

Design and Evaluation of a Renewable Energy–Integrated *Wasabia japonica* Plant Factory for Sustainable Regional Revitalization

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Abstract

This study proposes a renewable energy–integrated *Wasabia japonica* (wasabi) plant factory as a sustainable solution for regional revitalization in depopulated rural areas of Japan. The system combines photovoltaic (PV) generation, small-scale wind turbines, and battery storage to achieve partial energy self-sufficiency and CO₂ reduction. Hourly power balance simulations were performed for sixty combinations of PV (5–25 kW), wind (3–12 kW), and battery (25–75 kWh) capacities using meteorological data and the NEDO computational method. Results show that the optimal configuration—10 kW PV, 3 kW wind, and a 25 kWh battery—achieves a 42.5% reduction in grid electricity consumption, corresponding to a 40% energy self-sufficiency rate and an annual CO₂ reduction of about 20 tons for a five-unit installation. The findings confirm that the proposed model offers an effective balance between cost and performance, presenting a practical pathway toward low-carbon, high-profit agricultural infrastructure suitable for Japan’s rural communities.

Keywords: Renewable energy integration; Plant factory; Regional revitalization

1. Introduction

In recent years, Japan’s rural communities have faced an accelerating decline in population and aging demographics, threatening the very survival of regional societies.

According to the Ministry of Internal Affairs and Communications, nearly half of Japan’s municipalities are classified as “potentially disappearing cities,” particularly in

mountainous and cold regions where depopulation, aging, and industrial stagnation form a triple structural crisis⁽¹⁾.

In so-called “marginal settlements,” the shortage of working-age populations has caused the abandonment of farmland and forestry, resulting in a cascade of economic contraction and land degradation⁽²⁾.

Conventional measures—such as subsidies or temporary employment programs—have proven insufficient for long-term revitalization; instead, the challenge lies in establishing a self-sustaining regional economic cycle⁽³⁾.

Against this backdrop, high-profit plant factories have gained attention as a promising driver of rural regeneration.

These facilities enable stable, high-value crop production year-round through precise control of light, temperature, humidity, and nutrients, independent of external climatic conditions⁽⁴⁾.

The introduction of AI-based monitoring and IoT technologies has further transformed traditional agriculture into a data-driven industry, mitigating key issues such as labor shortages, climate risks, and unstable yields.

Compact modular designs—such as containerized systems—allow easy deployment with low initial cost, enabling the reuse of idle land, abandoned schools, and vacant stores.

However, the widespread adoption of plant factories has been constrained primarily by high electricity costs, as lighting, air conditioning, and pumps demand substantial power.

To ensure sustainable operation in rural regions, the plant factory must achieve energy autonomy through the integration of renewable energy sources such as photovoltaic (PV) and small wind generation, combined with energy storage⁽⁵⁾.

This study proposes a novel energy-integrated high-

profit plant factory model, in which PV and wind power are used as the main energy sources, with battery storage for load leveling and a water circulation system for resource recycling.

Through this configuration, the system aims to achieve approximately 40% energy self-sufficiency and 20 tons of annual CO₂ reduction, establishing a sustainable and economically viable Energy-Integrated Plant Factory framework for rural revitalization in Japan.

2. Overview of the Wasabi Plant Factory

The wasabi (*Wasabia japonica*) plant factory represents a next-generation agricultural system that combines controlled-environment cultivation with renewable energy integration (Fig.1). Traditionally, wasabi cultivation requires clean, cold running water and stable environmental conditions—factors that limit production to a few suitable regions in Japan. By adopting a fully enclosed and sensor-controlled hydroponic system, the wasabi plant factory enables year-round cultivation under optimized light, temperature, humidity, and nutrient conditions, independent of natural water sources.

Each production module consists of a container-type growing unit equipped with LED lighting, automated nutrient circulation, and air-conditioning systems. Environmental parameters are continuously monitored by IoT sensors and managed through an AI-based control platform, which dynamically adjusts light intensity, CO₂ concentration, and nutrient flow to maximize growth efficiency. The modular design allows for flexible expansion and relocation, making it suitable for rural deployment in limited spaces such as abandoned schools, empty warehouses, or idle farmland.

The factory's energy system is designed for partial self-sufficiency. Power is supplied primarily by a hybrid configuration of photovoltaic panels (10 kW) and small-scale wind turbines (3 kW), supported by a 25 kWh battery storage unit for peak load management. This setup achieves an estimated energy self-sufficiency rate of about 40%, significantly reducing both operational costs and CO₂ emissions—approximately 6 t-CO₂ per module per year, or about 30 t-CO₂ annually for a five-unit installation.

By integrating agricultural production, renewable energy utilization, and community engagement, the wasabi plant factory provides a replicable model for sustainable regional revitalization. It demonstrates how technology-driven agriculture can coexist with environmental



a) Exterior b) Interior

Fig.1 Wasabi Plant Factory

(cited: <https://www.macnica.co.jp/business/agritech/products/144765/>)

stewardship while generating stable income and new learning opportunities in depopulated rural areas.

3. Evaluation of Renewable Energy Integration

The current wasabi plant factory developed by Macnica relies on commercial grid power, resulting in an annual electricity cost of approximately one million yen. To reduce this dependency and operational expense, the effective utilization of solar and wind power generation is investigated. The conceptual framework of the proposed energy management system is as follows:

1. When (the combined output of solar and wind generation) is less than (the factory's total electricity demand): All renewable power is supplied directly to the wasabi plant factory.
2. When (the combined output of solar and wind generation) > (the factory's total electricity demand): The surplus electricity is stored in the battery system.
3. The state of charge (SOC) of the battery is managed within the operational range of $15\% < \text{SOC} < 90\%$, allowing controlled charging and discharging.
4. When the renewable output remains below demand (case 1), the battery discharges to supplement the deficit.
5. In all other cases, remaining demand is covered by commercial grid power.

This operational scheme is illustrated in Fig.2. Using this framework, a simulation was conducted to evaluate the reduction ratio of grid-electricity consumption for the wasabi plant factory, with three primary parameters: the rated capacity of solar power, wind power, and the battery system. The calculations were performed using the Comprehensive Infrastructure Simulator developed at Ishinomaki Senshu University, which models hybrid renewable systems and battery dynamics under real meteorological conditions.

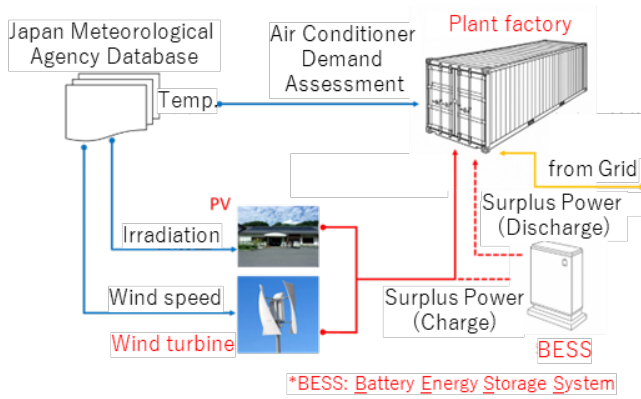


Fig.2 Concept of Simulator

3.1 Calculation conditions

3.1.1 Power consumption of Wasabi factory

The principal electrical equipment used in the wasabi plant factory is as follows:

- Cultivation LEDs and air conditioners — three units, operated continuously
- Chiller — in continuous operation
- Pumps — six units, operated continuously

Fig. 3 shows a prediction of the daily power demand curve.

3.1.2 Calculation of PV output

Solar radiation data for the target area were obtained from the database of the Japan Weather Association. Based on the calculation method developed by NEDO (New Energy and Industrial Technology Development Organization), the hourly output of the photovoltaic system was computed for all 365 days of the year ^{(6),(7)}.

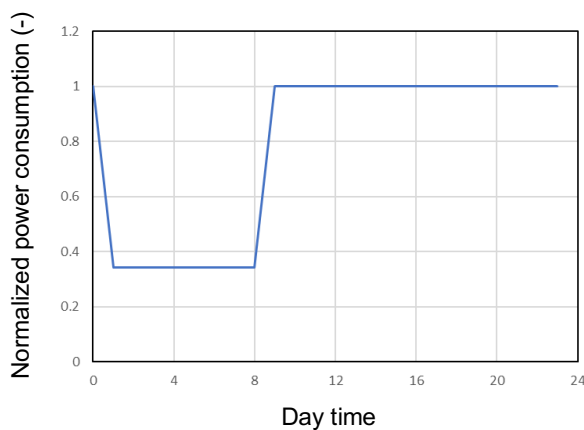


Fig.3 Example of Predicted Daily demand Curve

3.1.3 Calculation of wind power

The wind turbine examined in this study is a small vertical-axis unit with a rated output of 3 kW, designed to meet diverse small-scale power needs such as residential use, mobile housing, small business facilities, and marine applications. Under standard operating conditions (wind speed of 10 m s^{-1}), the power conversion efficiency is approximately 35–40 %. Assuming a regional average wind speed of 5 m s^{-1} and an operational availability of 25 %, the estimated annual energy yield is about $6,570 \text{ kWh yr}^{-1}$, demonstrating that the turbine possesses sufficient performance for integration into distributed renewable-energy systems. The operating curve of the target wind turbine is presented in Fig.4.

3.1.4 Calculation condition of battery system

Table 1 shows the specifications related to the battery system (BESS: Battery Energy Storage System). The range of SOC was set to 15–90%, which maximizes the battery lifetime.

Table.1 Battery System Specifications

Item	Value	Unit
PCS Output	37.00	kW
Battery Capacity	75.00	kWh
Maximum SOC	0.90	—
Minimum SOC	0.15	—
PCS Efficiency	0.95	—
Charge/Discharge Efficiency	0.90	—

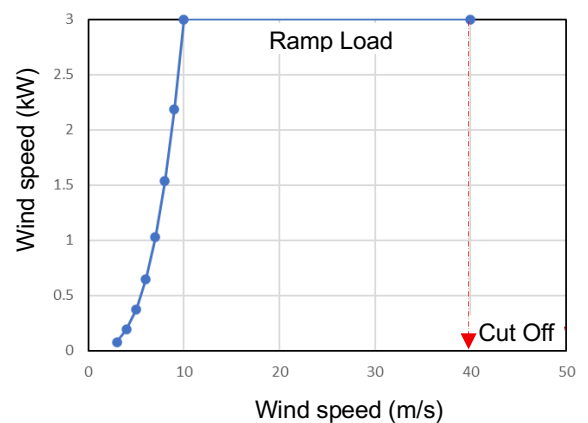


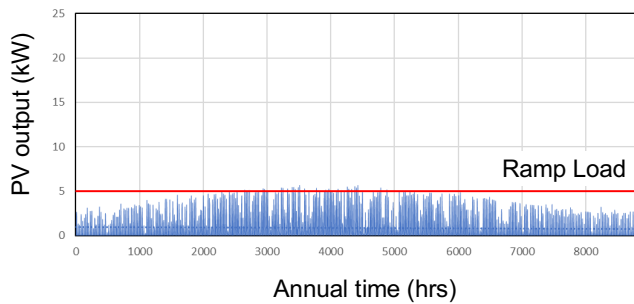
Fig.4. Operation curve of wind turbine

4. Simulation results

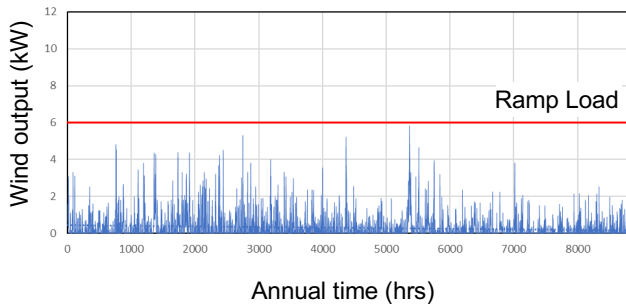
4.1 Parameter settings

In the following analysis, three parameters were varied — battery capacity, photovoltaic (PV) capacity, and wind power capacity — to evaluate their combined effects on the wasabi plant factory's energy consumption and cost performance. Specifically, the battery capacity was set to 25, 50, and 75 kWh; the PV capacity to 5, 10, 15, 20, and 25 kW; and the wind power capacity to 3, 6, 9, and 12 kW.

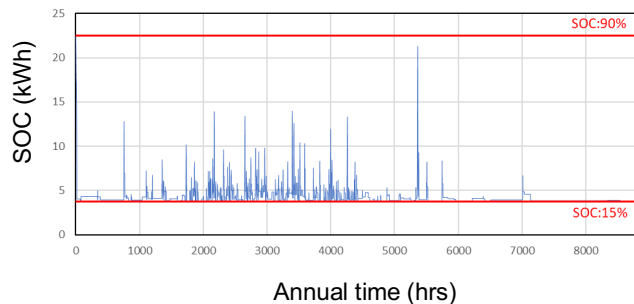
A total of 60 combinations were simulated, and for each configuration, the reduction rate of grid-electricity consumption and the corresponding system cost were quantitatively evaluated.



a) Simulated annual PV output



b) Simulated annual Wind output



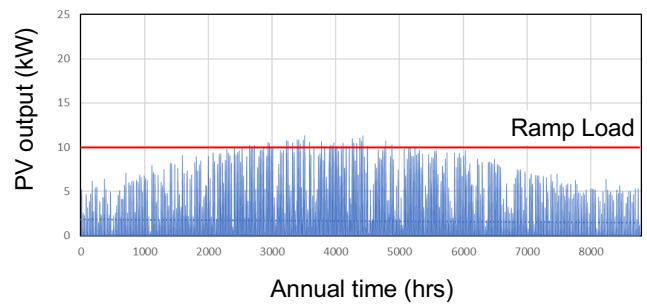
c) Simulated SOC of battery

Fig.5 Example of results

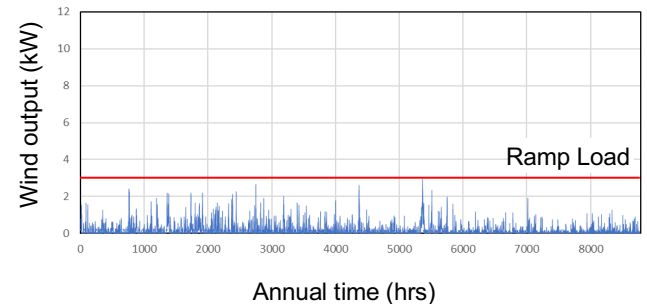
(PV:5kW, Wind:6kW, Battery:25kWh)

4.2 Example of results

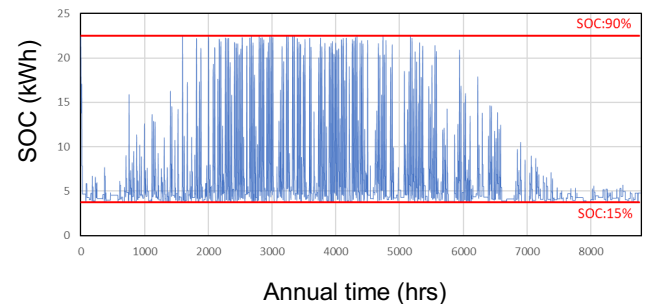
As representative examples among the sixty simulation cases, two configurations were selected for detailed analysis: (PV: 5 kW, Wind: 6 kW, Battery: 25 kWh) and (PV: 10 kW, Wind: 3 kW, Battery: 25 kWh). The corresponding annual profiles of PV output, wind power output, and battery state of charge (SOC) are presented in Figs 5 and 6, respectively. The reduction rates in grid-electricity consumption for these two configurations were 28.6% and 42.5%, respectively. As illustrated in Fig.5, the smaller capacities of both PV and wind generation result in insufficient battery charging, leading to relatively low SOC levels; meaning that the storage system is not effectively



a) Simulated annual PV output



b) Simulated annual Wind output



c) Simulated SOC of battery

Fig.6 Example of results

(PV:10kW, Wind:3kW, Battery:25kWh)

utilized in this case. In contrast, Fig. 6 demonstrates that increasing the PV and wind capacities enhances the charging of the battery, which in turn allows greater discharge activity and consequently improves the reduction in electricity consumption by the wasabi plant factory.

4.3 Evaluation of the Reduction Effect on Electricity Consumption in the Wasabi Plant Factory

The electricity price was assumed to be 30 JPY/kWh. The effects of battery capacity (25–75 kWh) on the ten-year reduction in electricity consumption of the wasabi plant factory are summarized below. For the estimation of initial system cost, the following unit prices were applied: photovoltaic system – JPY 240,000 per kW; wind turbine – JPY 150,000 per 3 kW; and battery storage – JPY 80,000 per kWh.

The results are summarized in Fig. 7. In the figure, the pink-shaded region represents the area where the 10-year electricity cost reduction achieved by renewable energy exceeds the initial system cost. Under the present simulation conditions, no configuration fell within this economically positive region. To achieve a rational cost structure for reducing reliance on grid electricity, it is desirable for the configuration to fall within the pink-shaded region in Fig. 7. However, since no combination in the present parameter range satisfies this condition, we define the optimal solution as the configuration whose position lies closest to the red dashed line in Fig. 7. In the same figure, blue circles correspond to the 25 kWh battery cases, orange circles to the 50 kWh batteries, and gray circles to the 75 kWh batteries, with twenty simulation cases for each capacity.

From the previously discussed SOC (state of charge) results, it can be inferred that for the electricity demand characteristics of the Macnica wasabi plant factory and the scale of deployable renewable generation, battery capacities of 50 kWh and 75 kWh are oversized, resulting only in unnecessary cost increases. Consequently, the optimal battery capacity is estimated to be 25 kWh.

Among all evaluated cases, the configuration whose initial system cost most closely matched the 10-year savings in electricity cost was the combination of 10 kW photovoltaic and 3 kW wind generation.

As a system, achieving 100% renewable energy supply is an ideal and beautiful goal; however, considering the cost relationship, a practical target would be around 40–50%.

This viewpoint is not only applicable to the wasabi plant factory but is also of fundamental importance.

Figure 8 shows the exterior view of the system combining a 3 kW wind turbine, a 10 kW photovoltaic array, and the wasabi plant factory. This configuration provides a

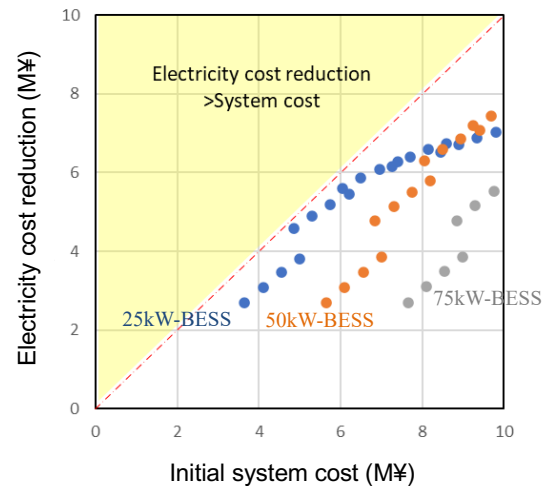


Fig. 7 Comparison between system cost and electricity cost reduction in the wasabi plant factory

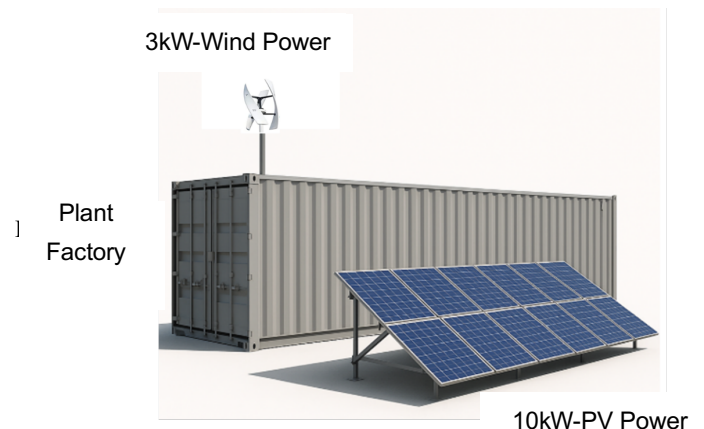


Fig. 8 Exterior view of the wasabi plant factory with the optimal renewable energy configuration

This viewpoint is not only applicable to the wasabi plant factory but is also of fundamental importance.

Fig. 8 shows the exterior view of the system combining a 3 kW wind turbine, a 10 kW photovoltaic array, and the wasabi plant factory. This configuration provides a visually clear representation of the application of renewable energy to plant factory operations. In this way, such a visually comprehensible configuration is expected to attract visitors to the area and promote local engagement.

In this study, the wind power capacity was set to its maximum output. However, given that favorable wind conditions cannot be expected in the target region, capacities above 9 kW were not considered. This constraint is inherently dependent on the local meteorological conditions at the site where the renewable energy–integrated wasabi plant factory is deployed. The key insight of this work lies in establishing the principle that, when aiming to reduce grid electricity costs through renewable integration, there exists an optimal point determined by the trade-off between installation cost and cost savings.

5. Conclusions

This study proposed and quantitatively evaluated a renewable energy–integrated model for a high-profit *Wasabia japonica* plant factory as a sustainable solution for regional revitalization. By combining photovoltaic, small-scale wind, and battery storage systems, the model aimed to achieve energy self-sufficiency and CO₂ reduction while maintaining stable agricultural productivity.

Simulation results demonstrated that the optimal configuration for the Macnica wasabi plant factory is a system composed of 10 kW photovoltaic, 3 kW wind generation, and a 25 kWh battery. Under this condition, the electricity consumption reduction rate reached approximately 42.5%, indicating a substantial contribution of renewable integration to operational efficiency. In contrast, larger battery capacities of 50 kWh and 75 kWh were found to be economically impractical, as they increased system cost without improving performance.

The findings confirm that the proposed configuration achieves a balanced trade-off between cost and energy autonomy, with an estimated 40% self-sufficiency rate and a CO₂ reduction of around 20 t yr⁻¹ for a five-unit installation. This demonstrates the technical feasibility of constructing a semi-independent, low-carbon agricultural facility powered primarily by renewable energy.

In recent years, a 100% renewable electricity supply has been widely discussed as a target for various facilities. However, our results indicate that the costs of renewable generation and battery deployment have not yet fallen sufficiently for such a scenario to be cost-effective. A more realistic pathway is to increase the on-site utilization of renewable energy while simultaneously reducing the CO₂ emissions associated with grid-supplied electricity.

Beyond its engineering significance, the energy-integrated wasabi plant factory can represent a scalable and replicable model for decarbonized rural economies, capable of generating local employment, fostering educational collaboration, and enhancing regional resilience.

These findings highlight that partial but substantial renewable integration, rather than full self-sufficiency, currently offers the most practical pathway for rural plant factories.

Future work will extend the system optimization to include seasonal operation control, dynamic pricing of electricity, and hybrid integration with hydrogen storage and thermal energy recovery.

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