Agrivoltaic System Design under Feed-in Premium Considering Self-Consumption by Greenhouses

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***Abstract*—Transition from feed-in tariff (FIT) to feed-in premium (FIP) has made agrivoltaic profitability more uncertain in Japan. This study optimizes agrivoltaic system size by jointly modeling FIP market sales and local self-consumption by commercial greenhouses. We couple a 1-minute greenhouse temperature-control simulation with a 30-minute greedy allocation algorithm that dispatches Photovoltaic (PV) output between self-consumption and FIP trading. Using Utsunomiya weather data and JEPX prices, we evaluate premium levels and panel areas. For 10,000 m^2, discounted payback (5%) is 27.28 years at 0 JPY/kWh premium and 15.59 years at 5 JPY/kWh. Under 0 JPY/kWh, reducing panel area to 100 m^2 improves payback to 17.44 years via a higher self-consumption ratio. Results show that robust agrivoltaic design under FIP requires coordinated selection of premium assumptions and installation scale.**

***Index Terms*—agrivoltaics, feed-in premium, greenhouse, optimization, self-consumption**

I. Introduction

Japan has announced an ambitious decarbonization pathway toward carbon neutrality by 2050, including a 73% greenhouse-gas reduction target by FY2040 and expansion of solar PV share in the electricity mix from 23% to 29% [1]. At the same time, Japan already exhibits one of the highest PV deployment densities per land area worldwide, and limited availability of flat land has become a major constraint on further expansion.

Under these conditions, agrivoltaics—the co-location of agricultural production and PV generation on farmland—has attracted increasing attention as a practical pathway to unlock additional deployment [2]. Diffusion has progressed particularly in open-field applications. According to the Ministry of Agriculture, Forestry and Fisheries of Japan, cumulative temporary farmland-conversion permits for agrivoltaic facilities reached 6,137 cases and 1,361.6 ha by FY2023 [3]. This growth appears to have been supported by stable investment recovery under the FIT scheme.

However, FIT purchase prices have declined in recent years, weakening project economics, especially in rural areas where renewable-energy deployment is expected to support regional revitalization. In 2022, Japan initiated the transition to the FIP scheme, under which generators receive market-linked prices plus a premium. Under this more complex market-linked framework, securing profitability for new PV projects has become increasingly challenging [4].

A practical way to stabilize revenue under low market prices is local self-consumption through nearby commercial greenhouses. Year-round controlled-environment horticulture requires substantial energy for heating, cooling, and ventilation, and greenhouse energy use is a major emissions source in Japan's agriculture and forestry sector [5]. Using renewable electricity can reduce these emissions [6] while potentially adding environmental value to crops and improving farm-level profitability.

Local consumption of agrivoltaic power also mitigates operational constraints that cannot be resolved by capacity expansion alone. By increasing in-region utilization, curtailment risks associated with transmission bottlenecks and supply-demand imbalance can be alleviated.

Most prior studies were conducted under FIT-type fixed purchase assumptions [7]. As the transition toward market-linked FIP progresses, the optimal operation of systems that simultaneously consider FIP market sales and greenhouse self-consumption remains insufficiently explored. This paper develops a dynamic allocation model that distributes PV output between self-consumption (valued at 20 JPY/kWh) and FIP sales (JEPX spot price plus premium), and evaluates the economic viability of agrivoltaic systems.

The main contributions are as follows: (1) development of a minute-resolution range-based greenhouse temperature-control model for one-year electricity-demand estimation across multiple seasons; (2) formulation of a revenue-maximization model integrating self-consumption and FIP trading; and (3) sensitivity analysis across premium levels and panel sizes to support rational investment decision-making.

The remainder of this paper is organized as follows. Section II presents the system configuration and optimization problem. Section III describes the greenhouse simulation, PV generation model, and greedy allocation algorithm. Section IV reports the Utsunomiya case study and robustness analysis across three historical years. Section V discusses policy implications and future agrivoltaic system design under the FIP framework.

II. Problem formulation

A. System configuration

As shown in Fig. 1, the target system consists of three components: Greenhouse, Photovoltaic, and Grid.

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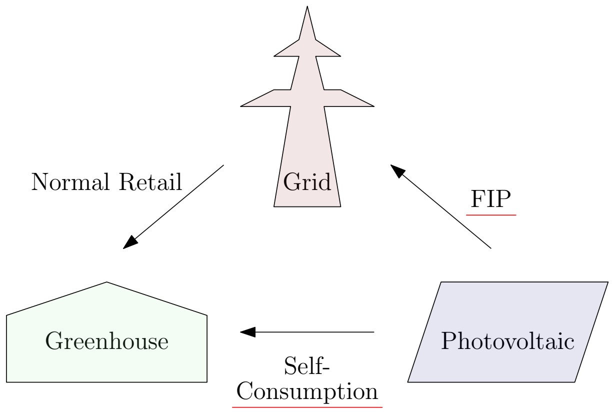

Figure 1. System configuration: PV-generated power is distributed between greenhouse consumption and the FIP market. Any energy shortfall is compensated through grid-purchased electricity.

The greenhouse is modeled as a medium-scale facility with a floor area of 300 m^2 (10 m width $\times$ 30 m depth), assuming strawberry cultivation. Because strawberry production requires strict year-round thermal management, the greenhouse is equipped with a heat pump for heating/cooling, forced-ventilation fans, and shading/thermal curtains, which constitute the primary electricity-demand sources.

The agrivoltaic system is installed on farmland near the greenhouse. PV panels are assumed south-facing with a 30° tilt and 10% conversion efficiency [8], [9]. To examine scale effects on the trade-off between self-consumption and FIP sales, panel area A^{PV} is varied from 100 to 10,000 m^2.

The grid provides both (i) electricity purchases to supply greenhouse deficits and (ii) market connection for selling PV surplus under the FIP scheme.

B. Optimization problem

The objective is to maximize annual revenue by optimally allocating PV output between greenhouse self-consumption and FIP market sales:

$$\max_{P_t^{\mathrm{house}}} \quad R^{\mathrm{total}} = \sum_{t=1}^{17520} \left(c^{\mathrm{self}} \cdot P_t^{\mathrm{house}} + c_t^{\mathrm{FIP}} \cdot P_t^{\mathrm{FIP}} \right) \Delta t \quad (1)$$

subject to the following power-balance constraints:

$$P_t^{\mathrm{house}} + P_t^{\mathrm{FIP}} = P_t^{\mathrm{PV}} \quad (2)$$

$$0 \leq P_t^{\mathrm{house}} \leq P_t^{\mathrm{demand}} \quad (3)$$

$$P_t^{\mathrm{FIP}} \geq 0 \quad (4)$$

Here, P_t^{demand} is the greenhouse electrical demand at time step t, P_t^{house} is PV power allocated to greenhouse demand, and P_t^{FIP} is PV power sold to the FIP market. The self-consumption value is fixed at $c^{\mathrm{self}} = 20$ JPY/kWh, while c_t^{FIP} is the time-varying FIP selling price (JEPX spot price plus premium). For market-clearing periods where JEPX price is 0.01 JPY/kWh, the premium is set to 0 JPY/kWh and not added [10]. The agrivoltaic installation cost is set to $C^{\mathrm{initial}} = 30{,}000$ JPY/m^2, assuming 10 m^2/kW, which is equivalent to 300,000 JPY/kW as a capacity-based reference value [7]. To compare policy support levels, three premium scenarios are evaluated: 0, 3, and 5 JPY/kWh.

TABLE I
SYSTEM PARAMETERS.

Parameter	Value	Unit
Greenhouse floor area	300	m^2
Greenhouse volume	1033	m^3
PV panel area range	100–10,000	m^2
PV tilt angle	30	°
PV conversion efficiency	10	%
PV area per 1 kW	10	m^2/kW
PV cost per 1 kW	300,000	JPY/kW
Self-consumption value	20	JPY/kWh
FIP premium scenarios	0, 3, 5	JPY/kWh
Discount rate	5	%

Equation (2) enforces conservation of PV output. Equation (3) limits self-consumption by greenhouse demand, preventing over-allocation. Equation (4) requires nonnegative market sales. Key parameters are summarized in Table I.

III. APPROACH

A. Greenhouse thermal simulation

Accurate estimation of greenhouse electricity demand requires high-resolution thermal modeling that captures rapid weather-driven changes. We therefore use hourly NEDO meteorological data (air temperature, solar irradiance, and wind speed) [11], linearly interpolated to 1-minute resolution (525,600 steps/year). The greenhouse thermal balance is governed by:

$$\rho C_p V \frac{dT_t^{\mathrm{in}}}{dt} = Q_t^{\mathrm{solar}} + Q_t^{\mathrm{trans}} + Q_t^{\mathrm{hp}} + Q_t^{\mathrm{vent}} \quad (5)$$

where $\rho = 1.21$ kg/m^3 is air density, $C_p = 1006$ J/(kg·K) is specific heat at constant pressure, $V = 1033$ m^3 is greenhouse volume, and T_t^{in} is indoor temperature at time step t (1-minute resolution). The right-hand-side terms represent solar heat gain, conductive/convective heat transfer through covers, heat-pump heating/cooling, and ventilation heat exchange. The cover transmittance coefficient is switched according to thermal curtain operation ($U = 6.0$ or 3.0 W/(m^2·K)).

Instead of strict setpoint control, we employ a range-based policy to emulate practical operation. Target temperature bands are determined by season and time of day based on strawberry cultivation requirements, ranging from 5°C (winter night) to 30°C (summer daytime).

When daytime temperature exceeds the upper threshold ($T > T^{\mathrm{max}}$ with $T^{\mathrm{target}} \geq 20$°C), forced ventilation is activated first; cooling is then applied only if ventilation is insufficient. Under severe summer conditions, 50% shading curtains are deployed, but only when overcooling is avoided. When nighttime temperature falls below the lower threshold ($T < T^{\mathrm{min}}$ with $T^{\mathrm{target}} < 20$°C), heating is activated.

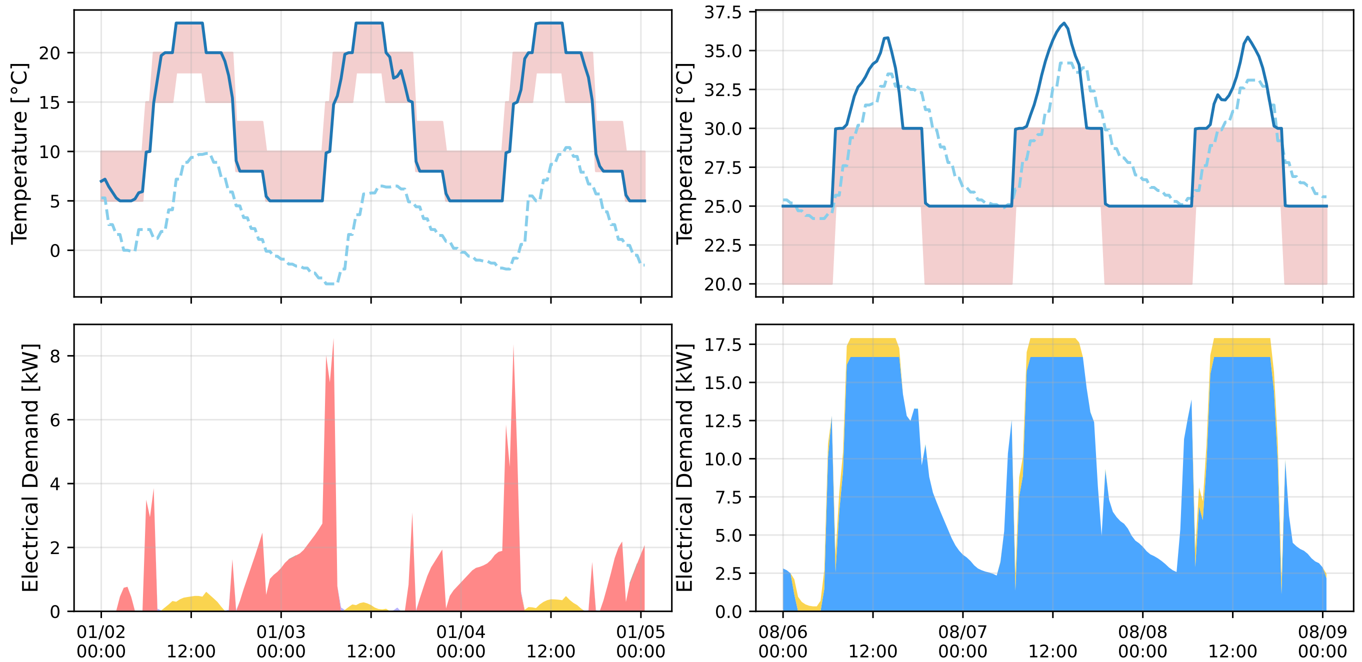

Figure 2. Time-series of greenhouse temperature control and power demand in winter (Jan, left) and summer (Aug, right). Top: Outdoor (dashed light blue), indoor (solid blue), and target temperatures (pink). Bottom: Demand breakdown for heating (red), cooling (blue), and ventilation (yellow). The values of shading curtain (green) and thermal curtain (purple) are very small and barely visible in the graph.

As shown in Fig. 2, this strategy maintains indoor temperature within the target band for most periods, except for limited intervals under extreme summer outdoor conditions above 30°C. Heat-pump COP is set to 3.0 for both heating and cooling.

B. Electrical demand calculation

Total greenhouse electricity demand is computed as

$$P_t^{\text{demand}} = P_t^{\text{hp}} + P_t^{\text{vent}} + P_t^{\text{shade}} + P_t^{\text{insul}} \tag{6}$$

where P_t^{hp} is heat-pump power ($|Q_t^{\text{hp}}|$/COP), P_t^{vent} is fan power (0.02 Wh/m^3), P_t^{shade} is shading curtain motor power (8.33 Wh per switching event), and P_t^{insul} is thermal curtain motor power (8.33 Wh per switching event). Minute-level demand is aggregated to 30-minute values for alignment with JEPX price data.

As shown in Fig. 2, heating dominates in winter, while ventilation and cooling dominate in summer.

C. PV generation model

PV output at each 30-minute time step is calculated from tilted-surface solar irradiance:

$$P_t^{\text{PV}} = \eta^{\text{PV}} \cdot I_t^{\text{tilt}} \cdot A^{\text{PV}} \tag{7}$$

where $\eta^{\text{PV}} = 0.10$ is panel efficiency, I_t^{tilt} is irradiance on a 30° south-facing tilted plane (kW/m^2), and A^{PV} is panel area (m^2). In Utsunomiya, annual generation reaches approximately 162 MWh for $A^{\text{PV}} = 1{,}000$ m^2.

D. Optimization algorithm

Because storage is not considered, no battery or other energy-storage equipment is available in the system. Therefore, the timing of PV generation and electricity supply cannot be shifted across time steps, and decisions at each step are independent. Under the present formulation, a greedy algorithm is expected to provide the optimal annual solution. In the 30-minute optimization at each time step t, allocation follows:

1) If $c_t^{\text{FIP}} \leq c^{\text{self}}$ and $P_t^{\text{PV}} > 0$: Allocate to self-consumption first up to P_t^{demand}, then surplus to FIP market.
2) If $c_t^{\text{FIP}} > c^{\text{self}}$: Allocate all P_t^{PV} to the FIP market, and supply greenhouse demand by grid purchase.

The algorithm is executed for all combinations of three premium levels (0, 3, and 5 JPY/kWh) and eight panel areas (100, 500, 1,000, 2,000, 3,000, 5,000, 7,000, and 10,000 m^2), totaling 24 cases.

The seasonal allocation results are illustrated in Fig. 3. In winter, most PV output is sold to the market because heating demand and daytime generation are weakly synchronized. In summer, stronger overlap between daytime PV output and cooling/ventilation demand increases self-consumption. The figure also confirms rational switching of allocation according to the relative values of FIP price and self-consumption.

IV. Validation

This section evaluates the developed agrivoltaic system using Utsunomiya meteorological data and real Japanese Elec-

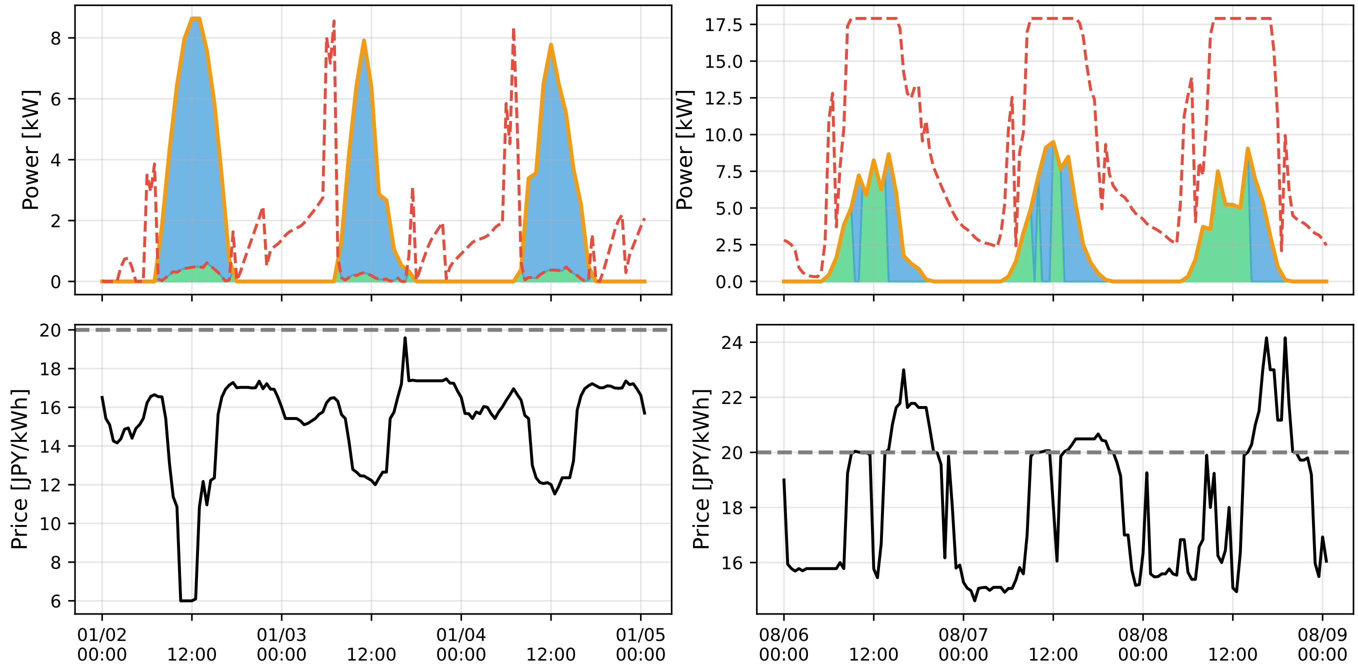

Figure 3. Power allocation and pricing in winter (Jan, left) and summer (Aug, right). Top: PV output (—), demand (- - -), self-consumption (■), and FIP sales (■). Bottom: Comparison between FIP price (JEPX + 3 JPY/kWh) (—) and self-consumption value (20 JPY/kWh) (- - -).

tricity Power Exchange (JEPX) market prices.

A. Case study setup and greenhouse demand

The base-case simulation combines Utsunomiya meteorological data from the NEDO database [11] with 2024 JEPX spot prices [12]. To evaluate sensitivity to installation and policy settings, panel area is varied across eight cases (100–10,000 m^2), and FIP premium is varied across three scenarios (0/3/5 JPY/kWh), yielding 24 combinations.

For robustness assessment under market volatility, additional simulations are conducted using 2022 and 2023 JEPX price series under the same physical-system assumptions. In this section, payback period denotes discounted payback at a 5% discount rate, assuming constant annual cash flow and no OPEX/degradation. Key parameters are summarized in Table I.

B. Trade-off between panel capacity and economics

As expected, higher premiums improved profitability. As shown in Fig. 4 and Fig. 5, at 10,000 m^2, premium 5 JPY/kWh yields annual electricity-sales revenue of 28.16 million JPY and a payback period of 15.59 years, whereas premium 0 JPY/kWh yields 20.39 million JPY and a payback period of 27.28 years. This premium advantage is also observed at all other panel areas: compared with premium 0 JPY/kWh, premium 5 JPY/kWh increases annual revenue by 0.05–7.78 million JPY and shortens payback by 3.77–11.69 years.

However, a more important insight is the within-premium scale effect: for the same premium level, larger panel areas lead to longer payback periods. This deterioration is driven by a decline in self-consumption share and a resulting drop in average selling price. As shown in Fig. 6, for premium 5 JPY/kWh, self-consumption decreases from 36.42% at 100 m^2 to 0.91% at 10,000 m^2. Because market-selling prices are frequently lower than the 20 JPY/kWh self-consumption value, this shift toward market sales reduces system-wide average selling price in Fig. 7; at 10,000 m^2, it is 12.56 JPY/kWh under premium 0 and 17.35 JPY/kWh under premium 5.

Therefore, increasing panel area expands annual revenue but can lengthen capital recovery time, revealing a clear trade-off between scale merit and investment risk. Project developers need to make rational decisions on installation scale based on this trade-off.

For example, if a project developer requires investment recovery within 25 years, all tested panel-area cases are investable under premium levels of 3 and 5 JPY/kWh. In contrast, under 0 JPY/kWh, cases with panel area of 2,000 m^2 or larger are not investable under this criterion, and 1,000 m^2 becomes the largest feasible installation size.

C. Robustness against market-price volatility

To assess the key risk of market-linked operation, JEPX data in 2022 and 2023 are compared with that in 2024. Annual mean market prices differ substantially across years: 23.50 JPY/kWh in 2022, 12.20 JPY/kWh in 2023, and 13.66 JPY/kWh in 2024. In practical FIP operation, higher market prices generally correspond to lower effective premium payments, while lower market prices tend to correspond to higher premium payments. Hence, the FIP mechanism itself provides partial hedging against market volatility.

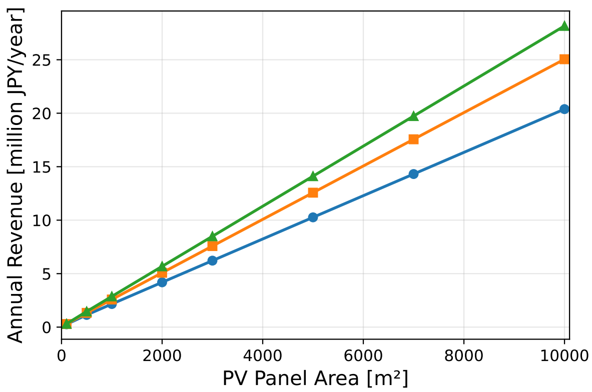

Figure 4. As the PV panel area increases, electricity-sales revenue increases. Premium is 0 JPY/kWh (—), 3 JPY/kWh (—), 5 JPY/kWh (—).

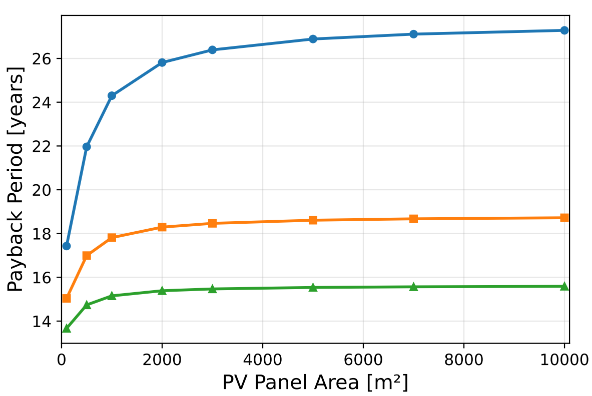

Figure 5. As the PV panel area increases, the payback period becomes longer. Premium is 0 JPY/kWh (—), 3 JPY/kWh (—), 5 JPY/kWh (—).

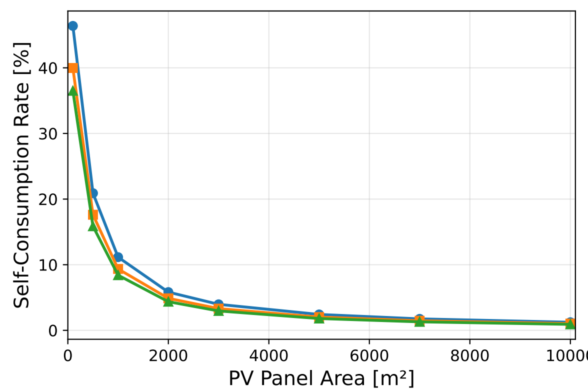

Figure 6. As the PV panel area increases, the self-consumption rate decreases. Premium is 0 JPY/kWh (—), 3 JPY/kWh (—), 5 JPY/kWh (—).

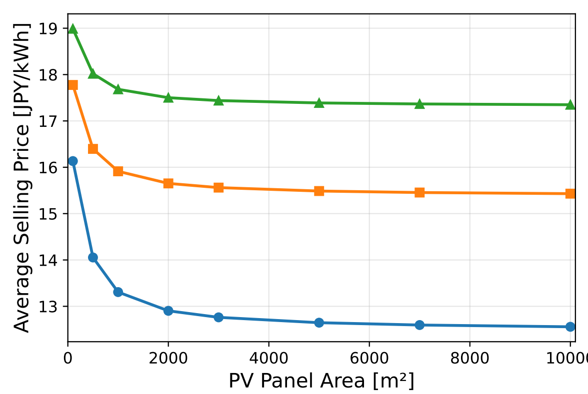

Figure 7. As the PV panel area increases, the average selling price decreases. Premium is 0 JPY/kWh (—), 3 JPY/kWh (—), 5 JPY/kWh (—).

The simulation results suggest that combining appropriate premium settings with self-consumption can maintain economic viability even in low-price years, supporting the robustness of agrivoltaic operation under market uncertainty.

V. Conclusion

This study investigated the economic feasibility and optimal power-allocation strategy of agrivoltaic PV systems by jointly considering market-linked FIP trading and greenhouse self-consumption. A minute-resolution temperature-control simulation was integrated with an optimization framework to estimate realistic operational demand and project economics.

The case study indicates that installation scale strongly affects both self-consumption ratio in Fig. 6 and average selling price in Fig. 7, which in turn determine payback period in Fig. 5. System design should therefore balance scale merit against the risk of lower unit revenue and longer capital recovery caused by declining self-consumption at large capacities.

Observed payback periods (15.6–27.3 years) exceed typical agricultural asset lives—equipment (5–7 years) and greenhouses (5–10 years)—creating a major barrier to farmer-led agrivoltaic investment. The situation is worsened by an aging workforce (average ages often >70) that typically avoids long-term debt and prioritizes near-term returns, so horizons beyond approximately 15 years are impractical without clear succession. Two policy responses can help: (1) differentiated FIP premiums targeted to agriculture (regional or sector tiers) to shorten effective payback toward 5–10 years; and (2) measures to raise near-term self-consumption value—greenhouse electrification and demand-response—to boost revenue per kWh and reduce payback. Time-limited, monitored support preserves market efficiency while addressing sectoral capital-recovery needs.

Future work includes: (1) panel-layout strategies such as orientation and tilt to improve temporal demand matching [13]; (2) explicit modeling of additional on-farm self-consumption loads, such as irrigation and food-processing demand [14]; (3) integration of storage technologies, including batteries and thermal storage for greenhouse HVAC; (4) real-time optimization under uncertainty in market prices and weather forecasts; and (5) field validation using operational greenhouse data. These efforts can provide practical guidance for risk-aware agrivoltaic deployment in rural communities pursuing local renewable use and decarbonization.

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