ProgeEnv
Progress in Energy and Environment

Progress in Energy and Environment

Journal homepage: https://progeenv.com/index.php/journal/index
Link to this article: https://doi.org/10.37934/progee.32.4.2439



Vol. 32 Issue 04 (2026) 24-39

Original Article

GREENERGY: Smart Energy-independent Greenhouse Powered by Hybrid Solar–Wind Energy

OPEN ACCESS

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Abstract

Limited access to reliable electricity constrains agricultural activities requiring energy for irrigation, ventilation, misting, lighting, and other equipment. This study develops GREENERGY, a compact greenhouse integrating a hybrid solar–wind energy system to support agricultural operation in areas with limited electricity infrastructure. The 6 × 8 m greenhouse was designed in SketchUp with a 2.42 kWp photovoltaic system, a 1.00 kW vertical-axis wind turbine, battery storage, and a system converter. HOMER Pro was used to evaluate its technical and economic performance under an electrical demand of 8.00 kWh/day. The system generated 5,655.09 kWh/year of renewable electricity (4,448.20 kWh/year photovoltaic; 1,206.89 kWh/year wind), meeting the 2,920 kWh annual demand with a 100% renewable fraction, no unmet load, and 2,605.44 kWh/year of excess electricity. The initial capital cost was $2,981.21, the net present cost $4,263.68, and the cost of energy $0.113/kWh. GREENERGY offers a viable renewable-powered greenhouse for areas lacking conventional electricity access.

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Article Info

Received 12 May 2026
Received in revised form 1 October 2026
Accepted 31 October 2026
Available online 3 November 2026

Keywords

Renewable Energy
Greenhouse
Photovoltaic System
Vertical-Axis Wind Turbine
HOMER Pro

1. Introduction

Agriculture plays an important role in supporting food production and rural development, particularly in areas where agricultural activities are an important source of livelihood [1]. However, agricultural

development in remote areas can be constrained by limited infrastructure and access to reliable electricity [2]. This condition can limit the adoption of modern agricultural technologies that require electrical energy, such as irrigation pumps, ventilation systems, and other supporting equipment [3]. Therefore, the availability of reliable and sustainable energy is an important factor in supporting agricultural development in areas with limited electricity infrastructure.

Greenhouse technology provides a controlled environment that can support crop cultivation by regulating important conditions such as temperature, humidity, irrigation, and ventilation [4]. However, the operation of these systems requires electricity for irrigation, ventilation, environmental control, and other agricultural equipment [5]. Renewable energy can provide an alternative electricity source while reducing dependence on conventional electricity infrastructure [6]. Among renewable technologies, photovoltaic (PV) systems have received considerable attention in greenhouse applications because electricity generation can be integrated with agricultural production within the same land-use area [7].

Recent studies have explored the application of renewable and hybrid energy systems in greenhouse and agricultural environments [8]. investigated the integration of photovoltaic and wind energy systems for a commercial greenhouse and evaluated their technical, economic, and environmental performance. Another study evaluated grid-connected and off-grid hybrid energy configurations consisting of solar, wind, diesel, and battery storage for a greenhouse facility using HOMER Pro. Hybrid renewable energy systems have also been investigated for agricultural and rural facilities, demonstrating the potential of combining renewable resources and energy storage to improve energy availability and system performance [9].

Although these studies demonstrate the potential of renewable energy for greenhouse and agricultural applications, most focus on energy-system optimisation, specific greenhouse energy demands, or techno-economic assessment. The integration of the energy system with a compact greenhouse design intended specifically for agricultural development in areas with limited electricity access remains an opportunity for further development. In this context, a greenhouse can serve not only as a controlled agricultural environment but also as an application platform for an integrated renewable-energy system. Therefore, GREENERGY is proposed as a compact greenhouse concept that combines solar PV, a vertical-axis wind turbine (VAWT), battery storage, and agricultural electrical loads within an integrated three-dimensional design. A comparison of previous studies and the proposed GREENERGY concept is presented in Table 1.

Based on the state-of-the-art comparison, GREENERGY is positioned as an application-oriented integration of greenhouse design and hybrid renewable energy for areas with limited electricity access. The three-dimensional greenhouse is developed using SketchUp, while HOMER Pro is used to evaluate and optimise the proposed PV–VAWT–battery system based on its technical, energy, and economic performance. The objective of this study is to develop a practical renewable-energy greenhouse concept that can support sustainable agricultural development while reducing dependence on conventional electricity infrastructure.

Table 1: State of the art and research gap.

No.	Study	Energy System	Application	Main Contribution	Remaining Gap
[10]	Hassanien et al.	PV	Greenhouse agriculture	Integration of photovoltaic generation with greenhouse agricultural production	Does not focus on a hybrid PV–wind system for areas with limited electricity access
[11]	Ozcan et al.	PV + Wind + Heat Pump	Commercial greenhouse	Evaluation of technical, economic, and environmental performance	Focuses on a large commercial greenhouse and heating demand
[12]	Nuri et al.	PV + Wind + Battery + Diesel	Greenhouse facility	Optimisation of grid-connected and off-grid energy configurations using HOMER Pro	Emphasises energy-system feasibility rather than an integrated compact greenhouse design

No.	Study	Energy System	Application	Main Contribution	Remaining Gap
[13]	Madani et al.	PV + Wind + Battery	Agriculture & irrigation	HOMER Pro optimisation for reliable power supply	No compact greenhouse-integrated design
-	This Study – GREENERGY	PV + VAWT + Battery	Agriculture in areas with limited electricity access	Integrated 3D greenhouse design, renewable energy system, agricultural loads, and HOMER Pro optimisation	—

2. Methodology

The overall research workflow of this study, from site selection and system design to HOMER Pro simulation and performance evaluation, is presented in Figure 1.

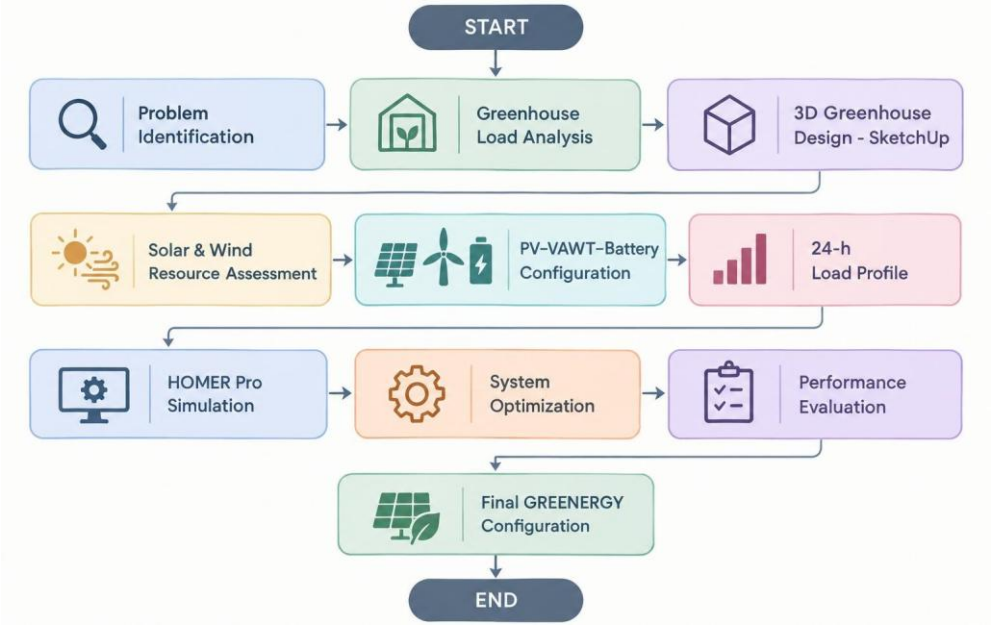


Figure 1. Flowchart.

2.1. Selected Site

The selected site for the GREENERGY system is located in Pesanggrahan, Batu, East Java, Indonesia, at approximately 7.878380°S and 112.512684°E. The location was selected as the study site because it represents an agricultural area where the proposed renewable-energy-powered greenhouse can be evaluated under local environmental conditions. The geographical position of the selected site is presented in Figure 2, which shows the location of the study area on the map and provides a spatial reference for the proposed greenhouse and renewable-energy system. Solar resource data for the selected site were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database and represented by global horizontal irradiation (GHI). The monthly GHI data were used as the solar resource input for the subsequent HOMER Pro simulation, with an annual average of 6.17 kWh/m^2/day, as presented in Table 2.

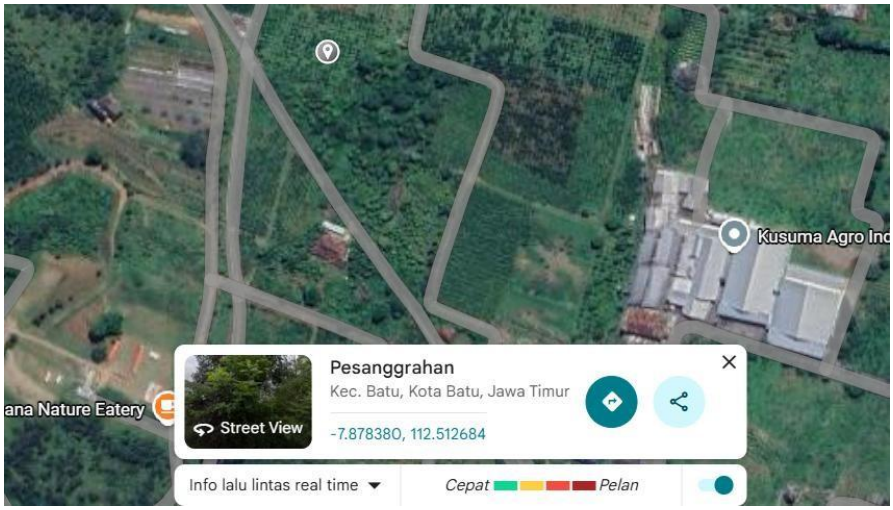


Figure 2. Location of the selected GREENERGY site in Pesanggrahan, Batu, East Java, Indonesia.

Table 2: Monthly Global Horizontal Irradiation (GHI) at the selected site.

Month	GHI (kWh/m²/day)
January	5.53
February	5.64
March	6.14
April	5.98
May	5.89
June	5.61
July	5.92
August	6.60
September	7.26
October	7.28
November	6.52
December	5.68
Annual Average	6.17

2.2. GREENERGY System Design

The GREENERGY system integrates photovoltaic (PV), a vertical-axis wind turbine (VAWT), battery energy storage, power conversion equipment, and greenhouse electrical loads as a unified renewable-energy system. The integration of photovoltaic and wind energy has been investigated for greenhouse applications to meet electrical and thermal energy requirements while evaluating the technical and economic performance of renewable-energy systems [14]. Battery energy storage can improve renewable-energy utilisation by storing surplus generation and supplying electricity when renewable generation is insufficient [15]. Based on this configuration, solar and wind energy are utilised to supply the greenhouse loads, while the battery supports the continuity of electricity supply during periods of insufficient renewable generation. The overall configuration and energy flow of the GREENERGY system are illustrated in Figure 3.

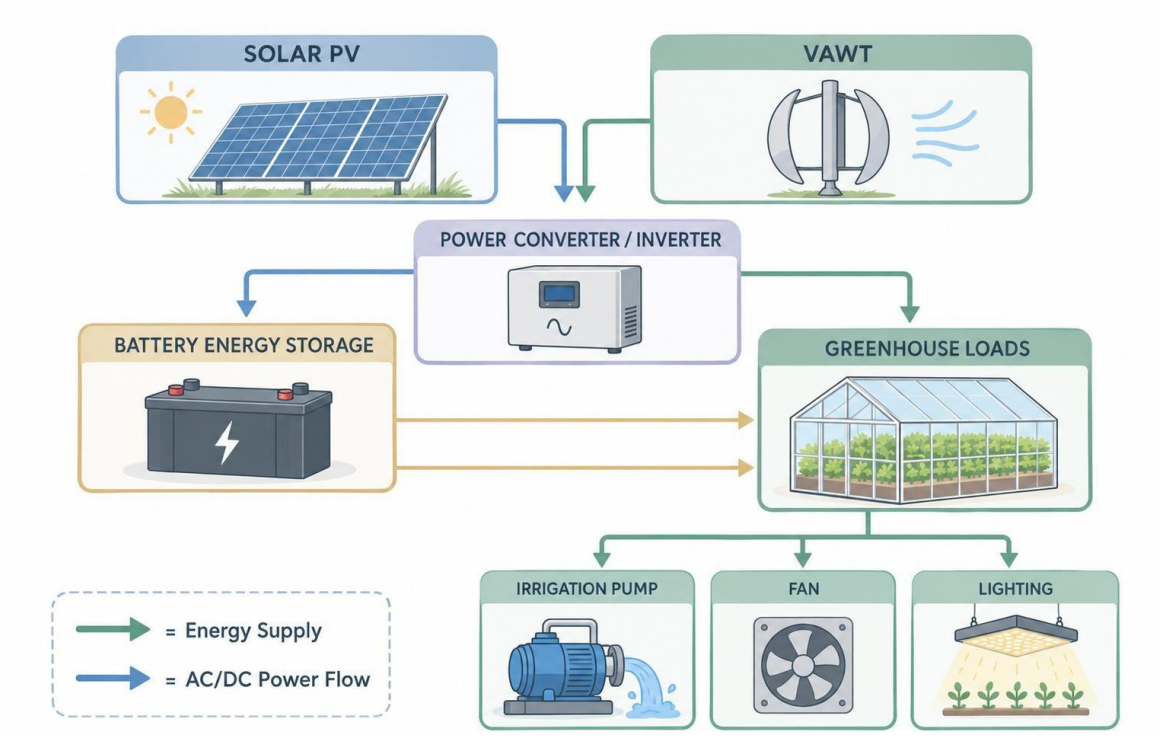


Figure 3. GREENERGY system architecture.

2.3. Three-Dimensional Greenhouse Design

The three-dimensional design of the GREENERGY greenhouse was developed using SketchUp to visualise the integration of the greenhouse structure with the hybrid renewable-energy system. The greenhouse has a rectangular configuration with dimensions of approximately 6 × 8 m and a transparent enclosure to provide natural sunlight for crop growth [16]. Seven 345 Wp PV modules were installed on one side of the roof, resulting in a total PV capacity of approximately 2.42 kWp, while the opposite roof side remains transparent. A 1 kW vertical-axis wind turbine (VAWT) was integrated into the upper part of the greenhouse to utilise wind energy while maintaining a compact and integrated design. The resulting three-dimensional model illustrates the integration of the agricultural space, PV system, VAWT, and transparent greenhouse structure as shown in Figure 4.

2.4. Energy and Load Analysis

The electrical load of the GREENERGY greenhouse was determined based on the main equipment required for agricultural activities, including irrigation, ventilation, misting, water circulation, lighting, and control systems. Each load was defined according to its rated power and expected operating duration to represent the electricity demand of the greenhouse. The loads were distributed over a 24-hour period to reflect the temporal variation in electricity consumption, following the load-based approach commonly used in greenhouse hybrid energy-system analysis with HOMER Pro [17]. The total daily electricity demand was determined from the operating schedule of each load and used as the input for the subsequent HOMER Pro simulation. The detailed load profile is presented in Table 3.

2.5. HOMER Pro Simulation and Optimisation

The GREENERGY system was modelled and simulated using HOMER Pro based on the component capacities and electrical load determined in the previous sections. The system consisted of photovoltaic (PV) modules, a vertical-axis wind turbine (VAWT), lead-acid battery storage, and a bidirectional system converter. Each component was selected based on its capacity, function, and suitability for the proposed

small-scale greenhouse system. The greenhouse electrical demand was represented by an average daily energy consumption of 8.00 kWh/day and a maximum load of 1.07 kW. The 24-hour load profile was used as the primary simulation input, while the technical and economic performance was evaluated based on renewable fraction, excess electricity, unmet electrical load, capacity shortage, net present cost (NPC), cost of energy (COE), and operating cost [18].

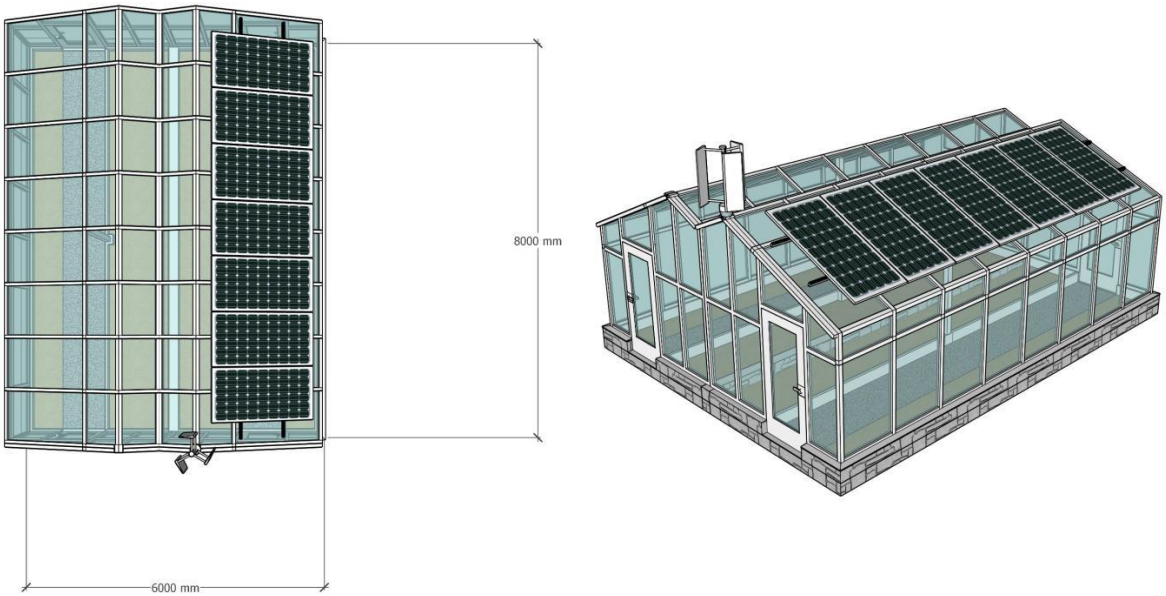


Figure 4. Three-dimensional design of the GREENERGY greenhouse.

Table 3: Electrical load profile of the GREENERGY greenhouse.

Load	Rated Power	Operating Time	Daily Energy
Irrigation pump	550 W	4 h/day	2.20 kWh
Ventilation fans	150 W	10 h/day	1.50 kWh
Misting pump	300 W	3 h/day	0.90 kWh
Water circulation pump	150 W	3 h/day	0.45 kWh
Supplementary LED lighting	150 W	5 h/day	0.75 kWh
Exhaust fan	200 W	4 h/day	0.80 kWh
Controller and sensors	20 W	24 h/day	0.48 kWh
Supporting agricultural equipment	200 W	4 h/day	0.80 kWh
Auxiliary agricultural load	120 W	1 h/day	0.12 kWh
Total	**—**	**—**	**8.00 kWh/day**

The photovoltaic subsystem consisted of seven Trina Tallmax M Plus modules, each rated at 345 Wp, resulting in a total installed capacity of approximately 2.42 kW. PV was selected as the primary renewable-energy source because solar energy can be utilised directly during daytime operation and integrated into the greenhouse roof design. The seven-module configuration was selected to provide sufficient generation capacity for the 8.00 kWh/day electrical demand while maintaining a compact system suitable for the proposed greenhouse. The selected PV module is shown in Figure 5.

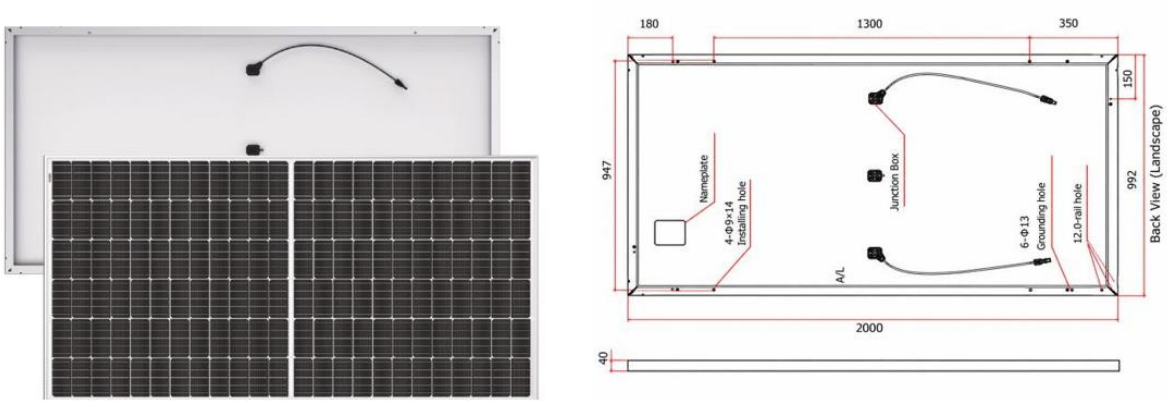


Figure 5. Trina Tallmax M Plus 345 Wp photovoltaic module.

The renewable-energy system was complemented by one Aeolos-V1kW vertical-axis wind turbine with a rated capacity of 1.00 kW, as shown in Figure 6. The VAWT was selected to complement solar generation by utilising wind energy when solar generation is unavailable or reduced. The vertical-axis configuration was selected because of its compact form and suitability for integration into the greenhouse design. The 1.00 kW capacity provides additional renewable generation while remaining appropriate for the scale of the greenhouse electrical demand.



Figure 6. Aeolos-V1kW vertical-axis wind turbine.

Energy storage was represented by two BAE SunDepot 24-350 lead-acid battery units, as shown in Figure 7. The batteries were selected to store excess electricity generated by the PV and wind systems and supply the greenhouse loads when renewable-energy generation is insufficient. The BAE SunDepot 24-350 was selected as the battery model used in the economic and HOMER Pro analysis, with two units representing the proposed battery storage configuration. The battery system provides an energy storage interface between renewable generation and the greenhouse electrical loads.

The power conversion stage consisted of one CyboEnergy Grid-Interactive C1-Mini-1000A bidirectional converter, as shown in Figure 8. The converter was selected to manage the transfer and conversion of electrical energy between the renewable-energy system, battery storage, and greenhouse loads. The CyboEnergy C1-Mini-1000A was used as the converter model in the HOMER Pro simulation and economic analysis. Its rated capacity was selected to accommodate the electrical demand of the proposed greenhouse system and to support the required power exchange between the generation, storage, and load components. The converter therefore serves as an important interface within the GREENERGY system, allowing the generated renewable electricity and stored energy to be supplied to the greenhouse loads

according to the system operating conditions. The integration of the converter with the PV, VAWT, and battery storage enables the proposed configuration to operate as a unified hybrid renewable-energy system.



Figure 7. BAE SunDepot 24-350 lead-acid battery.



Figure 8. CyboEnergy Grid-Interactive C1-Mini-1000A converter.

The main components and their specifications used in the HOMER Pro simulation are summarised in Table 4. The table presents the selected renewable-energy generation units, battery storage, system converter, and greenhouse electrical load, including their respective capacities and quantities. These parameters were used as the primary technical inputs for modelling and evaluating the performance of the proposed GREENERGY system in HOMER Pro.

2.6. Economic Assumptions and Component Costs

The economic analysis of the GREENERGY system was conducted by defining the initial capital cost, replacement cost, and operation and maintenance (O&M) cost for each major system component [19]. The costs used in the analysis represent assumed costs based on the capacity and specifications of the selected components, including the Trina Tallmax M Plus 345 Wp PV modules, Aeolos-V1kW VAWT, two BAE SunDepot 24-350 battery units, and CyboEnergy Grid-Interactive C1-Mini-1000A converter. These values were established based on representative costs for components with comparable capacities and functions to provide realistic economic inputs for the HOMER Pro simulation. O&M costs were assumed at 1% of the initial capital cost for the PV modules, batteries, and converter, while a 2% O&M rate was applied to the wind turbine because of its mechanical components. Replacement costs were determined based on the expected lifetime of each component relative to the 25-year project period, and the resulting economic

parameters were used as inputs for evaluating the economic performance of the GREENERGY system. The economic assumptions and component costs used in the analysis are presented in Table 5.

Table 4: Main components and specifications of the GREENERGY system.

Component	Model/Specification	Quantity	Capacity per Unit	Total Capacity
Photovoltaic module	Trina Tallmax M Plus, 345 Wp	7 units	0.345 kW	2.42 kW
Wind turbine	Aeolos-V1kW	1 unit	1.00 kW	1.00 kW
Battery	Generic Lead Acid	15 units	1.00 kWh	15.00 kWh
System converter	Bidirectional converter	1 unit	1.17 kW	1.17 kW
Greenhouse electrical load	Agricultural loads	—	—	8.00 kWh/day
Peak electrical load	Maximum demand	—	—	1.07 kW

Table 5: Economic assumptions and component costs.

Component	Quantity	Unit Cost	Cost per kW	Total Capital Cost	Replacement Cost	O&M Cost/year
PV module, Trina Tallmax M Plus 345 Wp	7 units	$69.83/panel	$202.41/kW	$488.81	$0.00	$4.89
Aeolos-V1kW wind turbine	1 unit	$446.91	$446.91/kW	$446.91	$0.00	$8.94
BAE SunDepot 24-350 battery	2 units	$837.97	—	$1,675.93	$837.97	$16.76
CyboEnergy Grid-Interactive C1-Mini-1000A	1 unit	$307.25	—	$307.25	$307.25	$3.07
Total	—	—	—	$2,918.91	$1,145.22	$33.66/year

2.7. System Performance Evaluation

The performance of the GREENERGY hybrid renewable-energy system was evaluated using technical and economic indicators obtained from the HOMER Pro simulation. The economic indicators included Net Present Cost (NPC) and Cost of Energy (COE), while the technical indicators included renewable fraction, excess electricity, unmet electrical load, and capacity shortage. These parameters were selected to evaluate the economic performance, renewable-energy utilisation, and reliability of the proposed hybrid system [20]. The evaluation results were subsequently used to assess the overall performance of the proposed PV–VAWT–battery configuration under the defined greenhouse load profile.

2.7.1. Net Present Cost (NPC)

Net Present Cost (NPC) represents the total present value of the costs and revenues associated with the system throughout the project lifetime. The calculation considers capital costs, replacement costs, operation and maintenance costs, fuel costs, electricity purchases, and applicable salvage value [20]. HOMER Pro uses NPC as the primary economic metric for comparing different system configurations. The NPC is expressed as:

$$\mathrm{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \tag{1}$$

where $C_{ann,tot}$ is the total annualised cost of the system (Rp/year), CRF is the capital recovery factor, i is the real annual discount rate, and R_{proj} is the project lifetime (year) [20].

2.7.2. Cost of Energy (COE)

Cost of Energy (COE) represents the average cost of useful electricity supplied by the system to the electrical load. In HOMER Pro, COE is determined from the total annualised cost and the amount of electrical load actually served by the system [20]. Excess electricity is therefore not included as useful electricity in the COE calculation. The COE is expressed as:

$$COE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC}} \tag{2}$$

where $C_{ann,tot}$ is the total annualised cost (Rp/year), $E_{prim,AC}$ is the annual primary AC electricity supplied to the load (kWh/year), and $E_{prim,DC}$ is the annual primary DC electricity supplied to the load (kWh/year) [20].

2.7.3. Renewable Fraction

Renewable Fraction represents the proportion of electricity delivered to the primary load that originates from renewable energy sources. This parameter indicates the contribution of renewable resources to meeting the electrical demand of the proposed hybrid system [21]. For the GREENERGY system, renewable electricity is supplied by the PV array and VAWT. The renewable fraction is calculated as:

$$RF = \frac{E_{\text{renewable,load}}}{E_{\text{total,load}}} \times 100\% \tag{3}$$

where $E_{\text{renewable,load}}$ is the annual electricity supplied to the load from renewable energy sources (kWh/year), and $E_{\text{total,load}}$ is the total annual electricity supplied to the load (kWh/year) [21].

2.7.4. Excess Electricity

Excess Electricity represents electricity produced by the system that cannot be used to serve the electrical load or absorbed by the available energy storage and other system components [21]. This parameter was used to evaluate the utilisation of electricity generated by the PV and wind turbine. The excess electricity fraction is calculated as:

$$EE = \frac{E_{\text{excess}}}{E_{\text{production}}} \times 100\% \tag{4}$$

where E_{excess} is the annual excess electricity (kWh/year), and $E_{\text{production}}$ is the total annual electricity production (kWh/year) [21].

2.7.5. Unmet Electrical Load

Unmet Electrical Load represents the portion of electrical demand that cannot be supplied by the hybrid energy system during the simulation period. This parameter is used to evaluate the ability of the proposed system to satisfy the electrical requirements of the greenhouse [21]. A lower unmet electrical load fraction indicates that a greater proportion of the electrical demand is supplied by the system. The unmet electrical load fraction is calculated as:

$$UEL = \frac{E_{\text{unmet}}}{E_{\text{load}}} \times 100\% \tag{5}$$

where E_{unmet} is the annual unmet electrical load (kWh/year), and E_{load} is the total annual electrical demand (kWh/year) [22].

2.7.6. Capacity Shortage

Capacity Shortage represents the amount of electrical demand that cannot be satisfied because the available generation capacity is insufficient to meet the load and required operating reserve [22]. This parameter provides an indication of the adequacy of the installed generation and storage capacity during periods of high electrical demand. The capacity shortage fraction is calculated as:

$$CS = \frac{E_{\text{shortage}}}{E_{\text{load}}} \times 100\% \quad (6)$$

where E_{shortage} is the annual capacity shortage (kWh/year), and E_{load} is the total annual electrical demand (kWh/year) [22].

3. Results and Discussion

3.1. HOMER Pro Simulation Results

The HOMER Pro simulation was conducted to evaluate the technical performance of the proposed GREENERGY system, consisting of a 2.42 kW Trina Tallmax M Plus photovoltaic (PV) array, a 1.00 kW Aeolos-V1kW vertical-axis wind turbine (VAWT), two BAE SUNDEPOT 24-350 battery units, and a CyboEnergy Grid-Interactive C1-Mini-1000A converter. The simulation resulted in a total renewable electricity production of 5,655.09 kWh/year, consisting of 4,448.20 kWh/year from the PV system and 1,206.89 kWh/year from the VAWT. PV was the dominant renewable source, contributing 78.7% of the total generation, while the VAWT contributed 21.3%. The greenhouse electrical demand was 2,920 kWh/year, equivalent to 8.00 kWh/day, and the complete simulation recorded 2,920 kWh/year of AC primary load served.

Table 6 summarises the main technical performance indicators obtained from HOMER Pro. The system achieved a renewable fraction of 100% and an unmet electrical load of 0 kWh/year, indicating that the modelled greenhouse demand was fully served during the simulation period. The system produced 2,605.44 kWh/year of excess electricity, corresponding to approximately 46.1% of total renewable production, while the reported capacity shortage was only 2.05 kW/year or 0.0701%. The battery recorded 910.74 kWh/year of charging energy and 868.31 kWh/year of discharge energy, demonstrating its role in balancing the temporal difference between renewable generation and greenhouse demand. These results indicate that the selected configuration provides a substantial renewable energy margin while maintaining the required electricity supply for the greenhouse.

Table 6: Technical performance of the GREENERGY system obtained from HOMER Pro.

Parameter	Value	Unit
PV capacity	2.42	kW
PV electricity production	4,448.20	kWh/year
PV contribution	78.7	%
VAWT capacity	1.00	kW
VAWT electricity production	1,206.89	kWh/year
VAWT contribution	21.3	%
Total renewable production	5,655.09	kWh/year
AC primary load	2,920.00	kWh/year
AC primary load served	2,920.00	kWh/year

Parameter	Value	Unit
Excess electricity	2,605.44	kWh/year
Excess electricity fraction	46.1	%
Unmet electrical load	0.00	kWh/year
Capacity shortage	2.05	kW/year
Capacity shortage	0.0701	%
Renewable fraction	100	%
Battery charge energy	910.74	kWh/year
Battery discharge energy	868.31	kWh/year

The monthly renewable production shown in Figure 9 demonstrates seasonal variation in both PV and VAWT generation. The highest total renewable production occurred in August at 586.70 kWh, followed by September at 568.51 kWh and July at 547.36 kWh, whereas the lowest production occurred in December at 376.69 kWh. PV production remained relatively dominant throughout the year, with its highest monthly output of 429.60 kWh occurring in October, while VAWT production reached its highest value of 167.70 kWh in August. This variation supports the design strategy of maintaining sufficient PV capacity rather than relying excessively on battery storage, as a larger renewable generation margin can help maintain energy availability during periods of lower renewable production. The resulting excess electricity is therefore considered an acceptable trade-off in GREENERGY, where maintaining reliable energy availability for essential agricultural loads is prioritised over minimising surplus generation alone.

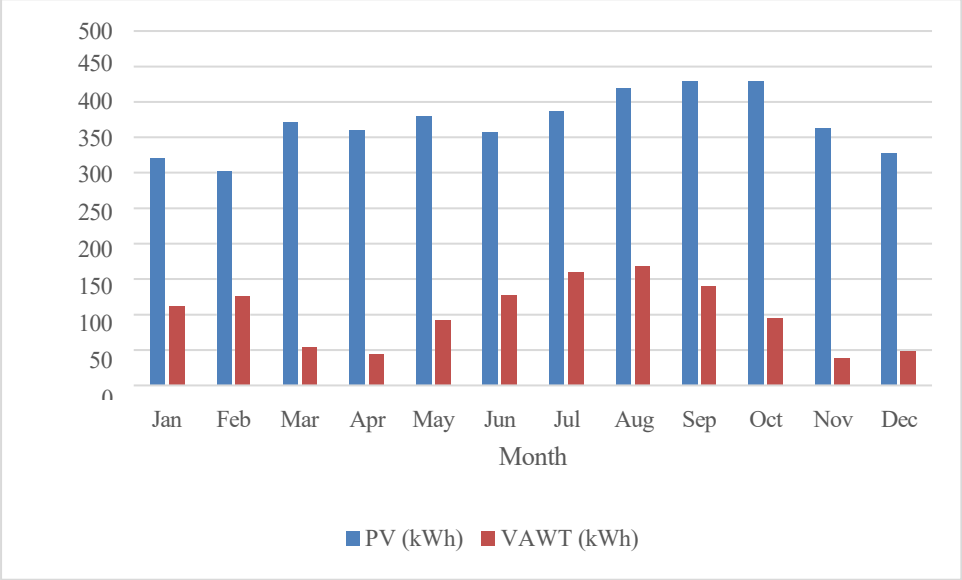


Figure 9. The monthly renewable production.

3.2. Economic Performance

The economic performance of the GREENERGY system was evaluated using the results obtained from HOMER Pro. The selected configuration has an initial capital cost of $2,981.21, with replacement and operation and maintenance (O&M) costs of $978.68 and $533.49, respectively. The annual operating cost is $99.20/year. These costs represent the economic requirements of the integrated PV, VAWT, battery, and converter system over the project lifetime.

The simulation resulted in a net present cost (NPC) of $4,263.68 and a cost of energy (COE) of $0.113/kWh. The NPC represents the total present-value cost of the system over the project lifetime, including the capital, replacement, and O&M costs considered in the simulation. Meanwhile, the COE represents the average cost of electricity generated by the system under the simulated operating conditions. These indicators provide an economic basis for evaluating the proposed hybrid renewable-energy system for greenhouse operation.

The economic results should also be considered together with the technical performance presented in Table 7. The system achieves a renewable fraction of 100% and zero unmet electrical load while supplying the greenhouse's electricity demand. Although the configuration produces excess electricity, increasing battery capacity would require additional investment and replacement costs. Therefore, the selected configuration prioritises PV and VAWT generation as the main energy sources, while the battery is primarily used for energy storage and balancing to support the greenhouse loads.

Table 7: Economic performance of the GREENERGY system obtained from HOMER Pro.

Economic Parameter	Value
Initial capital cost	$2,981.21
Replacement cost	$978.68
O&M cost	$533.49
Operating cost	$99.20/year
Net present cost (NPC)	$4,263.68
Cost of energy (COE)	$0.113/kWh

3.3. Overall GREENERGY System Performance

The overall performance of the GREENERGY system is summarised in Table 8. The table presents the main functional aspects of the proposed system, including renewable energy generation, energy storage, power conversion, and electricity supply to the greenhouse loads. The combination of PV, VAWT, battery storage, and converter enables the system to utilise renewable energy while supporting the electricity requirements of essential greenhouse operations. The results provide an overall representation of the functional performance of the proposed GREENERGY configuration under the defined greenhouse load profile.

The integration shown in Table 6 allows the renewable-energy system to function as part of the greenhouse rather than as a separate power-generation unit. Solar PV serves as the primary energy-generation source, while the VAWT provides additional renewable generation and the battery supports energy storage and balancing. Based on the HOMER Pro results, the configuration achieves a 100% renewable fraction and 0 kWh/year unmet electrical load, indicating that the defined greenhouse demand can be supplied by the simulated renewable-based system.

Overall, GREENERGY combines the physical greenhouse design, hybrid renewable-energy generation, energy storage, and agricultural electrical loads into an integrated system. The relatively high excess electricity reflects the design priority of maintaining adequate energy availability rather than minimising surplus generation. Therefore, the proposed configuration demonstrates how hybrid solar–wind energy can be incorporated into greenhouse infrastructure to support agricultural operation in areas with limited conventional electricity access, while the economic performance is evaluated separately in Section 3.2.

Table 8: Overall functional performance of the GREENERGY system.

System Aspect	GREENERGY Implementation	Functional Role
Renewable energy generation	2.42 kWp solar PV + 1 kW VAWT	Provides renewable electricity for greenhouse operation
Energy storage	2 × BAE SunDepot 24-350 batteries	Stores excess renewable energy and supports energy balancing
Energy conversion	CyboEnergy Grid-Interactive C1-Mini-1000A converter	Manages electrical energy supplied to greenhouse loads
Greenhouse operation	Irrigation, ventilation, misting, water circulation, lighting, and supporting equipment	Supplies electricity for essential agricultural activities
Energy management	Hybrid PV–VAWT with battery storage	Combines solar and wind generation with energy storage
Application context	6 × 8 m greenhouse in an area with limited electricity access	Supports renewable-based greenhouse operation

4. Conclusions

GREENERGY presents an integrated greenhouse concept that combines a three-dimensional greenhouse design with a hybrid solar–wind renewable-energy system consisting of a 2.42 kWp photovoltaic (PV) array, a 1.00 kW vertical-axis wind turbine (VAWT), battery storage, and a system converter. The greenhouse is designed with a 6 × 8 m configuration to support essential agricultural activities, including irrigation, ventilation, misting, water circulation, supplementary lighting, and supporting equipment. The proposed configuration is intended to provide a renewable-based electricity supply for greenhouse applications in areas with limited access to conventional electricity.

The HOMER Pro simulation produced 5,655.09 kWh/year of renewable electricity, consisting of 4,448.20 kWh/year from PV and 1,206.89 kWh/year from the VAWT. The system supplied the defined annual greenhouse demand of 2,920 kWh/year, achieving a 100% renewable fraction and 0 kWh/year unmet electrical load. The system also produced 2,605.44 kWh/year of excess electricity, reflecting the design priority of maintaining sufficient energy availability for essential agricultural loads. Economically, the simulated configuration resulted in an initial capital cost of $2,981.21, an NPC of $4,263.68, and a COE of $0.113/kWh.

Overall, the results demonstrate the technical integration of hybrid solar–wind generation, energy storage, and greenhouse electrical loads within the GREENERGY concept. The combination of the physical greenhouse design and renewable-energy system provides a practical framework for renewable-based greenhouse operation in areas with limited conventional electricity access. Further development can focus on physical prototyping and validation under actual greenhouse operating and environmental conditions.

Declaration of Conflict of Interest

The authors declared no conflict of interest with any other party on the publication of the current work.

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Acknowledgement

The authors would like to express their sincere gratitude to Universitas Negeri Malang, particularly the Department of Power Plant Engineering Technology, Faculty of Vocational Studies, for providing academic support and facilities during the development of this research. The authors also gratefully acknowledge the guidance and valuable support provided by the lecturers and all parties who contributed to the development of the GREENERGY concept, system design, and analysis. Their support and contributions were essential to the completion of this work.

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