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Original Article

# Techno-Economic Optimisation of a Hybrid PV-Wind-Battery Energy System for Adaptive Melon Greenhouse Using Priority-Based Load Management and HOMER Pro

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## Abstract

Greenhouse automation requires reliable power; a load profile mismatched to available renewables inflates generation, storage and capital costs. This study assessed how priority-based load management affects demand, component sizing and initial cost of a hybrid renewable energy system for a 200 m² melon greenhouse in Trenggalek, East Java. HOMER Pro simulations, using Indonesian prices, compared three scenarios: PV-battery and PV-wind-battery at full load, and PV-wind-battery with priority-based load shedding. Loads were classed critical (pumps, sensors), semi-critical (fans) or flexible (night lighting). Load shedding cut daily consumption from 5.00 to 3.24 kWh (35.2%) and peak load from 1.06 to 0.76 kW (28.3%). Scenario three required 2.00 kW PV, three $LiFePO_4$ batteries (3 kWh total), a 1.00 kW wind turbine and 1.00 kW converter, costing about $1,079.85. Relative to scenario one, PV and converter capacities halved and battery units fell 57.1%. Load prioritisation can therefore reduce demand, component size and capital cost.

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## 1. Introduction

### 1.1. Background

The energy demand of the modern agricultural industry has grown as a result of the introduction of automation technologies and sensor-based monitoring systems. Smart agriculture helps to boost productivity by allowing for the real-time control of the environment in which crops are grown, yet in order to introduce these technologies a reliable supply of electricity is necessary [1]. In greenhouse setups, electricity is

employed to power a range of equipment including automatic irrigation pumps, environmental sensors, ventilation systems and supplementary lighting. Depending on conventional energy sources may result in increased operating costs and hinder the establishment of standalone greenhouses, primarily in regions of agriculture where energy is not readily available. Renewable energy has now become one of the most extensively developed solutions for achieving sustainable agricultural systems [2]. Within the Hybrid Renewable Energy System (HRES) approach, photovoltaic (PV) systems, wind turbines and battery storage have all been widely used in order to offer a more environmentally friendly source of energy and to improve energy independence. Many studies make use of the Hybrid Optimization Model for Electric Renewable (HOMER Pro) software to find out the most suitable configurations by taking into account technical and economic factors such as Net Present Cost (NPC), Cost of Energy (COE) and the renewable fraction. Research into the optimisation of HRES shows that HOMER Pro can help in determining the most economical size for the various renewable energy components [3].

However, most research related to HRES still focuses on supply-side optimisation, namely determining the combination of photovoltaic, wind turbine, battery, and converter capacities to meet specific load requirements [4]. Recent studies on HRES optimisation using HOMER Pro indicate that the development of future energy systems requires a more complex approach, including improved component control strategies, system operation management, and more adaptive integration of energy usage factors [5]. In greenhouse applications, optimisation approaches based solely on generation capacity do not fully resolve energy efficiency issues. Not all electrical loads have the same level of importance for the success of crop cultivation. Irrigation pumps and environmental sensors are considered critical loads that must remain operational, whereas circulation fans and supplementary lighting can be classified as flexible loads that can be adjusted depending on available energy conditions [6]. Therefore, an energy management approach that takes into account operational priorities for crops is needed, so that the energy system capacity can be reduced without diminishing the primary functions of the greenhouse.

Based on these issues, this study proposes an adaptive renewable energy management system for melon greenhouses by integrating photovoltaic panels, small-scale wind turbines, $LiFePO_4$ batteries, and a priority-based load management strategy [7]. The research was conducted in a 200 $m^2$ melon greenhouse located in Mlinjon Village, Trenggalek Regency, East Java. The system was analysed using HOMER Pro through three configuration scenarios to evaluate the impact of hybrid energy integration and load reduction strategies on the system's technical and economic performance. This study aims to produce a more efficient and economical energy system design that can be applied as a supporting solution for smart agriculture in rural areas [8]. The related studies and research gap can be illustrated in Table 1.

**Table 1.** Summary of related studies and research gap.

| Method/Approach | Application/Context | Main Findings | Comparative Insight | Reference |
|---|---|---|---|---|
| Hybrid renewable energy system optimisation using HOMER Pro based on techno-economic analysis | Stand-alone renewable energy systems for remote areas | The optimal capacities of PV, wind turbine, battery, and converter can be determined based on economic parameters such as Net Present Cost (NPC) and Cost of Energy (COE). | Generally, a fixed load profile is used with a focus on generator capacity optimisation. Changes in energy consumption patterns and load priorities have not been widely considered. | [9] |
| HOMER Pro-based hybrid microgrid optimisation | Microgrid system with a combination of PV, wind turbine, battery, and converter | HOMER Pro is capable of determining the optimal system configuration based on the availability of renewable energy sources and user energy requirements. | Excess energy management is still carried out through dump/diversion loads, rather than adjusting consumption based on device priority levels. This study introduces priority-based load management to regulate energy consumption in greenhouses. | [10] |

| | | | | |
|---|---|---|---|---|
| Techno-economic optimisation of hybrid renewable energy system | Community buildings and public facilities with stand-alone renewable energy systems | System optimisation can reduce energy costs by selecting the optimal component capacities based on technical and economic NPC and COE. | Electrical loads are still considered as non-flexible needs (non-flexible loads). This approach does not take into account that some devices can be reduced or delayed in their use based on operational priority. | [11] |
| HOMER Pro-based techno-economic feasibility analysis | Stand-alone energy system using PV, fuel cell, battery, and inverter | Hybrid renewable energy systems can improve energy reliability and reduce dependence on conventional energy sources. | Current research primarily addresses the design of energy sources and storage systems. In contrast, the specific energy requirements of agricultural applications, including irrigation pumps, sensors, and ventilation systems, remain underexplored. | [12] |
| Literature review of hybrid renewable energy system optimisation trends | Various HRES applications in the building, community, industrial, and remote area sectors | Recent studies indicate a growing adoption of HOMER Pro for optimising renewable energy systems and conducting technical-economic evaluations. | Previous studies have identified the need for advancements in system control, reliability, battery modelling, and adaptive operation strategies. The present research addresses these gaps by integrating system optimisation with priority-based load management, and evaluates the effectiveness of this approach. | [13] |
| Review approach on HRES optimisation, reliability, and operational strategies | A review of the development of hybrid renewable energy system technology | Indicates that optimising component capacity alone is not sufficient to improve the overall energy system efficiency. | The majority of studies have not combined generation-side optimisation with demand-side management, especially in the case of small-scale greenhouses which have varying energy requirements. | [14] |

To address these limitations, this study proposes a priority-based load management approach that integrates generation-side energy optimisation with consumption management based on the priority levels of greenhouse devices [15]. This approach enables the energy system not only to determine the optimal capacities of photovoltaic panels, wind turbines, $LiFePO_4$ batteries, and converters, but also to consider operational decisions when energy availability is limited. Thus, the energy requirements of critical devices can still be met without excessively increasing system size [16]. The objective of this research is to develop an adaptive renewable energy management system for a 200 $m^2$ melon greenhouse in Mlinjon Village, Trenggalek Regency, East Java. The developed system consists of a combination of photovoltaic panels, small-scale wind turbines, $LiFePO_4$ batteries, and a priority-based load management strategy . Optimisation is carried out using HOMER Pro through several simulation scenarios to evaluate the impact of renewable energy source integration and flexible load reduction strategies on the system's technical, economic, and reliability performance [17]. The main contribution of this study is to shift HRES optimisation approaches from merely selecting generation configurations (generation-side optimisation) towards comprehensive energy system optimisation through the integration of generation design and load management strategies (demand-side management). This approach is expected to produce a greenhouse energy system that is more efficient, economical, and adaptive to changes in renewable energy availability [18].

# 2. Methodology

## 2.1. Research Flow Chart

This study employs a techno-economic optimisation approach to design an adaptive Hybrid Renewable Energy System (HRES) for a small-scale melon greenhouse, as shown in Figure 1. The developed system integrates renewable energy sources, namely photovoltaic (PV) panels and small-scale wind turbines, with an energy storage system using lithium iron phosphate ($LiFePO_4$) batteries. This research is conducted to address the limitations of conventional HRES optimisation approaches, which typically focus solely on determining the optimal capacity of generation components based on technical and economic aspects. In this study, energy system optimisation is combined with a priority-based load management strategy to regulate energy consumption according to the priority levels of greenhouse devices. System simulation and optimisation are performed using the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software. HOMER Pro is utilised to determine the optimal system configuration based on economic and technical parameters, including Net Present Cost (NPC), Cost of Energy (COE), Renewable Fraction, and system reliability.

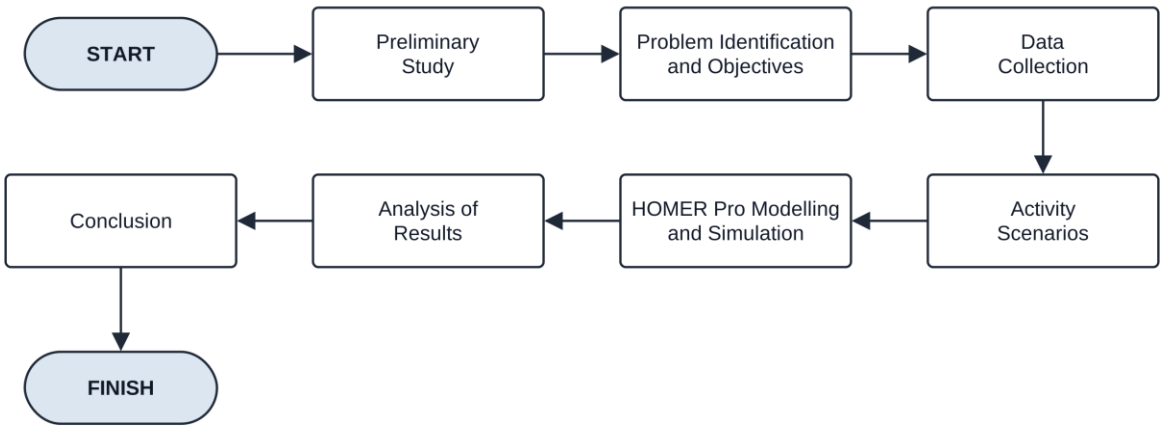



**Figure 1.** Methodology flowchart.

## 2.2. Study Location and Scope

This study was conducted at a melon greenhouse facility geographically located in Mlinjo Village, Suruh District, Trenggalek Regency, East Java Province, Indonesia. Specifically, the research site is situated at approximately 8°7'0.18" S and 111°39'54.99" E (see Figure 2). The greenhouse, which is the main object of this research, has a total building area of 200 m². This facility is specifically designed to support melon cultivation activities that apply modern agricultural system principles. In daily operations, this greenhouse system requires a stable and continuous electricity supply. This power supply is essential for operating various supporting automation devices, such as irrigation pumps, temperature and humidity sensors, air circulation fans, and supplementary lighting systems. The dynamic variation in energy demand within this facility requires reliable power management. These operational characteristics make this location highly representative and ideal as a case study site. Therefore, this area is highly suitable for the implementation of an adaptive renewable energy system based on priority load management.

## 2.3. Hybrid Renewable Energy System Configuration

The energy system developed in this study utilises a Hybrid Renewable Energy System (HRES) configuration, consisting of a combination of renewable energy sources, an energy storage system, and energy conversion devices to meet the electricity demands of the melon greenhouse. The system

configuration is designed to provide a stable energy supply by leveraging local energy potential and to improve energy use efficiency through a priority-based load management strategy. The HRES modelled in this research consists of four main components: a photovoltaic (PV) system, a small-scale wind turbine, a $LiFePO_4$ battery energy storage system, and a converter. The combination of multiple energy sources was chosen to address the intermittent nature of renewable energy, allowing energy production from one source to be compensated by the other sources. Such configuration is shown in Figure 3.




**Figure 2.** The location at Desa Mlinjo, Kecamatan Suruh, Kabupaten Trenggalek.

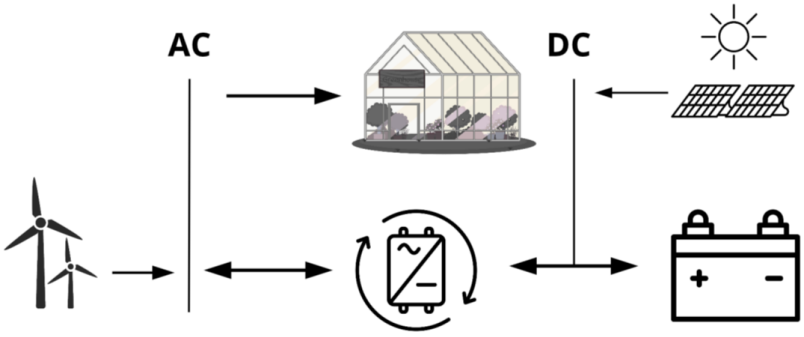



**Figure 3.** Configuration of hybrid renewable energy system for greenhouse application.

### 2.3.1. HRES Component Specification

The main parameters of each component used in the HOMER Pro modelling are shown in Table 2.

**Table 2.** Components and parameters of hybrid renewable energy system.

| Component | Function | Main Parameters Considered in HOMER Pro |
|---|---|---|
| Photovoltaic (PV) | Converts solar energy into DC electricity | PV capacity (kW), investment cost, operation and maintenance cost, lifetime, derating factor |
| Small-scale Wind Turbine | Generates electricity from wind kinetic energy | Turbine capacity (kW), power curve, investment cost, operation and maintenance cost, lifetime |
| $LiFePO_4$ Battery | Stores excess energy and supplies energy during low production | Battery capacity (kWh), charge/discharge efficiency, minimum SOC, lifetime, replacement cost |
| Converter | Converts DC power to AC for greenhouse load requirements | Converter capacity (kW), efficiency, investment cost, lifetime |

### 2.3.2. Photovoltaic System Model

In this study, the photovoltaic system is used as the main energy source because the greenhouse location has solar radiation potential that can be utilised to generate electricity. PV energy production is influenced by installed capacity, solar radiation intensity, peak sun hour (PSH), and system loss factor. The daily PV energy calculation can be expressed as:

$$E_{PV} = P_{PV} \times PSH \times SF \tag{1}$$

where $E_{PV}$, $P_{PV}$, *PSH, and SF* represent the electric energy produced by PV per day (Wh/day), the total installed PV capacity (Wp), the peak sun hours at the location (hour/day), and the system factor, respectively.

The *SF* value is used to account for losses due to inverter efficiency, cable losses, battery efficiency, panel temperature, dust, and shading. In PV systems, the SF value generally ranges from 0.75 to 0.85. For the HOMER Pro approach, PV output power can be calculated using the following equation:

$$P_{PV} = Y_{PV} f_{PV} \frac{G_T}{G_{T,STC}} \tag{2}$$

where $P_{PV}$, $Y_{PV}$, $f_{PV}$, $G_T$, and $G_{T,STC}$ represent the PV output power (kW), the nominal PV capacity (kW), the PV derating factor (%), the actual solar radiation (kW/m$^2$), and the solar radiation under standard test conditions (kW/m$^2$), respectively.

Daily electric energy produced by PV is calculated as:

$$E_{PV} = P_{PV} \times t \tag{3}$$

where $E_{PV}$ and $t$ represent the PV electric energy (kWh/day) and the effective operating time (hour/day), respectively.

### 2.3.3. Small-Scale Wind Turbine Model

For wind turbines, the previous equation is correct, but it can be simplified according to the HOMER Pro simulation. The energy produced by the wind turbine is calculated as:

$$E_{wind} = P_{wind} \times t \tag{4}$$

Meanwhile, the theoretical wind turbine power can be expressed as:

$$P_{wind} = \frac{1}{2} \rho A v^3 C_p \tag{5}$$

where *Pwind*, $\rho$, $A$, $v$, and $Cp$ represent the wind mechanical power (W), the air density (kg/m$^3$), the rotor swept area (m$^2$), the wind speed (m/s), and the turbine performance coefficient, respectively. However, in HOMER Pro, wind energy production is better calculated using the turbine power curve, as the software already computes the relationship between wind speed and output power.

### 2.3.4. Battery Energy Storage System Model

The battery section should use the State of Charge (SOC) concept as in PV system materials. The energy that can be stored by the battery:

$$C_{bat} = \frac{E_{load} \times N_{autonomy}}{V_{system} \times DoD \times \eta_{bat}} \tag{6}$$

where $C_{bat}$, $E_{load}$, $N_{autonomy}$, $V_{system}$, $DoD$, and $\eta_{bat}$ represent the battery capacity (Ah), the daily energy demand (Wh/day), the duration of energy reserve (day), the system voltage (V), the depth of discharge, and the battery efficiency, respectively. For $LiFePO_4$ batteries, the DoD can be set at around 80–90%, while the minimum SOC is maintained at around 10–20%.

The battery condition changes can be written as:

$$SOC_t = SOC_{t-1} + \frac{E_{ch}\eta_{ch} \times E_{ch} / \eta_{ch}}{C_{bat}} \quad (7)$$

### 2.3.5. Converter Model

The converter formula is still used:

$$\eta_c = \frac{P_{AC}}{P_{DC}} \times 100\% \quad (8)$$

where $\eta_c$, $P_{AC}$, and $P_{DC}$ represent the converter efficiency (%), the AC output power (kW), and the DC input power (kW), respectively.

### 2.3.6. Energy Balance Model

Since the HRES performance is simulated in HOMER Pro on a time-step basis, the energy generated by the system must be balanced against the load demand and the energy stored in or supplied by the battery. At each time interval, this energy balance can be expressed as:

$$E_{PV} + E_{wind} + E_{bat} = E_{load} + E_{loss} \quad (9)$$

where $E_{PV}$, $E_{wind}$, $E_{bat}$, $E_{load}$, and $E_{loss}$ represent the energy generated by the photovoltaic system, the energy generated by the wind turbine, the energy supplied by the battery, the energy demand of the greenhouse, and the energy losses in the system, respectively.

## 3. Results and Discussion

### 3.1. Characteristics of Greenhouse Energy Demand and the Impact of Adaptive Load Management

Before optimisation, the system was modelled with the assumption of a constant full load (Scenario 1), meaning all greenhouse devices operate without limitations during operational hours, resulting in an energy demand of 5.00 kWh/day with a peak load of 1.06 kW. After implementing the priority-based load management strategy in Scenario 3, the daytime circulation fan and nighttime LED lighting were turned off outside of critical conditions; thus, the load was maintained at 0.760 kW during the operational hours of critical loads (micro-sprinkler irrigation pump and environmental sensors) and dropped to the base load of 0.010 kW/day outside of those hours. Consequently, daily energy demand was reduced to 3.24 kWh/day and peak load decreased to 0.76 kW. Quantitatively, the application of load shedding reduced daily energy demand by 35.2% (from 5.00 to 3.24 kWh/day) and reduced peak load by 28.3% (from 1.06 to 0.76 kW). This reduction did not originate from changes in device efficiency, but was a direct consequence of classifying loads into three priority levels: critical, semi-critical, and flexible, which allows non-essential devices to be turned off without disrupting the melon cultivation process that relies on the irrigation pump and environmental sensors.

### 3.2. Comparison of HOMER Pro Simulation Scenarios

Three scenarios were evaluated using HOMER Pro to assess the impact of load management strategies on system sizing. Scenario 1 shows a basic PV-battery system without energy management. Scenario 2 adds a wind turbine to form a conventional PV-wind-battery hybrid, using the same full load assumption as in Scenario 1, serving as a comparison to isolate the effect of energy source diversification without load management. Scenario 3 combines wind turbines with a priority-based load management strategy, representing the approach proposed in this study. The summary of the comparison can be shown in Table 3.

**Table 3.** Comparison of HOMER Pro sizing results in three simulation scenarios.

| Parameter | Scenario 1 (Basic PV-Battery) | Scenario 2 (Conventional Hybrid) | Scenario 3 (Adaptive + Load Shedding) | Unit |
|---|---|---|---|---|
| Daily load | 5.00 | 5.00 | 3.24 | kWh/day |
| Peak load | 1.06 | 1.06 | 0.76 | kW |
| Load management | None | None | Priority-based load shedding | - |
| Wind turbine | None | Present (not yet optimal) | 1 unit (Aeolos-V1kW) | unit |
| PV capacity | 4.00 | Same as Scenario 1 | 2.00 | kW |

Scenario 2 confirms that adding only wind turbines, without accompanying consumption-side management, does not significantly change the required component size compared to Scenario 1, as the reference load profile used by HOMER Pro still assumes all devices are operating at full capacity. In other words, diversification of generation-side sources without demand-side management is not sufficient to significantly reduce system size, in line with the research gap identified in Table 1. Major changes in component sizing are only observed in Scenario 3, when load shedding strategies are included in the modelling.

### 3.3. Optimal Configuration and the Impact of Load Shedding on System Sizing

Scenario 3 simulation establishes the final system architecture as consisting of 2.00 kW solar panels, 3 kWh $LiFePO_4$ batteries (3 units), 1 unit of small-scale Aeolos-V1kW wind turbine, and a 1.00 kW converter/inverter. Compared to Scenario 1, the implementation of priority-based load management successfully reduced PV capacity by 50% (from 4.00 to 2.00 kW), the number of battery units by 57.1% (from 7 to 3 units), and inverter capacity by 50% (from 2.00 to 1.00 kW). This reduction pattern is consistent with the principles of demand-side management, where reducing peak load and daily load through the shutdown of non-critical devices (daytime circulation fans and nighttime lighting) proportionally decreases the required generation and storage capacity, without compromising the operation of critical devices (micro-sprinkler irrigation pump and environmental sensors) that are essential for successful melon cultivation. These results confirm that load management strategies can be as significant a tool for minimising system size as generation-side optimisation itself.

### 3.4. Economic Analysis of the System

The reduction in component size in Scenario 3 has a direct impact on the system's economic aspect. All components were calibrated using current market prices in Indonesia ($LiFePO_4$ batteries at $121,63/kWh with a lifespan of 15 years, and a Huawei 2 kW inverter at $548,74with 95% efficiency) to ensure that simulation results are economically realistic. With the smaller configuration, the initial capital expenditure (CAPEX) in year 0 decreases to approximately $1,079.85 which is significantly lower than the projected CAPEX for Scenarios 1 and 2 that assume much larger components (4 kW PV and battery units). This reduction in CAPEX directly leads to a decrease in the system's Net Present Cost (NPC) and Cost of Energy (COE), as both parameters are closely related to the magnitude of component investment and battery replacement costs over the project lifetime. With much lower CAPEX, Scenario 3 becomes the most competitive and feasible configuration to implement compared to conventional approaches that assume a fixed load.

### 3.5. Implementation of Strategy for Priority-Based Load Management

The effectiveness of Scenario 3 is largely due to the classification of greenhouse loads into three priority levels. Critical loads, namely the micro-sprinkler irrigation pump and environmental sensors, are kept operational throughout working hours because they directly determine the success of melon cultivation.

Semi-critical loads, such as air circulation fans and exhaust systems, can have their operation reduced under limited energy conditions without significant short-term risk to the plants. Flexible loads, such as the nighttime LED lighting system, can be completely turned off since they are not directly related to the plant's physiological processes at night. This prioritisation structure enables the energy system to be designed based on actual functional needs, rather than the assumption that all devices must operate simultaneously at all times. This approach shifts the HRES optimisation paradigm from merely generation-side optimisation towards integration with demand-side management, as proposed as the main contribution in the introduction.

### 3.6. Research Limitations

This study has several limitations that need to be highlighted. First, the sizing results in all three scenarios are outputs of HOMER Pro simulations based on representative load profiles, not the result of actual load measurements in the field; therefore, further validation with real operational data from the greenhouse is still required. Second, the component prices (PV, $LiFePO_4$ batteries, and Huawei inverter) refer to market prices in Indonesia at the time of calibration, which may change over time and depending on the procurement location. Third, the specifications of the Aeolos-V1kW wind turbine used are generic with respect to wind potential data at the site; actual wind speed measurements in Mlinjo village would improve the accuracy of the wind turbine energy production estimates. Fourth, the priority-based load management strategy tested only covers three load categories and two operating conditions (critical hours and non-critical hours), so further development with a more granular control profile remains open. Therefore, the results of this research are best positioned as a proof-of-concept system design, not as a final procurement specification.

### 3.7. Physical Design and Spatial Configuration of the System (3D Greenhouse Layout)

A three-dimensional (3D) model was created in order to achieve a realistic physical realisation of the optimisation results from HOMER Pro (as shown in Figure 4). The design makes use of a spatial fusion method which reconciles the agronomic requirements for growing melons with the efficiency of the hybrid renewable energy system. The greenhouse's roof is tunnel-type and is covered with transparent material. This curved shape was chosen because it maximises sunlight transmission from different solar angles along an east-west path, which is important for physiological processes and for developing sugar content (Brix) in melon plants. In contrast to conventional setups, the roof structure of the greenhouse remains unobstructed (using a roof-free approach) with no solar panels attached to it. Rather, a 2.00 kW photovoltaic (PV) array is installed on the ground right beside the main greenhouse building. This ground-mounted setup has two benefits: firstly, since the greenhouse roof is not shaded, 100% of the sunlight can get through; and secondly, the solar panels enjoy considerably better air circulation (passive cooling) than they would if they were mounted on the roof, which helps to avoid voltage drops resulting from thermal runaway and keeps the system factor at an optimal level. In order to supplement the energy supply, a small-scale wind turbine (Aeolos-V1kW) is mounted on a single tower in the same area, next to the solar panel array. The fact that the components are arranged in this central physical configuration (thus forming an "Energy Island") is intended to reduce the power losses that occur in the DC cable transmission from both the solar panels and the wind turbine to the cyber-physical panel box (which includes a 1.00 kW inverter and a 3 kWh $LiFePO_4$ battery storage system). This kind of design is architected as a compact, autonomous and cost-effective way of integrating a hybrid renewable energy system, in keeping with the adaptive load management philosophy set out in this study.

## 4. Conclusion

This study successfully developed an adaptive renewable energy management system for a 200 m² melon greenhouse in Mlinjo Village, Trenggalek Regency, by integrating photovoltaic (PV), small-scale wind turbines, $LiFePO_4$ batteries, and a priority-based load management strategy, simulated using HOMER Pro. The simulation results show that the application of priority-based load management in Scenario 3 was able

to reduce daily energy demand by 35.2% (from 5.00 to 3.24 kWh/day) and decrease peak load by 28.3% (from 1.06 to 0.76 kW), without disrupting the operation of critical devices such as the micro-sprinkler irrigation pump and environmental sensors. This reduction was achieved through the classification of loads into three priority levels (critical, semi-critical, and flexible) rather than through increased device efficiency. The comparison between scenarios confirms that diversification of generation sources alone (the addition of a wind turbine in Scenario 2) without consumption-side management does not significantly reduce system size. In contrast, the optimal configuration in Scenario 3 (2.00 kW PV, 3 kWh/3 units of $LiFePO_4$ batteries, 1 unit of Aeolos-V1kW wind turbine, and 1.00 kW converter) successfully reduced PV capacity by 50%, the number of battery units by 57.1%, and inverter capacity by 50% compared to Scenario 1.

Economically, this reduction in component size lowers the initial investment cost (CAPEX) to around $1,079.85 which is much lower than the scenario without load management, making Scenario 3 the most competitive and feasible configuration for implementation. Overall, this study demonstrates that demand-side management strategies play an equally important role as generation-side optimisation in designing efficient and economical hybrid renewable energy systems for smart agriculture applications. Nevertheless, these results should still be considered as proof-of-concept, as they are based on representative load profiles (not actual measurement data), so further validation with real greenhouse operational data, local wind speed data, and the development of more granular load control schemes is still needed before it can be adopted as a final procurement specification.

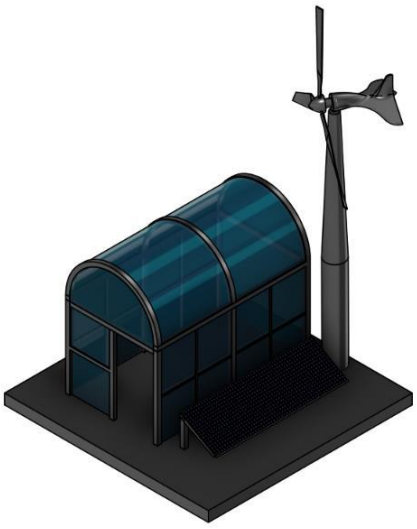


**Figure 4.** A conceptual design of a 3D hybrid renewable energy system (HRES) model for a melon greenhouse.

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## 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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