic response of the optimized configuration under different solar irradiance levels and pump operating durations. Increasing the pump operating duration from 4 to 8 h/day increased the daily electrical energy demand from 2.20 to 4.40 kWh/day and resulted in greater battery utilization. The most demanding condition among the evaluated scenarios occurred at an irradiance of 400 W/m² with 8 h/day pump operation, where the minimum battery SOC reached approximately 65%. In contrast, under 1000 W/m² irradiance, the minimum SOC remained approximately 90–91% across the evaluated operating durations, indicating a lower dependence on stored battery energy.

Overall, the results demonstrate that the optimized PV-battery configuration can supply the modeled irrigation demand under the conditions evaluated in this study, while battery storage provides an energy buffer when PV generation is insufficient. The combined HOMER Pro and MATLAB approach provides both techno-economic optimization and dynamic evaluation of battery behavior under different irrigation and solar conditions. Further research should include field-scale experimental validation, actual irrigation water-demand profiles, seasonal weather variations, battery degradation, and long-term component performance to assess the system under real operating conditions.

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper. The authors have no financial, commercial, or personal relationships that could have influenced the design, analysis, interpretation, or reporting of the results. No financial support or other forms of compensation were received that could be perceived as influencing the outcomes of this research.

Author Contributions Statement

Camilla Izzati Hendarto and Zaskia Putri Ramadhani conducted the literature review and wrote the Introduction. Azmi Fadhal Fauzan and Billy Bintang Jatmiko developed the methodology, performed the analysis, and wrote the Methodology and Results sections. Andika Agung Cahya wrote the Conclusion. Misbahul Munir supervised the research process and reviewed the manuscript. All authors contributed to the manuscript revision, read the manuscript, and approved its final version.

Data Availability Statement

All data generated or analyzed during this study are included in this manuscript. The simulation data, system configuration parameters, and performance evaluation results obtained from HOMER Pro optimization and MATLAB analysis are presented within the manuscript. The solar radiation data used in this study were obtained from the publicly available NASA Prediction of Worldwide Energy Resources (POWER) database, which is cited in the references. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement

This study did not involve human participants, animal subjects, or the collection of personal or sensitive data. Therefore, ethical approval and informed consent were not required. The research was conducted in accordance with applicable institutional and research integrity standards.

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