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Analysis of the Rice Yield under an Agrivoltaic System: A Case Study in Japan

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Abstract: Agrivoltaic systems, comprising photovoltaic panels placed over agricultural crops, have recently gained increasing attention. Emerging interest in these systems led us to investigate their influence on rice crops. Various factors affecting rice crop yield, including fertilizer application, temperature, and solar radiation, were directly observed, and measured to evaluate changes associated with the shading rates of photovoltaic systems installed above rice crops. The results suggest that the allowable upper limit of the shading rate for agrivoltaic installations ranges from 27 to 39%, which sustains at least 80% of the rice yield, a condition set by the Japanese Ministry of Agriculture, Forestry and Fisheries for these systems. If such systems are applied to rice paddies in Japan at 28% density, they could generate 284 million MWh/yr. This is equivalent to approximately 29% of the total Japanese electricity demand, based on 2018 calculations. This projection indicates the potential of agrivoltaic systems for efficient land use and sustainable energy generation.

Keywords: agrivoltaic; photovoltaic system; rice paddy field; shading; sustainable energy; land use

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1. Introduction

1.1. Energy Situation in Japan

Following the 2011 Great East Japan Earthquake and the shutdown of its several nuclear power plants, energy importation into Japan increased significantly in 2015, reaching 85 million tons of natural gas and 190 million tons of coal [1]. While coal combustion is still the largest source of greenhouse gas emissions in the power generation sector, a trend has been observed in coal-fired power plant project divestments, to comply with the Paris Agreement and meet its objective of limiting global warming to 1.5–2 °C [2,3]. Japan plays a significant role in sustaining the global coal importation market [4]. The demand for establishing an alternative energy supply structure in the country has led to the promotion and utilization of renewable energy, which has favorable mitigating effects on carbon dioxide and energy security [5].

The government introduced a feed-in-tariff (FIT) scheme in 2012 to provide additional income to people who produce energy through renewable sources [1,6], and to promote decarbonisation through the large-scale development of renewable energy [3]. This scheme increased the renewable capacity, particularly the solar power capacity [7], which accounted for 33.50 GW in 2017 after enforcement of the FIT [8]. As the renewable energy capacity had been increasing for a decade [9], the government declared that Japan would aim for a

46% reduction in the 2013 greenhouse gas emissions by 2030, a significant increase from its previous commitment of a 26% reduction, becoming a carbon-neutral society (zero greenhouse gas emissions) by 2050 [10].

1.2. Current Studies of Agrivoltaic Systems

Rooftop photovoltaic panels and mega-solar power plants have mainly been used for photovoltaic power in Japan. The limited area available for photovoltaic panel installation will be a critical problem in increasing the spread of photovoltaic systems to achieve greenhouse gas emission goals. One solution to increase the diversification portfolio of renewable energy is the implementation of agrivoltaic systems [11,12]. The combination of photovoltaics and crops is commonly known as agrivoltaics, a system that promotes agricultural productivity while also reducing environmental impacts [12]. Moreover, photovoltaic panels have been used as roofs for greenhouse structures in several developed countries [13–15].

Poncet et al. [14] affirmed that agrivoltaics can obtain lower environmental impacts than using the land for energy and food production separately. However, Dupraz et al. [16] raised concerns over the long-term effects of agrivoltaics on monoculture crops, suggesting instead a diversified mixed-crop system. The solar energy generated from agrivoltaics can have the following benefits: an increase of more than 30% in the economic value of the land [17], the expansion of opportunities for farmers to obtain long-term profitability [18], environmental improvement [19], and an increase of 60–70% in overall land productivity [12]. This approach also overcomes the challenge of the lower power densities of photovoltaic systems, by expanding their system footprint in rural areas [20,21]. In addition, a preliminary evaluation of agrivoltaic land use in India produced 16,000 GWh/year of energy potential, signifying that agrivoltaics on grape farms could conservatively serve 15 million people in India [22].

These promising developments in photovoltaic cumulative installation capacity encourage the expansion of agrivoltaic energy production and efficient land use [23]. Investments in renewable energy, specifically in photovoltaics, have increased substantially, while energy demand and carbon dioxide emissions related to climate change have become more pronounced. With a decrease in the costs of photovoltaic systems and an increase in their capacity, research on the impacts of large-scale solar installations is needed [11]. As integrated photovoltaic systems that alleviate both energy and food shortages [24], agrivoltaics may be the most optimal means of sustainable development in agricultural areas [12,25].

1.3. Challenges in Agrivoltaic System Application to Different Crops

The main challenge faced by these systems is the physiological constraints they can impose on crop productivity and quality owing to shading [26]. Light quantity is a vital component of crop cultivation that links plant photosynthetic rates and morphological processes to their growth and development [27,28]. A decrease in the solar radiation intercepted by the crops, owing to shading by the panels, can negatively impact harvested fruit quality, unless carefully managed [29].

Thus, using agrivoltaic systems requires modifications, in terms of the shading effects of the system and using the appropriate crops for the fluctuating shade [17,30]. In addition to shading, the light requirements of each crop used in agrivoltaics should be carefully chosen and managed [31]. Thus, the effects of shading must be considered when exploring potential agrivoltaic conditions.

Furthermore, extreme weather conditions [32] related to climate change [33], such as high temperatures and humidity, are often detrimental to the crops [34,35]. Thus, agrivoltaics should preferably be used in a more open structure than a greenhouse because sufficient air circulation below the open structure prevents the air temperature and vapor from being significantly affected by the panels, unlike those in a greenhouse [17,36].

While previous studies on agrivoltaic systems mostly focused on greenhouse-based crops such as tomatoes [15,37,38], lettuce [28,30,31,39–41] and cucumbers [30,38,40] and few studies on open field crops such as corn [23,36,39] and grapes [22], this study explores the application of agrivoltaics to rice paddies. Shading experiments on rice paddy fields were only conducted for limited periods in previous studies [35,42]. Thus, no prior research has explored the effects of shading from photovoltaics on rice yields throughout the rice cultivation cycle. While some studies have examined the negative effects of shading on crops integrated with agrivoltaics, none have reported the impact on rice yield and quality. Nevertheless, the value of shading rate in the cultivation process is accentuated by the application of agrivoltaic systems.

1.4. Agrivoltaic System Challenges in Japan

The time required to recover photovoltaic costs depends on the electricity selling price, which is determined by the FIT scheme [43]. Because the FIT electricity selling price has decreased over time, the economy has been a limitation in implementing agrivoltaics. Agrivoltaics may create additional land footprints on farms, but the dual use of these farmlands can also increase the economic value of the land [39]. Agrivoltaics may also have negative impacts on the physical and visual aspects of the land, obstructing views of the landscape if not carefully located, and raising safety concerns regarding installation facilities [5].

Although agrivoltaic technology can be easily implemented in Japan and the Ministry of Agriculture, Forestry, and Fisheries (MAFF) has recently become more inclined toward such systems, some local agricultural committees remain conservative and tend to observe conventional customs. In some regions, farmers face difficulties in starting agrivoltaic systems because of a lack of agreement with their local agricultural committees [44].

In Japan, rice (*Oryza sativa*) is one of the most widely cultivated crops, covering a total area of 1.47 million hectares [45]. Given that rice is a valuable crop, especially in Asia, the risks posed by agrivoltaic systems to rice quality and quantity may be deemed too great. Despite these risks, installing agrivoltaic systems in rice paddies shows great potential. For this reason, MAFF set particular conditions concerning the yield of crops, including rice, subjected to agrivoltaic systems in Japan; yield should not fall below 80% of the yield of crops grown under normal conditions in the surrounding area [44], otherwise, the system should be removed from the farm. Thus, the primary objective of this study is to identify the shading rate that complies with this MAFF condition to ensure 80% crop yields.

This is the first study to investigate the influence of installing photovoltaic systems on the productivity of paddy-field rice, which is a staple crop cultivated in agricultural areas in Japan. This study provides novel results that may prove useful, not only in Japan, but also in other rice-producing countries.

2. Materials and Methods

2.1. Topographical Analysis and Layout

The authors considered the four case study sites shown in Figure 1, as their proximity allowed meaningful comparisons by eliminating differences in solar irradiance. The scale and design of these study sites differ depending on the scope of each project.

2.1.1. Experimental Farm A

The Farm A experimental area is affiliated with the Institute for Sustainable Agro-ecosystem Services of the University of Tokyo and is located in Nishitokyo, Tokyo. The field used for the experiment from 2016 to 2018 had an area of 336 m^2 (14 m long and 24 m wide). As shown in Figure 2, the experiments were conducted using a split-plot design, where the field was divided into six rows (from A to F in the horizontal direction) and three sections (in the vertical direction), for a total of 18 plots. Each plot was 12 m^2 (4 m long and 3 m wide). In 2016, the rice cultivar used was *Nihonbare*, and in 2017 and 2018, the cultivar was changed to *Koshihikari*, which is the most common rice cultivar in Japan.

Planting densities of 22.2 rice seedlings/m^2 (30-cm intervals, 15 cm between seedlings) in 2016 and 16.7 rice seedlings/m^2 (30-cm intervals, 20 cm between seedlings) in 2017 and 2018 were applied to the area.

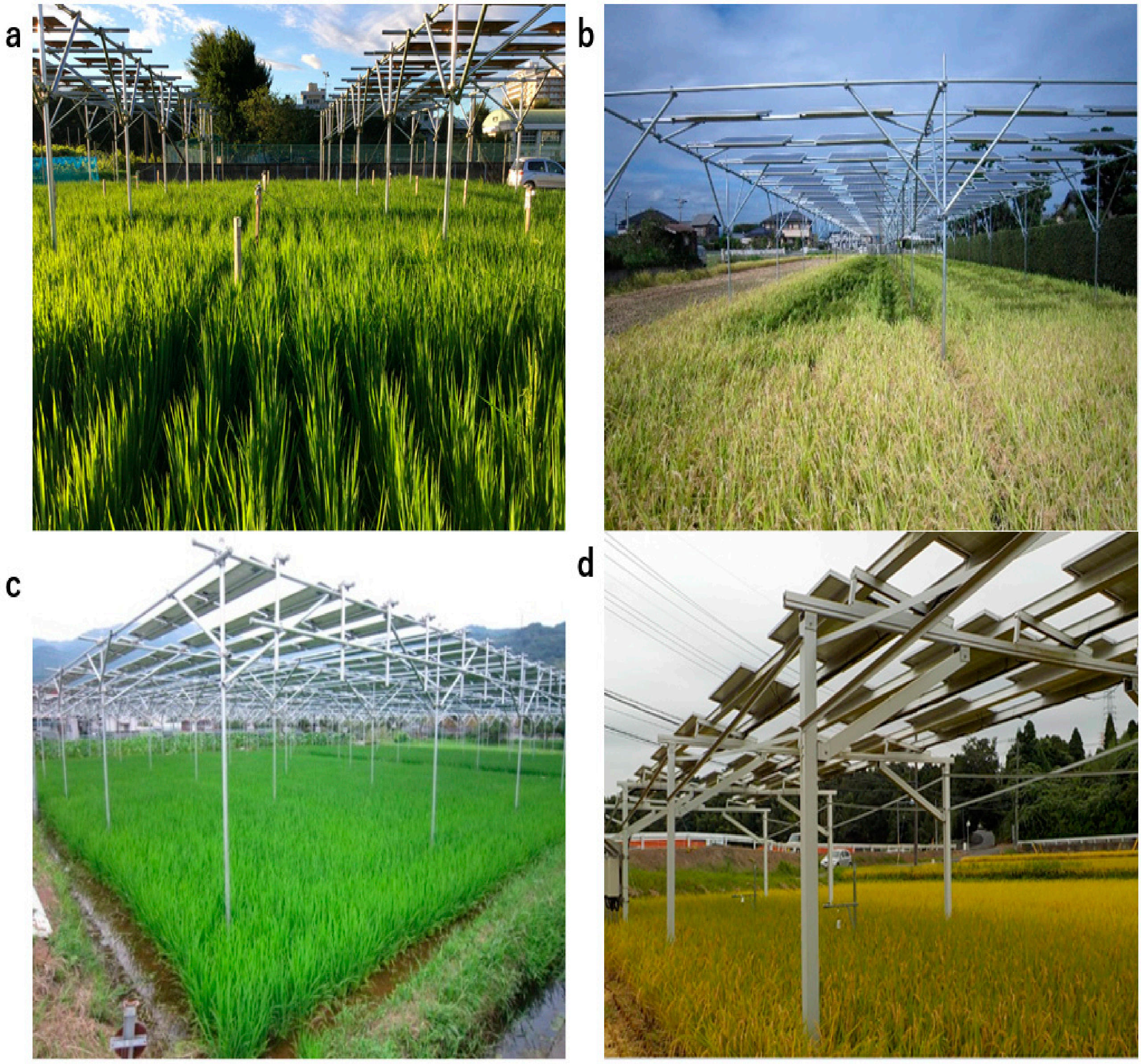

Figure 1. Case study sites of agrivoltaic systems at experimental Farm A and private Farms B, C, and D. (**a**) Experimental Farm A, located in Tokyo, with wooden boards replicating solar panels. Large and small boards are visible on the right and the left sides of the picture, respectively. (**b**–**d**) Private farms: Farms B and C are in the Shizuoka Prefecture, while Farm D is located in the Chiba Prefecture.

Wooden boards imitating solar panels were placed at a fixed horizontal angle 3 m above the ground to allow easy access to modern machinery and tractors for planting and harvesting purposes. Since the emissivity of wood (0.90–0.98) is similar to that of plastic products (approximately 0.90) which are utilized for solar panels, the thermal effects of the replicated wooden panels are negligible. In addition, a 3-m height complies with the MAFF regulations regarding the installation of agrivoltaics in fields, making height a constant variable in our experiment. While transplanting the rice crops, three setups were applied to observe the influence of light shading on each plot. As shown in Figure 2, large panels (hereafter, the "strongly shaded plots") with an area of 0.88 m^2 were placed in the first row (plots A1, B1, C1, D1, E1, and F1), while small panels ("weakly shaded plots") with an area of 0.41 m^2 were placed in the third row (A3, B3, C3, D3, E3, and F3). The second row (A2, B2, C2, D2, E2, and F2) served as control plots, as no panels were placed over them. The shading treatments were initiated at the beginning of the vegetative stage of rice until its maturity. The ratio of the solar panels to the area occupied was 29% in the strongly shaded area and 14% in the weakly shaded area. As shown in Figure 2, meteorological parameters such as solar radiation, air temperature, and water temperature were measured.

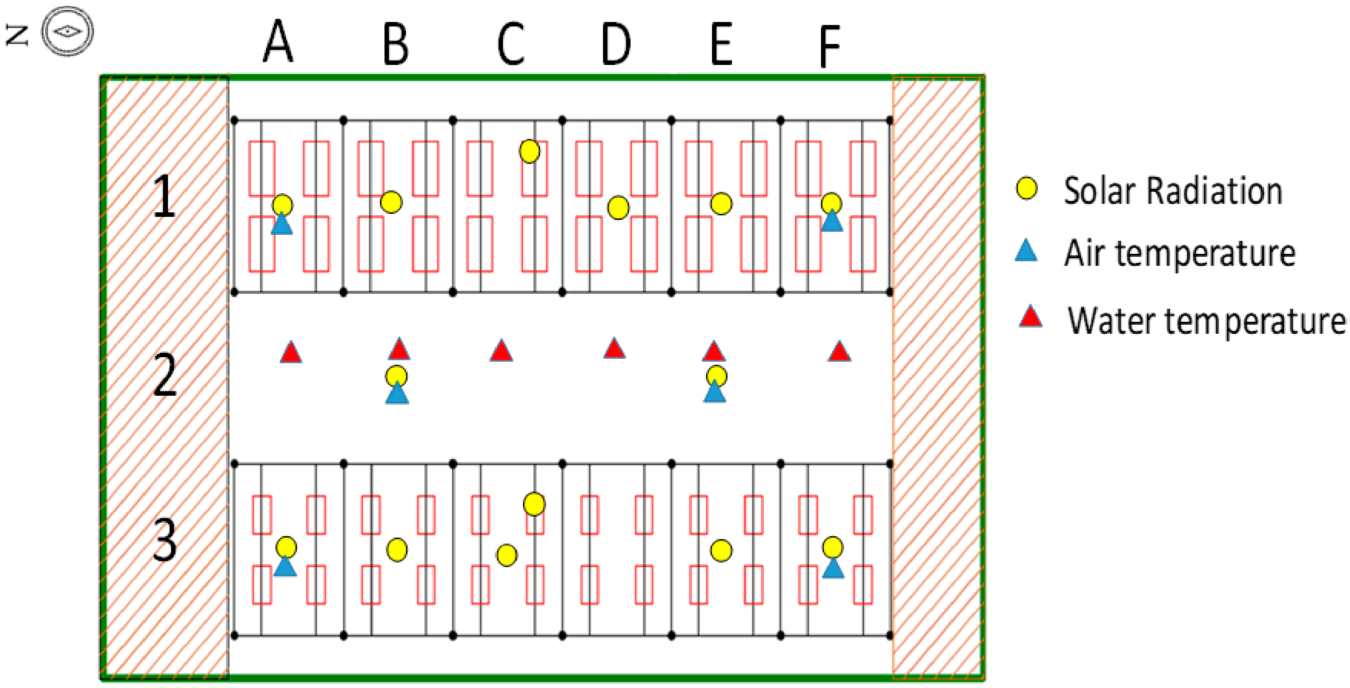

Figure 2. Agrivoltaic layout of the treatments performed at farm A.

In this study, we also controlled the fertilizer applied to each plot. Nitrogen, a primary component of fertilizer, can affect dry matter production by influencing leaf area development and photosynthetic efficiency [46]; nitrogen use leads to increases in rice crop yields. In contrast, nitrogen deficiency can reduce radiation interception, radiation use efficiency, dry matter partitioning to reproductive organs, and the leaf area index [47]. Additionally, a strong positive correlation was found between the photosynthetic capacity of leaves and nitrogen fertilizer [48]. Hence, at the experimental site, three different nitrogen fertilizer application rates were used.

To examine the influence of fertilizer on rice crops with shading, different amounts of nitrogen fertilizer (6 g N m^{-2}, 24 g N m^{-2}, and 48 g N m^{-2}) were used [49] in 2016 and 2017. A total of 6 g N m^{-2} fertilizer was applied to plots A1, A2, A3, D1, D2, and D3; 24 g N m^{-2} fertilizer was applied to plots B1, B2, B3, E1, E2, and E3; and 48 g N m^{-2} fertilizer was applied to plots C1, C2, C3, F1, F2, and F3. Of these three variations, 6 g N m^{-2} corresponds to basal fertilization, while 24 g N m^{-2} and 48 g N m^{-2} include additional fertilization. In 2018, on the other hand, 6 g N m^{-2} of nitrogen fertilizer was applied to plots B1, B2, and B3, and 24 g N m^{-2} of nitrogen fertilizer was applied to plots A1, A2, A3, C1, C2, and C3, while plots D, E, and F were not used.

Plastic barriers were placed between adjacent plots to prevent nitrogen transport and root extension between the plants. A water depth of 4–10 cm was maintained until 7 days before maturity, after which the field was drained. Standard chemical products were used to manage diseases, insects, and weeds.

2.1.2. Other Experimental Sites (Farm B, C, and D)

Other private farm sites were also used in this research, at which we mounted actual solar panels (refer to Figure 3). We also considered multiple varieties of rice from different farms for comparison. Private Farm B, located in Fujieda City, Shizuoka Prefecture, used a 55-kW single-crystal silicon photovoltaic array in the field. The area of the entire field was 983 m^2. The ratio of the projected shaded area to the total surface area under the panels was 30%. The rice variety used was *Kinumusume*, with chemical fertilizer added. The experiment was conducted over two years, 2014 and 2015. Farm C was located in Izunokuni City, Shizuoka Prefecture. Single-crystal silicon 50-kW photovoltaic arrays were placed in the field. The entire field had an area of 900 m^2. The ratio of the projected shaded area to the total surface area under the panels was 39%. The rice variety used in this area was *Aichinokaori*, and chemical fertilizer was added. The experiment was conducted in 2014. Finally, private Farm D was in Shisui, Chiba Prefecture, where solar panels (12.2 kW) were placed in the field. The entire field covered an area of 3350 m^2. The ratio of the projected shaded area to the total surface area under the panels was 34%. The rice cultivar used in this area was *Koshihikari*, which was the same as that used at experimental Farm A in 2017 and 2018, with organic fertilizer added. The experiment at this farm was conducted for two years in 2017 and 2019.

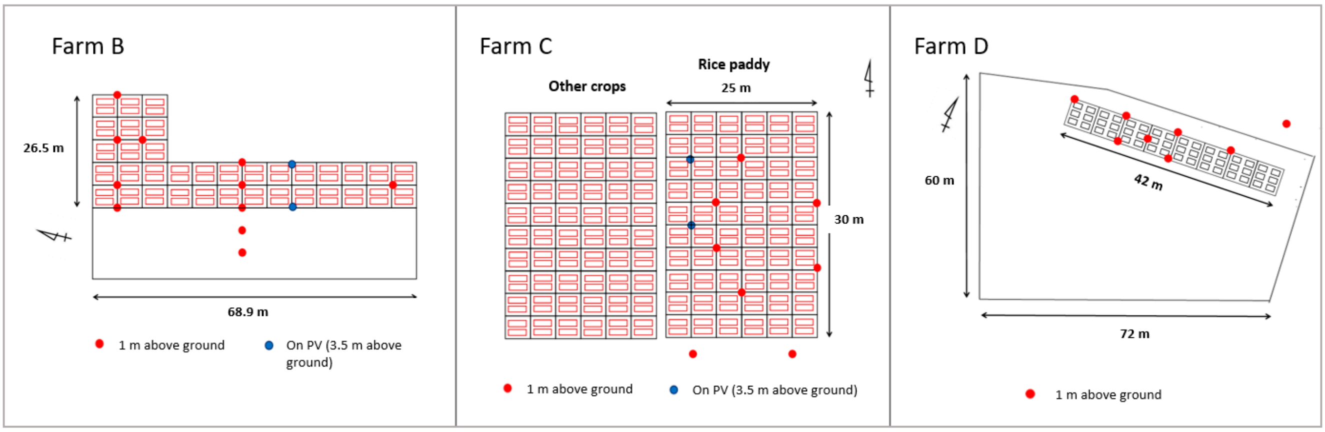

Figure 3. Block diagrams and positions of sensors at Farms B (**left**), C (**middle**), and D (**right**).

2.2. Meteorological Parameters

To determine the site weather conditions, meteorological instruments were installed to measure air temperature, water temperature, and solar radiation. The details of the parameters used at Farm A are described below.

The atmospheric temperature of each site was obtained using copper-constantan thermocouple sensors, which were placed through metal poles 1.2 m above the ground. The water temperatures were measured using thermocouples. The photosynthetic photon flux density (PPFD; μmol s^{-1} m^{-2}), which is a unit of measurement that quantifies the light effect of solar energy (at specific wavelengths) related to photosynthesis [49], was used. PPFD measures the amount of photosynthetically active radiation (PAR) or the irradiance from 400 to 700 nm that arrives at the plant [50]. It correlates with the widely used units of spectral irradiance. The measurements were performed using a PAR light quantum sensor (PAR-02D, Climatec Co., Ltd., Tokyo, Japan).

The plot shading rate was calculated by dividing the difference between the average solar radiation measured above and below the panels by the average solar radiation measured above the panels. All data measured by the equipment were stored at intervals of 10 min.

2.3. Crop Sampling and Yield

The grain weights of the control and shaded plots were compared. Subsequently, panicle number, spikelet number per panicle, percentage of ripened grain, and thousand grain weight were measured as the four components of grain yield, as theoretical grain yield is expressed as

$$Grain\ Yield\ \left[g{\cdot}m^{-2}\right] = P \times G \times M \times W \times 10^{-3} \tag{1}$$

where P is the panicle number per square meter, G is the spikelet number per panicle, M is the percentage of ripened grains (%), and W is the thousand grain weight (g/10^3 grains) [51].

During the heading stage, the tiller number, plant height, and soil–plant analysis development (SPAD) values were observed. Nitrogen fertilizer is correlated with the chlorophyll content of the plant leaves (SPAD value) [46]. To evaluate the SPAD value, we used a SPAD-502 Plus meter (Konica Minolta Co., Ltd., Tokyo, Japan). Grain quality parameters, such as protein content, color, and size, were also evaluated and analyzed by the Shizuoka Seiki Company. This information was used to obtain greater accuracy in terms of the physiological characteristics of the rice grains.

Table 1 shows the list of plant components measured in this study from the early growth (heading) to harvesting stages of the crop. When the plants were heading in July or August, the tiller number, plant height, and SPAD value were measured. At harvest, the number of panicles, plant height, and other characteristics were measured on the same day. After threshing and milling, the grain weight of the sample, as well as other quantitative and qualitative items (refer to Table 1), were determined. Table 2 shows the sample numbers of plants from each farm. We collected approximately 20–30 plants in each control or shaded plot as a representative sample.

Table 1. Description of measurement items.

Early growth (heading) stage		Till number per plant Plant height SPAD value of a flag leaf
Harvest time	At harvesting	Panicle number per plant Panicle length Plant height SPAD value of a flag leaf
	After threshing and milling	Grain weight Spikelet number per panicle Percentage of ripened grains Thousand grain weight Protein content Green kernelled rice ratio

Table 2. Sample number of plants from each farm.

Farm	Year	Crop Sampling
Farm A	2016	Two bundles of 40 plants from each of the 18 experimental plots for measuring the grain weight, panicle number, panicle length, plant height, and SPAD value. In addition, another bundle of 10 plants from each of the18 plots for measuring spikelet number per panicle, percentage of ripened grains, and thousand grain weight.

Table 2. *Cont.*

Farm	Year	Crop Sampling
Farm A	2017	A bundle of 30 plants from each of the 18 experimental plots for measuring the grain weight, panicle number, panicle length, plant height, and SPAD value. In addition, another bundle of 15 plants from each of the 18 plots for measuring spikelet number per panicle, percentage of ripened grains, and thousand grain weight.
	2018	A bundle of 25 plants from each of the nine plots in the northern area of the site for measuring the grain weight, panicle number, panicle length, plant height, and SPAD value. In addition, a bundle of 15 plants from each of the same nine plots for measuring spikelet number per panicle, percentage of ripened grains, and thousand grain weight.
Farm B	2014	A bundle of 20 plants each from the two control plots and two shaded plots.
	2015	
Farm C	2014	
Farm D	2017	A bundle of 21 plants each from the one control plot and two shaded plots.
	2019	A bundle of 25 plants each from the one control plot and one shaded plot.

The shading and fertilization effects, particularly on Farm A, were verified using multiple samples collected from the control and shaded plots on each farm. To verify the effects of shading and fertilization statistically, two-way analysis of variance (ANOVA) was employed for Farm A. One-way ANOVAs were employed for Farms B and C to verify only shading effects.

3. Results

3.1. Meteorological Data Analysis

Table 3 depicts the air temperature and solar radiation data measured in the 2017 experiment performed on Farm A. As the positions of the panels remained the same from 2016 to 2018, we further examined the continuously measured microclimatic result of the one-month cultivation period in 2017, as a representative sample. The different treatment areas are referred to as the strongly shaded, weakly shaded, and control plots. These measurements were used to compare the shading rates of each treatment plot and their effects, with the average panel top surface result as a reference point.

Table 3. Air temperature and solar radiation at experimental Farm A in 2017.

		Strongly Shaded Plots	Weakly Shaded Plots	Control Plots	Top Surface of Panel
Air Temperature in Daytime * (°C)	**Mean**	28.3	28.4	28.5	-
	Standard Deviation	4.2	4.5	4.5	-
PPFD ** (μmol m^{-2} d^{-1})	**Mean**	194	236	275	297
	Max	2166	2265	2413	2482
Shading Rate		34.5%	20.4%	7.4%	-

* Daytime was assumed to be from 6:00 to 18:00, from 27 July 2017 to 22 August 2017. ** Measurement period was from 27 July 2017 to 9 September 2017.

The average air temperature collected from 27 July 2017 to 22 August 2017 for each point did not depend on the presence of panels on Farm A. Regardless of the shading rate, the average daytime air temperature collected using a thermocouple was approximately 28 °C. This is similar to the results of the experiment conducted by Xiong et al. [52], where the overall optimal ambient temperature for rice photosynthesis was approximately 30 °C. In addition, the average water temperature collected at experimental Farm A was 26.7 °C, and no large deviations were observed in the paddy field. The water use efficiency in agrivoltaic-shaded areas may be better during water stress [30,32].

The average solar radiation was measured using PPFD sensors. The shading rate was defined by dividing the difference between the average solar radiation measured above and below the panels by the average solar radiation measured above the panels. The shading rates measured at experimental Farm A (refer to Table 3) were 34.5% in the strongly shaded plots, 20.4% in the weakly shaded plots, and 7.4% in the control plots. The shading rate in the control plots was primarily caused by shadows from the adjacent large and small panels, because the control plots were in the middle of the experimental field (refer to Figure 2). The panels from the other treatments therefore blocked the light as the position of the sun changed.

Figure 4 displays the change in PPFD on Farm A on a typical sunny day, 22 August 2018, and on a cloudy day, 20 August 2018. The left-hand figure shows that the PPFD sensor values under the panels fluctuated on the sunny day, owing to shading from the panels and direct exposure to sunlight through the spaces between them. Because the control plots were located between the two shaded plots, the PPFD sensors in the control plots were also shaded during certain periods. On the cloudy day (shown in the right-hand figure) when the light intensity was evenly spread, the PPFD values did not oscillate as much. The disparity between the two periods was caused by the different weather conditions and is similar to the results of Tani et al. [53]. Light shortages owing to seasonal variability may appear to be a challenge for crops under agrivoltaics. However, rice crops are commonly planted only during the summer season in Japan; thus, the microclimatic parameters were only monitored during the summer.

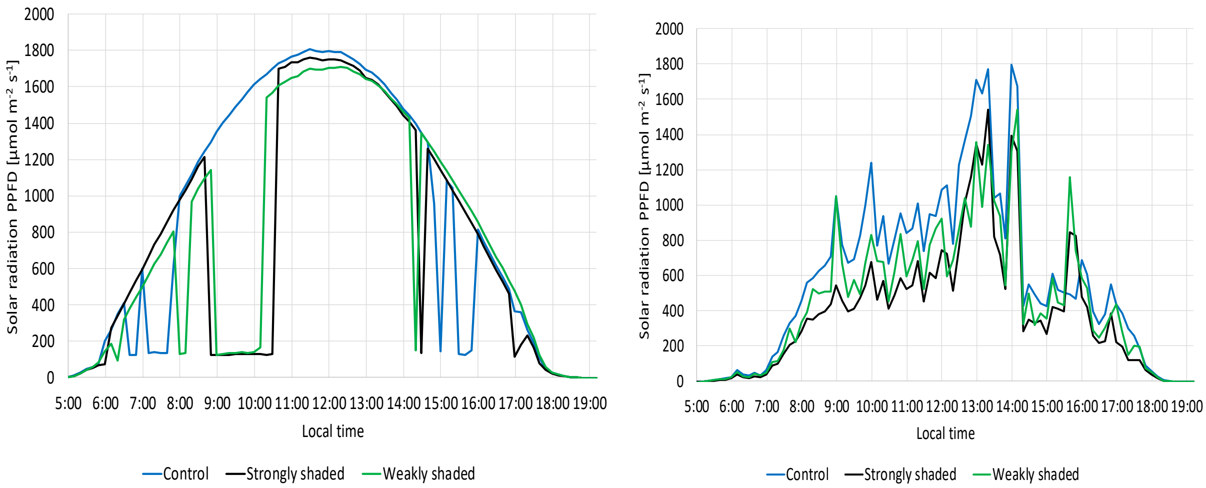

Figure 4. Changes in PPFD on a typical sunny day (**left**) and cloudy day **(right)** at Farm A.

As shown in Figure 5, we used a thermo-camera (TH9260, Nippon Avionics, Tokyo, Japan) on peak summer days on Farms B and C and found that the surface temperatures decreased by 2–4 °C in the shaded agrivoltaic plots. Previous studies have observed that, when the surface temperature increases owing to high exposure to sunlight in summer, the expected yield declines sharply because of the effects of high temperatures on leaves [52,54]. Such increases shorten the duration of phenological development of the crops [55,56]. Thus, installing panels above the crops can lessen crop exposure to high temperatures that may lead to stress [19,32,41,57].

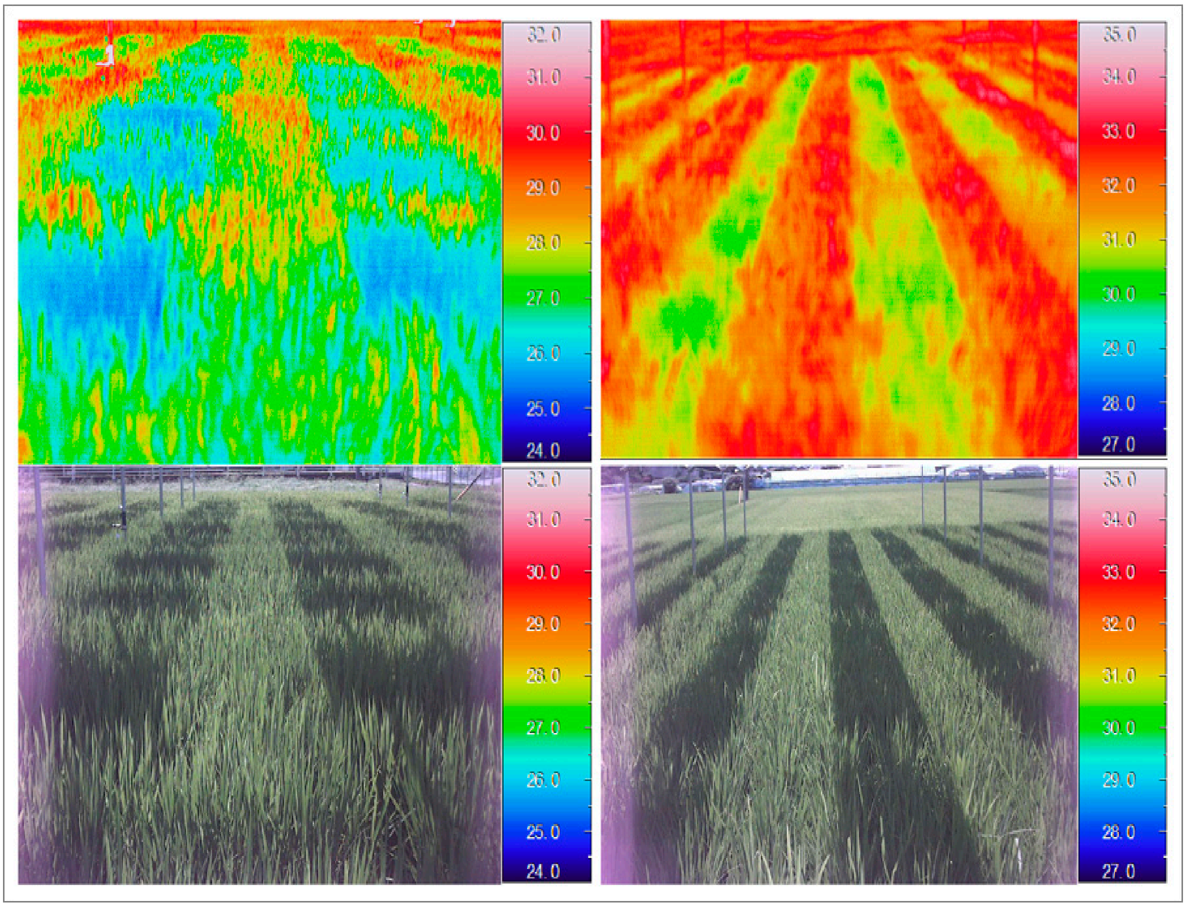

Figure 5. Surface temperature measurements using a thermo-camera on Farm B (**left**) and Farm C (**right**).

3.2. Correlation between Shading Rate and Rice Productivity

After threshing and milling the samples from each plot on each farm, as shown in Table 2, we measured the weight of the sample grains. Figure 6 shows the grain weight per plant with respect to the shading rate. Each plotted point represents the average grain weight per plant. For example, the number of samples per plot on Farm A in 2016 was 240 ($= 40 \times 6$) because we had six plots for each shading condition, as shown in Figure 2, and 40 plants were harvested from each plot to measure grain weight, as presented in Table 2. The grain weight on all the farms decreased with increasing shading rate. ANOVA was employed to statistically test the decrease in grain weight owing to shading. Table 4 shows the ANOVA results. Shading significantly influenced grain weight on the three farms at the 5% level. However, Farm A (2018) and Farm B (2014) were not significantly influenced by shading, despite seeming to show a decrease in grain weight. The influence of varying the amount of fertilizer applied (6 g N m^{-2}, 24 g N m^{-2}, and 48 g N m^{-2}) as well as shading (strongly shaded, weakly shaded, and control) were tested in 2016 and 2017 on Farm A. Although varying the amount of fertilizer had a significant effect on grain weight in these two years, an interaction effect between shading and fertilization was not observed.

Based on the MAFF regulations in Japan, which state that the crop yield should be greater than 80% for an agrivoltaic system to be installed on a farm [44], in Figure 6 we present a simplified linear relationship between grain weight and shading rate to estimate the probable upper limits of the shading rate that comply with MAFF conditions. To estimate the slope statistically, we employed a linear regression with random effects between the grain weight W_{ij} (g/plant) and shading rate S_{ij} of sample i on farm j, as shown below:

$$W_{ij} = \alpha + a_j + (\beta + b_j)\, S_{ij} + \varepsilon_{ij} \quad (2)$$

where α and a_j are intercept terms, β and b_j are slope terms, and ε_{ij} is an error term. The terms a_j and b_j express the effects of a different farm j. The regression analysis results show that the standard deviation of b_j is not statistically significant; however, the other coefficients α, β, and the standard deviation of a_j are significant. This is consistent with Figure 6, where the average grain weight without shading varied among farms; however, the slope of the lines does not vary significantly. Using the regression model, we deleted b_j from Equation (2); the resulting estimates are $\hat{\alpha} = 24.3$, $\hat{\beta} = -15.3$, and the standard deviation of $a_j = 4.4$. Based on these estimates, the upper limit of the shading rate that complies with the MAFF conditions was estimated to be 32%. At a 95% confidence interval of $\hat{\beta}$, the confidence interval of the upper limits of the shading rate was estimated to be 27–39%. If the shading rate is converted to the proportion of land area above which solar panels can be placed, then the limit of the ratio of solar panels to rice paddy area should be approximately 28% with a confidence interval between 23% and 36%.

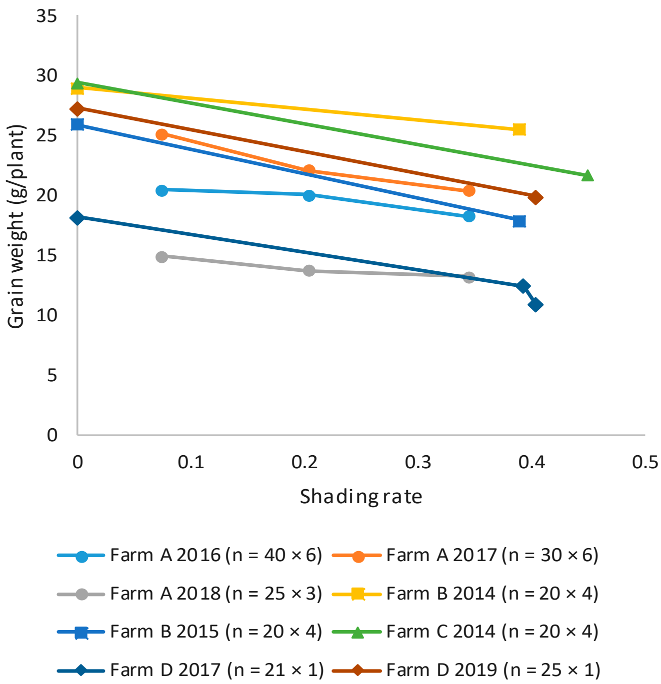

Figure 6. Relationship between average grain weight and shading rate.

Table 4. Influence of shading and fertilization on grain weight.

Farm	Year	Number of Samples for ANOVA	Shading	Fertilization	Interaction of Shading and Fertilization
Farm A	2016	18	*	*	n.s.
	2017	18	**	**	n.s.
	2018	9	n.s.	-	-
Farm B	2014	7	n.s.	-	-
	2015	9	*	-	-
Farm C	2014	7	*	-	-

**: 1%; *: 5%; n.s.: not significant. Note: Farm D is not listed as only a single observation was performed for each of the shaded and control plots.

3.3. Factors Affecting Rice Productivity

Table 5 summarizes the shading effect on rice growth indices. For each farm, the statistical significance of the shading effect on various rice growth indices, such as panicle number and SPAD value, was tested. The grain weight is the product of four components: panicle number per square meter, spikelet number per panicle, percentage of ripened grains, and thousand grain weight, as shown in Equation (1). The first four rows of harvest time (quantity) in Table 5 show the shading effect on these four factors. Among them, panicle number was significantly affected by shading in four of the six fields from which data were available. The decrease in grain yield owing to shading, shown in Figure 6, is primarily caused by the decrease in panicle number.

Table 5. Shading effects on rice growth indices.

		Farm A 2016	Farm A 2017	Farm A 2018	Farm B 2014	Farm B 2015	Farm C 2014	Farm D 2017	Farm D 2019
Shading rate		35%, 20%	35%, 20%	35%, 20%	39%	39%	45%	40%	40%
Fertilizer		Chemical	Chemical	Chemical	Chemical	Chemical	Chemical	Organic	Organic
Cultivar		*Nihonbare*	*Koshi-hikari*	*Koshi-hikari*	*Kinu-musume*	*Kinu-musume*	*Aichino-kaori*	*Koshi-hikari*	*Koshi-hikari*
Harvest time (Quantity)	Panicle number per plant	** (*n* = 485)	** (*n* = 432)	n.s (*n* = 225)	n.a.	* (*n* = 10)	n.a.	** (*n* = 63)	n.s. (*n* = 50)
	Spikelet number per panicle	n.s. (*n* = 18)	n.s. (*n* = 18)	n.s. (*n* = 9)	n.a.	n.a.	n.a.	n.a.	n.a.
	Percentage of ripened grains	n.s. (*n* = 18)	n.s. (*n* = 18)	n.s. (*n* = 9)	n.s. (*n* = 8)	n.s. (*n* = 10)	n.s. (*n* = 8)	n.a.	n.a.
	Thousand kernel weight	n.s. (*n* = 18)	n.s. (*n* = 18)	n.s. (*n* = 9)	* (*n* = 8)	n.s. (*n* = 10)	n.s. (*n* = 8)	n.a.	n.a.
	Panicle length	** (*n* = 486)	** (*n* = 432)	* (*n* = 225)	n.s (*n* = 18)	n.s (*n* = 10)	n.s (*n* = 18)	n.s. (*n* = 63)	n.a.
	Plant height	n.s. (*n* = 485)	** (*n* = 432)	n.s. (*n* = 225)	n.s. (*n* = 18)	n.s. (*n* = 10)	n.s. (*n* = 18)	** (*n* = 63)	n.a.
	SPAD value	** (*n* = 485)	** (*n* = 270)	** (*n* = 162)	* (*n* = 18)	* (*n* = 10)	n.s. (*n* = 18)	n.a.	n.a.
Harvest time (Quality)	Protein content	n.s. (*n* = 36)	** (*n* = 18)	n.s. (*n* = 9)	* (*n* = 8)	* (*n* = 10)	* (*n* = 8)	n.a.	n.a.
	Green kernelled rice ratio	n.s. (*n* = 36)	n.s. (*n* = 18)	n.s. (*n* = 9)	* (*n* = 8)	n.s. (*n* = 10)	* (*n* = 8)	n.a.	n.a.
Early growth (heading) stage	Till number	n.s. (*n* = 54)	** (*n* = 431)	n.s. (*n* = 144)	n.a.	n.a.	n.a.	n.s. (*n* = 30)	n.a.
	Plant height	** (*n* = 54)	** (*n* = 216)	n.a.	n.a.	n.a.	n.a.	n.s. (*n* = 30)	n.a.
	SPAD value	* (*n* = 54)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

**: 1%; *: 5%; n.s.: not significant; n.a.: not available.

The SPAD value of rice increases during the early growth stage and gradually decreases thereafter [46]. At the harvesting stage, the shading rate had a significant effect on the SPAD value in most fields. At the harvesting stage, the SPAD value of the shaded area was higher than that of the unshaded area. This indicates that shading delays grain growth.

Regarding quality, protein content was significantly affected by shading in four fields. Shading positively influences the protein content, which, in turn, worsens the taste of the rice as a high protein content increases the viscosity of cooked rice, affecting its texture [58].

3.4. Electricity Generation Potential of Using Agrivoltaic Systems in Japan

In Japan, 1.47 million hectares of land are allocated to rice paddy farming alone [45]. To consider the uncertainty of the energy calculation while complying with the 80% yield security of MAFF, we performed a sensitivity analysis using the ratio of panel area to total paddy which was estimated in Section 3.2 (23–36%). Assuming a solar panel density to land area limit of 28%, 411 thousand hectares of solar panels can be installed for agrivoltaic rice production systems. The area required for installing a 1-kW photovoltaic panel on a rooftop depends on the mounting angle of the panel, which is approximately 10 m^2 in Japan. However, in the case of an agrivoltaic system, based on Farm B (19.9 m^2/kW), Farm C (16.3 m^2/kW), and Farm D (18.3 m^2/kW), the necessary land area for a photovoltaic power system that produces 1-kW electricity ranges from 16 to 20 m^2, and we used the average area of 18 m^2, considering the gap between the panels to decrease the shading effects on the crops. This approach yielded an installed capacity of 231 million kW. The Institute of Energy Economics, Japan (IEEJ) estimates a capacity factor of 14% for photovoltaic power in Japan [59,60]. Assuming a 14% capacity, using agrivoltaic systems in rice paddy areas leads to an annual electricity production of 284 million MWh. As of 2018 (Figure 7), renewable electricity (excluding hydroelectricity) accounted for only 8.9% of electricity generation in Japan [61]. The estimated annual electricity production of agrivoltaic systems could account for 29% of the electricity generation in Japan as of 2018. Considering the above-mentioned panel area ratio, photovoltaic panel size, and capacity factor ranges, the minimum and maximum agrivoltaic potentials are displayed in Figure 7 (approximately 178 million MWh and 464 million MWh, respectively).

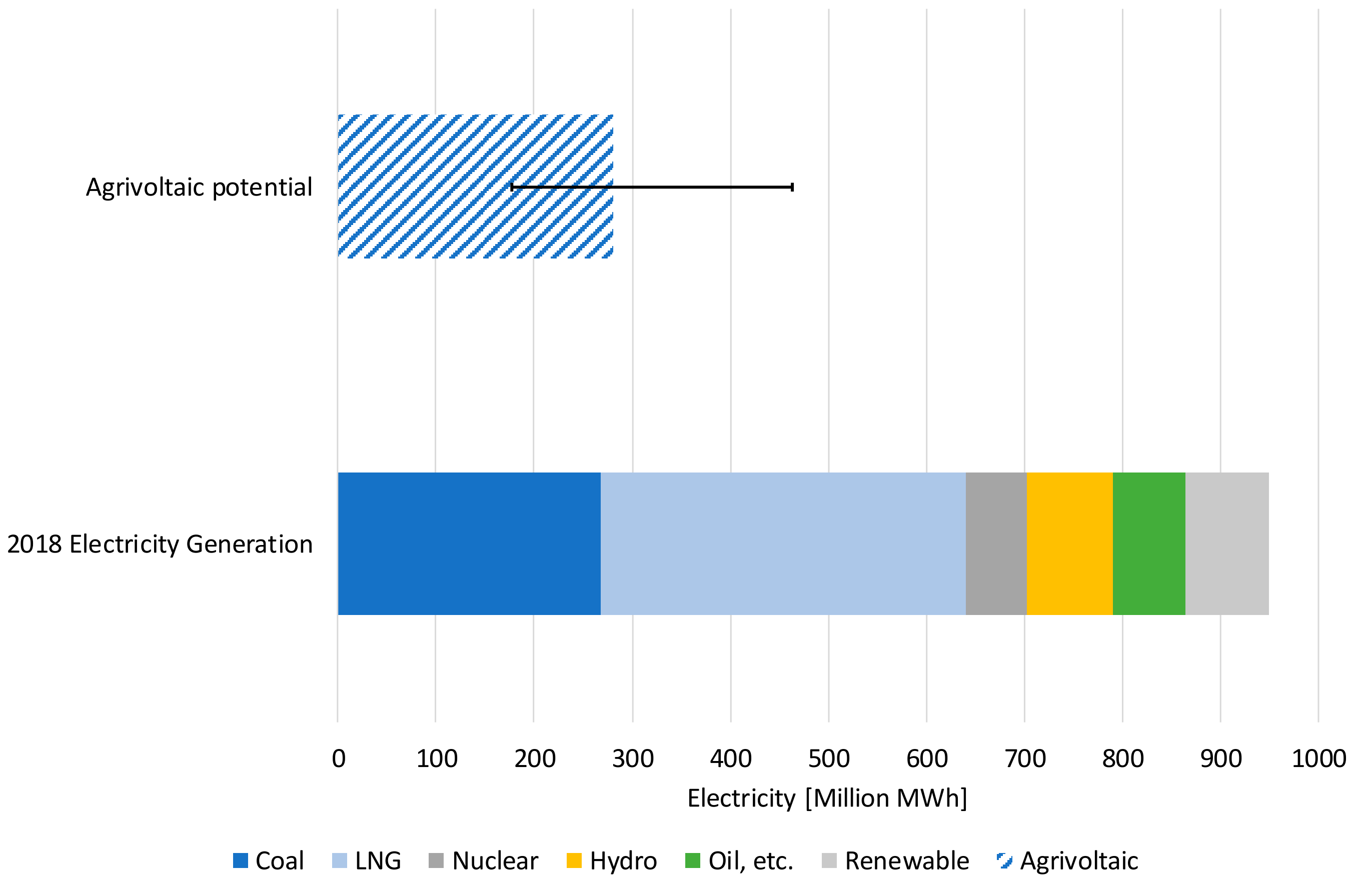

Figure 7. Potential energy output of agrivoltaic systems above rice paddies in Japan.

Agrivoltaic systems have the potential to increase the value of renewable energy, while adding functional value to the land, as opposed to the conventional function of only crop production [23,37]. In contrast to fallow fields, which are typically located in isolated areas, farmed paddy fields can easily be connected to the grid network in Japan. Similarly, Farms B, C, and D are located near residential areas, which makes it easier to connect them to the grid network, as no additional grid investment is required. However, grid network connections, integrated with agrivoltaics, should be further studied and developed to track various electricity generation indices and fault occurrences.

4. Discussion

In contrast to European countries, where offshore wind power has been rapidly increasing, deep coastal waters and steep coasts make offshore wind power systems difficult to establish in Japan. Although public opinion is supporting the transition of the new energy system with renewable energy [62], preference is more particular in the construction of photovoltaics than wind turbines [63,64]. Hence, incorporating agrivoltaics into large-scale commercial rice farming operations would provide the economic and environmental benefits of low-costs and distributed electricity generation.

This research has expanded the use of rice fields to provide sustainable energy production using agrivoltaics. It is worth noting that, to broaden the use of agrivoltaics to include many crops, it is first necessary to identify the optimal shading capacities to contribute to the existing standard policies of agrivoltaics in the country. In addition to research conducted in greenhouses, empirical studies are still limited to shade-tolerant crops [23]. Our experimental results show that grain yield is positively correlated with solar radiation, which is consistent with the correlation between grain yield and solar radiation during the reproductive and ripening stages [65]. As shading significantly affects major components of rice crops, such as panicle number, SPAD value, and grain quality, more experiments and analyses are required to further explore not only photovoltaic cell efficiency in agrivoltaic systems, but also mitigating solutions to decrease the effects of these systems on the crops under the varying microclimate conditions of each area [30,66]. The negative effects of decreasing light can also be reduced by placing the photovoltaics on the northern side of the field to lessen the shadow casted by the panels to the crops [53].

The effect of shading in this case may not have been limited to light intensity but could also have influenced light quality or the spectral light distribution and its duration of absorption by the crop. Hence, finding the critical sunlight period requirements of the crop during cultivation is important to avoid a decrease in crop yield. In addition, determining the proper SPAD threshold would help adjust for the nitrogen needs of the crop during shaded periods, while timely and adequate fertilizer application could considerably reduce nitrogen fertilizer application without reducing grain yield [67]. Reliable estimates of the rice yield indices and design modifications of the rice field are critical for establishing the long-term economic and logistical viability of rice production while accommodating this system [68].

Policies that provide incentives to enhance the sustainability of renewable energy technologies should encourage the development of new innovations, such as agrivoltaics. While complying with the regulations which state that crop yields should remain greater than 80% for agrivoltaic systems to be installed on farms, such systems could generate 284 million MWh/year, which is equivalent to approximately 29% of the total Japanese electricity demand based on 2018 calculations. Cutting the 2013 levels of greenhouse gases by 46% by 2030 and reducing them to zero by 2050 will not be easy. In addition, the available area for installing photovoltaic panels, such as the roofs of buildings or unused land, is limited. Agricultural farms are a suitable place to install photovoltaic panels as an agrivoltaic system. It will be a promising option to achieve the greenhouse gas emission reduction goals of 2030 and 2050. Agrivoltaics will also be economically beneficial in rural areas, as they could encourage reclamation of abandoned land areas that are suitable for farming, and provide employment opportunities and rural electrification that could induce economic growth [68–70].

The expansion of the use of agrivoltaic systems would increase the share of photovoltaic energy not only in Japan, but also in other rice-producing countries, which are mostly situated in Asia. The major rice-producing countries in Asia include India, China, Indonesia, Bangladesh, and Thailand [45,71]. The main drivers of energy-generated growth in Asia are China, India, and Asian Pacific countries [72]. As rice is widely cultivated in vast land areas in these countries [71], it can be deduced that these countries, with their high potential for further technological penetration, have higher agrivoltaic potentials for improving their renewable energy cumulative capacities. In addition, future studies should consider measures to alleviate the reduced shading rate that affects crop productivity, such as the installation of plastic film [53], semi-transparent solar panels [73], or bifacial photovoltaic systems [74] that are designed to improve the efficiency of electricity generation.

5. Conclusions

Agrivoltaic systems are still a new concept; thus, empirical studies on their effects, specifically on their underlying effects on crop yields, are limited. Therefore, we wanted to expand agrivoltaic research, development, and capacity building by understanding the impact of photovoltaic shading on crops. This study aimed to experimentally expand the available information on rice growth under agrivoltaic systems. The relationship between lighting conditions and rice cultivation was examined using different treatments. As expected, solar panels and rice crops compete for radiation. With the current MAFF regulations in mind, various configurations of agrivoltaic planning designs were assessed, based on their harvest yields. Hence, proper control of the accumulated shading rate is required, as it greatly affects yield.

Based on the experimental results, the upper limits of the shading rate ranged from 27 to 39%. A significant decrease in the number of panicles owing to shading was observed on Farm A. This finding was validated by experiments performed on three private farms. In compliance with MAFF regulations, we calculated that, when the shading rate was converted to the proportion of land area covered by solar panels, the limit of the ratio of solar panels to rice paddy area should be approximately 23–36%. If the potential maximum photovoltaic energy generation is achieved, we can considerably reduce the gap separating Japan from its 2030 goal, which is to reduce greenhouse gas emissions by 46% from the 2013 levels [10]. This study demonstrates the high potential for agrivoltaic systems as a renewable energy source and revenue growth opportunities for farmers [33]. Furthermore, the expansion of the use of such agrivoltaic systems would increase the amount of photovoltaic energy generated not only in Japan, but also in other rice-producing countries, which are mostly situated in Asia.

This research can simultaneously benefit various sectors, such as by increasing the sustainability of the energy and agriculture sectors. However, as agrivoltaic research on rice paddies is still in its infancy, it is imperative to explore the existing policies of the local economy and the regulatory environments in greater detail in order to evaluate the national and international potential of agrivoltaic systems.

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Abbreviations

MAFF	Ministry of Agriculture, Forestry and Fisheries
IEEJ	Institute of Energy Economics, Japan
FIT	Feed-in-Tariff
PPFD	Photosynthetic Photon Flux Density
PAR	Photosynthetically Active Radiation
SPAD	Soil–Plant Analysis Development
MWh	Megawatt-hour
TWh	Terawatt-hour

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