On-grid vs. off-grid photovoltaic systems for smart greenhouses: a techno-economic case study

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ABSTRACT

Integrating photovoltaic (PV) systems into agricultural applications has gained significant attention as a sustainable energy solution. However, the feasibility of on-grid and off-grid PV systems for smart greenhouse applications in Indonesia remains unclear. This study compares both systems' technical performance, economic viability, and regulatory challenges through simulations and case studies in Lembang, Bandung. The analysis considers solar radiation levels, shading effects, installation costs, energy independence, and long-term operational efficiency. Results indicate that while on-grid systems offer lower initial investment and seamless integration with the utility grid, regulatory constraints and limited capacity approvals pose significant barriers. Despite higher initial costs, off-grid systems provide energy independence and long-term cost benefits by eliminating dependency on grid electricity and avoiding bureaucratic hurdles. The study concludes that off-grid PV systems are a more practical and sustainable solution for smart greenhouse applications in Indonesia, mainly where grid connection processes are complex or unreliable.

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1. INTRODUCTION

The demand for sustainable agriculture is increasing due to the need for efficient resource management and climate resilience in farming practices. Improving resource efficiency is crucial for sustainable agriculture. Sustainable agriculture balances human nutritional needs with environmental preservation and economic viability, addressing food security, energy sustainability, and ecological stewardship [1]. Climate-smart agriculture practices, such as soil and water conservation, nutrient management, early maturing seeds, and innovative greenhouse, are vital for building resilience against climate variability [2], [3].

Photovoltaic (PV) systems have been widely adopted for renewable energy generation, providing a clean and sustainable alternative to fossil fuels. Agrivoltaic systems optimize land use by combining solar energy generation with agriculture, reducing competition for land resources [4]-[6]. Studies show that agrivoltaic systems can maintain or even improve crop yields and quality. For instance, grape sugar content remained stable under PV panels, and maize yield was higher under agrivoltaic conditions compared to whole light, especially under drought stress [7]-[9].

Smart greenhouses integrate automation technologies, such as real-time monitoring and controlled irrigation, to optimize crop growth while reducing manual labor. IoT devices enable precise tracking and control of greenhouse environments, including temperature, humidity, and soil moisture. This technology supports automation in irrigation and climate control, reducing the need for manual intervention and improving crop management [10]-[12]. Smart greenhouses contribute to sustainable agriculture by minimizing resource use and environmental impact, supporting food security in challenging climates [13], [14].

On-grid PV systems are commonly used in urban and industrial settings, offering stability, reliability, and the ability to export excess energy to the grid. In contrast, off-grid systems are preferred for remote locations without reliable grid access. These systems are ideal for urban and industrial applications where grid infrastructure is readily available, providing a seamless integration with existing energy systems [15]. Off-grid systems are crucial for electrification in remote or rural areas where grid extension is not feasible due to geographical constraints and high costs [16]-[18].

However, the technical and economic trade-offs between on-grid and off-grid PV systems for smart greenhouse applications in Indonesia remain unclear. On-grid PV systems generally have lower electricity generation costs than off-grid systems, benefiting from State Electricity Company (PLN's) net metering scheme. Unfortunately, recent regulatory changes, such as Ministerial Regulation No. 2 of 2024 (Permen ESDM No. 2/2024), have eliminated net metering and introduced quotas for rooftop solar installations, limiting their economic attractiveness [19]. Meanwhile, off-grid systems can be economically viable in remote areas with costly grid extensions. They offer a lower net present cost than diesel generation, especially when integrated with high-value crop cultivation [20], [21].

There is limited research on how local solar radiation levels, regulatory constraints, and energy demand patterns affect the feasibility of each system. Indonesia's tropical climate provides abundant solar radiation, but variations in seasonal irradiance and shading effects can significantly impact the performance of PV systems. Shading can cause significant power losses in PV systems. For instance, shading a quarter, half, and three-quarters of a PV module can reduce power output by 33.7%, 45.1%, and 92.6%, respectively [22]. Shading also leads to multiple peaks in the power-voltage curve, complicating power output optimization [23]. Additionally, regulatory challenges, such as PLN's grid connection approvals, technical capacity restrictions, and administrative delays, have created barriers to on-grid PV adoption in agriculture [24], [25]. Meanwhile, energy demand patterns in smart greenhouses fluctuate due to the operation of automated irrigation, ventilation, and monitoring systems, requiring a well-matched energy supply.

Moreover, the long-term costs and maintenance challenges of integrating PV systems with automated greenhouses remain underexplored despite their potential to reduce fossil fuel dependence and greenhouse gas emissions. However, the initial costs of PV modules and battery storage units are significant challenges [26]. Additional barriers, such as local land-use regulations and environmental impact assessments (EIAs), must also be considered for off-grid systems. Furthermore, previous case studies, such as the solar-powered microgrid project in Muara Enggelam, Kalimantan, highlight the importance of community engagement and regulatory compliance for successfully deploying off-grid systems in rural Indonesia [27].

Research comparing on-grid and off-grid PV systems for smart greenhouses in Indonesia is limited, making it challenging for stakeholders to determine the most effective solution amid complex factors such as strict PLN regulations, limited incentives, and high battery costs. This study comprehensively compares both systems through a case study of a smart greenhouse in Lembang, Bandung, evaluating their performance, costs, and installation challenges under current regulatory and technical conditions. The findings provide practical insights to support informed renewable energy investments, enhance agricultural productivity, reduce fossil fuel reliance, and align with Indonesia's national sustainability objectives.

2. METHOD

This research employed a mixed-methods approach. The study began with a comprehensive literature review to establish a theoretical framework and identify relevant existing research, as shown in Figure 1.

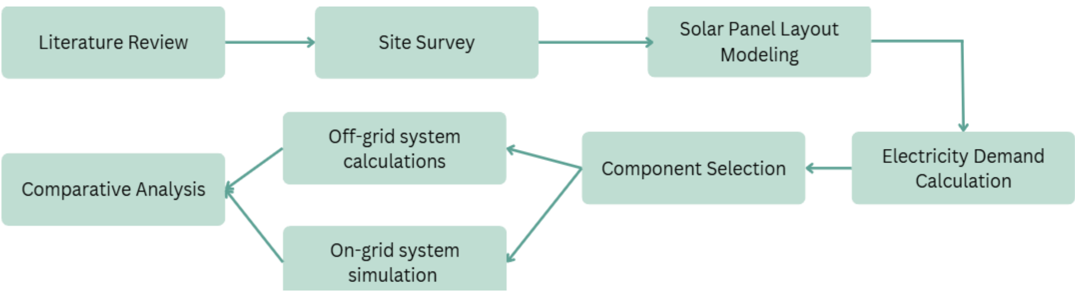

Figure 1. Methodology flowchart

The research began with selecting an innovative greenhouse in Lembang, Bandung, based on its suitable climatic conditions for PV-based agriculture. This was followed by a detailed site survey to collect meteorological data, including solar irradiation, air temperature, and weather patterns, obtained from Meteonorm 8.1 and local sensors. Concurrently, power sensors were installed to measure the energy consumption of the greenhouse's automated irrigation system, ventilation, and IoT monitoring devices. Next, the PV system components—including solar panels, inverter selection, batteries, and cable lengths—were specified based on collected data and manufacturer specifications. Energy requirements for the automated irrigation system were calculated precisely. Both on-grid and off-grid PV systems were then simulated using PVsyst 7.2, adjusted to local conditions. Finally, comparative performance and economic analysis were carried out using life cycle cost analysis (LCCA) to identify the most optimal and economically viable PV system for the greenhouse over 25 years.

Some formulas are used to decide the specifications of the components for the design of the off-grid PV system. In (1) shows the calculation for the solar panel capacity.

$$WP = \frac{Total\ Load\ (Wh)}{GHI\ (kWh/m^2/day)} \quad (1)$$

Solar panel capacity (Wp) represents the maximum power output of the panels, measured in watt-peak. The total daily energy requirement (total load, in kWh) is determined by the household's or system's energy consumption. Global Horizontal Irradiance (GHI, in kWh/m²/day) indicates the amount of solar energy received per square meter per day at a given location, a crucial factor in determining the necessary solar panel size. In (2) is used to calculate the number of solar panels.

$$Number\ of\ Solar\ Panels = \frac{Wp}{Wp\ Solar\ Panel} \quad (2)$$

The total solar panel system capacity (Wp) represents the overall power output required, measured in Watt-peak. The energy demands of the system determine this value. The Wp solar panel, or individual panel capacity, indicates the maximum power output of a single solar panel, which is also measured in Watt-peak. To determine the number of solar panels needed, you would divide the total system capacity (Wp) by the individual panel capacity (Wp solar panel).

The off-grid PV system requires a battery; the battery capacity based on the daily total load can be calculated using (3).

$$Battery\ Capacity\ (Ah) = \frac{Total\ Load\ (Wh) \times AD}{DoD \times Battery\ Voltage\ (V)} \quad (3)$$

The required battery capacity (Ah) is calculated considering several key factors. These include the efficiency of the battery system (expressed as a decimal or percentage), the battery's voltage (V), the total daily energy consumption in watts (W), and the desired number of backup days—the number of days the system must operate without recharging which is named autonomous days (AD). The formula balances these elements to determine the appropriate battery capacity to meet the system's energy demands:

$$SCC = \frac{WP}{System\ Voltage\ (V)} \quad (4)$$

The solar charge controller's current capacity (SCC), measured in amperes, is crucial for managing the flow of electricity from the solar panels to the battery bank. This capacity is determined by the peak power (Wp) of the solar panel array, measured in watts, and the voltage (V) of the battery system, measured in volts, as shown in (4). The SCC ensures that the charge controller can handle the maximum current output of the solar panels while protecting the battery bank from overcharging.

On the other hand, the economic calculation will consider several calculations such as net present cost (NPC), levelized cost of electricity (LCOE), return on investment (ROI), total savings, and payback period.

$$NPC = C_{initial} + \sum_{t=1}^{N} \frac{C_{O\&M}}{(1+r)^t} + \sum \frac{C_{replacement}}{(1+r)^t} \quad (5)$$

The NPC is calculated to assess the total investment and operational costs over the system's lifetime. The initial investment cost ($C_{initial}$), represents the upfront expenses incurred for purchasing and installing the PV system, including solar panels, inverters, batteries (for off-grid systems), and installation costs. The operational and maintenance cost ($C_{O\&M}$), refers to the annual expenses required for routine inspections, solar panel cleaning, inverter repairs, and minor component replacements. The replacement cost ($C_{replacement}$) accounts for the cost of replacing major components that have a shorter lifespan than the overall PV system, such as batteries in off-grid systems and inverters. The discount rate (r) calculates the present value of future costs and typically ranges between 3-10%. The year (t) represents a specific year within the analysis period, indicating when operational, maintenance, or replacement costs occur. Lastly, the lifetime (N), measured in years, defines the system's total operational period, typically 25 years for PV systems, as shown in (5).

$$LCOE = \frac{NPC}{\sum\frac{E_t}{(1+r)^t}} \tag{6}$$

The LCOE, as shown in (6) is an economic metric used to calculate the cost of electricity generation per kilowatt-hour (USD/kWh) over the system's lifetime. It is a key indicator for comparing the cost-effectiveness of different power generation technologies, including on-grid and off-grid PV systems. NPC represents the net present cost, E_t denotes the total energy output per year in kilowatt-hours, while r is the discount rate applied to adjust future energy values to present terms, t represents a specific year within the analysis period, and N is the total lifetime of the system, typically 25 years for PV systems.

$$ROI = \frac{Total\ Electricity\ Cost\ Savings}{Total\ Initial\ Investment} \times 100\% \tag{7}$$

ROI is a financial metric used to evaluate the profitability of an investment in a PV system. It measures the percentage return relative to the initial investment by considering the total electricity cost savings over the system's lifetime. Total electricity cost savings represents the total amount of money saved by generating electricity with the PV system instead of purchasing it from the grid using (8).

$$Total\ Savings = E_t \times P_{electricity} \times N \tag{8}$$

Total Initial Investment includes the upfront costs of purchasing and installing the PV system. A higher ROI indicates a more profitable investment, with on-grid PV systems typically achieving higher returns due to lower initial costs and potential revenue from grid export. Meanwhile, off-grid systems may have a lower ROI due to additional battery costs but provide energy independence, as shown in (7).

$$Payback\ Period = \frac{Initial\ Investment\ Cost}{Annual\ Cost\ Saving} \tag{9}$$

The payback period, as shown in (9), is a financial metric that measures the time required for an investment to recover its initial cost through accumulated savings or revenue. A shorter payback period indicates a faster ROI, making the project more financially attractive.

3. RESULT AND DISCUSSION

The coordinate location of the Smart Greenhouse is (6°49'16" S 107°40'36" E). The total daily load of the greenhouse is assumed to be 2640 Wh for the off-grid system, which will be explained in Section 3.2. However, the total power load for on-grid systems differs, as the farmer's house is factored into the calculation and has a total load of 7.1 kW, based on an on-site survey.

3.1. Design and simulation of on-grid PV system

PVsyst software was utilized to design and simulate the on-grid PV system. PVsyst is a widely used simulation software in the solar energy industry for designing solar panel systems [28]. PVsyst simulation software requires several inputs, including the location of the PV system installation, the daily load of the greenhouse, the tilt angle and orientation of the solar panels, and any surrounding objects that may cast shadows on the panels.

PVsyst encompasses several important concepts focused on modeling and analyzing solar energy systems. The software enables users to predict the performance of solar panel systems based on several factors, such as climate conditions, solar panel orientation, module efficiency, and system capacity.

3.1.1. Iso shading diagram

The results of the Iso-shadings diagram simulation consist of various information, namely tilt and azimuth angles, the sun's path with altitude and azimuth, and the sun's position spread across seven paths in 1 year, and sun time (07.00-17.00). Figure 2 This is an iso-shading analysis performed with a 15° tilt and 0° azimuth, showing the sun's position around 4 PM. The iso-shading results indicate that the highest solar irradiance level on the PV panel occurs between 11 AM and 12 PM. The simulation shows 7 months of sun paths with varying sun positions. June 22nd (path 1) receives significantly more sunlight than December 22nd (path 7). On June 22nd, before 10 AM, the azimuth is approximately 65° (northeast), with the sun in the northeast relative to the north (the research location). From 10 AM to 2 PM, the sun is positioned north (azimuth 0°) at a higher altitude than usual due to the southern hemisphere's summer (closer to the equator). From 2 PM to 6 PM, the sun moves towards 65° (northwest) relative to the north before setting. Therefore, the optimal panel position and angle are determined to be 15° facing north.

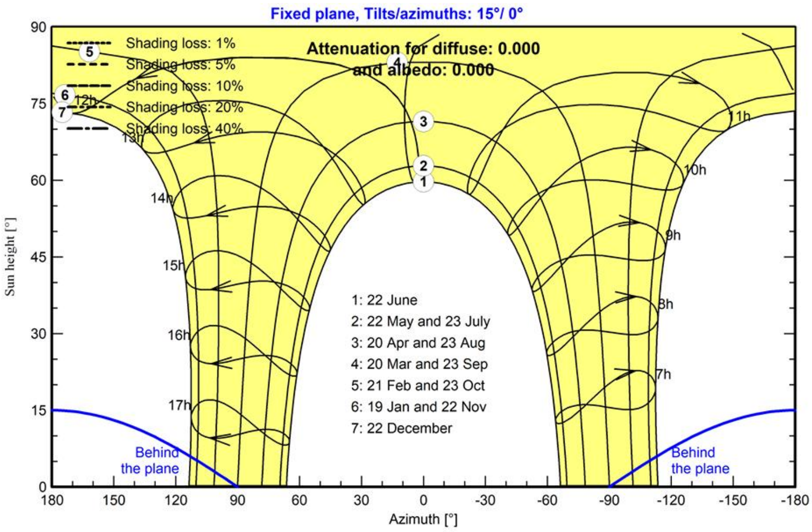

Figure 2. Iso shading diagram PVsyst

3.1.2. System production

The simulation results of the production system consist of several pieces of information, namely the energy generated per year after deducting system losses with monthly variations and the annual operating ratio. The system Production in Figure 3 illustrates the annual energy output of the PV system, peaking in June and reaching its lowest point in January. Key performance indicators for this on-grid system include string losses (Lc) of 0.5 kWh/kWp/day, system losses (Ls) of 0.14 kWh/kWp/day, and the net energy delivered to the user (Yf) of 4.55 kWh/kWp/day.

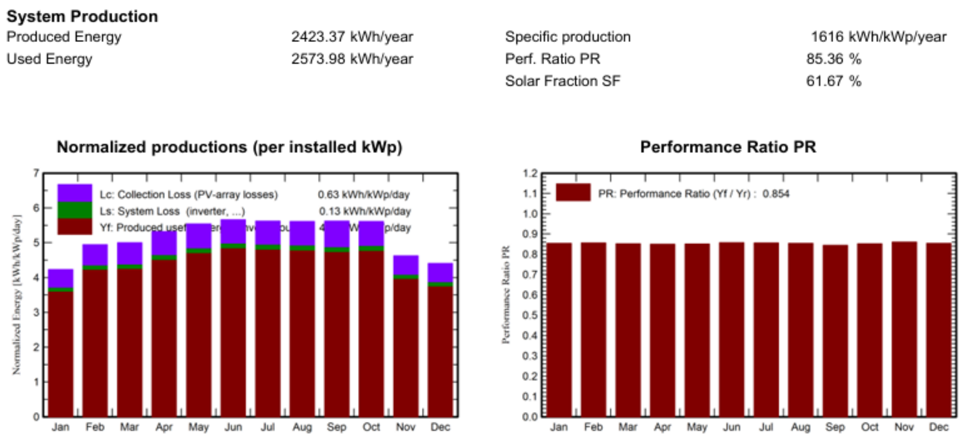

Figure 3. System production PVsyst

3.1.3. Balances and main results

Meteorological data from Meteonorm 8.1 simulations identified several key aspects for further analysis of PV system performance. These include Global Horizontal Irradiation (measuring total solar radiation on a horizontal surface), Diffuse Horizontal Irradiation (measuring scattered and indirect solar radiation), average monthly ambient temperature, Global Incident Irradiation (measuring solar radiation received by the solar panel surface), and Global Effective Irradiation (measuring the effective solar radiation for electricity generation, accounting for factors like incident angle and optical losses).

Table 1 presents key data for calculating on-grid PV system performance. This includes EArray (total energy generated by all solar panels over a specific period, monthly or annually), E-User (total energy consumed by connected loads), E-Solar (total solar energy collected by the panels), the actual energy generated by the system, E-Grid (total energy fed into the utility grid), and EFrGrid (total energy drawn from the utility grid to supplement insufficient PV system generation). These five data points are crucial for on-grid PV system analysis.

Table 1. Balances and main results PVsyst

	GlobHor kWh/m^2	DiffHor kWh/m^2	T_Amb °C	GlobInc kWh/m^2	GlobEff kWh/m^2	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EfrFrid kWh
January	143.5	74.01	16.12	131.1	123.4	173.3	218.6	120.7	47.42	97.94
February	146.4	71.54	15.87	138.5	131.1	183.4	197.5	120.7	57.32	76.77
March	156.8	72.69	16.64	155.1	147.1	204.4	218.6	131.0	67.39	87.65
April	152.5	63.96	16.90	159.8	152.1	209.7	211.6	130.5	73.12	81.04
May	156.0	59.11	17.37	171.9	163.8	225.8	218.6	138.1	81.18	80.49
June	150.4	54.17	16.86	169.8	162.2	224.9	211.6	137.4	81.10	74.18
July	155.9	57.60	16.64	174.4	166.7	230.7	218.6	139.5	84.52	79.07
August	162.9	64.04	16.73	174.0	166.2	229.6	218.6	140.0	83.00	78.63
September	165.5	58.47	16.67	168.7	160.6	220.1	211.6	132.7	80.96	78.81
October	181.4	77.89	17.06	174.0	165.3	229.0	218.6	144.6	77.90	74.05
November	149.7	82.06	16.52	138.8	131.2	184.5	211.6	126.9	52.26	84.69
December	151.7	70.46	16.52	136.6	128.8	180.5	218.6	125.2	49.91	93.39
Year	1872.8	805.99	16.66	1892.7	1798.5	2496.0	2574.0	1587.3	836.11	986.72

3.1.4. Loss diagram

Pvsyst's loss diagram simulation reveals several key factors impacting solar panel system energy output. These include shading from surrounding objects, reduced sunlight penetration due to dust and dirt accumulation, variations in sunlight incidence angle, predicted panel degradation over time, temperature-related efficiency losses, irradiance levels below standard expectations, material defects within the panels themselves, energy losses from cable resistance, and the crucial role of regular system maintenance in minimizing overall losses Figure 4 illustrates loss diagram PVsyst.

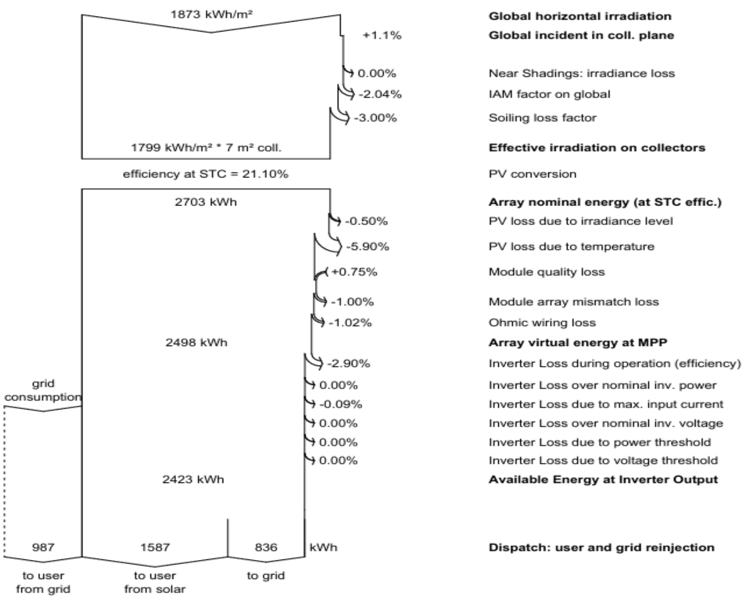

Figure 4. Loss diagram PVsyst

3.2. Design and calculation of off-grid PV system

The greenhouse in this study case has a variable daily load. Several sensors require continuous 24-hour operation, while motors and pumps operate only twice daily for one hour. Table 1 provides a comprehensive breakdown of the sensors, motors, and pumps used in the greenhouse system. It lists each component, specifying its daily usage duration in hours and the total number of units employed. This detailed information is crucial for accurately assessing the overall energy demand of the greenhouse and designing an appropriate solar energy system.

Based on the Table 2, the smart greenhouse is assumed to have a daily load of 2640 Wh. The greenhouse location has a Global Horizontal Irradiance (GHI) of 1632 kWh/m²/day. As shown in the Method section, first, we have to calculate the number of solar panels and the size of the solar panels, which is using (1) and (2), which will result in (10) and (11).

$$WP = \frac{Total\ Load\ (kWh)}{GHI\ (kWh/m^2/day)} = \frac{2640\ Wh}{1632\ W/m^2} \approx 1617\ Wp \tag{10}$$

$$Number\ of\ Solar\ Panels = \frac{Wp}{Wp\ Solar\ Panel} = \frac{1617\ Wp}{550\ Wp} \approx 3\ unit \tag{11}$$

Table 2. Greenhouse component usage and quantity

Component	Quantity	Daily usage (Hours)	Power (W)	Total (Wh)
DHT	10	24	1	240
DS18B20	5	24	0.5	60
ESP32	5	24	1	120
Soil Sensor	10	24	1	240
Raspi 4	1	24	15	360
Power Supply	1	24	25	600
Exhaust Fan	2	2	60	240
Cooling Fan	2	2	45	180
Water Pump	1	2	100	200
Motor	1	2	200	400
		Total		**2640**

In (6), the Wp solar panel, which is the peak power of the panel under standard test conditions, is used to determine the maximum output and performance. The selection of 550 Wp represents the peak power of the solar panel available in the local market.

On the other hand, the battery specification will be calculated considering a daily solar panel load of 2640 Wh and a chosen autonomy days of 2, a maximum battery charge limit (depth of discharge – DoD) of 75% was set to preserve battery health. Given a 12V battery system, a required capacity of 586 Ah was calculated by using (3). This led to the calculation of approximately 586 Ah and the selection of six 100 Ah, 12V batteries, shown in (12).

$$Battery\ Capacity\ (Ah) = \frac{Total\ Load\ (Wh) \times AD}{DoD \times Battery\ Voltage\ (V)} = \frac{2640\times 2}{75\% x 12} \approx 586Ah \tag{12}$$

The solar charge control (SCC) calculation was performed by dividing the total PV energy by 1650 Wp by the system voltage of 12V using (4). The result of the SCC specification was 137.5 Ah, which led to the selection of the SCC specification of 150 A, as shown in (13).

$$SCC = \frac{WP}{System\ Voltage\ (V)} = \frac{1650}{12} \approx 137.5A \tag{13}$$

3.3. Economic calculation

PV systems have a budget plan for their development. Two types of BoQ are presented: BoQ on-grid and BoQ off-grid, based on the design of each system. Table 3 details the components of an on-grid PV system, while Table 4 outlines the components of an off-grid PV system. This BoQ is based on the local market price in early 2025 with an assumed rate of IDR 16,373 for 1 USD.

For off-grid system, the NPC is calculated to assess the total investment and operational costs over the system's lifetime (25 years), shown in (14) and (15) for off-grid and on-grid systems, respectively.

$$NPC = C_{initial} + \sum_{t=1}^{N} \frac{C_{O\&M}}{(1+r)^t} + \sum \frac{C_{replacement}}{(1+r)^t} = 2{,}436.09 + 2{,}791.20 + 2{,}972.00 = \text{USD } 8{,}227.29 \tag{14}$$

Table 3. On-grid PV system BoQ

Component	Quantity	Unit	Unit Price (USD)	Total (USD)
Solar Panel (500 Wp)	3	unit	91.62	275.08
Inverter 1.5 kw	1	unit	378.72	378.72
DC Wire 2.5 mm²	160	meter	0.49	78.31
AC Wire 2.5 mm²	160	meter	0.92	146.78
MC4 connector	2	unit	2.44	4.89
Bi-Directional electricity meter	1	unit	79.44	79.44
Voltage controller	1	unit	91.62	91.62
Solar panel structure	2	unit	30.81	61.88
Digital multimeter	1	unit	18.95	18.95
Wire cutter and crimping tool	1	unit	12.63	12.63
DC circuit brake	1	unit	18.95	18.95
Grounding Kit	1	set	18.95	18.95
PVC Pipe 1 ¼ inch	40	unit	4.59	183.80
			Total	1,364.50

Table 4. Off-grid PV system BoQ

Component	Quantity	Unit	Unit Price (USD)	Total (USD)
Solar panel (550Wp)	3	unit	183.80	550.72
Inverter 3 kw	1	unit	512.60	512.60
DC wire 2.5 mm²	10	meter	0.49	4.89
AC wire 2.5 mm²	10	meter	0.92	9.78
Battery 100 Ah 12V	6	unit	152.87	917.20
SCC 150 A	1	unit	305.73	305.73
Solar panel structure	2	unit	30.81	61.88
Digital multimeter	1	unit	18.95	18.95
Wire cutter and crimping tool	1	unit	12.63	12.63
DC circuit brake	1	unit	18.95	18.95
Grounding Kit	1	set	18.95	18.95
			Total	2,436.09

The $C_{initial}$ of USD 2,436.09 represents the upfront expense required for purchasing and installing the PV system, including solar panels, an inverter, a battery (for off-grid systems), and installation fees. This cost is not discounted since it occurs at the beginning of the project. The total $C_{O\&M}$ of USD 2,791.20 represents the assumed sum of all annual epenses over 25 years, discounted at a 5% rate to reflect their present value. The yearly O&M cost of USD 200 covers routine inspections, solar panel cleaning, minor repairs, and inverter servicing. Since these costs occur annually, they are discounted as $\sum_{t=1}^{25} \frac{200}{(1.05)^t}$, with key values including USD 190.48 in year 1, USD 156.71 in year 5, USD 122.78 in year 10, and USD 59.72 in year 25, resulting in a total discounted value of USD 2,791.20.

Meanwhile, the $C_{replacement}$ of USD 2,972.00 accounts for battery replacements, which occur every 10 years at an assumed cost of USD 3,000 per replacement. Since replacements happen in years 10 and 20, they are discounted using $\frac{3000}{(1.05)^{10}} + \frac{3000}{(1.05)^{20}}$, yielding present values of USD 1,840.59 for year 10 and USD 1,131.41 for year 20, summing up to USD 2,972.00. Combined with the initial investment cost of USD 2,436.09, the total NPC of the off-grid system is USD 8,227.29, representing the lifetime cost in today's monetary value.

$$NPC = C_{initial} + \sum_{t=1}^{N} \frac{C_{O\&M}}{(1+r)^t} + \sum \frac{C_{replacement}}{(1+r)^t} = 1{,}364.50 + 1{,}595.11 + 1{,}000.00 = \text{USD } 3{,}959.61 \quad (15)$$

For an on-grid system, the $C_{initial}$ (USD 1,364.50) represents the upfront expense required for purchasing and installing the PV system. Since this cost is incurred at the beginning of the project, it is not subject to discounting. the total $C_{O\&M}$ (USD 1,595.11) accounts for all annual system operation and maintenance expenses over 25 years. These costs are discounted at a 5% rate using the formula $\sum_{t=1}^{25} \frac{150}{(1.05)^t}$, with key values such as USD 142.86 in year 1, USD 118.59 in year 5, USD 92.08 in year 10, and USD 44.79 in year 25, leading to a total discounted value of USD 1,595.11.

Finally, the Total Replacement Cost (USD 1,000.00) accounts for the inverter replacement in year 15, which is discounted using $\frac{1000}{(1.05)^{15}}$, resulting in a present value of USD 481.02. Adding up all these components, the total NPC for the on-grid system is USD 3,959.61. This calculation highlights the cost-effectiveness of the on-grid system compared to the off-grid alternative, as it avoids the high expenses associated with battery replacements.

On the other hand, LCOE is calculated to determine the cost of electricity generated by the PV system throughout its lifetime, shown in (16) and (17) for off-grid and on-grid system, respectively.

$$LCOE = \frac{USD\ 8{,}227.29}{\sum \frac{1{,}587\ kWh}{(1+0.05)^t}} = USD\ 0.37/kWh \quad (16)$$

The NPC for the off-grid system is USD 8,227.29, representing the total lifetime cost, which includes the initial investment, operational and maintenance expenses, and battery replacement costs. The system generates an E_t of 1,587 kWh per year. A 5% discount rate (r) is applied to adjust future energy production to its present value, considering economic fluctuations over the system's 25-year lifetime (N). Based on these values, the LCOE for the off-grid system is calculated as USD 0.37/kWh. This higher cost is primarily due to the need for battery replacements every 10 years and the lower efficiency associated with energy storage.

While the off-grid system provides energy independence, its significantly higher electricity generation cost makes it a more expensive alternative than the on-grid system.

$$LCOE = \frac{USD\ 3{,}959.61}{\sum \frac{2{,}574\ kWh}{(1+0.05)^t}} = USD\ 0.11/kWh \quad (17)$$

The NPC for the on-grid system is USD 3,959.61, representing the total lifetime cost. The system generates an E_t of 2,574 kWh per year, which is assumed to be a consistent electricity supply. A 5% discount rate (r) is applied to adjust future energy production to its present value, reflecting economic conditions over the system's 25-year lifetime (N).

Based on these values, the LCOE for the on-grid system is calculated as USD 0.11/kWh. This relatively low cost results from the absence of battery replacement expenses and lower operational costs, making the on-grid system a cost-effective option where grid connectivity is available.

The ROI calculation for the off-grid system involves determining the total electricity cost savings and comparing it to the initial investment cost. The total electricity cost savings are calculated using (18), and the ROI Calculated is shown in (19).

$$Total\ Savings = 1{,}587\ \times 0.15\ \times 25 = USD\ 5{,}949.38 \quad (18)$$

where $E_t$represents the amount of electricity generated by the PV system each year, which is 1,587 kWh/year. $P_{electricity}$ refers to the cost of grid electricity, assumed to be USD 0.15/kWh. N (System Lifetime) is the total number of years the system is expected to operate, set at 25 years. Plugging these values into the equation results in total savings of USD 5,949.38 over the system's lifetime. Next, the ROI formula is applied to determine the return percentage, as shown in (21).

$$ROI = \left(\frac{\text{USD 5,949.38}}{\text{USD 2,436.09}}\right) \times 100\% = 244.30\% \quad (19)$$

This result indicates that the on-grid PV system returns 244.30% over 25 years, meaning the cost savings from electricity generation far exceed the initial investment. The high ROI highlights the economic advantage of adopting an on-grid system in locations with stable grid access, as it offers significant long-term financial benefits with minimal ongoing costs.

For an on-grid system, the total electricity cost savings is calculated using (18), and the ROI Calculated is shown in (19).

$$Total\ Savings = 2{,}574\ \times 0.15\ \times 25 = USD\ 9{,}652.50 \quad (20)$$

where $E_t$represents the amount of electricity the PV system generates each year, which is 2,574 kWh/year. $P_{electricity}$ refers to the cost of grid electricity, assumed to be USD 0.15/kWh. N is the total number of years the system is expected to operate, set at 25 years. Plugging these values into the equation results in total savings of USD 9,652.50 over the system's lifetime. Next, the ROI formula is applied to determine the return percentage, as shown in (19).

$$ROI = \left(\frac{\text{USD 9,652.50}}{\text{USD 1,364.50}}\right) \times 100\% = 707.40\% \quad (21)$$

This result indicates that the on-grid PV system provides a return of 707.40% over 25 years, meaning the cost savings from electricity generation far exceed the initial investment. The high ROI highlights the economic advantage of adopting an on-grid system in locations with stable grid access, as it offers significant long-term financial benefits with minimal ongoing costs.

Lastly, the payback period for the on-grid system is calculated to be 3.54 years, demonstrating a rapid ROI. In contrast, due to high battery expenses, the off-grid system requires 10.10 years to recover its initial costs. The payback period on-grid and off-grid is calculated as shown in (22) and (23), respectively.

$$Payback\ Period = \frac{USD\ 2{,}436.09}{\left(1{,}587\frac{kWh}{Year}\times 0.15\right)} = 10.10\ Years \quad (22)$$

$$Payback\ Period = \frac{USD\ 1{,}364.50}{\left(2{,}574\frac{kWh}{Year}\times 0.15\right)} = 3.54\ Years \quad (23)$$

3.4. Comparative analysis

This comparative analysis assesses the suitability of on-grid and off-grid PV systems for a greenhouse. On-grid systems offer superior efficiency due to the existing grid connection and lower initial costs (as shown in Table 1 compared to Table 2). The limited 6×4.5 m greenhouse space favors on-grid systems since off-grid systems require additional battery space, reducing crop availability. Furthermore, on-grid systems are easier to maintain, eliminating the need for battery replacements every 5-10 years, unlike off-grid systems, making them more practical for greenhouse operations.

The Indonesian regulatory environment presents significant practical challenges for on-grid PV system installations. Obtaining the necessary permission from the national electricity company is a restrictive process. Applications are only accepted twice yearly, in January and July, creating lengthy delays. Furthermore, the national electricity company dictates the system's power capacity, often necessitating a reduction in the desired capacity to secure approval. These limitations severely constrain design flexibility and have forced projects to downsize their PV systems to meet regulatory requirements.

While off-grid systems have a higher initial cost, they offer several advantages in the long run. Firstly, they provide energy independence, allowing farmers to generate electricity without relying on the grid and reducing their electricity bills. Secondly, off-grid systems are not subject to the exact permitting requirements as on-grid systems, which can be a significant advantage in some areas. This is because off-grid systems operate independently and do not require a connection to the main grid. Finally, the maintenance cost for off-grid systems tends to decrease over time. For example, battery replacement costs will likely be less expensive in the future than they are today. This makes off-grid systems more attractive for farmers who value energy independence, reduced permitting hurdles, and long-term cost savings.

A lifetime cost analysis comparing on-grid and off-grid PV systems highlights significant financial trade-offs. Off-grid systems have higher long-term costs due to frequent battery replacements every 5–10 years and annual PV panel degradation of 0.5%, leading to increased LCOE. On-grid systems, lacking battery expenses, typically offer lower operational costs; however, regulatory constraints such as removing net metering (Permen ESDM No. 2/2024) diminish their economic attractiveness, potentially making off-grid solutions favorable for areas with limited or unreliable grid access. Table 5 summarizes key financial and technical parameters to clarify these differences.

Table 5. Greenhouse component usage and quantity

Parameter	On-grid system	Off-grid system
Initial Cost (USD)	USD 1,364.50	USD 2,436.09
O&M Cost (USD/year)	USD 150	USD 200
LCOE (USD/kWh)	USD 0.11	USD 0.37
Lifetime (Years)	25	25
Total NPC (USD)	USD 3,959.61	%8,227.29
Annual Energy Production (kWh/Year)	2,574	1,587
Self-Sufficiency Ratio (SSR, off-grid)	N/A	100%
Grid Reliance Ratio (GRR, On-Grid)	60%	N/A
Payback Period (Years)	3.54	10.10

The on-grid system is economically more attractive, with a lower initial cost (USD 1,364.50), reduced annual maintenance (USD 150/year), lower LCOE (USD 0.11/kWh), and significantly lower NPC (USD 3,959.61) compared to the off-grid system (USD 2,436.09 initial cost, USD 200/year maintenance, USD 0.37/kWh LCOE, and USD 8,227.29 NPC). The on-grid system offers higher annual energy production (2,574 kWh/year), a shorter payback period (3.54 years), and more excellent reliability due to grid support, offsetting periods of low solar generation. Conversely, the off-grid system provides complete energy independence (100% SSR). Still, it requires a higher investment, frequent battery replacements, faces potential energy deficits during unfavorable weather, and has a more extended payback period (10.10 years). The long-term economic viability of off-grid systems could improve with anticipated battery cost reductions. Still, the on-grid system remains the most practical and cost-effective option for locations with reliable grid access.

A simple sensitivity analysis shows that a 50% reduction in battery prices lowers the NPC of off-grid systems to USD 6,581.83 and reduces the LCOE to USD 0.296/kWh; however, this remains higher than the on-grid NPC of USD 3,959.61. Conversely, a 50% battery price increase raises the off-grid NPC to USD 9,872.75, making it even less competitive. These results indicate that while off-grid systems may become economically competitive with future battery price reductions, on-grid systems currently remain the most cost-effective solution.

Comparative analysis of on-grid and off-grid systems reveals a significant difference in their impact on the farmer's household electricity consumption. In an on-grid system, the excess electricity generated by the PV system is fed back into the home's electrical supply, supplementing the household's energy needs. However, when solar generation is insufficient, the greenhouse will draw power from the farmer's home electricity supply. Conversely, an off-grid system utilizes battery storage to meet the greenhouse's energy demands, operating independently of the farmer's household electricity. This independence is a significant advantage, as it eliminates additional electricity costs for the farmer. Therefore, an off-grid system offers farmers more significant financial benefits by avoiding any burden on their household electricity bill.

4. CONCLUSION

The research concludes that off-grid PV systems, despite higher initial costs (USD 2,436.09), more significant operational expenses, and more extended payback periods (10.10 years), provide more excellent suitability for smart greenhouse applications in Indonesia due to energy independence, long-term operational cost savings, and freedom from regulatory constraints imposed by PLN. On-grid systems are economically attractive with lower initial investment (USD 1,364.50), reduced maintenance costs, shorter payback period (3.54 years), and lower overall costs (NPC of USD 3,959.61), but practical challenges, including stringent regulatory requirements and capacity limitations, reduce their feasibility. The sensitivity analysis also indicates that off-grid systems could become increasingly competitive with anticipated battery price declines, underscoring their potential for future adoption, particularly in remote or regulation-sensitive agricultural contexts.

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CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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