Study on Cost Performance of Gain and Payback Period in a Plant Factory of Spinach in a Cold District

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***Abstract*—Energy supply and demand of a plant factory facility on our campus were investigated for the purpose of energy saving in a cold region plant factory with renewable energy. The average value of the highest temperatures in November to March is 20 degree Celsius or less in Kitami. Therefore, the environment temperature of the plant factory was adjusted to 20 degree Celsius by air cooling with a ventilation fan. In addition, by supplying surplus heat of cogeneration to an external greenhouse, an increase in the harvest volume of spinach was expected. Moreover, a facility consisting of a cold region plant factory and a greenhouse is defined as a "plant cultivation system". When spinach is cultivated in this system, cost performance of gain is 2.57 (price of farm products to production costs) and the payback period is 9.70 years, so a general introduction can be expected.**

***Index Terms*—cold district, plant factory, spinach, cost performance of gain, payback period**

I. Introduction

Due to snow covering all land in Hokkaido, Japan during winters, farmers are unable to work the whole year through, though this is strongly desired [1]. This study aims to develop a plant factory for cold region with renewable energy (the facility ratio of renewable energy aims at more than 75% output against the electricity consumption) and a cogeneration interconnected energy system. In addition, the proposed system supplies waste heat of cogeneration to the external greenhouse in order to raise vegetables in winter. In this paper, a facility consisting of a plant factory and a greenhouse is defined as a "plant cultivation system". Moreover, here a plant cultivation system is considered to be independent from the commercial electricity network.

II. Outline of a Plant Factory for Cold Region

Fig. 1 shows the configuration of the proposed plant cultivation test system installed at Kitami Institute of Technology. The optimal temperature of spinach cultivation is 20 degrees Celsius [2]. Although room temperature is controlled by an electric heat pump in a general plant factory, in order to reduce the power purchase cost of commercial electric power, the whole plant factory energy is supplied by a cogeneration and renewable energy interconnection system. On the other hand, because average outside temperature of Kitami in winter season (from November to March) is less than 20 degrees Celsius, the room temperature adjustment of low energy consumption by a ventilation fan accompanied by open air introduction is applicable.

A. Details of a Cultivation Rack in a Plant Factory

The cultivation rack installed in the plant factory has four shelves, three upper shelves are used for cultivation and the bottom shelf is used for a nutrient storage tank. The number of cultivations per shelf of the rack considers the space of the rack and the occupied area of spinach per shelf. Then 240 strains of spinach in rack of "A", 294 strains in rack of "B" and 196 strains in rack of "C" can be cultivated. From this, it is possible to cultivate 7,584 strains of spinach at the proposed plant factory if 4 racks of "A", 4 racks of "B" and 2 racks of "C" are installed. Moreover, the cultivation period of spinach is 5 months from November to March.

III. Analysis Method and Analysis Condition

Heat balance and power balance of the plant factory are calculated using equation (1) and equation (2). Equation (1) is the heat balance equation of the energy system of the proposed plant factory. The left side of equation (1) is input of heat of the amount of solar radiation (H_{sh}[kW]) and the heat generation amount of the LED lighting (H_{ll}[kW]) and the right side is the cold heat quantity by the ventilation fan (H_{vf}[kW]) and the heat radiation quantity to the outside air (H_r [kW], convective heat transmission from the outer wall). Equation (2) is the electricity balance equation. The left side of equation (2) is supply of electricity of the gas engine generator (P_g[kW]) and the photovoltaic (P_{pv}[kW])

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and the right side shows the electricity consumption of the ventilation fan (P_{vf} [kW]) and the LED lighting (P_{ll} [kW]) and the pump (P_{cp} [kW]). Moreover, the sampling time (t) is 1 hour in this analysis.

Furthermore, as an analysis condition, 54 LEDs are installed in the proposed plant factory, and the environment of unnatural daytime and night time is given by turning on and off the LEDs. Therefore, as shown in Fig. 2, 54 LEDs are divided into two groups, and the environment of daytime (27 LEDs) and night time (27 LEDs) is simultaneously prepared in the plant factory. The artificial environment of every morning and evening is parted at 18:00 to 6:00, and 6:00 to 18:00 in a day. In this paper, LED lighting is assumed to be the pattern of broken lines shown in Fig. 2.

$$H_{sh,t} + H_{ll,t} = H_{vf,t} + H_{r,t} \quad (1)$$

$$P_{g,t} + P_{pv,t} = P_{vf,t} + P_{ll,t} + P_{cp,t} \quad (2)$$

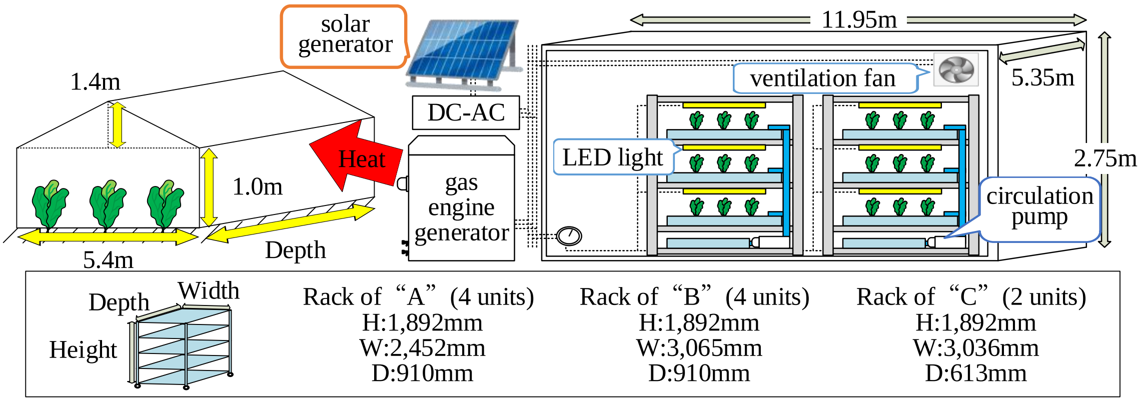


Figure 1. Outline of a plant cultivation system.

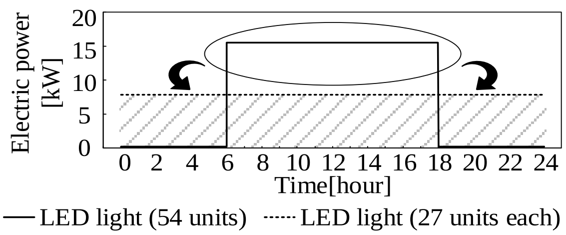


Figure 2. Power consumption of LED lighting.

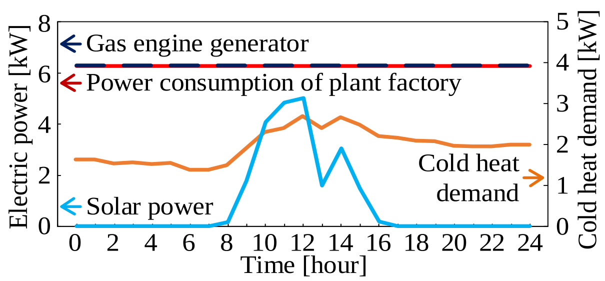


Figure 3. Electricity supply and demand of each component of the representative day of January.

IV. Analysis Result

Fig. 3 shows the amount of electricity consumption and cold energy demand in the plant factory on a representative day of January in Kitami. Outside air temperature and solar radiation referred to the NEDO solar radiation database [3]. As a result of calculation using the equations (1) and (2), cold heat is necessary in the plant factory in winter. Almost all the electricity consumption of the factory is not air cooling load but LED lighting. Moreover, because the maximum power consumption is 6.27 kW, photovoltaics of rated power 6.5 kW and gas engine generator of rated power 6.3 kW are introduced. The power conditioner is 95% efficient. From this, the plant factory can be separated from the commercial electricity network. However, because the exhaust heat of the gas engine generator can't be consumed in the plant factory, this exhaust heat is supplied to an external greenhouse and further spinach can be cultivated.

V. The Amount of Crop Produced in the External Greenhouse

A. *Structure of the External Greenhouse*

The greenhouse shown in Fig. 1 has a double covering structure and the covering material is a vinyl chloride film. The dimensions of the greenhouse are 5.4 m in width, 2.4 m in height. Based on this structure and size, the depth of the greenhouse can be calculated. Moreover, the room temperature of the greenhouse is kept at 20 degrees Celsius by quantity of exhaust heat 12.2 kWh of the gas engine generator.

B. *Heat Balance in the Greenhouse*

Equation (3) is a heat balance equation in the greenhouse at night [4]-[6]. The left side of the equation (3) is the exhaust heat quantity (Q_g) of the gas engine generator and the heat radiation quantity from the soil (Q_s). The right side is the covering area (A_g), heat passage rate (q_t), gap ventilation transmission rate (q_v), floor area of the greenhouse (A_s), underground heat transfer load (q_s), wind speed correction coefficient (f_w).

Calculated values in each section referred to in Reference [7]. In this calculation, the sampling time interval (t) sets to 1hour.

$$Q_{g,t} + Q_{s,t} = \{A_g(q_{t,t} + q_{v,t}) + A_s q_{s,t}\} f_w \quad (3)$$

C. Calculation Conditions and Results

The room temperature of the greenhouse is kept at 20 degrees Celsius even when the outside air temperature is the lowest. As the calculation condition, the outside air temperature is referred to the representative day of January (14th) in Kitami from the NEDO solar radiation database [3]. The lowest temperature is -17.8 degree Celsius. The spinach is separated from the side of the greenhouse by 45 cm so that the covering material of the greenhouse does not influence the growth of the spinach. In addition, the space around the spinach is left open 14 cm in the front and back and 6 cm on the left and right. From this condition, the depth of the greenhouse was obtained from equation (3). In addition, Table I shows the rate of increase in the number of the cultivation of spinach by comparing the plant factory and the plant cultivation system.

TABLE I. PARAMETERS OBTAINED BY CALCULATION

	Unit	Parameter
Depth	m	6.28
Floor area (Seeding area)	m ²	24.2
The number of the cultivation of greenhouse	stump	2,970
The number of the cultivation of plant factory	stump	7,584
Increase in the number of the cultivation	%	39.2

As shown in Table I, 2,970 strains of spinach can be cultivated when the exhaust heat quantity of the gas engine generator is 12.2 kWh and the depth of the external greenhouse is 6.27 m.

VI. COST PERFORMANCE AND PAYBACK PERIOD

A. In the Case of 6.3 kW Rated Output of Gas Engine Generator with 6.5 kW Photovoltaics

From equation (4), cost performance of gain (η) is obtained by using harvest profit (M_{sa}) per spinach cultivated in the plant cultivation system and fee of seed (M_{se}), gas (M_g), water (M_w) and liquid fertilizer (M_{lf}) used until harvest. At this time, the weight of spinach is 40 g per stump, about 90% of the spinach cultivated can be available for sale and about 10% of the spinach cannot sell due to insufficient growth. Under this condition, the harvest amount of spinach was calculated [8]. Further, the payback period (Y) of the plant cultivation system is obtained from the initial cost (M_{ic}) and spinach profit (M_p) of the plant cultivation system of Fig. 1 from equation (5). Fig. 4 shows the calculation results of cost performance of gain and payback period when spinach cultivation is set to 50 days and 30 days. Here, the selling price of spinach shall be three patterns of the average price (1,037 JPY/kg) of 2016, 1,250 JPY/kg, and the highest price (1,509 JPY/kg) of 2016.

$$\eta = \frac{M_{sa} - M_{se}}{M_g + M_w + M_{lf}} \tag{4}$$

$$Y = M_{ic}/M_p \tag{5}$$

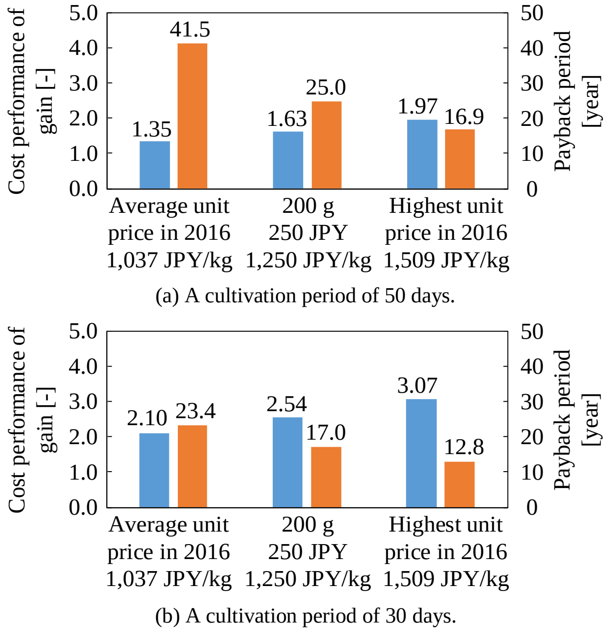


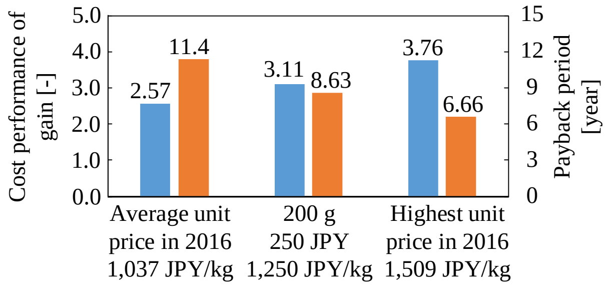
Figure 4. Cost performance of gain of spinach and payback period of the plant cultivation system in case of 6.3 kW rated output of gas engine generator with 6.5 kW photovoltaics.

From the results in Fig. 4, when cultivating spinach for 50 days and selling the spinach price at the highest price (1,503 JPY/kg) of 2016, the cost performance of gain will be 1.97 and the payback period will be 16.9 years. On the other hand, when the harvesting days are 30 days, the cost performance of gain is 3.07 and the payback period is 12.8 years, but it exceeds the 10 years that general introduction can be expected. The reason for this result is that the initial cost is too high. Therefore, in the following section 6.2, the case of expanding the scale of the plant cultivation system and reducing the initial cost is considered.

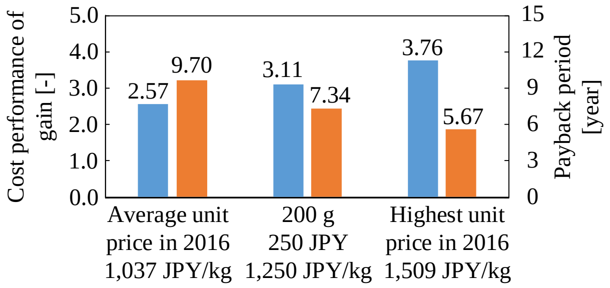
B. 35kW Rated Output of Gas Engine Generator with 26.8kW Photovoltaics

From the results in section 6.1, because the payback period of the plant cultivation system of the scale in Fig. 1 exceeds 10 years, in this section a plant cultivation system using the gas engine generator with a rated output of 35kW with 26.8 kW photovoltaics is discussed. Because the power consumption of the plant cultivation system shown in Fig. 1 is 6.3kW at the maximum, the scale of the plant cultivation system is 5.5 times that in Fig. 1. For equipment such as LED lighting, it is expected that the price per unit is lower than list price when purchasing in large quantities. Therefore, the cost performance of gain and the payback period calculated when these prices are halved and when these prices are list price.

Fig. 5 shows the cost performance of gain and the payback period in the scale of 5.5 times the plant cultivation system. From this result, when purchasing the LED lighting and the nutrient storage tank at the list price and selling spinach at the highest unit price of 2016, the cost performance of gain became 3.76, and the payback period was 6.66 years. On the other hand, when purchasing the LED lighting and the nutrient storage tank at 1/2 of the list price, the cost performance of gain became 3.76, and the payback period was 5.67 years. However, the price of vegetables changes every month, so 5.6 years is not realistic. In the case of selling spinach at the average price of 2016, the cost performance of gain was 2.57, and the payback period took 9.70 years but it was less than 10years. As a result, introducing a rated output of 35kW gas engine generator to a plant cultivation system with a scale of 5.5 times, and cultivating spinach, the payback period is 9.70 years, and introducing general use can be expected.



(a) When purchasing LED lighting and nutrient storage tank at list price.



(b) When purchasing LED lighting and nutrient storage tank at 1/2 of the list price.

Figure 5. Cost performance of gain of spinach and payback period of the plant cultivation system in case of 35 kW rated output of gas engine generator with 26.8 kW photovoltaics.

VII. Conclusion

In this study, energy demand of the plant factory facility with renewable energy installed on the campus was investigated for the purpose of energy saving of the plant factory for cold region. Because the room temperature of the general plant factory becomes warm by heat generation of the lighting, the room temperature is regulated by air cooling. However, in Kitami, there is a long period (December - March) where the high temperature does not reach 20 degrees Celsius and this can reduce the consumption of electricity by adjusting the room temperature of the plant factory by the air cooling with the ventilation fan. Moreover, the lighting time of LED lighting was turned on by half at every 12 hours to level the power consumption of the day. When investigating the energy demand under these conditions, it was found that it is necessary to supply cold heat to a plant factory by air cooling with the ventilation fan because the room temperature exceeds 20 degrees Celsius by an LED light even in winter. Also, in a plant cultivation system consisting of a plant factory and a greenhouse, the payback period takes a minimum of 12.8 years. Therefore, the cost performance of gain of the spinach and the payback period were calculated when the rated output of the gas engine generator of 35 kW with 26.8 kW photovoltaics was introduced to a plant cultivation system with a scale of 5.5 times that in Fig. 1. As a result, at the average price (1,037 JPY/kg) in 2016, the cost performance of gain will be 2.57 and since the payback period will be 9.70 years, commercial use can be expected. From these results, it is necessary to consider ways to reduce the initial cost by using the merit of the scale by enlarging the system.

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