Performance of Agrivoltaic Systems for Shade-Intolerant Crops: Land for Both Food and Clean Energy Production

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Performance of Agrivoltaic Systems for Shade-intolerant Crops:
Land for Both Food and Clean Energy Production

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Abstract

The purpose of this research was to examine the performance of agrivoltaic systems, which produce crops and electricity simultaneously, by installing stilt-mounted photovoltaic (PV) panels on farmland. As PV power stations continue to enjoy remarkable growth, land occupation with the purpose of establishing solar farms will intensify the competition for land resources between food and clean energy production. In a bid to reduce this competition, previous studies have suggested that agrivoltaic systems can produce shade-tolerant crops such as lettuce under PV modules. However, if agrivoltaics work well only for some shade-tolerant crops, as existing studies seem to infer, their practical applicability would be very limited. Thus, the research considered three related questions: 1) Is it possible to grow shade-intolerant crops under the shade of agrivoltaic PV panels? 2) Can stilt-mounted agrivoltaic systems mitigate the trade-off between crop production and clean energy generation even when applied to shade-intolerant crops? 3) Is it financially feasible for farmers to adopt stilt-mounted agrivoltaic systems for shade-intolerant crops? In order to answer these questions, this research explored the performance of an agrivoltaic farm producing corn, a typical shade-intolerant crop.

The research was conducted at a 100-m^2 experimental farm with three sub-configurations: no modules (control), low-module density, and high-module density. Eight 0.76-m-wide PV module arrays, spaced at 0.71 m intervals, comprised the high-density configuration, while four PV module arrays spaced at 1.67 m intervals comprised

the low-density configuration. In each configuration, 25 corn stalks were planted 0.5 m apart (9 stalks/m^2).

The results showed that the stilt-mounted agrivoltaic system can mitigate the trade-off between crop production and clean energy generation even when applied to shade-intolerant crops. First, the biomass of corn stover grown in the low-density PV module configuration was larger than that of the no-module control configuration by 4.9%. Second, the corn yield per square meter of the low-density configuration was larger than that of the control by 5.6%. Third, the total annual revenue of the high-density configuration was 8.3 times larger than that of the control, while that of the low-density configuration was 4.7 times larger. Furthermore, according to the cost-benefit analysis for this case study, a good return on the investment is likely for such agrivoltaic systems. The cost-benefit ratios of high-density and low-density configurations over a 20-year period were 1.90 and 1.78, respectively, indicating that both systems would be financially feasible.

The results of this research should encourage more conventional farmers, clean energy producers, and policy makers to consider adopting stilt-mounted PV systems. Beyond its applications in agriculture, this system has the potential to generate electricity on pasture land, water surfaces, roads, and many other places without devastating the natural environment. Particularly in densely populated regions, mountainous areas, small inhabited islands, and barren desert areas, where land resources are relatively scarce, this system could exploit limited land resources for simultaneous food and clean energy production.

Acknowledgements

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Definition of Terms

Agrivoltaic: Co-developing the same area of land for agriculture and photovoltaic power generation

EIA: United States Energy Information Administration

IEA: International Energy Agency

JSSA: Japan Solar Sharing Association

MAFF: Japanese Ministry of Agriculture, Forestry and Fisheries

METI: Japanese Ministry of Economy, Trade and Industry

NREL: United States National Renewable Energy Laboratory

PV: Photovoltaic

SEIA: Solar Energy Industries Association

Chapter I

Introduction

Our society relies heavily on fossil fuels, which is not sustainable. The major fossil fuels including coal, oil, and natural gas dominate global energy consumption and, while their benefits are undeniable, they also cause serious environmental problems, from air pollution to global warming. Fossil fuels are also non-renewable; they draw on finite resources that will eventually dwindle. Thus, our continued reliance on fossil fuels is not possible, neither environmentally nor materially.

In contrast to fossil fuels, renewable energy resources are constantly replenished and more environmentally friendly. Commonly used renewable energy sources include biomass, hydropower, geothermal, wind, and solar. Today, the use of renewable energy is increasing. In 2017, 11% of total U.S. energy consumption and approximately 17% of U.S. electricity generation was from renewable energy sources (EIA, 2018). In addition, renewable energy plays an important role in reducing greenhouse gas emissions. Non-biomass renewable sources of energy such as hydropower, geothermal, wind, and solar do not directly emit greenhouse gases. Despite these strengths, renewable energy is typically more expensive to produce and use than fossil fuels and energy sources are not always available. For example, clouds reduce electricity generation from solar power plants, low-wind days reduce electricity generation from wind farms, and droughts reduce the water available for hydropower.

Among renewable energy technologies, photovoltaic (hereafter called “PV”) power generation has enjoyed remarkable growth over the past decade. PV systems have several advantages. First, PV systems can supply electricity in locations where electricity distribution systems do not exist, and they can also supply electricity to the electric power grid. Second, PV arrays can be installed quickly and at any size. Also, PV systems do not directly emit air pollutants, which harm human health and the global climate. PV systems designed for the supply of commercial power into the electricity grid are known as PV power stations, solar farms, or solar parks. Commercial PV power stations are different from building-mounted and other decentralized solar power applications because they supply power at the utility level, rather than to a local user or users. Most existing large-scale solar power plants are owned and operated by independent power producers (SEIA, 2018).

According to International Energy Agency (hereinafter called “IEA”), the installed capacity of PV in major countries was approximately 402 GW in 2017, 70 times higher than in 2006. Additions in 2017 alone amounted to at least 96 GW. Although PV’s overall share of global power generation remains low at 2.1%, Honduras, Germany, Greece, Italy, and Japan now have enough PV capacity to theoretically produce more than 5% of their annual electricity demand with PV. Solar is beginning to have a noticeable impact among sources of power generation growth. By the end of 2017, 29 countries had at least 1 GW of cumulative PV system capacity and eight countries had installed at least 1 GW. China alone accounts for 32% of the global installed capacity. The United States ranks second (51 GW) with Japan third (49 GW) and Germany fourth (42 GW) (IEA, 2018a).

Government incentives have promoted the recent growth of PV power stations. Compared with fossil fuel systems, the levelized cost of PV systems is higher. Investors of residential and commercial PV systems are typically faced with fundamental economic challenges: the cost of electricity from such systems exceeds that of electricity from fossil fuel-based utilities and other sources. Consequently, without financial incentives, building and land owners will not invest in PV systems, and utilities will not purchase electricity from these systems. Therefore, the feed-in-tariff initiatives favored in Europe, together with comparable measures adopted in the United States, China, and Japan, have played an indispensable role in promoting PV systems in these countries.

As PV power stations continue to enjoy remarkable growth, land occupation intended for solar farms will intensify competition for land resources between food and clean energy production (e.g., Nonhebel, 2005). The question remains as to how competition for land resources between food and energy production can be resolved. Although PV systems require less land than other renewable energy options (Fthenakis & Kim, 2009), in reality, commercial PV power stations can occupy a considerable land area at local scales. In many cases, the most suitable sites for solar power plants, which perform optimally with long daylight hours and minimal cloud cover, are classified as agricultural land. This presents an issue in that land supporting viable and diverse agriculture is likely to have more value as agricultural land than as a solar farm (Neil, Stapleton, & Martell, 2017). This competition could be particularly serious in densely populated regions, mountainous areas, and small inhabited islands.

However, this competition could be reduced by agrivoltaic systems, which produce crops and electricity at the same time by installing compact solar panels on farmland. Although previous studies have indicated that this system effectively produces shade-tolerant crops and electricity simultaneously (e.g. Marrow et al., 2013), further studies are required to evaluate its practical applications. In particular, the performance of shade-intolerant crops, which are expected to grow poorly in low-light environments, has not yet been fully explored for agrivoltaic systems. As well as the feasibility of crop production, the financial feasibility of agrivoltaic systems should also be determined via cost-benefit analyses in different countries and regions.

Research Significance and Objectives

The fundamental problem tackled by this research was how to reduce competition for land resources between food production and PV power generation. In other words, the main objective was to identify a PV system that can help reduce the tension between limited land resources and increasing demands for food and clean energy. Roof-top PV systems can partially satisfy home electricity demands, but other sectors consume more electricity. In the United States, for example, the residential sector accounts for only 37.1% of the final electricity consumption, while 36.0% and 21.3% of the total is consumed by the commercial sector and industry, respectively (IEA, 2018b). As a major renewable energy source, large (commercial-scale) PV power stations are key for meeting the demands of those sectors. Although lifecycle studies of PV systems show a lower requirement for land than other renewable energy options (Fthenakis & Kim, 2009), commercial PV power stations nevertheless occupy vast tracts of land at local scales.

This problem could be solved by agrivoltaic systems. Thus, this thesis has the following objectives:

- To evaluate the effectiveness of agrivoltaic systems at reducing competition for land resources between agriculture and PV power generation.
- To examine the applications of agrivoltaic systems to shade-intolerant crops.
- To determine the financial feasibility of agrivoltaic systems in countries where detailed agrivoltaic farm experiments have not yet been reported.

Background

To date, three types of agrivoltaic systems, which simultaneously enable crop and electricity production on farmland, have been proposed (Figure 1). The first type was proposed in the early 1980s, using the space between PV rows for crops (Goetzberger, 1982). The second type is a PV greenhouse, in which part of its transparent covering is replaced by PV modules. The use of PV for greenhouses is a promising solution for the competition for land resources between food and energy production because it allows

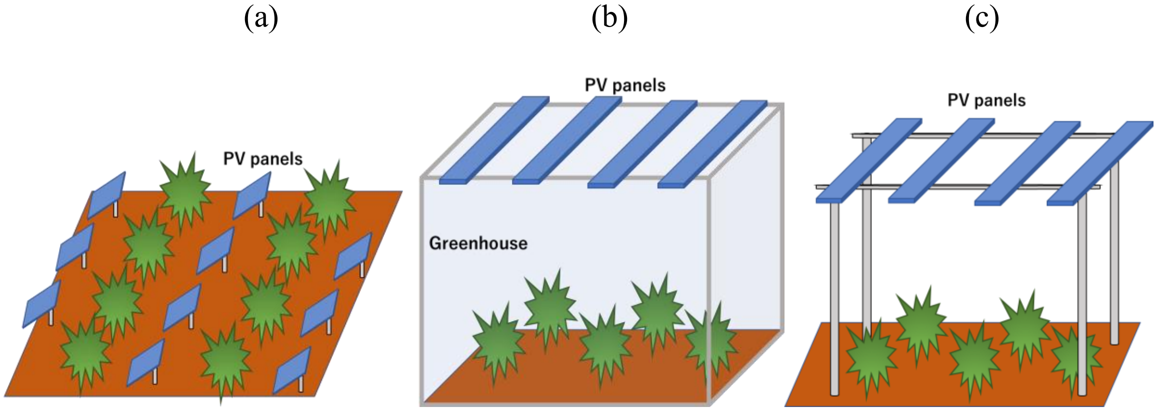

Figure 1. Three different types of agrivoltaic system: (a) using the space between PV panels for crops, (b) a PV greenhouse, and (c) **a** stilt-mounted system.

continuous food production and electricity generation throughout the year (Scognamiglio, 2014). The third type consists of stilt-mounted PV modules above the crops.

Stilt-mounted agrivoltaic systems were originally invented by Akira Nagashima, an agricultural machinery engineer, in 2004. Nagashima devised and patented a special structure similar to a garden pergola (Japan Patent No. 2005-277038, 2005). The structure is made of pipes and rows of PV panels mounted above the ground and arranged at certain intervals to allow enough sunlight for photosynthesis to penetrate to the ground. The system is designed to guarantee adequate sunlight for crops and sufficient space for agricultural machinery. Moreover, the structure has no concrete footing so can be easily dismantled.

Existing studies have focused on agrivoltaics with stilted solar arrays. Farm experiments with stilt-mounted PV modules were recently reported in France (e.g. Marrow et al., 2013), Japan (Nagashima, 2014), and the United States (Majumdar & Pasqualetti, 2018). They indicated that the system of planting shade-tolerant crops does not decrease land productivity. Adoption of agrivoltaic systems may therefore require minimal adaptation of cropping practices. The first reported agrivoltaic farm experiment was performed in Montpellier, France, in 2013 (Marrow et al., 2013). Marrow and colleagues grew lettuce crops with a system consisting of 0.8-m-wide stilt-mounted PV modules, mounted at a height of 4 m and tilted at an angle of 25°. The same area of land was used to successfully produce both electricity and food. Their results showed that shading created by the PV arrays had no significant effect on the lettuce yield. The growth rate below the PV panels was not reduced except during the juvenile phase of the crop.

Interestingly, field experiments performed by Dupraz and colleagues found that agrivoltaic systems even increased land productivity for durum wheat by 35–72% (Dupraz et al., 2011). They used land equivalent ratios to compare conventional options (separation of agriculture and energy harvesting) and two agrivoltaic systems with different PV panel densities. Light transmission at the crop level by an array of solar panels was modeled, and a crop model was developed to predict the productivity of partially shaded crops. According to another field experiment, solar-generated electricity coupled with shade-tolerant lettuce production resulted in an increase in economic value of over 30% over conventional agriculture (Dinesh & Pearce, 2016).

Gaps in Current Agrivoltaics Research

In order to evaluate the practical value of agrivoltaic systems, however, further studies are required. For example, the potential of PV greenhouses has yet to be explored as previous farm experiments have mainly focused on agrivoltaic systems consisting of stilt-mounted PV modules above crops. Nevertheless, further research on stilt-mounted PV systems is still vital, particularly in terms of their application to shade-intolerant crops and their financial feasibility in different regions and countries.

Application to shade-intolerant crops. The studies reviewed above only indicate that agrivoltaics are effective for plants that are shade resistant, namely, arugula, Asian greens, chard, collard greens, kale, mustard greens, parsley, sorrel, spinach, scallions, broccoli, kohlrabi, cabbage, hog peanut, alfalfa, yam, taro, cassava, and sweet potato (Dinesh & Pearce, 2016). However, the effectiveness of the system for shade-intolerant crops, which are expected to grow poorly in a low-light environment, has not yet been explored. Many major commercial crops, such as corn, watermelon, tomato, cucumber, pumpkin, cabbage, turnip, and rice are shade intolerant and presumably require abundant sunlight. If agrivoltaics are only applicable to commercially less viable and shade-tolerant crops, the system is not likely to produce enough food and clean energy to meet the increasing global demands.

However, it is possible that shade-intolerant crops can grow under the shade of agrivoltaic PV panels. Shade tolerance is a plant trait that describes its ability to tolerate low light levels. Only limited screening studies of crop tolerance to shade are available (e.g., Johnston & Onwueme, 1998; Lin, Zhang, & Chen, 2007). In practice, corn, watermelons, tomatoes, and taro are reputed to have high saturation points, which means that they need strong light to grow. Examples of crops that prefer moderate light include cucumbers, turnips, pumpkins, cabbage, and green peppers. Mushrooms show a preference for growth in comparatively dark places.

For example, Nagashima (2014) reported that corn, a typical shade-intolerant crop, could grow well under the shade of agrivoltaic PV panels. Surprisingly, some stalks under the panels grew even higher than those without shade at his experimental farm. Unfortunately, however, he compared the height of corn stalks by sight alone and only reported qualitative results. Thus, quantitative research is necessary to examine the applicability of agrivoltaic systems to shade-intolerant crops such as corn.

Financial feasibility in different countries and regions. More cost-benefit analyses in different countries and regions are necessary to examine the feasibility of agrivoltaic systems. A study on a stilt-mounted agrivoltaic system cultivating lettuce in Kansas indicated that the system could earn a farmer 8–30% more than conventional farming (Dinesh & Pearce, 2015). Installation of this system was determined financially feasible for conventional farmers under several assumptions including US residential electric rates, a discount rate of 4.5%, a loan term of 30 years, a degradation rate of 0.5%/year, insurance costs of 1.5%, O&M costs of 9%, and a zero interest loan of 100% debt.

However, the costs of PV systems vary significantly among countries or even within a country because they are largely determined by local resource availability. While the price of PV modules has been reduced due to technological advances and the scale of the economy (Fraunhofer, 2015), soft costs such as different supply chains, local regulatory requirements, labor and permitting costs, and different financing mechanisms lead to wide regional differences (IEA, 2015). As a result, prices for entire PV systems vary more widely than those for PV modules, which tend to be global commodities. Small systems such as rooftop systems are usually more expensive than their larger counterparts, especially ground-based, utility-scale systems.

Prices for similar system types also vary significantly among countries (Table 1). Thus, to boost the global adoption of agrivoltaic systems, it is necessary to study their

Table 1. Typical prices of PV systems in selected countries in 2013 (IEA, 2014).

(unit: USD/W)

	Australia	China	France	Germany	Italy	Japan	UK	US
Residential	1.8	1.5	4.1	2.4	2.8	4.2	2.8	4.9
Commercial	1.7	1.4	2.7	1.8	1.9	3.6	2.4	4.5
Utility-scale	2.0	1.4	2.2	1.4	1.5	2.9	1.9	3.3

financial feasibility in countries where detailed agrivoltaic farm experiments have not yet been reported, at least in English journals. In light of the relatively high installation costs, it is important to examine the feasibility of agrivoltaic systems in Japan.

Agrivoltaic Systems in Japan

Although scarce information is available in English publications, the implementation of agrivoltaic systems has been rapidly spreading in Japan. Agrivoltaic systems are known as "Solar Sharing" in Japan. Although the concept was originally developed in 2004 by Akira Nagashima, the Japanese Agricultural Land Act had prohibited solar generation on farmland at the time. In April 2013, however, the Japanese Ministry of Agriculture, Forestry and Fisheries gave its approval to install agrivoltaic systems on farmland under the following conditions:

1. The support posts must be easily constructed and easily removed.
2. They must be designed to ensure a suitable amount of sunlight for the growth of crops from the perspective of panel angle, gaps, and so forth.
3. Reports on the status of the produce grown on the agricultural land underneath the agricultural power equipment must be given every year.
4. The conversion period pertaining to each application shall be a term of no more than three years, and approval must be obtained for extensions if there are no problems.

These conditions are to ensure that farmers remain farmers, and do not fully convert productive farmland into PV power stations. Farmers, therefore, are required to report their annual crop cultivation, and if the crop yield of the solar-shared farmland falls below 80% compared to the original level, they will be required to dismantle the PV system.

In addition, the onset of the feed-in tariff scheme made agrivoltaic systems more attractive. The Japanese Ministry of Economy, Trade, and Industry adopted the feed-in tariff scheme in July 2012, whereupon electric power companies are obliged to buy electricity generated from renewable sources at a fixed price for a certain period. Under this policy, Japanese electric power companies have been purchasing electricity generated from solar and wind power systems of independent power producers and customers (METI, 2012). These deregulation measures as well as financial support have encouraged Japanese farmers to install agrivoltaic systems on their farmland.

As of March 2017, 1296 Japanese farms had registered to install agrivoltaic systems (MAFF, 2018a). As seen from Table 2, many different crops have been planted under PV panels on these registered agrivoltaic farms: blackberry, blueberry, broad bean, carrot, chestnut, eggplant, grape, ginger, leek, lettuce, mandarin orange, mushroom, pasture, peanut, persimmon, potato, radish, red bean, rice, spinach, tea, tomato, turnip, and wheat. Their electricity generation capacity ranges from 10–393 kW, but the typical capacity is approximately 50 kW (Solar Sharing Network, 2018b) (Table 2).

The installation of agrivoltaic systems can be financially feasible in Japan. For example, an agrivoltaic farmer in Chiba prefecture (Movellan, 2013) installed 348 stilt-mounted PV panels on a 750-m^2 farm, and cultivated peanuts, yams, eggplants, cucumber, tomatoes, taros, and cabbages under the PV panels. The installation cost of the PV system,

Table 2. Examples of agrivoltaic farms in Japan.

Name of Farm	Location	Generation Capacity	Crops
Yachimata	Chiba prefecture	392.7 kW	Blueberry
Isezaki	Gunma prefecture	140 kW	Grape
Makinohara	Shizuoka prefecture	56 kW	Tea
Wakaba	Chiba prefecture	50 kW	Wheat
Hatano	Kanagawa prefecture	50 kW	Orange
Kasu	Saitama prefecture	50 kW	Red bean
Imabari	Ehime prefecture	33 kW	Rice

Source: Solar Sharing Network (2018b)

which produces 35,000 kWh a year, was approximately 12.6 million yen (approximately 114,500 USD). Having secured the feed-in-tariff rate of 42 yen per kWh for 20 years, he should be able to earn 1.47 million yen (approximately 13,000 USD) annually, while making only 100,000 yen (approximately 900 USD) from agriculture.

In summary, existing studies suggest that agrivoltaic systems are effective for simultaneously producing shade-tolerant crops and electricity. Considering the requirements stated above, however, it is meaningful to study the possibility of coupling agrivoltaic systems with shade-intolerant crops such as corn. It is important to check whether an increase in the overall productivity of land could be achieved even with crops that need plenty of sunlight. In addition, more cost-benefit analyses in different countries and regions are necessary. It could be particularly useful to learn from Japan's rich experience in agrivoltaic farming.

Research Questions, Hypotheses, and Specific Aims

The goal of this research was to examine the effectiveness of agrivoltaic systems for reducing the tensions between limited land resources and increasing demands for food and clean energy. Particularly, this research focused on the stilt-mounted type of agrivoltaic system, which is the most widely adopted system in existing studies and practice. In order to achieve this goal, the research considers three related questions: 1) Is it possible to grow shade-intolerant crops under the shade of agrivoltaic PV panels? 2) Can stilt-mounted agrivoltaic systems mitigate the trade-off between crop production and clean energy generation even when applied to shade-intolerant crops? 3) Is it financially feasible for farmers to adopt stilt-mounted agrivoltaic systems in a country such as Japan?

Therefore, the hypotheses examined in this research are as follows:

- The biomass of corn stover grown in an agrivoltaic farm will be no less than 90% that of corn plants grown without the agrivoltaic system. (Stover refers to dried stalks and leaves of a field crop.)
- The annual revenue from PV power generation and corn harvest in an agrivoltaic farm will be larger than that of a traditional corn field.
- The cost benefit ratio of a stilt-mounted agrivoltaic system will be larger than 1.0 in Japan, indicating financial feasibility.

Specific Aims

To test the hypotheses stated above, the specific aims of this research were as follows:

- Establish field experimental plots.
- Monitor the growth and yield of corn plants in the experimental plots.
- Gauge the biomass of corn plants harvested in the experimental plots.
- Calculate the annual profits per square meter of the experimental plots.
- Develop a spreadsheet for a cost benefit analysis.

Research Presentation

Chapters II and III of this thesis are presented in the form of discrete journal articles with their own methods, results, and summary sections. Chapter II examines the sensitivity of corn yield and annual revenue per square meter to changes in the level of crop shading. Chapter III evaluates the financial feasibility of the agrivoltaic system in Japan. While the articles are related as part of this thesis, they are intended to be published independently.

Chapter II

Sensitivity of Corn Yield per Square Meter to Changes in Shading Level

Previous studies have suggested that agrivoltaic systems are effective for simultaneously producing electricity and shade-tolerant crops such as lettuce. However, if agrivoltaics are effective only for a few shade-tolerant crops, the system's practical applications would be very limited. Thus, this research explored the applicability of agrivoltaic systems to corn, a typical shade-intolerant crop.

Methods

Data necessary for this research were collected from a case study plot at the agrivoltaic experimental farm operated by the CHO Technical Research Institute in Ichihara City, Chiba Prefecture, Japan (Latitude: 35.378929, Longitude: 140.138549).

Data Collection

The size of the experimental farm was 100 m^2 and contained three sub-configurations; no modules (control), low-module density, and high-module density (Figure 2). The solar PV modules were mounted on the ground, with the area underneath the stilts used for agriculture and large enough to accommodate farming equipment. The total output capacity of the PV system was 4.5 kW. The feed-in-tariff rate of 48 yen (approximately 0.44 USD) per kWh was secured for this PV system.

This system consisted of 72 PV modules (1354 mm x 345 mm) mounted at a height of 2.7 m and tilted at an angle of 30°. In the high-density configuration, there were eight PV module arrays (48 modules) spaced at 0.71 m intervals. In the low-density configuration, there were four PV module arrays (24 modules) spaced at 1.67 m intervals. Both the stilt-mounted PV panel configurations casted shade on the crop below. The shading from the PV module varied according to the time of year and height of the crops planted between the module rows. The no-module (control) configuration had no PV modules above the ground.

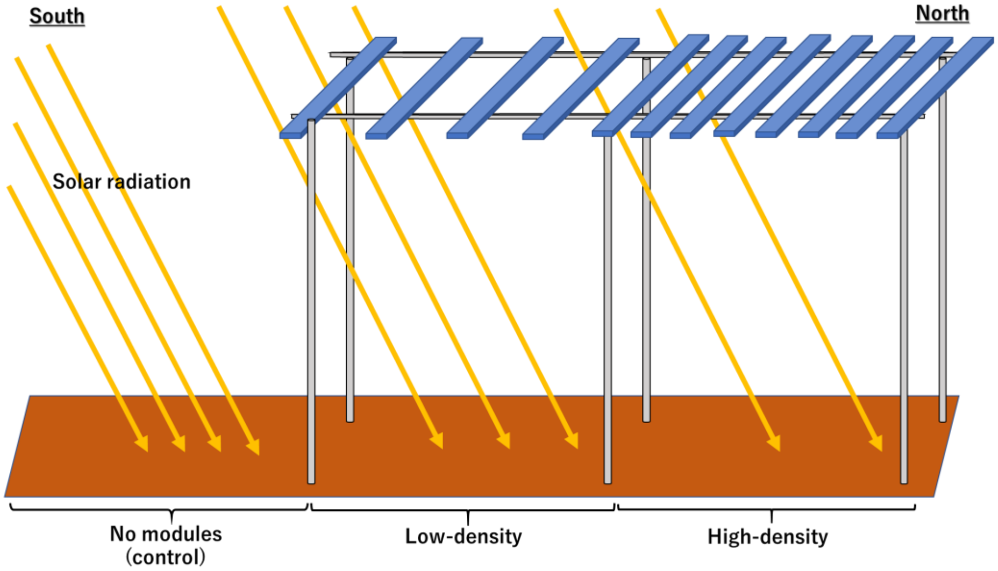

Figure 2. PV module configurations at the agrivoltaic experimental farm.

The PV modules used in this research had a self-cleaning glass surface. Farming equipment spreads dust, which causes soiling of the PV modules and affects the electricity output. This dust diminishes the transmittance capacity of the transparent collectors on the PV module surface. Therefore, periodic cleaning of the panels is required to maintain optimum power output. The PV modules in this research, however, could maintain clean surfaces without the need for frequent cleaning.

For this research, sweetcorn was planted on the experimental farm in early April 2018 and harvested in late July. Corn is a typical shade-intolerant crop and a major global commodity. Corn has a growth period of approximately 90 days and grows up to a height of 2 m. In each configuration, there were 25 corn stalks spaced 0.5 m apart (nine stalks per 1 m^2). The same soil, fertilizer, and water were used to grow all corn crops. After harvesting, the weight, size, and market value of the reproductive part of the crop were evaluated. The market value was calculated using the 5-year average of the market price obtained by the Agriculture & Livestock Industries Corporation, a Japanese governmental agency. The corn stover was dried to measure its biomass.

Sensitivity Analysis

This research evaluated the sensitivity of the corn yield per square meter with respect to changes in the level of shading. If the biomass of corn plants grown in an agrivoltaic farm is no less than 90% that of corn plants grown separately, the corn can be said to grow well under the shade of agrivoltaic PV panels, as predicted by Nagashima (2014). Thus, this research tested this hypothesis using equation 1. Here, $B_{\mathrm{C(trad)}}$ is the traditional amount of crop biomass (dry basis) per square meter without an agrivoltaic installation, and B_{C} is the amount of the crop biomass per square meter with agrivoltaic intervention:

$$90\% \times B_{\mathrm{C(trad)}} =< B_{\mathrm{C}} \tag{1}$$

Also, when the annual revenue from PV power generation and corn harvest in an agrivoltaic farm is larger than that of a traditional corn field, equation 2 should be true, where $V_{\mathrm{C(trad)}}$ is the traditional value of the crop per square meter per year without an agrivoltaic installation, V_{C} is the revenue of the crop per square meter per year with agrivoltaic intervention, and S is the solar revenue per square meter per year:

$$V_{\mathrm{C(trad)}} < (V_{\mathrm{C}} + S) \tag{2}$$

Results

To examine the corn production performance of the experimental agrivoltaic farm, this research explored the sensitivity of corn yield per square meter to changes in shading level.

Corn Yield

The growth of corn planted under the PV modules was gauged in terms of the fresh weight of corn crops as well as biomass of corn stover. As mentioned earlier, the corn was planted in early April 2018 and harvested in late July. Surprisingly, the corn yield of the low-density configuration was larger not only than that of the high-density configuration, but also than that of the no-module control configuration (Table 3 and Table 4). The relationship between the crop biomass per square meter in the low-density configuration ($B_{c(low)}$) and the crop biomass per square meter without the agrivoltaic PV modules ($B_{\mathrm{C(trad)}}$) is shown by the following equations:

$$B_{\mathrm{C(low)}} / B_{\mathrm{C(trad)}} = 1.049$$

$$\therefore B_{\mathrm{C(trad)}} < B_{\mathrm{C(low)}} \tag{3}$$

Table 3. Average fresh weight of corn crops grown in different configurations.

	Configurations		
	Control	Low-density	High-density
Average fresh weight (g)	372.2	393.0	358.8
Comparison with Control	1	1.056	0.964

Table 4. Average biomass (dry basis) of corn stover grown in different configurations.

	Configurations		
	Control	Low-density	High-density
Average biomass (kg/m^2)	1.63	1.71	1.58
Comparison with Control	1	1.049	0.969

Similarly, the relationship between $B_{c(high)}$, the crop biomass per square meter in the high-density configuration, and $B_{C(trad)}$ is shown in the following equations:

$$B_{C(high)} / B_{C(trad)} = 0.969$$

$$\therefore\ 90\% \text{ x } B_{C(trad)} < B_{C(high)} \qquad (4)$$

As shown in Figure 3 and Figure 4, the corn yield depends on the shading. Shading affects the amount of incident solar irradiation, which in turn affects the yield including the weight of crops and biomass of plants. The sensitivity of the corn yield can be described as the change in fresh weight of reproductive parts and amount of biomass (dry basis) of corn stover with respect to the spacing between modules.

The crop yield (Y) can be calculated by:

$$Y\ [kg/m^2] = (W \text{ x } d)/1000 \qquad (5)$$

where W is the average fresh weight of crops (g) and d is the number of plants per square meter, which is nine in this study. Values of W for the control configuration, low-density

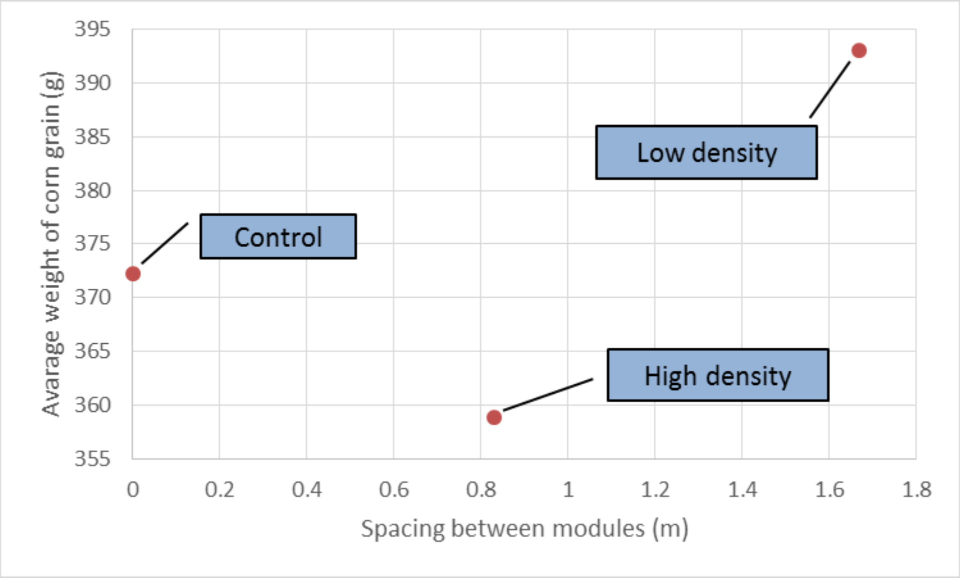

Figure 3. Sensitivity of fresh weight of reproductive corn parts with respect to the spacing between modules.

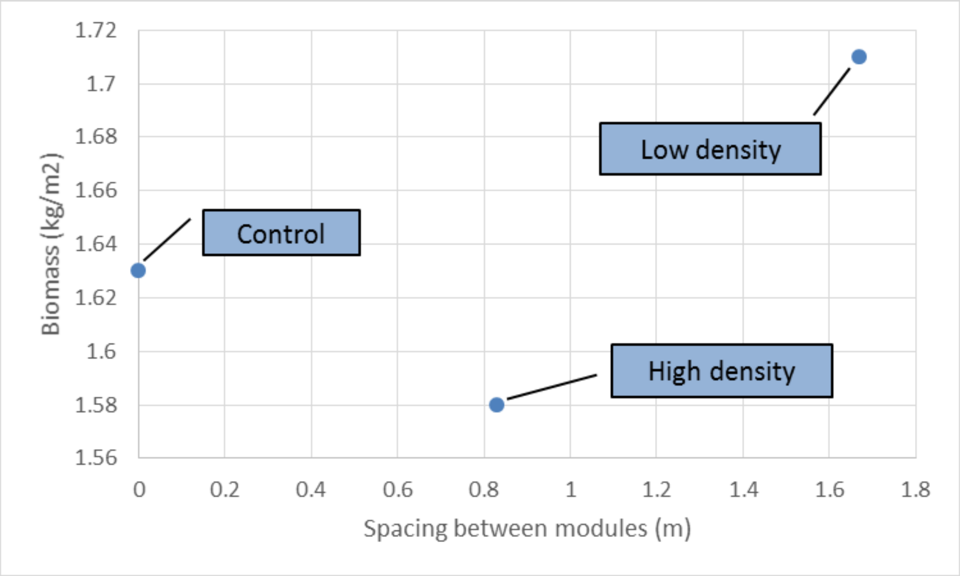

Figure 4. Sensitivity of crop biomass of corn stover with respect to the spacing between modules.

configuration, and high-density configuration are 372.2, 393.0, and 358.8, respectively, which resulted in the low density configuration exhibiting the highest corn yield, as shown in Table 5.

Table 5. Corn yields per square meter for different configurations.

	Configurations		
	Control	Low-density	High-density
Corn yield (kg/m^2)	3.35	3.54	3.23

Performance of the PV System

The monthly kWh output of the PV modules for different configurations is shown in Table 6 and Table 7. Figure 5 reveals that the high-density configuration produced

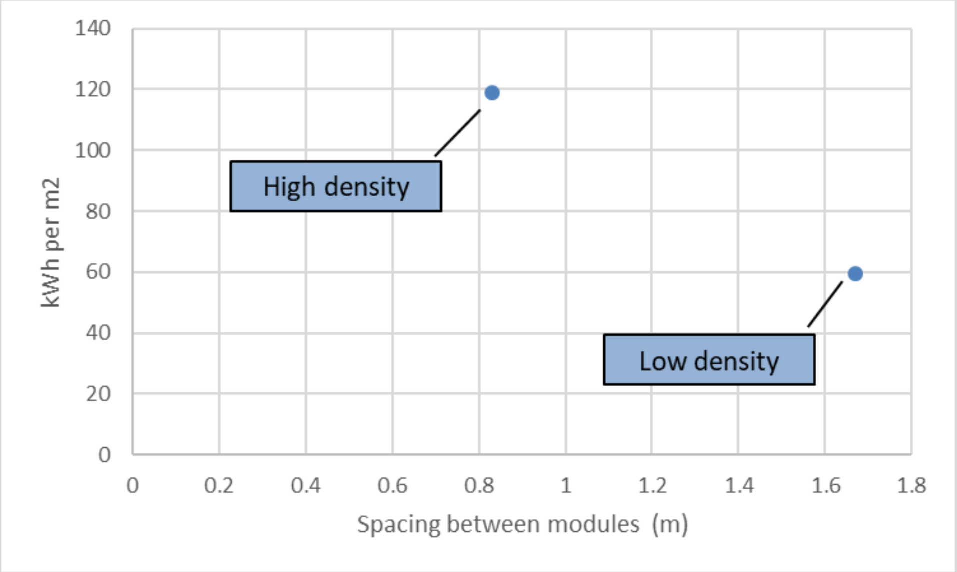

Figure 5. Sensitivity of annual PV power output with respect to the spacing between modules.

Table 6. Power output (kWh) of stilt-mounted agrivoltaic PV modules in the high-density configuration from September 2017 to August 2018.

Year	Month	kWh per day	kWh per month	kWh per m2	Revenue per m2 (Yen)	Revenue (Yen)
2017	9	2.55	227	9.09	436	10912
2017	10	1.65	142	5.68	273	6816
2017	11	1.74	171	6.85	329	8224
2017	12	1.80	150	6.00	288	7200
2018	1	1.99	183	7.33	352	8800
2018	2	2.36	218	8.72	419	10464
2018	3	2.99	267	10.69	513	12832
2018	4	3.64	303	12.13	582	14560
2018	5	3.79	373	14.91	716	17888
2018	6	2.73	236	9.44	453	11328
2018	7	3.97	355	14.19	681	17024
2018	8	3.65	348	13.92	668	16704
Total			2974	118.96	5710	142752

Table 7. Power output (kWh) of stilt-mounted agrivoltaic PV modules in the low-density configuration from September 2017 to August 2018.

Year	Month	kWh per day	kWh per month	kWh per m2	Revenue per m2 (Yen)	Revenue (Yen)
2017	9	2.546	114	4.55	218	5456
2017	10	1.645	71	2.84	136	3408
2017	11	1.745	86	3.43	164	4112
2017	12	1.800	75	3.00	144	3600
2018	1	1.987	92	3.67	176	4400
2018	2	2.363	109	4.36	209	5232
2018	3	2.994	134	5.35	257	6416
2018	4	3.640	152	6.07	291	7280
2018	5	3.795	186	7.45	358	8944
2018	6	2.735	118	4.72	227	5664
2018	7	3.973	177	7.09	340	8512
2018	8	3.654	174	6.96	334	8352
Total			1487	59.48	2855	71376

double the electricity per square meter than the low-density configuration. In other words, although the low-density configuration was able to exploit more sunlight for the crop plants underneath the PV modules, it clearly has a reduced PV output compared with the high-density configuration.

Crop Revenues

The revenue per square meter from crop yields can be calculated by:

$$V_c\ [\text{yen/m}^2] = Y \times P \qquad (6)$$

where Y is the average fresh weight of crops (kg) and P is the wholesale price of the crop per kg. According to data from the Agriculture & Livestock Industries Corporation, the historical prices of sweetcorn produced in Chiba prefecture over a period of 5 years from 2013 through 2017 are shown in Table 8. Using the 5-year average price, the revenue of corn grown in the different configurations was calculated (Table 9).

Table 8. Annual average price of sweetcorn in Tokyo Metropolitan Central Wholesale Market from 2013 to 2017.

Year	2013	2014	2015	2016	2017	5-year average
Annual average price (yen per kg)	223	245	265	213	224	**234**

Source: Agriculture & Livestock Industries Corporation (2018).

Table 9. Annual revenue per square meter from corn crops grown in different configurations.

	Configurations		
	Control	Low-density	High-density
Crop revenue (yen/m^2)	783.90	828.36	755.82

The revenue of power generation for different configurations is shown in Table 6 and Table 7. The CHO Institute of Technology has secured the feed-in-tariff rate of 48 yen (approximately 0.44 USD) per kWh for 20 years. The annual revenue per square meter from PV power generation (S) can be calculated by:

$$S\ [\text{yen/m}^2] = E \times r \qquad (7)$$

where the annual power output per square meter of agrivoltaic PV modules is E (kWh) and r is the feed-in-tariff rate. Utilizing the corresponding values for each configuration, the annual revenue per square meter from PV power generation was 2855 JPY and 5710 JPY for the low-density and high-density configuration, respectively. Thus, the annual total revenue per square meter from corn crops and PV power generation ($V_c + S$) can be calculated as shown in Table 10.

Table 10. Annual total revenue per square meter from corn crops and PV in different configurations.

	Configurations		
	Control	Low-density	High-density
Total revenue (yen/m^2)	783.90	3683.36	6465.82

Therefore, if the annual revenues per square meter from corn crops in low-density and high-density configurations are $V_{c(low)}$ and $V_{c(high)}$, respectively, and those from PV power generation in low-density and high-density configurations are $S_{(low)}$ and $S_{(high)}$, respectively, their relationship with the annual revenue per square meter without agrivoltaic PV panels in the control configuration ($V_{c(trad)}$) can be described as:

$$V_{c(trad)} < V_{c(low)} + S_{(low)} < V_{c(high)} + S_{(high)} \qquad (8)$$

This relationship will not change even with lower fit-in-tariff rate. Although the CHO Institute of Technology secured the feed-in-tariff rate of 48 yen per kWh in 2010, the rate has nonetheless been declining (Figure 6).

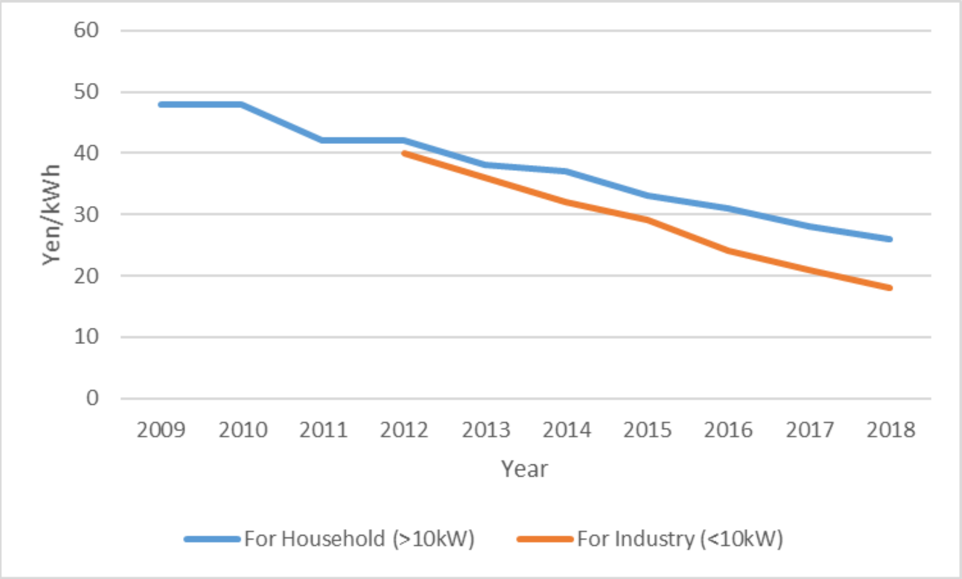

Figure 6. Change in feed-in-tariff rate for PV power generation in Japan (Data: METI, 2018).

The Japanese government is planning to set the rate at 11 JPY per kWh for household-level generators (less than 10 kW) and at 8 JPY per kWh for industry-level generators (more than 10 kW) around the mid-2020s (METI, 2018). Even with these lower fit-in-tariff rates, the annual revenue from PV power generation and the corn harvest in an agrivoltaic farm could be larger than that of a traditional corn field (Table 11 and Figure 7).

Table 11. Annual total revenue per square meter with different feed-in-tariff rates.

Configuration	Feed-In-Tariff Rates			
	48	26	11	8
High-density	6465.82	3848.736667	2064.361667	1707.486667
Low-density	3683.36	2374.818333	1482.630833	1304.193333
Control	783.9	783.9	783.9	783.9

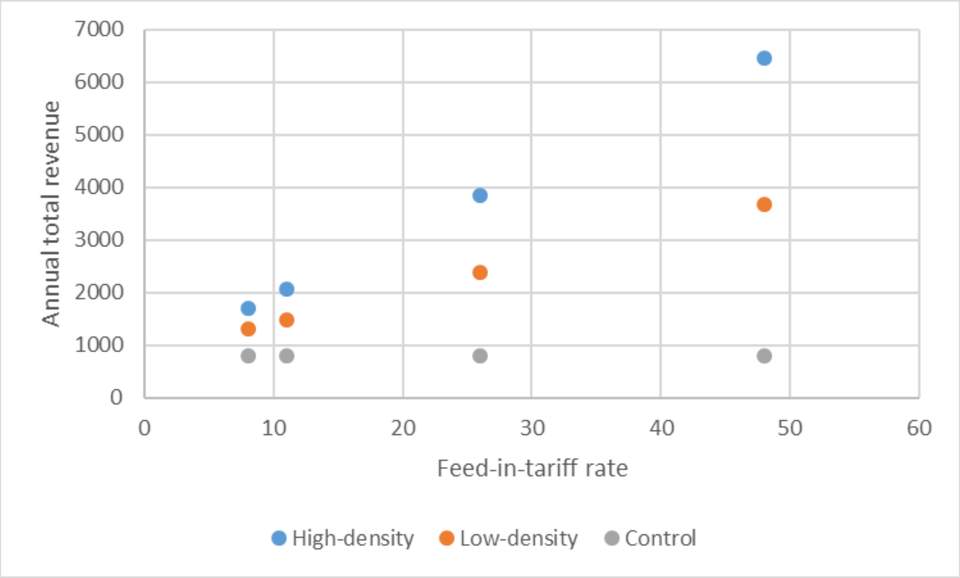

Figure 7. Sensitivity of annual total revenue per square meter to changes in the feed-in-tariff rate.

Discussion

This case study showed that it is possible to grow corn, a typical shade-intolerant crop, under the shade of agrivoltaic PV panels. The biomass of corn stover grown under PV module arrays spaced at 0.71 m intervals was no less than 96.9% that of corn without PV modules. Furthermore, the biomass of corn stover grown under PV module arrays spaced at 1.67 m intervals was even greater than that of corn without PV modules by 4.9%. In fact, the corn yield per square meter of the low-density configuration was 3.54 kg, which was larger not only than that of the high-density configuration, but also than that of the no-module control configuration by 5.6%.

This study also indicated that the annual revenue from PV power generation and the corn harvest in an agrivoltaic farm could be larger than that of a traditional corn field. Actually, the total revenue of the high-density configuration was 8.3 times larger than that of the control configuration, whereas that of the low-density configuration was 4.7 times larger.

Possible Reasons for High Crop Yield

This result implies that not only shade-tolerant crops but also shade-intolerant crops can achieve high yields, despite growing under the shaded area created by agrivoltaic PV panels. Several factors may explain why incorporating PV panels into agriculture can be beneficial for crops. First, the light saturation point of each crop seems to be a key concept. Actually, only a small fraction of the incident sunlight is required for plants to reach their maximum rate of photosynthesis. As light intensity increases, a level is eventually reached where light is no longer the factor limiting the overall rate of photosynthesis. Just as a sponge becomes saturated with water, increasing the light no longer boosts photosynthesis after the light saturation point (Table 12).

Second, too much sunlight hinders crop growth. Daily exposure to harsh ultraviolet radiation can cause serious damage to plant DNA. In fact, plants have evolved mechanisms to protect themselves from sun damage; they produce special molecules and send them to the outer layer of their leaves to protect themselves. These molecules, called sinapate esters, block ultraviolet-B radiation from penetrating deeper into leaves (Dean, et al., 2014).

Third, the shading caused by the PV panels reduces water evaporation. This is beneficial, especially in the hot and dry season. It has been observed that shading results in water savings of 14–29% depending on the level of shade (Marrou, Dufour & Wery, 2013). Also, PV panels reduce the diurnal variations in crop and soil temperatures, while daily air temperature and vapor pressure deficit remain constant, even for the area located under the panels (Marrow et al., 2013). PV modules also alleviate soil erosion by reducing moisture evaporation (Wu et al., 2014).

Table 12. Light saturation points of selected crops (Solar Sharing Network, 2018a).

Crops	Light Saturation Points (KLX)	Crops	Light Saturation Points (KLX)
Corn	80–90	Rice	40–45
Water melon	80–90	Carrot	40
Tomato	80	Turnip	40
Taro	80	Sweet potato	30
Cucumber	55	Lettuce	25
Pumpkin	45	Green pepper	20–30
Blueberry	45	Spring onion	25
Cabbage	45	Mushroom	>20

Financial Feasibility of Agrivoltaic Systems

This research indicated that the annual total revenue from an agrivoltaic farm could be larger than its respective monosystem, not only for a high feed-in-tariff rate but also with lower rates. The question remains, however, whether the revenue from agrivoltaic systems can equal the investment costs. In this chapter, the installation costs of the agrivoltaic system were not considered. The costs of PV systems, however, vary significantly among countries and even within a country because they are largely determined by local resource availability. Although there are some reports that the installation of agrivoltaic system can be financially feasible in Japan, it is important to confirm the financial feasibility of the system in this specific case study. Thus, Chapter

III presents a cost-benefit analysis to explore the financial feasibility of the agrivoltaic system at the experimental farm.

Chapter III

Financial Feasibility of an Agrivoltaic System in Japan

In this chapter, a cost-benefit analysis is conducted to explore the financial feasibility of an agrivoltaic system at the experimental farm of the CHO Institute of Technology in Japan (latitude: 35.378929, longitude: 140.138549). Chapter II indicated that the annual total revenue from the agrivoltaic farm could be larger than that of its monosystem equivalent. The question remains however whether agrivoltaic system revenue can exceed the investment. While the price of PV modules has been reduced due to technological advances and the scale of the economy, prices for complete PV systems vary more widely than those for PV modules. Soft costs such as different supply chains, local regulatory requirements, labor and permitting costs, and different financing mechanisms lead to wide regional differences. As a result, the installation costs of PV systems vary significantly among and even within countries. Thus, to boost the global adoption of agrivoltaic systems, it is necessary to study their financial feasibility in many different countries. In light of their relatively high installation costs, it is particularly important to examine the feasibility of agrivoltaic systems in Japan.

Methods

A cost-benefit analysis was conducted for agrivoltaic systems over 10-year and 20-year periods after the initial investment. The agrivoltaic system of the experimental farm consisted of 72 PV modules (1354 mm x 345 mm) mounted at a height of 2.7 m and tilted at an angle of 30°. The area underneath the stilts could still be used for agriculture and was large enough to accommodate farming equipment.

Electricity Generation

The experimental farm had three sub-configurations: no modules (control), low module density, and high module density. In the high-density configuration, there were eight PV module arrays (48 modules) spaced at 0.71 m intervals. In the low-density configuration, there were four PV module arrays (24 modules) spaced at 1.67 m intervals. Both stilt-mounted PV panel configurations casted shade on the crop below, whereas the no-module (control) configuration had no PV modules above the ground.

The total output capacity of the PV system was 4.5 kW. The CHO Institute of Technology secured a feed-in-tariff rate of 48 JPY (approximately 0.44 USD) per kWh for 20 years. The installation cost of the high-density configuration agrivoltaic system was 1.35 million JPY (approximately 12,300 USD) and that of the low-density configuration was 720,000 JPY (approximately 6,500 USD).

Crop Production

For this research, sweetcorn was planted on the experimental farm in early April 2018 and harvested in late July of the same year. Corn is a typical shade-intolerant crop and a major global commodity. Corn has a growth period of approximately 90 days and grows up to a height of 2 m. In each configuration, there were 25 corn stalks spaced 0.5 m apart (nine stalks per 1 m^2). The same soil, fertilizer, and water were used to grow all crops. The shading from the PV module varied according to the time of year and the height of crops planted between the module rows. The market value of the corn was calculated using the 5-year average of the market price obtained from the Agriculture & Livestock Industries Corporation, a Japanese governmental agency.

Assumptions

The cost-benefit analysis of the financial feasibility of the agrivoltaic system assumed a discount rate of 0.1% (the interest rate of a 10-year Japanese government bond as of October 2018) and a 1% interest (the long-term prime rate in Japan as of October 2018) loan of 100% debt. The revenue from PV power generation was assumed to be constant and set based on the actual value at the experimental farm from September 2017 through August 2018. That is, the revenue was assumed to be 142,752 JPY for the high-density configuration and 71,376 JPY for the low-density configuration (Table 1 and Table 2).

The profitability of the agrivoltaic system at the experimental farm was expressed as a cost benefit ratio (CBR). CBR is the ratio of the monetary benefits of a project relative to the costs required to carry out the project. When the CBR of the system is larger than 1, the system is said to be financially feasible. All benefits and costs are expressed in discounted current values. CBR can be obtained by the following equation, where C is the discounted cost of the system and R is the discounted revenue from PV power generation:

$$\mathrm{CBR} = R/C \tag{9}$$

Results

The result of the estimation showed that it would take almost ten years or more before the investment in agrivoltaic systems equaled the revenue in this case (Table 13 and Table 14). The discounted revenues from PV power generation were almost the same as the discounted cost of the system in this case study. For the low-density configuration containing four PV module arrays, the discounted revenues from PV power generation was less than the discounted costs. The 10-year cost benefit ratio of the low-density configuration was 0.94, while that of the high-density configuration containing eight PV module arrays was 1.00.

However, the cost-benefit analysis for the 20-year period indicated that investment in agrivoltaic systems would be profitable (Table 15 and Table 16). In this case study, the cost benefit ratios of the high-density and low-density configurations for the 20-year period were 1.90 and 1.78, respectively. This means that the discounted revenues from PV power generation and corn production would be almost twice the discounted cost of the system for both configurations.

Discussion

The cost benefit analysis indicates that it can be financially feasible to adopt stilt-mounted agrivoltaic systems in this case study. As seen in Table 3, the discounted revenue (R) from PV power generation for the high-density configuration over a 20-year period was 2,825,281 JPY, and the discounted cost (C) was 1,488,930 JPY. Thus, the discounted profit ($R - C$) from PV power generation for the high-density configuration was 1,336,351 JPY for a 20-year period. As the area of this configuration was 50 m^2, the discounted annual profit per square meter from PV power generation would be 26,727 JPY. The annual revenue per square meter from corn crops was 6465.82 JPY (Table 10); thus, the annual profit per square meter from PV power generation was 35 times more than that from corn production. Similarly, because the discounted revenue from PV power generation for the low-density configuration over a 20-year period was 1,412,640 JPY and the discounted cost was 794,030 JPY (Table 6 and 7), the discounted annual profit per square meter from PV power generation was 12,372 JPY, which was 15 times the annual revenue per square meter from corn crops.

These results indicate that a good return would likely be obtained on investment in agrivoltaic systems within 20 years under the assumptions of this case study, although it would take almost 10 years or more to break even. As the service life of PV modules is typically at least 20 years, it is rational to examine the financial feasibility of an agrivoltaic system for a 20-year period. If the installation costs of stilt-mounted PV modules are further reduced, agrivoltaic systems would become an attractive investment for more farmers.

However, it should be noted that these results were obtained for a feed-in-tariff rate of 48 JPY per kWh. Yet, as seen from Figure 6, the feed-in-tariff for PV power generation has been continuously declining. Although the CHO Institute of Technology secured the feed-in-tariff rate of 48 JPY per kWh in 2010, the Japanese government is planning to set the rate at 11 JPY per kWh for household-level generators (less than 10 kW) and 8 JPY per kWh for industry-level generators (more than 10 kW) around the mid-2020s. Therefore, it might become difficult to make a profit with low feed-in-tariff rates when the installation costs are considered. Thus, the key to future financial feasibility of stilt-mounted agrivoltaic systems would be a reduction in the installation costs, which is largely influenced by wide regional differences of soft costs such as different supply chains, local regulatory requirements, labor and permit costs, and different financing mechanisms. In other words, the feed-in-tariff rate should not be lowered without also reducing the installation costs.

Table 13. Financial feasibility of high-density configuration agrivoltaic system (10-year period).

(Unite: Yen)

Year	Discount Rate	Investment		Loan Interest		Discounted Cost	Revenue	
t	$(1/1+i)^t$	Value	Discounted Value	Value	Discounted Value		Value	Discounted Value
0	1	1350000	1350000					
1	0.999			12906	12893		142752	142609
2	0.998			11610	11587		142752	142467
3	0.997			10298	10267		142752	142325
4	0.996			8976	8940		142752	142182
5	0.995			7640	7602		142752	142040
6	0.994			6293	6255		142752	141898
7	0.993			4931	4897		142752	141757
8	0.992			3554	3526		142752	141615
9	0.991			2165	2146		142752	141474
10	0.990			759	751		142752	141332
Total		1350000	1350000	69132	68864	1418864	1427520	1419700
							Discounted Profit=	836
							CBR=	1.001

Table 14. Financial feasibility of low-density configuration agrivoltaic system (10-year period).

(Unite: Yen)

Year	Discount Rate	Investment		Loan Interest		Discounted Cost	Revenue	
t	$(1/1+i)^t$	Value	Discounted Value	Value	Discounted Value		Value	Discounted Value
0	1.000	720000	720000					
1	0.999			6880	6873		71376	71305
2	0.998			6188	6176		71376	71233
3	0.997			5490	5474		71376	71162
4	0.996			4784	4765		71376	71091
5	0.995			4074	4054		71376	71020
6	0.994			3354	3334		71376	70949
7	0.993			2626	2608		71376	70878
8	0.992			1893	1878		71376	70808
9	0.991			1151	1141		71376	70737
10	0.990			402	398		71376	70666
Total		720000	720000	36842	36699	756699	713760	709850
							Discounted Profit=	-46849
							CBR=	0.938

Table 15. Financial feasibility of high-density configuration agrivoltaic system (20-year period).

(Unite: Yen)

Year	Discount Rate	Investment		Loan Interest		Discounted Cost	Revenue	
t	$(1/1+i)^t$	Value	Discounted Value	Value	Discounted Value		Value	Discounted Value
0	1	1350000	1350000					
1	0.999			13215	13202		142752	142609
2	0.998			12597	12572		142752	142467
3	0.997			11977	11941		142752	142325
4	0.996			11349	11304		142752	142182
5	0.995			10713	10660		142752	142040
6	0.994			10074	10014		142752	141898
7	0.993			9426	9360		142752	141757
8	0.992			8772	8702		142752	141615
9	0.991			8112	8039		142752	141474
10	0.990			7444	7370		142752	141332
11	0.989			6771	6697		142752	141191
12	0.988			6090	6017		142752	141050
13	0.987			5405	5335		142752	140909
14	0.986			4710	4645		142752	140768
15	0.985			4009	3949		142752	140628
16	0.984			3301	3249		142752	140487
17	0.983			2586	2542		142752	140347
18	0.982			1865	1832		142752	140207
19	0.981			1133	1112		142752	140067
20	0.980			396	388		142752	139927
Total		1350000	1350000	139945	138930	1488930	2855040	2825281
							Discounted Profit=	1336351
							CBR=	1.898

Table 16. Financial feasibility of low-density configuration agrivoltaic system (20-year period).

(Unite: Yen)

Year	Discount Rate	Investment		Loan Interest		Discounted Cost	Revenue	
t	$(1/1+i)^t$	Value	Discounted Value	Value	Discounted Value		Value	Discounted Value
0	1	720000	720000					
1	0.999			7045	7038		71376	71305
2	0.998			6716	6703		71376	71233
3	0.997			6385	6366		71376	71162
4	0.996			6050	6026		71376	71091
5	0.995			5711	5683		71376	71020
6	0.994			5369	5337		71376	70949
7	0.993			5024	4989		71376	70878
8	0.992			4676	4639		71376	70808
9	0.991			4324	4285		71376	70737
10	0.990			3966	3927		71376	70666
11	0.989			3606	3567		71376	70596
12	0.988			3245	3206		71376	70525
13	0.987			2879	2842		71376	70455
14	0.986			2509	2474		71376	70384
15	0.985			2135	2103		71376	70314
16	0.984			1757	1729		71376	70244
17	0.983			1376	1353		71376	70173
18	0.982			990	972		71376	70103
19	0.981			601	590		71376	70033
20	0.980			207	203		71376	69963
Total		720000	720000	74571	74030	794030	1427520	1412640
							Discounted Profit=	618610
							CBR=	1.779

Chapter IV

Discussion

This research has shown that stilt-mounted agrivoltaic systems could mitigate the trade-off between crop production and clean energy generation, even when applied to shade-intolerant crops.

Summary of Sensitivity Analysis

Chapter II showed that it could be possible to grow corn, a typical shade-intolerant crop, even under the shade of agrivoltaic PV panels. The biomass of corn stover grown under PV module arrays spaced at 0.71 m intervals was no less than 96.9% of that of corn without PV modules. Furthermore, the biomass of corn stover grown under PV module arrays spaced at 1.67 m intervals was even greater than that of corn without PV modules by 4.9%. In fact, the corn yield per square meter of the low-density configuration was 3.54 kg, which was larger not only than that of the high-density configuration, but also than that of the no-module control configuration by 5.6%.

Chapter II also indicated that an increase in the overall productivity of land could be achieved even with crops that require plenty of sunlight. Annual revenue from PV power generation and the corn harvest in an agrivoltaic farm could be larger than that of a traditional corn field. In fact, the total revenue of the high-density configuration was 8.3 times larger than that of the control configuration, while the total revenue of the low-density configuration was 4.7 times larger.

Summary of Cost-Benefit Analysis

According to the cost-benefit analysis in Chapter III, a good return should be obtained on investment in agrivoltaic systems within 20 years under the assumptions of this case study. Although it would take almost ten years or more before the investment in agrivoltaic systems broke even in this case, the cost-benefit ratios of the high-density and low-density configurations over a 20-year period were 1.90 and 1.78, respectively. This indicates that it could be financially feasible to adopt stilt-mounted agrivoltaic systems in Japan.

The key to financial feasibility of stilt-mounted agrivoltaic systems in Japan seems to be a reduction in the installation costs. The generous feed-in-tariff of 48 JPY per kWh enabled a good return on investment in this case study; however, the planned lower rates of 11 JPY per kWh and 8 JPY per kWh for household-level and industry-level generators by the mid-2020s would result in greater difficulty making a profit unless the installation costs also declined. Thus, the feed-in-tariff rates should not be lowered without also reducing the installation costs.

Even without a full life cycle analysis, the results from the cost-benefit analysis in Chapter III indicate that agrivoltaic systems could be profitable for conventional farmers. As population and energy use continue to increase, more efficient land use might become possible in the future.

Conclusions

Stilt-mounted agrivoltaic systems could reduce tensions between limited land resources and increasing demands for food and clean energy. In Japan, for example, it might be possible to supply the entire country's electricity with agrivoltaic systems. In this research, the low-density configuration with 1354 mm x 345 mm PV module arrays spaced at 1.67 m intervals generated 59.48 kWh per square meter per year. The relationship between the amount of the country's electricity demand, D, the annual energy production per m^2 of an agrivoltaic system, e, and the area of land necessary to generate D, L, is shown in equation (10).

$$
\begin{aligned}
L &= D / e \\
&= 797.1 \text{ billion kWh} / 59.48 \text{ kWh per m}^2 \\
&\fallingdotseq 13 \text{ billion m}^2 \\
&= 1.3 \text{ million ha} \qquad (10)
\end{aligned}
$$

With Japan's annual electricity demand of 797.1 billion kWh as of 2015 (Federation of Electric Power Companies of Japan, 2016), L is 1.3 million ha. Thus, just 30% of farm land (or 4.4 million ha, MAFF, 2018b) adopting the same low-density stilt-mounted agrivoltaic modules would meet the country's electricity demand.

Although existing studies have reported that agrivoltaics work well only for shade-tolerant crops, this research showed that even corn, a typical shade-intolerant crop, could grow well under the shade of agrivoltaic PV panels. This implies that stilt-mounted agrivoltaic systems could be applicable a wider range of commercially important crops. If so, the practical availability of stilt-mounted agrivoltaic systems would be highly promising. This research should encourage more conventional farmers, clean energy producers, and policy makers to consider adopting stilt-mounted agrivoltaic systems. Particularly in densely populated regions, mountainous areas, and small inhabited islands, where land resources are relatively scarce, this system could simultaneously take advantage of limited land resources for both food and clean energy production.

It would be an exaggeration to claim that agrivoltaic systems could drive out other energy sources, but it is true that this system offers important advantages over fossil fuels as well as traditional PV systems. Solar power is a sustainable source of energy because it will be available as long as the sun exists, is free of charge, and emits no pollutants or gases. Thus, PV power generation may be one of the most promising ways to generate electricity from renewable energy sources. Limitations related to installation area are one disadvantage of traditional PV power generation. This is less important for households, where PV modules installed on rooftops can generate sufficient electricity, but industry requires a huge area for PV power plants to provide a sufficient and constant electricity supply. As this research demonstrates, agrivoltaic systems can help to overcome the problem of limited land resources, negating this disadvantage of PV power generation.

Nevertheless, there are some disadvantages of agrivoltaic systems. Similar to traditional PV power generation, agrivoltaics cannot reliably generate constant energy; the system cannot adequately function if sunlight is not available during the night or on cloudy days. Thus, it is difficult to rely on agrivoltaic systems as a main power source even if the total generation capacity is large enough to meet the country’s electricity demand. The key to solving this is employing battery backup systems that can store electricity for use when sunlight is not available. Another issue affecting the expansion of PV generation, including agrivoltaics, is PV panel recycling. Although PV power generation itself does not cause pollution, disposing of PV panels may have serious impacts on the environment. The impact could be particularly serious if agrivoltaic systems are adopted by large areas of farmland, resulting in huge volumes of PV panels requiring disposal. Thus, it is necessary to develop effective methods for recycling large volumes of PV panels whilst also promoting agrivoltaic systems.

Future Work

This research expanded the potential applications of agrivoltaic systems to shade-intolerant crops, but many crops have still not been evaluated for agrivoltaic applications. Future work is necessary to extend its use to shade-intolerant plants other than corn including water melon, tomato, cucumber, pumpkin, cabbage, turnip, and rice. However, information on the shade tolerance of crops remains limited. Therefore, as Dinesh and Pearce (2016) reported, it is important to study the morphological traits of such crops to understand their behavior and light requirement patterns during different life stages from germination to harvest. Many different factors; i.e., radiation interception efficiency, light saturation point, damage from ultraviolet radiation, water evaporation, and crop temperature potentially affect the shade tolerance of crops.

It should also be noted that this research only employed a limited number of samples. The case study was conducted at a small 100 m^2 experimental farm with three configurations and only dozens of corn stalks in each configuration. Whilst this case study showed that corn could grow well even under the shade of agrivoltaic PV panels, it is necessary to verify the reliability of these results with a larger sample size in future research. In addition, more studies on the financial feasibility of agrivoltaic systems should be conducted. The case of this study obtained a good return on the investment in agrivoltaic system, however, it would be worthwhile examining the financial feasibility of the system under many different assumptions with different installation cost and feed-in-tariff rates.

Furthermore, more advanced PV systems could be designed to improve the efficiency of electricity generation and reduce the impact on agricultural yields. For example, PV module tilt can be adjusted to enhance the power generation efficiency. One proposal involves an agrivoltaic system equipped with a programmed microcomputer and a motor that automatically adjusts the tilt to be perpendicular to the sun as it moves from east to west (Nagashima, 2015), solving the issue of fixed PV panels not fully converting solar energy to electricity. This problem can be solved by arranging PV panels to track the Sun. The proposed system may equip a programmed microcomputer and a motor that maintains the tilting of PV panels almost perpendicular to the Sun. In this way maximum sun light is incident on the panel at any time of the day so that the power generation efficiency can be improved. Additionally, bifacial PV panels could increase the electricity production per square meter of the PV module through the use of light absorption from the albedo (Guerrero-Lemus et al., 2016). Other ideas have been proposed to enhance crop productivity. Semi-transparent PV panels, which combine the benefits of visible light transparency and light-to-electricity conversion, could reduce shading on crops under agrivoltaic systems. In fact, semi-transparent PV panels have already been developed for greenhouse roof applications (Yano, Onoe & Nakata, 2014). PV panels with mirrored backings might also increase the availability of sunlight for crops by multiplying the reflection of incoming light to the ground. Further research is required to couple new PV panel technology to agrivoltaic systems.

Another area of research is the development of suitable PV modules for agrivoltaic systems. PV modules should be lightweight because they are mounted in high locations. The modules also need to be small to reduce the shadows cast on the ground as well as the influence of wind. As the output of modules for home use has been increasing, larger modules are becoming more popular; however, major manufacturers have not yet marketed modules of a suitable size and output for agrivlotaic systems. Also, the effect of dust spread by agricultural activity onto the PV panel surface on the power output of the system should be considered. Instead of periodically cleaning the PV modules, it could be possible to maintain optimum electricity output with a hydrophilic coating on the PV panel surface.

Future work is also necessary to explore the potential of PV greenhouses. Previous farm experiments, including this research, have focused on agrivoltaic systems consisting of stilt-mounted PV modules installed above the crops. The use of PV for greenhouses, however, would be a good solution to the land resource competition between agriculture and PV power generation because the greenhouse allows continuous food production and electricity generation throughout the year. In fact, a Japanese agricultural corporation produces tomato, another typical shade-intolerant crop, in their PV greenhouse (Solar Sharing Network, 2018c) that has a cultivated area of 515 m^2 on the ground and 84 100-w solar panels on the roof. Their annual crop yields of tomato are approximately 3,300 kg, which is worth around 2 million JPY. The electricity generated on the roof is used for air-conditioning in the greenhouse, and the excess electricity is sold to the local electric power company for approximately 170, 000 JPY per year. By referring to such examples, the optimum design and performance of PV greenhouses should be evaluated further.

Further Solar-Sharing Potential with Stilt-mounted PV Modules

As PV power stations continue to enjoy remarkable growth, a contradiction has gradually come to light. Now, the occupation of vast amounts of land for solar farms is becoming a problem. PV power generation began with panel installation on roofs and was followed by mega solar power plants built on old factory sites and barren and unused land. Presently, vast forests are sometimes cut down to construct solar power plants. Although solar power is a promising renewable energy source, it should not involve destruction of the environment.

Stilt-mounted PV modules installed at moderate intervals may be an effective way to achieve coexistence of PV power generation and environmental sustainability. Possible applications of stilt-mounted PV modules are not limited to agriculture; they can be installed in any location where other commercial activities are run simultaneously. One example is the livestock industry. If a large-scale stilt-mounted PV system is built on pasture land, the land can generate energy and livestock products at the same time without destroying the environment. As this research shows, PV panels can promote plant growth by moderating excessive sunlight and reducing water evaporation. Thus, stilt-mounted PV modules could maintain grazing land and livestock in desert areas that would otherwise suffer from severe sunlight and water evaporation.

Furthermore, the idea of stilt-mounted PV modules can be applied to the water surface. Some companies have been developing floating PV systems on large bodies of water such as inshore and offshore waters, drinking water reservoirs, quarry lakes, irrigation canals, and hydroelectric dam reservoirs (Ciel & Terra, 2018; Oceans of Energy, 2018). Vast PV modules on the water surface, however, block sunlight into water and affect the activity of aquatic plants and animals. If a floating stilt-mounted PV system is adopted, it can not only decrease the influence on aquatic plants and animals, but also enable the use of space between PV modules and the water surface for fisheries and aquaculture.

Akira Nagashima, who invented the stilt-mounted agrivoltaic system, said the following: “Rather than using all of the sunlight pouring on a land for power generation, it is important for a sustainable society to share it with many different creatures. That is the philosophy of Solar-Sharing” (Nagashima, 2015). Although the stilt-mounted PV system was originally developed to generate electricity from incoming sunlight on farmland, this system may also be an effective way to produce sustainable energy without devastating the environment. This system enables people to generate electricity on farmland, pasture land, water surfaces, roads, and anywhere people, animals, and plants are living. Moreover, even barren deserts can be changed into habitable lands where people can produce food and energy simultaneously with a system consisted of tilt-mounted PV modules installed at moderate intervals.

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