Investigation of Installation Conditions of a Complete Artificial Light Type Savoy Spinach Plant Factory for Cold Regions

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***Abstract*—This paper considers energy consumption and choice of the optimal area for plant factory with low-temperature treatment of spinach. When exposed to a low-temperature (less than 7 ℃) environment, spinach increases the sugar content. In order to process by exposure to the coldness of spinach, it is necessary to hold the inside of the proposed plant factory at 7 ℃. The maximum air temperature from December to March of Kitami in Okhotsk is less than 7 ℃. Therefore, in this period, a ventilation fan is used to air cooling the plant factory. On the other hand, the plant factory is cooled by an absorption refrigerator from April to November. Because many regions where the maximum temperature of winter is less than 7 ℃ were located in Hokkaido, the payback period of the proposed system based on equipment cost and energy consumption were investigated about seven regions (Wakkanai, Asahikawa, Abashiri, Kutchan, Obihiro, Hiroo, Kitami) of them. When the proposed plant factory is installed in seven regions, because the analysis results of payback period are 6.83 years, the proposal plant factory and energy system for low-temperature treatments of spinach can be introduced enough commercially.**

***Index Terms*—plant factory, SOFC cogeneration, spinach, energy saving, cold regions**

I. Introduction

Farmers in cold regions are not able to work outside in the winter because of snow covers the ground. In addition, reduction of employed in agriculture by aging is also an important issue [1]-[3]. From these, the plant factories with an electricity-saving type for cold regions are expected. The plant factory has the advantage of ensuring a stable yield regardless of the weather, but it has the disadvantage that it is difficult to make a profit because of high initial costs and running costs [4]-[7]. The previous study examined the energy system in the complete artificial light type savoy spinach (which is a typical special product in the Okhotsk region of Hokkaido) plant factory for cold regions, in order to carry out stable and energy-saving cultivation of high added value crops [8]. In the complete artificial light type savoy spinach plant factory (the proposed plant factory), power and exhaust heat of the cooperation system by Photovoltaics (PV) and Solid Oxide Fuel Cell (SOFC) cogeneration are used. In addition, a system with low energy consumption was developed by supplying the exhaust heat of SOFC cogeneration to an absorption refrigerator and the heat storage tank to cover energy demand of the plant factory.

This paper considers energy consumption and choice of the optimal area for plant factory with low-temperature treatment of spinach. When exposed to low temperature (less than 7 ℃) environments, savoy spinach leaves tend to shrink. Also, savoy spinach has a higher nutritional value such as sugar content and vitamin C than ordinary spinach, so the selling price is higher. In order to process by exposure to the coldness of spinach, it is necessary to hold the inside of the proposed plant factory at 7 ℃. Because maximum air temperature from December to March of Kitami is less than 7 ℃ [9], the room temperature of the plant factory is air-cooled by a ventilation fan from December to March and cooled by an absorption refrigerator from April to November.

In the previous study, the analysis was conducted assuming that the proposed plant factory was set up in Kitami. As a result, the minimum payback period was 6.64 years, and the target payback period (ten years or less) was achieved [8]. However, it is not investigated whether the proposed plant factory can be introduced in regions other than Kitami. Also, if the annual average temperature in the region where the proposed plant factory is located is around 7 ℃, it can be expected that annual energy consumption will be reduced and the payback period will be shortened. Therefore, in this paper, assuming that the proposed plant factory will be introduced in seven regions (Wakkanai, Asahikawa, Abashiri, Kutchan, Obihiro, Hiroo, Kitami) in Hokkaido, the payback period of capital investment of the proposed plant factory and the installation conditions that shorten the payback period will be investigated. Also, the target of the payback period of the proposed plant factory proposed shall be ten years or less.

II. Composition of a Proposed Plant Factory

Fig. 1 shows the configuration of the proposed plant factory that assumes process by exposure to the coldness of spinach. Furthermore, Fig. 2 shows the change of daily maximum temperature in Kitami and the room

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temperature in the plant factory. In the plant factory, the SOFC cogeneration with rated output 370kW and PV with rated output 370kW will be installed to cover the power consumption of the plant factory. From spring to autumn (April to November), the room temperature of the proposed plant factory is cooled to 7 ℃ by an absorption refrigerator. On the other hand, the maximum air temperature from December to March of Kitami is less than 7 ℃. Therefore, in this period, a ventilation fan is used to air cooling the plant factory. By using this cooling cycle, the energy consumption for air conditioning in winter can be reduced.

Typical plant factories are prefabricated houses or glass greenhouses, but the initial cost is high. Therefore, in the proposed plant factory, the initial cost is suppressed by using a vinyl greenhouse. The proposed plant factory has a double structure in which two greenhouses are stacked, and the gaps in the greenhouse are filled with a heat-insulating material (glass wool 24K). A heat shielding sheet is used for the outer covering material, and an agricultural specialty polyolefin film is used for the inner covering material. The plant factory has a structure in which 10 greenhouses with an opening of 5.4m and a height of 3.4m are arranged side by side, and the total opening of the plant factory is 54m. Based on this structure and dimensions, when the room temperature of the plant factory is maintained at 7 ℃ using the exhaust heat of SOFC cogeneration, the depth of the plant factory is 133.5m according to the heat balance calculation.

In a plant factory, spinach is processed by exposure to coldness with the leaves hanging down. This method is called aerial cultivation (hanging cultivation) and is introduced in this paper for the following reasons. In general spinach cultivation, the interrow spacing of spinach is about 20cm and the planting distance of spinach is about 5 to 7cm. However, in savoy spinach cultivation at processing by exposure to coldness, the occupied area of spinach increases because the leaves of spinach are open. So the interrow spacing of savoy spinach becomes about 20cm and the planting distance of savoy spinach become about 10 to 20cm [10]. Therefore, the cultivation area of savoy spinach is about twice that of general spinach. However, in the case where spinach is processed by exposure to coldness using aerial cultivation, the cultivation area can be made smaller than that of ordinary savoy spinach cultivation. This makes it possible to reduce the size of the plant factory system and is expected to reduce initial costs.

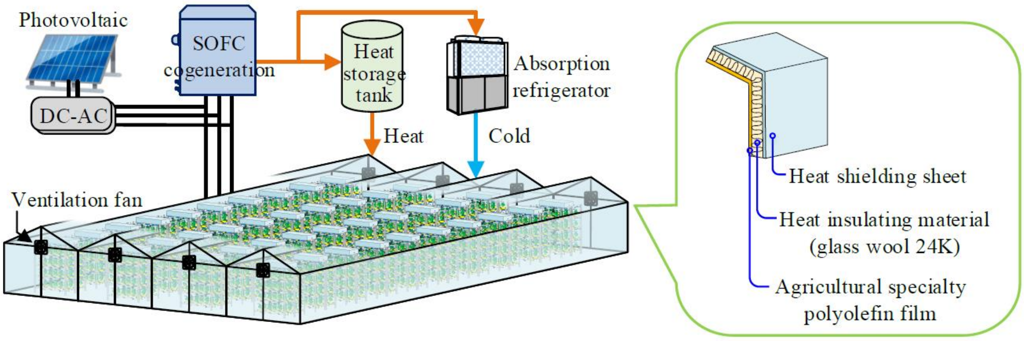

Figure 1. Configuration of a proposed plant factory.

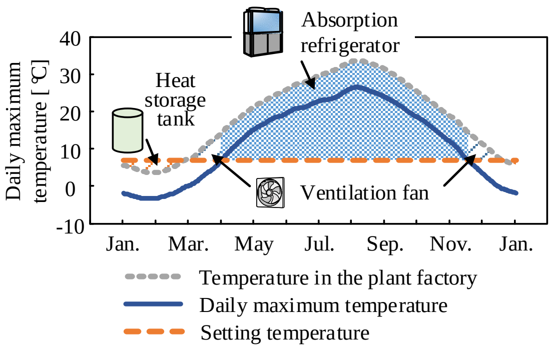

Figure 2. Change of the daily maximum temperature in Kitami for one year.

III. Analysis Method

A. Objective Function to Calculate the Payback Period of the Plant Factory

In this paper, the payback period of the proposed plant factory (F_{year} [year]) is minimized using the objective function of equation (1). The numerator of equation (1) is the initial cost of the plant factory ($C_{initial}$ [USD]), and the denominator is the profit (c_{profit} [USD/year]) when cultivating savoy spinach.

$$F_{year} = \sum_{m}^{12}\sum_{d}^{30}\sum_{t}^{24}\frac{C_{initial,t,d,m}}{c_{profit,t,d,m}} \rightarrow minimize \quad (1)$$

B. Electricity Balance and Heat Balance

Equation (2) is the electricity balance equation. The left side of equation (2) is the electricity of SOFC cogeneration (P_{sofc} [kW]) and the electricity of PV (P_{pv} [kW]), the right side is power consumption of the LED (P_{ll} [kW]) and power consumption of an absorption refrigerator (P_{ar} [kW]). The electricity balance equation for April to November is equation (2).

Equation (3) is a heat balance equation. The left side of equation (3) is the amount of solar radiation (H_{sh} [kW]), the heat generation amount of the LED (H_{ll} [kW]), the heat supplied from the heat storage tank (H_{hst} [kW]), the cold heat quantity by the absorption refrigerator (H_{ar} [kW]), the heat input (H_i [kW]) to the set temperature at the start of cultivation. The right side is the heat radiation quantity to the outside air (H_{ra} [kW], convective heat transmission from the outer wall). There is the balanced formula between April and November, and the electricity balance and heat balance between December and March are expressions in which the terms of absorption refrigerator (P_{ar} [kW], H_{ar} [kW]) in equation (2) and equation (3) are replaced with ventilation fan (P_{vf} [kW], H_{vf} [kW]). Also, in this calculation, the sampling time (t [hour]) is 1 hour.

$$P_{sofc,t} + P_{pv,t} = P_{ll,t} + P_{ar,t} \tag{2}$$

$$H_{sh,t} + H_{ll,t} + H_{hst,t} + H_{ar,t} = H_{ra,t} \tag{3}$$

IV. Analysis Conditions

In the previous study, power consumption and heat demand were analyzed using equation (2) and equation (3) based on the data of the outside air temperature and solar radiation on the representative day of each month in Kitami. Therefore, this paper investigates the installation conditions that shorten the payback period when the proposed plant factory is assumed to be installed in each region in Hokkaido.

From Fig. 3, the candidate region for the proposed plant factory is 23 regions where the meteorological observatory of the Meteorological Agency is installed. In the proposed plant factory, the room temperature of the plant factory is set to 7 ℃ to cultivate savoy spinach. Also, if the annual average temperature in the region where the proposed plant factory is located is around 7 ℃, it can be expected that annual energy consumption will be reduced and the payback period will be shortened. Fig. 4 summarizes the annual average temperatures in the 23 candidate regions, and seven regions (Wakkanai, Asahikawa, Abashiri, Kutchan, Obihiro, Hiroo, Kitami) fall within 7 ℃ ± 0.5 ℃. From this, this paper assumes that the proposed plant factory will be installed in these seven regions. At this time, the annual average temperature in the 23 candidate areas quoted the published values of the NEDO solar radiation database and the published values of the Japan Meteorological Agency [9], [11].

In addition, outside temperature and solar radiation used for the analysis were quoted from the published values of the NEDO solar radiation database [11].

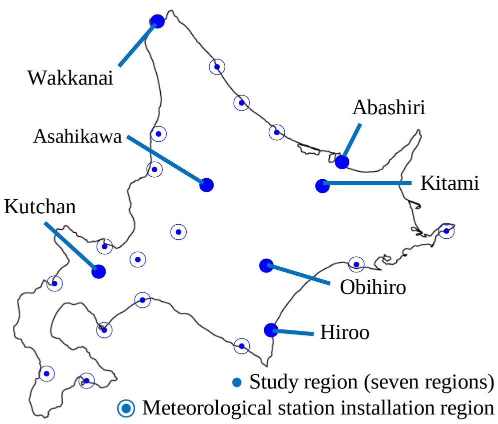

Figure 3. Investigation region in Hokkaido.

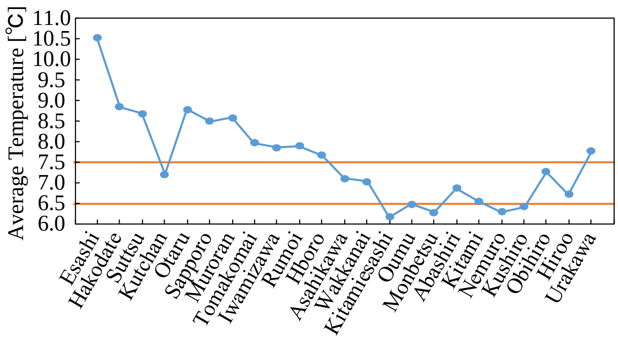

Figure 4. Annual average temperature in 23 regions.

V. Analysis Result

The purchase price of spinach is the average price (9.42 USD//kg) of 2017 [12], and the selling price of savoy spinach is 14.1 USD/kg. Based on these conditions, the PV introduction amount was analyzed from 0 % to 100 % in 10 % steps. Fig. 5 shows the analysis results of the payback period of the proposed plant factory for the quantity of PV introduction.

As a result of analysis using equation (1), the region with the shortest payback period was Hiroo, and the minimum payback period was 5.85 years (PV introduction percentage of 0 %). Also, the region with the longest payback period was Asahikawa, and the maximum payback period was 6.83 years (PV introduction percentage of 100 %). From this result, when the proposed plant factory is introduced in the seven selected regions, the payback period of the all regions are less than the target of 10 years, so commercial use can be expected.

In addition, the region where the annual average temperature is closer to the plant factory set temperature (7 ℃) is expected to consume less energy and shorten the payback period. From Table I, it was expected that the payback period would decrease in order from the top of the table, but the relationship between the temperature range (the difference between the set temperature of the proposed plant factory and annual average temperature) and the payback period could not be confirmed. However, there seems to be a relationship between the annual average temperature and the payback period. From Fig. 6, except for Asahikawa and Kitami, regions with low annual average temperatures tend to have a short payback period, and regions with high annual average temperatures tend to have a long payback period. The reason why Asahikawa and Kitami deviate from this trend is that the annual temperature range is large. From Fig. 7, the highest temperatures in Asahikawa and Kitami are higher than in other regions, also the annual temperature range is larger than in other regions. So the energy consumption (fuel consumption by an absorption refrigerator) in summer increases and the payback period is seemed to be longer.

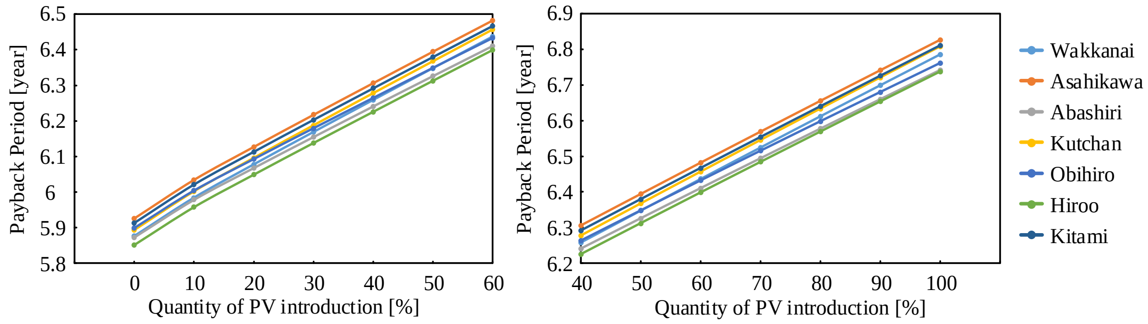

Figure 5. Proposed payback period of the plant factory to quantity of PV introduction.

TABLE I. SEVEN REGIONS PARAMETERS. (PAYBACK PERIOD, SOLAR RADIATION, MAXIMUM TEMPERATURE, ETC.)

	Payback period (PV = 0%)	Temperature range between set temperature and average temperature	Solar radiation	Average temperature	Maximum temperature	Annual temperature range
	[year] ※1	[℃] ※1	[MJ/m^2] ※2	[℃] ※1	[℃] ※1	[℃] ※1
Wakkanai	5.88 (3)	0.02 (1)	0.92 (7)	7.02 (4)	20.8 (3)	25.4 (1)
Asahikawa	5.93 (7)	0.10 (2)	1.02 (5)	7.10 (5)	27.6 (7)	38.4 (6)
Abashiri	5.87 (2)	0.14 (3)	1.14 (2)	6.86 (3)	20.3 (2)	28.6 (3)
Kutchan	5.89 (4)	0.20 (4)	0.93 (6)	7.20 (6)	22.6 (4)	29.6 (4)
Obihiro	5.90 (5)	0.26 (5)	1.22 (1)	7.26 (7)	24.7 (5)	37.1 (5)
Hiroo	5.85 (1)	0.29 (6)	1.10 (3)	6.71 (2)	19.4 (1)	26.2 (2)
Kitami	5.91 (6)	0.47 (7)	1.07 (4)	6.53 (1)	27.0 (6)	39.4 (7)

※1 Parentheses indicate descending order in seven regions ※2 Parentheses indicate ascending order in seven regions

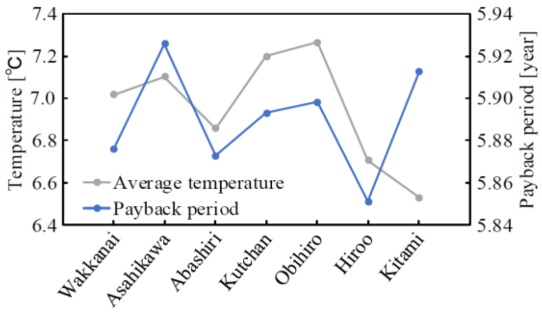

Figure 6. Transition in average temperature and payback period.

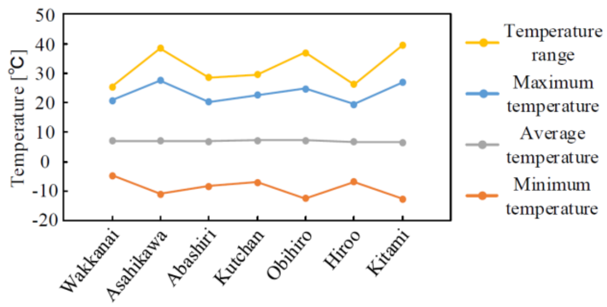

Figure 7. Each temperature data for the investigation region.

From this, when introducing the proposed plant factory in Hokkaido, it can be expected that the payback period will be shortened by installing it in the region where the annual average temperature is low and the annual temperature range is small.

VI. CONCLUSION

This paper investigated the installation conditions that shortened the payback period when the proposed plant factory was assumed to be installed in each region of Hokkaido. The proposed plant factory has set the temperature to 7 ℃ to process by exposure to the coldness of spinach. For this reason, if the annual average temperature in the region where the proposed plant factory is located is around 7 ℃, it is assumed that annual energy consumption will be reduced and the payback period will be shortened. Therefore, in this paper, the introduction regions of the proposed plant factory were set to seven regions (Wakkanai, Asahikawa, Abashiri, Kutchan, Obihiro, Hiroo, Kitami) where the difference between the set temperature (7 ℃) of the plant factory and the annual average temperature was ±0.5 ℃.

From the results of the analysis, the minimum payback period was 5.85 years for Hiroo (PV introduction percentage is 0%), and the maximum payback period was 6.83 for Asahikawa (PV introduction percentage is 100%). From this, the payback period in all the study regions are less than the target of 10 years, so commercial use can be expected.

In addition, the relationship between the temperature range (the difference between the set temperature of the proposed plant factory and annual average temperature) and the payback period could not be confirmed, which was not expected. On the other hand, the payback period tended to be shorter when the proposed plant factory was installed in the region where the annual average temperature was low. From this trend, it is considered that there is a proportional relationship between the annual average temperature and the payback period. However, in regions with large annual temperature range such as Asahikawa and Kitami, the payback period may be long even if the average annual temperature is low. From the above, it can be expected that the payback period will be shortened by installing the proposed plant factory in the region where the annual average temperature is low and the annual temperature range is small.

Based on the results of this analysis, future research will investigate in detail the conditions that minimize the payback period when the proposed plant factory is introduced in a cold region (Hokkaido) by analyzing mainly in regions where the annual average temperature is low and the annual temperature range is small. Furthermore, in this paper, it is assumed that the proposed plant factory was introduced only in Hokkaido in Japan. Therefore, future research will examine whether the proposed plant factory can be introduced even in regions where the outside air temperature is even lower (such as North Europe) or where crop cultivation is difficult (such as Antarctica).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Naoki Kikuchi conducted the research and analyzed the data; Naoki Kikuchi and Shin'ya Obara wrote the paper; all authors had approved the final version.

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