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Techno-Economic Design of an On-Grid Solar-Powered Greenhouse for Highland Vegetable Farming Using HOMER Pro

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ABSTRACT

The dependence of Indonesia's electricity system on fossil fuels, particularly coal, remains a challenge in achieving a sustainable energy system. The use of coal for electricity generation produces carbon emissions and various pollutants, making the increased utilization of renewable energy an important approach to supporting the energy transition and reducing emissions. One renewable energy source with significant potential is solar energy, which can be directly utilized in the agricultural sector that requires electricity to support greenhouse operations. This study aims to design and analyze the techno-economic feasibility of an on-grid solar photovoltaic (PV) power system to support paprika cultivation using HOMER Pro. The analysis focuses on energy cost efficiency and the potential for carbon emission reduction through the integration of photovoltaic (PV) systems with the electricity grid. The simulation results indicate that the optimum configuration consists of a 0.345 kW PV system, a 1 kW converter, one 51.2 V Li.ONESS battery system, and grid connection, with a Net Present Cost (NPC) of IDR 11,319,780 and a Levelized Cost of Energy (LCOE) of IDR 351.71/kWh. The system produces 2,513 kWh/year, consisting of 538 kWh/year from PV and 1,975 kWh/year from the grid. Annual CO_2 emissions decrease from 1,571 kg/year to 1,248 kg/year, corresponding to a reduction of approximately 20.6%. These results indicate that the implementation of an on-grid PV system can reduce grid electricity consumption while supporting greenhouse energy needs and reducing carbon emissions.

1. Introduction

The need for clean energy continues to increase along with the dependence of the electricity system on fossil fuels which produce carbon emissions and various pollutants [1].This condition encourages the use of renewable energy as part of the transition to a more sustainable energy system [2]. Renewable energy has the potential to reduce dependence on fossil fuels through the use of resources such as solar, wind, water, geothermal, and biomass [3]. One renewable energy source

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that has great potential for electricity generation is solar energy because it can be utilized through photovoltaic (PV) technology and applied to various sectors, including agriculture [4].

The use of solar energy in the agricultural sector can be used to meet the electricity needs of various equipment supporting cultivation activities [5]. Integrating PV with agricultural activities also has the potential to increase renewable energy utilization while supporting the sustainability of food production systems. Previous studies [6] have shown that integrating solar energy with agriculture can provide benefits to land use, water use, and energy production. The use of PV for agricultural purposes has also been applied to irrigation systems [7], demonstrating the use of PV to meet the energy needs of irrigation pumping systems, while research [8] shows that solar-powered irrigation systems can provide benefits from both energy and environmental aspects.

One of the agricultural applications that requires an electricity supply to support cultivation activities is a greenhouse [9]. Growing peppers in a greenhouse requires electricity to support the irrigation and fertigation systems, as well as other supporting equipment [10]. The use of PV can be an alternative to meet some of these electricity needs and reduce dependence on grid electricity [11]. On-grid configuration allows PV energy to be used when it is available, while the electricity grid can still supply the load when PV generation is insufficient [12]. Therefore, it is necessary to design a system that takes into account the potential of solar energy, the greenhouse's electricity needs, component capacity, as well as economic and environmental aspects [13].

Techno-economic analysis can be used to evaluate the feasibility of an energy system based on the generator configuration and load profile. Prasetyo et al. [14] used HOMER Pro to analyze PV systems with on-grid and off-grid configurations, while Pujangga and Apriliyansah [15] used HOMER Pro to evaluate photovoltaic systems by considering energy production and economic indicators such as Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). The study showed that HOMER Pro can be used to evaluate renewable energy systems based on technical and economic aspects [16].

However, based on previous research summarized in Table 1, studies specifically integrating on-grid PV systems with the electricity needs of bell pepper greenhouses and evaluating them using techno-economic analysis are still limited. A summary of relevant previous research on solar energy utilization in the agricultural sector and the evaluation of renewable energy systems is presented in Table 1. This study aims to design and analyze an on-grid solar power system to partially meet the electricity needs of a paprika greenhouse in Pasuruan Regency using HOMER Pro. The analysis was conducted based on the technical configuration, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and potential carbon emission reductions. The results are expected to provide a basis for evaluating the application of solar energy as a renewable energy source to support paprika greenhouse operations.

Table 1
Summary of Recent Studies on Solar Photovoltaic Applications in Agriculture and Techno-Economic Energy Systems

Method/Approach	Location	Main Findings	Comparative Insight	Reference
Systematic review of agrivoltaic systems, focusing on agricultural productivity, PV electricity generation, profitability, and environmental co-benefits.	Various agricultural locations worldwide.	Agrivoltaic systems can improve land-use efficiency, water-use efficiency, and profitability while simultaneously producing renewable electricity. Reported benefits include a 150–300% improvement in water-use efficiency, up to 200% higher land-use efficiency, and reduced	Demonstrates the broader potential of integrating solar energy with agricultural activities but focuses on agrivoltaics rather than an electricity supply system specifically designed for a greenhouse.	[17][18]

		irrigation demand under certain conditions.		
Review of agrivoltaics across the food–energy–water nexus, examining technical, ecological, environmental, and socioeconomic aspects.	Multiple locations and agricultural systems.	Agrivoltaics has the potential to support both food and energy production and improve resilience, but uncertainties remain regarding ecological, environmental, and socioeconomic impacts. The review emphasizes the need for interdisciplinary and location-specific assessments.	Establishes the importance of site-specific evaluation of PV–agriculture integration, while the present study focuses specifically on the techno-economic design of an on-grid PV system for greenhouse electricity demand.	[19]
Solar-powered irrigation system design, including crop water-demand estimation, pump selection, and PV array sizing.	Karshi, Abuja, Nigeria; 1-ha agricultural field.	Daily irrigation demand was estimated at 10,000 L/day. A pump requiring approximately 258 W was selected, and three 110-W PV modules were proposed to supply the pumping system.	Demonstrates the direct application of PV to agricultural electricity demand, particularly irrigation. However, the study focuses on standalone irrigation pumping rather than grid-connected greenhouse energy management and techno-economic optimization.	[20]
Solar-powered smart irrigation system combining PV-powered irrigation, real-time monitoring, and economic and environmental evaluation.	Urban agricultural settings; rooftop peppermint cultivation.	The smart irrigation system reduces water and energy consumption by 28.1% compared with conventional irrigation and reduces the carbon footprint. The economic assessment reported a payback period of approximately 5.6 years.	Shows that renewable-powered agricultural systems can simultaneously address energy consumption, resource efficiency, emissions, and economic performance. However, it uses a smart irrigation application rather than HOMER-based optimization of an on-grid greenhouse power system.	[21]
Techno-economic analysis using HOMER Pro for a large-scale floating photovoltaic system with a representative medium-voltage load profile.	Ranu Grati Lake, Indonesia; 10 MW FPV.	The proposed 10 MW FPV system was estimated to generate approximately 15.35 GWh/year, with an NPC of USD 12.9 million, an LCOE of USD 0.053/kWh, and an estimated annual CO_2 reduction of approximately 11,000 tonnes.	Demonstrates the use of HOMER Pro to connect PV generation with a realistic electricity load and evaluate technical, economic, and environmental performance. The scale and application, however, differ substantially from the small-scale greenhouse systems examined in this study.	[22][23]

2. Methodology

2.1 Research Flowchart

This research was conducted through several stages, starting from identifying the electrical energy needs of the paprika greenhouse, collecting solar radiation and electrical load data, designing the proposed photovoltaic (PV) system, and conducting techno-economic analysis using HOMER Pro. The research process includes determining the research location, estimating solar energy potential, determining the electrical load profile, selecting the main system components, and determining the system's economic parameters. The proposed PV system configuration was then simulated using HOMER Pro to obtain the optimal system configuration based on technical

and economic performance. The simulation results were evaluated based on energy production, electricity consumption from the grid, Net Present Cost (NPC), Cost of Energy (COE), and changes in carbon emissions. All research stages are shown in the research flowchart in **Figure 1**.

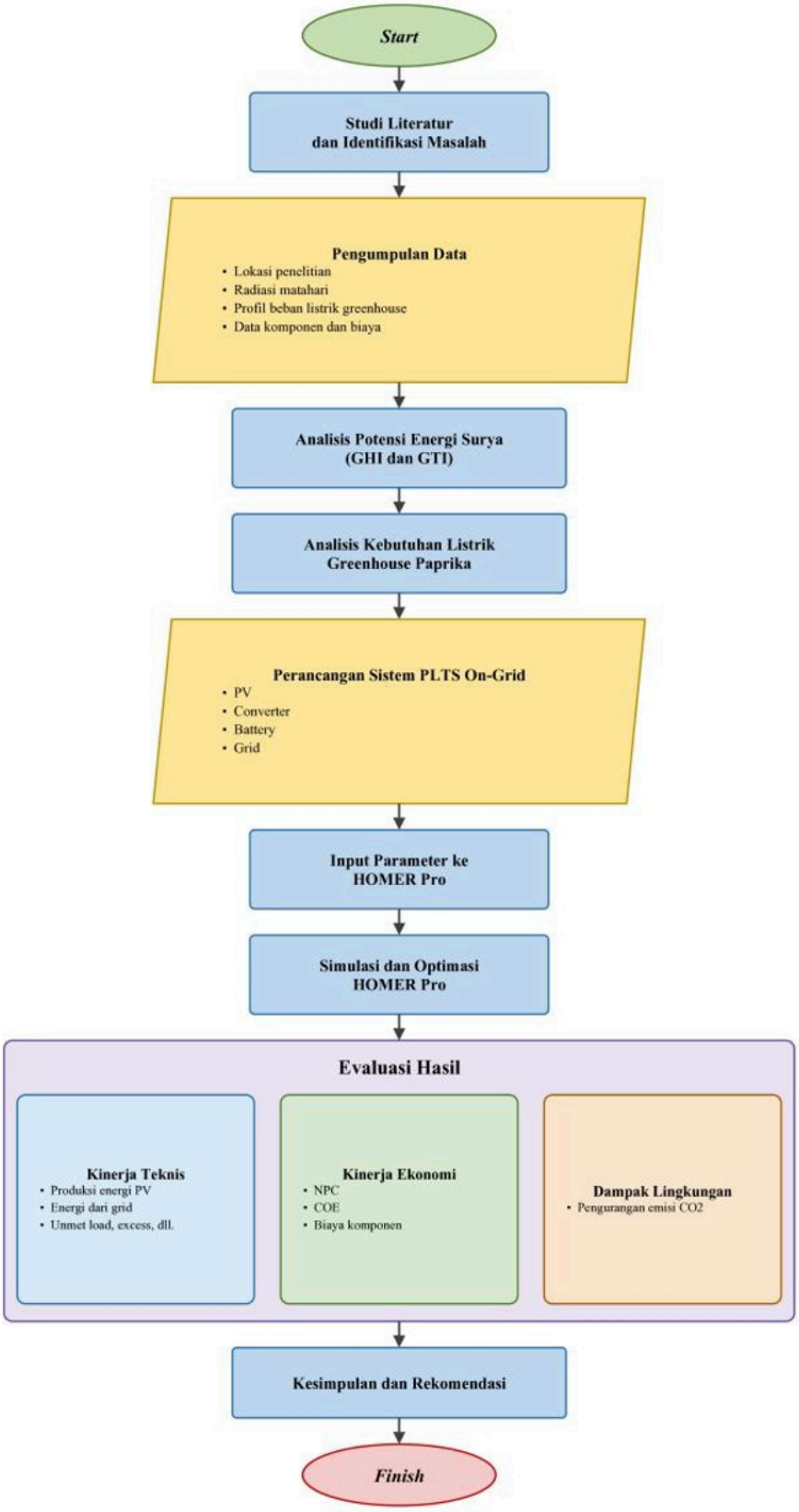


Fig. 1. Flowchart of PV system design simulation

2.2 Electrical Load Profile

The electrical energy requirements for the greenhouse in this study were determined based on the system design and equipment requirements used in Putri et al.'s study [25]. through a study entitled Design and Performance Testing of a Solar Power Generation System (SPGS) for a Smart Greenhouse with Tower Hydroponic Support. The types of loads used include pumps, misting systems, and exhaust fans, while the greenhouse size used as a design reference also adapts the greenhouse design in the study. The use of data from previous studies was carried out to provide a technical basis in determining electricity requirements, so that the load parameters used were not determined arbitrarily. Details of the type of load, power, operating time, and daily energy consumption used in this study are presented in Table 2 below.

Table 2
Greenhouse Electrical Load Profile

Electrical load	Quantity	Power (W)	Operating hours (h/day)	Energy consumption (Wh/day)
Pump	3	36	12	1,296
Misting	1	60	0.13	7.8
Exhaust fan	1	45	6	270
Total				1,573.8

Based on Table 2, three pump units with a power of 36 W each have an energy consumption of 1,296 Wh/day, while the misting system and exhaust fan consume energy of 7.8 Wh/day and 270 Wh/day, respectively. Thus, the total electrical energy requirement based on the reference design is 1,573.8 Wh/day or approximately 1.574 kWh/day. This value is used as the basis for compiling an electrical load profile which is then adjusted to the load profile used in the HOMER Pro simulation. The load data refers to the greenhouse system design in the study by Putri et al. (2025), including the design and size of the greenhouse used as a reference in this study. Furthermore, this data is used as the basis for compiling an electrical load profile for the simulation of the on-grid solar power system using HOMER Pro.

Figures 2 and 3 show the greenhouse's electrical load profile during the simulation period. This profile illustrates changes in electrical power demand according to the greenhouse's equipment operating hours. Load variations occur because equipment such as pumps, misting systems, and exhaust fans have different operating times. Figure 3 shows the distribution of the greenhouse's electrical energy demand over a one-year period. Monthly profiles are used to illustrate variations in energy demand throughout the simulation period, allowing the solar PV system to be evaluated not only based on daily electricity demand but also on the energy demand for the entire year. This data serves as the basis for determining the balance between PV energy production and the greenhouse's electricity demand.

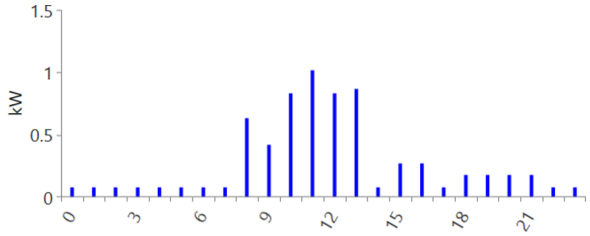


Fig. 2. Daily load profile

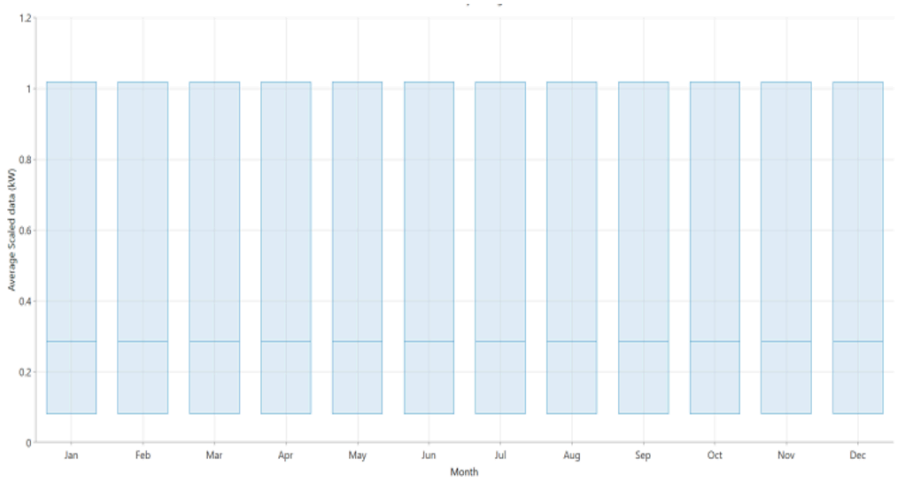


Fig. 3. PV electricity load profile every month

2.3 Description of the Solar Power Plant System Design Model

The solar PV system is designed as an on-grid photovoltaic system to supply part of the electricity needs of the paprika greenhouse. Figure 4 shows a schematic of the on-grid solar PV system used in the study. The system consists of PV panels, batteries, a converter, greenhouse loads, and the electricity grid. Energy generated by the PV panels is used to meet the load requirements, while the batteries serve as energy storage, and the electricity grid provides supply when the PV system's energy is insufficient. This configuration allows the system to utilize solar energy without eliminating the electricity grid as a supporting energy source.

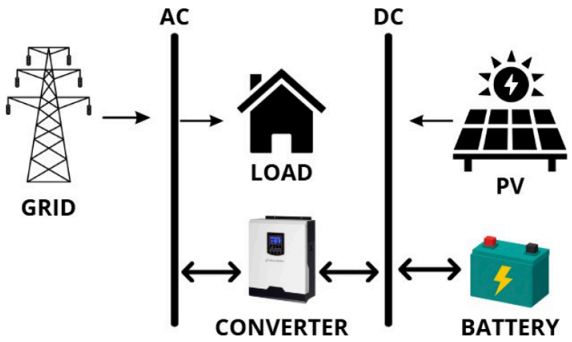


Fig. 4. On-grid PV system design scheme

The system was modeled and optimized using HOMER Pro. The simulation considered the greenhouse's electrical load profile, solar resource availability, component capacity, component cost, replacement cost, operation and maintenance (O&M) cost, grid electricity cost, discount rate, inflation, and project lifespan. Table 3 shows the components used in the simulation and the economic data for each component.

Table 3
Economic Parameters of the PLTS Components

Parameter	Trina Tallmax M Plus	Li.ONESS 51.2 V	System converter
Capital cost	Rp7,000,000	Rp15,000,000	Rp3,000,000
Replacement cost	–	–	–
O&M cost	Rp100,000	Rp700,000	Rp50,000
Lifetime	25 years	10 years	15 years

2.4 Description of the Design Location of the Solar Power Plant and the Size of the Greenhouse

A solar power system was designed to support the electricity needs of a paprika greenhouse located in Pasuruan Regency, East Java, Indonesia, as shown in Figure 5. The research location is in a highland agricultural area with suitable environmental conditions for paprika cultivation. This location was chosen as the design location for the on-grid solar power system because the greenhouse's electricity needs can be supplied through a combination of solar energy and the PLN electricity grid.

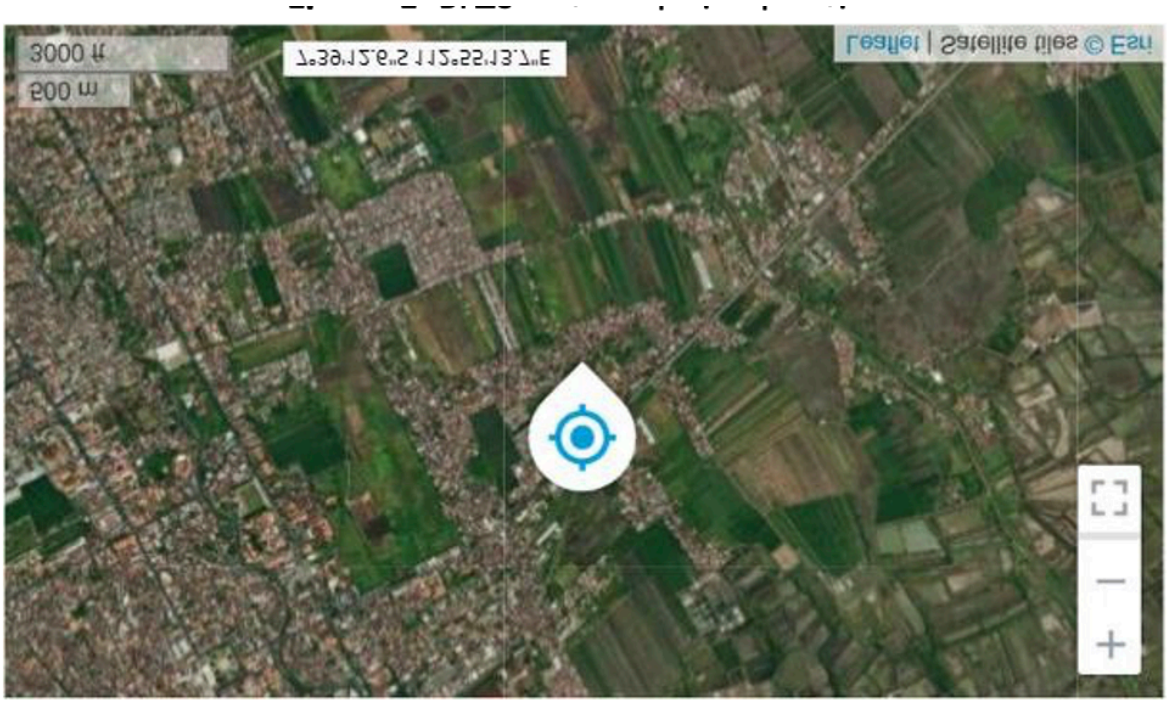


Fig. 5. PV system design location

The greenhouse requires electrical energy to operate the fertigation system and various other supporting equipment. The current electricity source comes from the conventional electricity grid. Therefore, this location was chosen as a case study to evaluate the implementation of an on-grid solar power system to supply part of the greenhouse's operational electricity needs. Geographical characteristics and solar resources at the research site are important parameters in determining the performance of the proposed solar power system. Solar radiation data at the research site is used as the main input for renewable energy sources in the HOMER Pro simulation.

In determining the dimensions of the greenhouse, this study refers to the greenhouse design used by Putri et al [25] which has dimensions of 5.85 m × 4.30 m with a height of 2 m and an area of 25.155 m² as shown in Figure 6. These dimensions are used as a reference to determine the electrical equipment requirements and greenhouse load profiles, while the on-grid PV system is designed and

analyzed using HOMER Pro to evaluate the contribution of solar energy to the greenhouse's electricity needs.

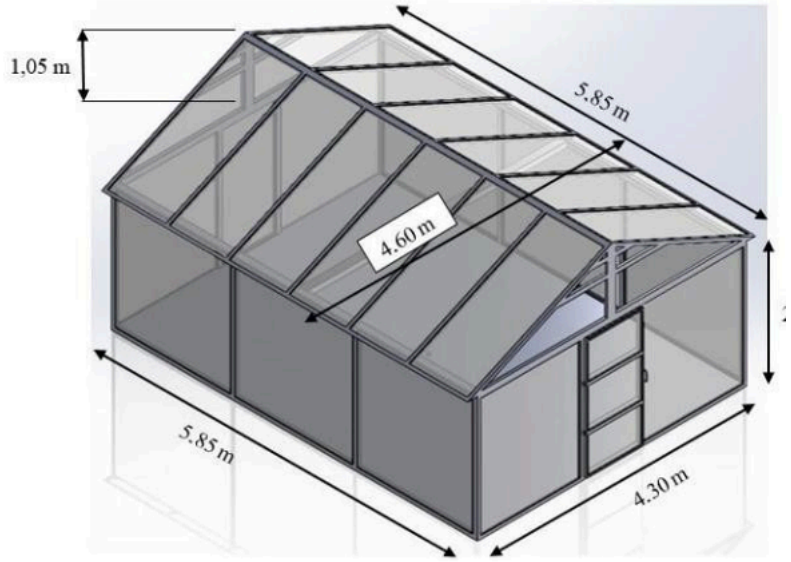


Fig. 6. Greenhouse Design

2.5 Potential Use of Solar Energy

The distribution of solar radiation and sunlight intensity in a region influence the process of converting electrical energy from solar energy. The higher the solar intensity, the greater the electrical energy that can be generated. **Figure 7** shows the distribution of Direct Normal Irradiation (DNI) in Pasuruan Regency over the course of a year. The irradiance values show intermonthly variations, with the highest value occurring in September at 351 kWh/m² and the lowest in February at 139 kWh/m². This variation indicates that solar energy availability is not constant throughout the year, so PV electricity production can also change depending on solar resource conditions. The DNI data is used as one of the renewable energy source inputs in the HOMER Pro simulation.

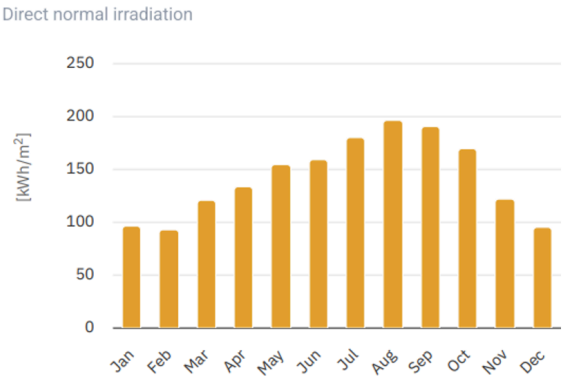


Fig. 7. Direct normal irradiation

Table 4
Direct normal irradiation data in Pasuruan

Month	Direct normal irradiation (kWh/m²)
January	156
February	139
March	167
April	217
May	239
June	249
July	231
August	289
September	351
October	324
November	237
December	153
Annual	155.5

2.6 Main Components of the System
2.6.1 Total Expense

The daily load data applied in the system analysis in **Figure 8** shows the daily electrical load profile used as input for the HOMER Pro simulation. The load pattern illustrates the change in power demand over 24 hours according to the operating hours of the greenhouse equipment. Higher loads occur during periods when operational equipment is running simultaneously, while lower loads occur when most equipment is idle. This daily profile is used to represent the greenhouse's electricity consumption pattern in the on-grid solar PV system simulation.

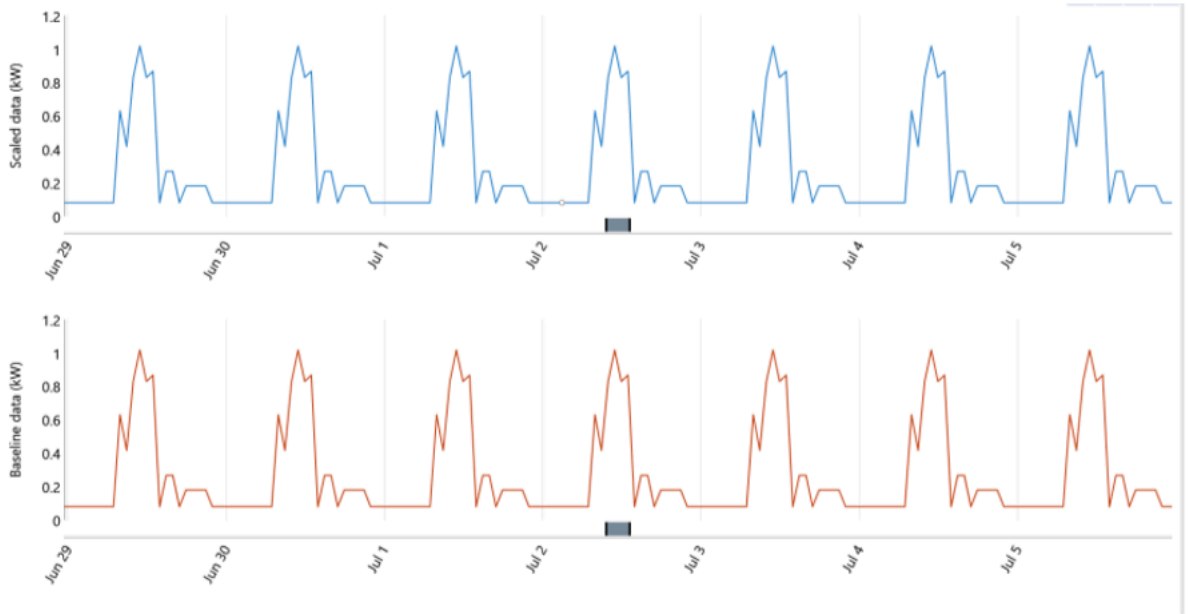


Fig. 8. Daily load graph

2.6.2 Main Component Specifications

The main components used in modeling an on-grid solar PV system consist of photovoltaic (PV), converter, battery, and electricity network (grid). The determination of component capacity is carried out in two stages: initial calculations based on the greenhouse's energy and electrical power requirements, and optimization using HOMER Pro. The initial calculation is used to determine the minimum capacity and capacity range of candidate components, while the final configuration is determined based on the optimization results, taking into account the energy balance, electricity production, and system economic aspects. This approach is used to ensure that the component capacities included in the simulation have a technical basis and are not determined solely based on assumptions.

Based on the load profile obtained, the greenhouse's electrical energy requirement is 1.5738 kWh/day. In addition to energy requirements, the maximum load power is also used to determine the converter capacity. Assuming all loads are operating simultaneously, the maximum power requirement can be calculated using the following equation.

$$\begin{aligned} P_{\text{load,max}} &= (3 \times 36) + (1 \times 60) + (1 \times 45) \\ &= 213 \text{ W} \end{aligned}$$

The minimum converter requirement based on initial calculations is approximately 0.21 kW. This value is used as the basis for determining candidate converter capacities in HOMER Pro, while the final system capacity is determined through an optimization process. Based on the optimization results, HOMER Pro selected a 1 kW converter in the configuration with the lowest Net Present Cost (NPC). PV capacity is also determined using the same approach. Daily energy demand is used as the basis for estimating the initial PV capacity, taking into account potential solar radiation and system efficiency. In general, the initial PV capacity can be calculated using the following equation.

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

where P_{PV} is PV capacity (kW), E_{load} is daily energy demand (kWh/day), PSH is peak sun hours (h/day), and η_{sys} is overall system efficiency. The results of the initial calculations are used to determine the range of candidate PV capacities which are then evaluated by HOMER Pro. Based on the optimization results, the configuration with the lowest system cost uses the Trina Tallmax M Plus PV module with a total capacity of 0.345 kW or one module with a power of 345 W. The technical specifications of the components used as candidates in the HOMER Pro simulation are shown in Table 5.

Batteries are also included in the model as an alternative energy storage option. Theoretically, battery capacity can be estimated based on energy demand, autonomy, depth of discharge (DoD), and battery efficiency. The initial calculation can be expressed as follows.

$$C_{\text{bat}} = \frac{E_{\text{load}} \times N_{\text{aut}}}{DoD \times \eta_{\text{bat}}}$$

where C_{bat} is battery capacity (kWh), N_{aut} is autonomy (days), DoD is depth of discharge, and η_{bat} is battery efficiency. The battery is not specified as a mandatory component in the final configuration, but is included as a candidate so that HOMER Pro can compare configurations with and without energy storage. Thus, battery usage in the final system is determined based on the optimization

results, not based on initial assumptions. The final parameters to be entered into HOMER Pro based on the calculations are shown in Table 5 below.

Table 5
Main component specifications for PLTS system

Component	Parameter	Value
PV	Maximum power (Pmax)	345 W
PV	Maximum voltage (Vmp)	37.0 V
PV	Open-circuit voltage (Voc)	45.6 V
PV	Short-circuit current (Isc)	9.6 A
PV	Module efficiency	17.8%
PV	Maximum power	0.345 kW
Converter	Output power	1 kW
Converter	Output frequency	50 Hz
Converter	Input DC voltage	DC
Converter	Efficiency	95%
Battery	Maximum capacity	75 (unit unspecified)
Battery	Nominal capacity	51.2 V system (as reported)
Battery	Nominal voltage	51.2 V
Battery	Maximum charging current	75 (unit unspecified)
Battery	Efficiency	98%

2.7 Economy
2.7.1 NPC

Net Present Cost (NPC) is the cost incurred during the installation process and throughout the project period. In the HOMER simulation, NPC values are sorted from lowest to highest. NPC costs include component costs, component replacement costs, operation and maintenance costs, fuel costs, minus the residual value of the components at the end of the project period, and take into account the annual interest rate. The NPC value can be calculated using the following equation.

$$NPC = \frac{C_{\text{ann,tot}}}{CRF(i, R_{\text{proj}})}$$

with the following information:

- NPC = Net Present Cost (Rp)
- $C_{ann,tot}$ = total annual costs (Rp/year)
- i = interest rate
- R_{proj} = project lifetime (years)

2.7.2 COE

The energy cost is calculated by comparing the total annual cost of the system with the amount of energy produced during the same period. The COE value can be calculated using the following equation.

$$COE = \frac{C_{\text{ann,tot}}}{L_{\text{prim,AC}} + L_{\text{prim,DC}}}$$

Where:

- COE: Cost of energy
- $L_{prim, AC}$: AC loads per year (kWh/year)
- $L_{prim, DC}$: DC loads per year (kWh/year)

3. Results and Discussion

3.1 Homer Pro Optimization Results

On-grid solar power system simulations were performed using HOMER Pro software to evaluate various component combinations based on technical and economic parameters. The optimization process considered the capacity of photovoltaic (PV), batteries, converters, and the electricity network (grid) to obtain a system configuration capable of meeting load requirements with the lowest system cost. The main parameters used in the evaluation process include component capacity, energy production, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), operating costs, and renewable energy contributions. Batteries were included as energy storage candidates so HOMER Pro could compare configurations with and without batteries.

Figure 9 shows the results of the configuration optimization with the lowest NPC value consisting of one Trina Tallmax M Plus PV module with a capacity of 0.345 kW, a System Converter with a capacity of 1.00 kW, and a grid with a capacity of 5.00 kW. In this configuration, there is no battery as an optimal system component. The operating strategy used is HOMER Cycle Charging. This system configuration produces an NPC of IDR 10,026,780 and an LCOE of IDR 1,037/kWh. These values indicate that based on the technical parameters, resources, and economic parameters used in the simulation, HOMER Pro chooses the PV and grid configuration without battery storage as the configuration with the lowest overall cost.


Export...

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost				System		TrinTallM+		
TrinTallM+ (kW)	LiFe2413N	Grid (kW)	Converter (kW)	Dispatch	NPC (Rp)	COE (Rp)	Operating cost (Rp/yr)	Initial capital (Rp)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (Rp)	Production (kWh/yr)	Autonomy (hr)
0.345		5.00	1.00	CC	Rp10.0M	Rp1,037	Rp322,457	Rp5.42M	75.6	0	2,415,000	538	
		5.00		CC	Rp11.8M	Rp1,445	Rp828,057	Rp0.00	0	0			
0.345	1	5.00	1.00	CC	Rp16.1M	Rp1,669	Rp141,129	Rp14.1M	75.6	0	2,415,000	538	15.7
	1	5.00	1.00	CC	Rp21.7M	Rp2,643	Rp696,729	Rp11.7M	0	0			15.7

Fig. 9. Homer simulation results

Table 6
Optimization Results of the On-Grid PV System

Parameter	Optimal configuration
PV	0.345 kW
Battery	0
Converter	1.00 kW
Grid	5.00 kW
Dispatch strategy	HOMER Cycle Charging
NPC	Rp10,026,780
LCOE	Rp1,037/kWh
Initial capital	Rp5,420,000
Operating costs	Rp322,457/year
PV production	538 kWh/year
Grid purchases	165 kWh/year
Unmet electrical load	0 kWh/year
Excess electricity	0 kWh/year

The optimization results also show the cost difference between the battery- and battery-free configurations. Based on the Optimization Results in Table 6, a 0.345 kW grid-connected PV configuration without a battery generates an NPC of approximately Rp10.0 million, while the addition of a battery unit to the PV and grid configuration increases the NPC to approximately Rp16.1 million. The grid configuration without either PV or battery has an NPC of approximately Rp11.8 million, while the configuration combining only the battery and grid has an NPC of approximately Rp21.7 million. These results indicate that, under the simulation parameters used, the addition of a battery increases the overall system cost, so the battery was not selected in the optimal configuration with the lowest NPC.

3.2 Energy Performance of the Proposed System

The system's energy performance is analyzed based on the balance between energy production from the photovoltaic (PV) system, energy obtained from the electricity grid, and the greenhouse's electricity needs. Based on the HOMER Pro simulation results, the system configuration consists of a 0.345 kW PV system and a 5 kW electricity grid with a 1.00 kW converter. The PV system produces 538 kWh/year of energy, while the energy obtained through purchases from the grid is 165 kWh/year. Thus, the total energy recorded on the system production side is 703 kWh/year, consisting of 76.6% PV production and 23.4% energy from the grid as shown in Figure 10 below.



Fig. 10. Electrical Optimization Results

Overall, the simulation results shown in Table 7 indicate that the optimized configuration is capable of meeting the greenhouse's electrical energy needs with a combination of PV generation and grid supply. The 0.345 kW PV system contributes 538 kWh/year, while the grid provides 165 kWh/year. The unmet electrical load value of 0 kWh/year indicates that there is no unmet electricity demand during the simulation period. This energy performance serves as the basis for further evaluating the system's economic aspects through NPC, LCOE, and cash flow.

Table 7
Annual Energy Production and Consumption

Parameter	Value	Percentage
PV production	538 kWh/year	76.6%
Grid purchases	165 kWh/year	23.4%
Total production	**703 kWh/year**	**100%**
AC primary load	573 kWh/year	84.0%*
Excess electricity	0 kWh/year	–
Unmet electrical load	0 kWh/year	–
Capacity shortage	0 kWh/year	–

3.3 Economic Performance

The economic performance of the on-grid solar PV system was analyzed based on the HOMER Pro optimization results by considering the initial investment cost, system operating cost, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE). The economic analysis was used to determine the financial consequences of implementing the solar PV system compared to the grid-only system. Based on the optimization results, the selected configuration consists of a photovoltaic (PV) with a capacity of 0.345 kW, a 1 kW converter, and a 5 kW grid, while the battery is not used in the optimal configuration. This configuration results in an initial capital of Rp5,420,000 and an operating cost of Rp322,457 per year. These results indicate that the implementation of solar PV should not only be analyzed based on energy production, but also based on the costs incurred during the system's operating period.

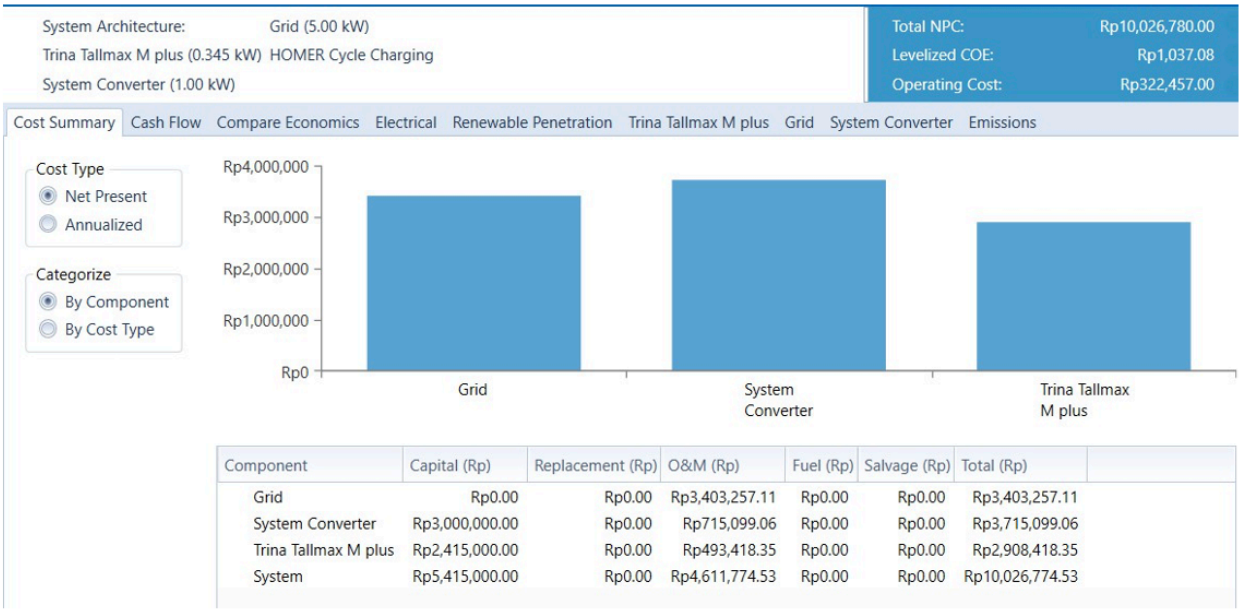


Fig. 10. Optimal Simulation Results

a. Net Present Cost (NPC)

Net Present Cost (NPC) is an indicator used to show the total system cost over the project period in present value terms. The NPC value considers the initial investment cost, operation and maintenance costs, component replacement costs, and the cost of purchasing energy from the

electricity grid over the project period. Thus, the NPC can be used to compare the economic consequences between grid-only configurations and those using solar power plants.

Based on the HOMER Pro optimization results, the selected on-grid solar PV configuration generates an NPC of Rp10,026,780. This value is obtained from a 0.345 kW PV configuration, a 1 kW converter, and a 5 kW grid without the use of batteries. The initial capital value of the system is Rp5,420,000, while the operating cost is recorded at Rp322,457 per year. The non-use of batteries in the optimal configuration indicates that the addition of a storage system does not provide better economic benefits under the modeled load and energy source conditions.

The optimization results also show that the grid-only configuration has an NPC of approximately IDR 11.8 million, while the PV and grid configuration produces an NPC of approximately IDR 10.0 million. This difference indicates a decrease in total system costs when part of the energy demand is met by PV generation. However, these NPC values are calculated based on economic parameters and system assumptions entered into HOMER Pro, so the results are highly dependent on component costs, electricity tariffs, project lifespan, and the economic parameters used in the simulation.

b. Levelized Cost of Energy (LCOE)

Levelized Cost of Energy (LCOE) is used to describe the average cost of energy produced or served by a system during the analysis period by considering the system costs throughout the project's lifetime. This parameter provides an overview of the relationship between system costs and the energy that can be supplied to the load. HOMER Pro optimization results show that the selected on-grid solar PV configuration has an LCOE of Rp1,037/kWh. This value is lower than the grid-only configuration, which has a value of around Rp1,445/kWh based on the optimization results. The difference in LCOE is related to the energy contribution from the PV system, which produces 538 kWh/year, so that some energy needs are not entirely dependent on electricity purchased from the grid.

However, the LCOE in this study should be understood as an economic indicator resulting from the HOMER Pro simulation, not as the electricity tariff paid by users to the electricity provider. This value reflects energy costs based on the configuration, investment, operation, and economic parameters used in the model. Therefore, the LCOE is used in conjunction with the NPC and other economic parameters to provide a more comprehensive picture of the system's economic performance.

c. Cash Flow Analysis

Cash flow analysis is used to identify the cost components that make up the overall system cost over the project period. The main cost components consist of initial investment costs (capital costs) and operating costs. Based on the optimization results, the system has an initial capital of Rp5,420,000, while operating costs are Rp322,457 per year.

The optimal configuration does not use batteries. This differs from the configuration that includes batteries, which results in higher system costs in the optimization results. Based on the HOMER Pro configuration comparison, the PV and grid system generates an NPC of approximately IDR 10.0 million, while the PV, battery, and grid configuration generates an NPC of approximately IDR 16.1 million. This difference indicates that under the load profile used in this study, the addition of batteries increases system costs without being part of the configuration selected by the optimization process.

Overall, the economic analysis results indicate that the configuration of 0.345 kW PV + 1 kW converter + 5 kW grid without battery is the configuration used as the proposed system in this study.

This configuration has an NPC of Rp10,026,780 and an LCOE of Rp1,037/kWh, with an initial investment of Rp5,420,000.

3.4 Environmental Performance

The system's environmental performance was analyzed based on changes in carbon emissions due to the integration of the photovoltaic (PV) system with the electricity grid. The grid-only condition was used as the base system, while the on-grid solar PV system optimized by HOMER Pro was used as the proposed system. Based on the simulation results, the base system produces emissions of 362 kg CO_2/year, while the proposed system produces emissions of 104 kg CO_2/year. This comparison shows that PV integration in the greenhouse's electricity system can reduce carbon emissions associated with the use of electrical energy from the grid.

The amount of carbon emission reduction is calculated using the equation:

$\Delta CO_2 = CO_2,\text{base} - CO_2,\text{proposed} = 362 - 104 = 258$ kg CO_2/year

The percentage of emission reduction is calculated by:

CO_2 reduction (%) = [(362 − 104) / 362] × 100 = 71.3%

(%) = $CO2,\text{base} - CO2,\text{proposed} \times 100\%\ CO2,\text{base}\ 362 - 104$

CO_2 reduction (%) = [(362 − 104) / 362] × 100 = 71.3%

CO_2 reduction (%) = [(362 − 104) / 362] × 100 = 71.3%

Table 9
System Carbon Emission Comparison

Parameter	Base system	Proposed system
Power generation system	Grid-only	PV + grid
CO_2 emissions	362 kg/year	104 kg/year
Emission reduction	–	258 kg/year
Percentage reduction	–	71.3%

The results in Table 9 show that the implementation of an on-grid solar PV system resulted in an emission reduction of 258 kg CO_2/year, or approximately 71.3% compared to grid-only conditions. This reduction occurred because some of the electrical energy previously supplied through the grid was replaced by energy generated by the PV system. In the optimal configuration, a 0.345 kW PV system produces 538 kWh/year of energy, while the grid is still used as a supporting energy source. Thus, the proposed system does not completely replace the grid, but rather reduces dependence on grid electricity supply through the utilization of solar energy.

The results of this environmental analysis also need to be understood in conjunction with the technical and economic results in the previous subsection. HOMER's chosen system does not use batteries, so emission reductions are achieved through direct PV integration with the grid, rather than through an energy storage system. With this configuration, the system is still able to meet the modeled load demand while producing lower NPC and LCOE values than the baseline system. These results demonstrate that the benefits of the proposed system are not only viewed from the aspects of cost and load fulfillment, but also from the potential for carbon emission reduction.

4. Conclusion

Based on simulation and optimization results using HOMER Pro, the optimal configuration of the on-grid solar power system to support the energy needs of the paprika greenhouse consists of a Trina PV with a capacity of 0.345 kW, a 1 kW converter, and a 5 kW electricity network, without the use of

batteries. The system produces 538 kWh/year of PV energy and purchases energy from the grid of 165 kWh/year, with an AC primary load requirement of 573 kWh/year. The selected configuration is able to meet all load requirements with an unmet electrical load of 0 kWh/year, a capacity shortage of 0%, and excess electricity of 0 kWh/year, while the PV capacity factor reaches 17.8%. From an economic aspect, the system generates an initial capital of Rp5,420,000, an operating cost of Rp322,457/year, an NPC of Rp10,026,780, and an LCOE of Rp1,037/kWh. Compared to a grid-only system with an NPC of approximately IDR 11.8 million and an LCOE of approximately IDR 1,445/kWh, the PV and grid configuration yields a lower cost based on the economic parameters used in the simulation. Batteries were not selected in the optimal configuration because their addition results in higher system costs.

From an environmental perspective, the implementation of the on-grid solar PV system produces 104 kg of CO_2/year, compared to 362 kg/year in the base system, resulting in a reduction in emissions of 258 kg CO_2/year or 71.3%. The optimization results also show that renewable energy production contributes 79.6% to the load and 76.6% to total generation based on the renewable production indicator in the HOMER Pro results. Overall, the results show that the integration of on-grid solar PV with the electricity grid can meet greenhouse energy needs without supply shortages, generate cost savings based on simulation parameters, and provide significant carbon emission reductions. However, these results are still influenced by the load profile, solar resources, component specifications, investment and operating costs, electricity tariffs, and economic assumptions used in HOMER Pro, so the use of actual operational data is needed to validate system performance under actual greenhouse conditions.

Data Availability

The data used to support the results of this study are available from the corresponding author on reasonable request.

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Conflict of Interest

The author declares that there is no conflict of interest in this research.

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