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Reducing Land Competition for Agriculture and Photovoltaic Energy Generation – A Comparison of Two Agro-Photovoltaic Plants in Japan

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Abstract: ***Photovoltaic energy generation has great potential to reduce green house gas emissions compared to conventional sources of electricity. However, its wide-spread application can cause competition of land-use to arise due to the large areas required. To lessen this competition, concepts for co-usage of photovoltaics and agriculture have been proposed. In an agro-photovoltaic plant electricity is generated from photovoltaic (PV) panels mounted in designed spacing and height, so that limited shading allows for productive agriculture on the land below. A well-designed agro-photovoltaic system can potentially reduce land-use competition and provide additional income and employment opportunities in rural areas which are currently under pressure of depopulation and over-aging in Japan. This work looks at the implementation of two realizations of the concept within the present framework in Japan. The light distribution underneath the PV arrays is calculated. Total received sun light at ground level varies greatly between the two designs with 81% and 43% compared to unobstructed condition. Homogeneity and time-variability of direct sun light incidence are discussed.***

Keywords: photovoltaics, agro-photovoltaic power plant, land-use competition, light management

1. Introduction

Renewable energies represent one attractive option decrease green house gas emissions and provide a more environmentally friendly energy generation compared to conventional energy sources. The evaluation of different technologies in the context of sustainability is however still a new and challenging field, which tries to combine strict technical evaluation schemes such as e.g. life-cycle assessment but additionally incorporates criteria concerning social impact as well as complex feedback with the natural environment [1]. Intrinsically, such technology deployment has to deal with uncertainties and incomplete knowledge of the future [2], for which the facilitation of a learning process by continues assessment and soft factors such as adaptability of technical concepts become important considerations.

Photovoltaic (PV) power generation is developed in several different concepts such as roof-top PV, building-integrated PV, or ground mounted PV power plants. In the case of large-scale ground mounted PV power plants, a conflict of land-use can arise due to competition with agriculture. The idea of agro-photovoltaics has been proposed to lessen the competition in land-use by co-usage for the dual purpose of agriculture and PV electricity generation [3], [4].

In Japan the concept of agro-photovoltaics is also known as “solar sharing”, in the sense that the incoming sun light can be shared for energy generation and crop production. In Japan the concept was proposed by A. Nakashima in 2004 and has since been developed with the specific goal of keeping the limited agricultural land intact, providing income opportunities in farmers to alleviate the problem of a shrinking and aging rural population, and realizing a wide-spread use of PV electricity generation as a renewable energy source.

Two factors make this approach promising: (1) with adequately designed spacing PV installations permit considerable sun light to reach the ground level and (2) plant species exhibit different tolerance levels to shading and different levels of light saturation point. While plant growth generally increases with the amount of incident light, beyond a certain limit, called the light saturation point, any further increase in light intensity does not lead to further growth. Therefore, depending on species there is excess sun light which is not utilized for further plant growth and can even be detrimental to the plant or fruit quality. In principle, a well-designed agro-photovoltaic power plant could therefore produce similar agricultural yields compared open plot and generate electricity as additional output. Designing the spacing and arrangement of the PV installation and matching the shading condition to the intended plant species is essential for the successful realization. A limited number of recent studies have looked at plant species in the context of argo-photovoltaics. For example lettuce [5] and turf grass [6] have been shown to profit from limited shading, while a study on rice showed a 20% decrease in light intensity resulted in a 20% decrease in rice harvest [7]. Some plants have the ability to adapt and compensate partially or totally to reduce light availability [8]. Providing full sun light at critical stages of plant growth (e.g. seed germination or flowering) could offset detrimental effects from shading. For the technical design of an agro-photovoltaic power plant, tools for simulating panel spacing, angle, and energy yield are readily available [9]. Implementations for calculation of shading at ground level have recently been presented [9], [10].

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Figure 1: a) Project A: small-scale 50 kW agro-photovoltaic project, b) Project B: large-scale 20 MW agro-photovoltaic project, in Tsukuba, Japan. Note that the picture b) is taken shortly after finishing construction; therefore no agricultural activity is yet visible

In this work, I study two early implementations of representative agro-photovoltaic power plants in Japan exhibiting different designs. Special focus is given to the analysis of light distribution underneath the solar arrays which determines the feasibility and scope of agricultural activity on the land.

2. Method

After introducing the current legal framework for agro-photovoltaic plants in Japan, two implementations of the concept are compared in terms of their general designs in a case study. Full calculation of light distribution under the two simplified PV array geometries are performed by using algorithm implemented in Mathematica software [10]. The light distribution is analyzed by stereographically projecting the PV array geometry to plot it in a chart of the yearly sun path to qualitatively discuss the amount of shading from direct sunlight and its timely variability.

3. Case study

Present legal requirements and regulatory scheme
In March 2013, the Ministry of Agriculture, Forestry and Fisheries (MAFF) allowed the development of photovoltaic power plants on existing agricultural land as agro-photovoltaic power plants in Japan. Under these rules a temporary use permit is issued for three years which allows the installation of the photovoltaic power plant on farm land if the following conditions are met [11]:

- Comprehensive judgment if sufficient consideration is given to farming conditions during the period of converted use
- Agricultural activities are continued appropriately
- Design allows suitable amount of sunlight for crop growth
- Mounting structure provides sufficient space and height (at least 2 m) for use of efficient agricultural machinery
- Positioning etc. allow effective use of neighboring farm land
- Condition for the temporary change of use permit is obligation to report once a year that the agricultural produce etc. is not negatively affected

In case of negatively affected agricultural yield etc., it is the obligation to remove the installation and restore the land to its original state. Re-assessment is necessary ever three years.

Table 1: Comparison of two agro-photovoltaic power plants in Tsukuba, Japan

	Project A	**Project B**
Total rated power	58 kW	20 000 kW
PV sub array size	4.5 m × 0.52 m (3×1 modules)	8.30 m × 4.04 m (4×5 modules)
Array arrangement	Single rows with 0.50 m interruptions in E-W direction, 2.52 m pitch of rows in N-S direction	0.20 m between arrays in E-W direction, 6.13 m pitch of rows in N-S direction
PV module size	1.48 × 0.52 m	1.64 × 0.99 m
PV module power	115 W	265 W
Tilt angle	36°, manually adjustable	15°, fixed
Height of PV installation above ground	3.5 m	2.0 m
Orientation	SSW (193°)	S (180°)
PV panel coverage (vertical projection)	19 %	59 %
Proposed agricultural crop	Buckwheat (Fagopyrum esculentum), Welsh onion (Allium fistulosum), …	Shade loving plants: Dokudami (Houttuynia cordata), Ashitaba (Angelica keiskei), Ginseng (Panax)

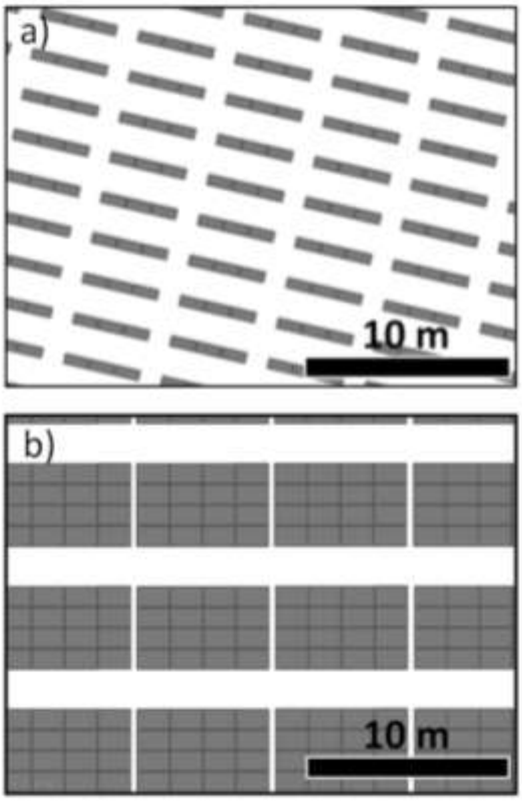

Figure 2: Top view of section of a) Project A and b) Project B.

General design comparison of two agro-photovoltaic power plants in Tsukuba.

Two recent implementations of agro-photovoltaic power plants in Tsukuba City, Japan (36°5N, 140°4E) are compared. The respective sites were chosen since their proximity makes a comparison meaningful, by eliminating differences in solar irradiance or climate. At the same time, the scale and deigns of the two implementations are largely different giving a representative scope of approved projects.

Figure 1 shows a picture of project A, a 50 kW agro-photovoltaic plant, and project B, a 20 MW agro-photovoltaic plant. Both power plants are developed on agricultural land with permission by MAFF to be used as solar sharing facilities. Table 1 gives a comparison of the basic parameters such as size, panel arrangement and intended agricultural crop. The most striking difference is the scale of the two projects, where project A is a small-scale implementation of 58 kW while project B reassembles a MW-scale sized project. The top-view of the PV array layouts in Fig. 2 illustrates the difference in PV array coverage of 19% for project A and 59% for project B. From these basic geometries the implications on shading and options for agricultural crop can be roughly inferred, however a more thorough analysis is necessary to qualitatively and quantitatively judge the light distribution under the installation as well as their seasonal dependence and ratio of direct to diffuse sun light which will be given in the following section. In a previous, a strong influence on microclimate under shading conditions under a PV installation comparable to project B was shown [12]. The difference in coverage is also reflected in the intended agricultural crops, where various crops are proposed for project A, however project B focuses exclusively on shade tolerant species and varieties of edible wild plants.

4. Light distribution

For the full calculation of yearly light distribution at ground level underneath the PV installations, the two plant layouts are simplified by omitting spacing between arrays in E-W direction. In this periodic structure as shown in Fig. 3 a) and b) for project A and B, respectively, the light distribution of global sunlight is calculated along the indicated lines under an installation of 50 × 30 meter for which edge effects, i.e. more sunlight reaching ground level near the edges of the installation, are negligible. The yearly global irradiance is calculated using a time resolution of 30 min.

Figure 3 c) and d) show the relative total received sunlight at ground level underneath the simplified plant layouts for project A and B. The tilt angle of the solar panels is 36° and 15° for project A and B, respectively. 100% global light incidence corresponds to the completely unobstructed sunlight incidence. Calculated along the indicated lines, the relative light intensity for project A and B is given in Fig. 3 e), which is periodically expanded to give the shadow maps of Fig. 3 c) and d).

Due to the largely different coverage of the two projects, the average yearly global sunlight underneath project A and B is 81% and 43%, respectively. The variation with position ranges from 73% to 86% of relative light intensity in project A, and 29% to 64% in Project B. The increased homogeneity of light intensity in project A is mainly due to the smaller array size and a significant contribution is attributed to the shift in orientation by 13° off south, as will become apparent from stereographic projection overlaid with the yearly sun chart.

To discuss design aspects of agro-photovoltaic plants as well as to reveal the seasonal and daily variability of received direct sunlight, the stereographic projection of the PV array layout is plotted together with the sun chart in Fig. 4. Figure 4 a) shows the projection of project A oriented 13° off south while Fig. 4 b) shows the projection of the layout directly oriented toward south. From this comparison it can be seen that orienting the PV installation off south helps to increase light homogeneity of daily received sunlight at ground level by allowing the sun path to cross over the PV array rows (for sufficiently narrow array rows). In case of direct south orientation, complete shading or illumination during a particular day can occurs in one and the same observation point. Since project A includes a manually adjustable PV panel tilt, Fig. 4 c) shows the projection of the south oriented project A at a panel tilt of -54°, 90° turned from the optimal spring and autumn angle of 36°. Under this condition the PV panels intercept the least amount of sunlight, so that this technique might be used to supply maximum amount of sunlight at ground level during critical growth stages of the agricultural crop. PV panels will intercept the least direct sunlight when they are turned 90° off the seasonal optimal panel tilt angel. Electricity output will be severely reduced under this condition. However, the potential to offset agricultural output loss might justify the well-timed application of manual tilt for maximum sun light at ground level and should be further investigated.

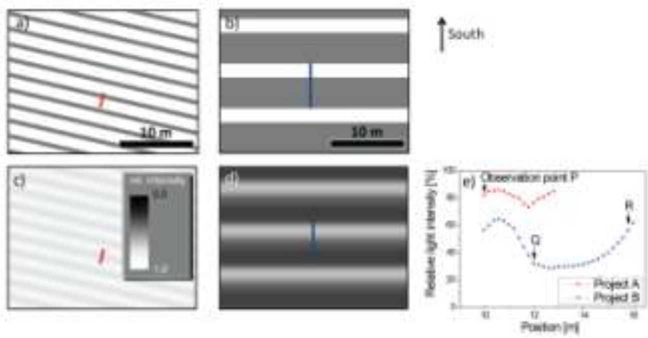

Figure 3: Simplified PV layout for a) project A and b) project B. c) and d) show the calculated shadow maps for the project A and B, respectively. Relative intensity scale for c) and d) is the same, shown in the inset of c). The relative intensity of total received sunlight, direct + diffuse, along the indicated lines is plotted in e)

Figure 4 d) and e) show the projection of project B for two different observation points, Q and R, respectively, as indicated in Fig. 3 e). With the dense PV coverage, large array size, and direct south orientation Fig. d) reveals that some areas receive almost no direct sunlight during the whole year and only diffuse sunlight reaches these areas at ground level. In contrast, Fig. e) shows a position which from April to October receives full direct sunlight while during the rest of the year it is completely shaded from direct sun. To understand the time variability of sunlight and to qualitatively distinguish the irradiation of direct and diffuse sunlight the simple projections plotted with the yearly sun path are complementing the full calculation of light distribution. Measures to spatially better balance the amount of received direct and diffuse sunlight could be additional spacing between PV arrays in E-W direction or employing a checker board layout for the PV array. Note that the omitted spacing in E-W directions in project A and B only account for 10% and 2%, respectively, and has minor effect in this regard.

In summary, project A exhibits limited shading and allows an average of 81% of global sunlight to reach ground level. Incidence of direct sunlight is timely variable and homogeneity of total received sunlight is enhanced by small array size oriented 13° off south. In project B an average of 43% of sunlight reaches ground level which qualitatively is governed by complete shading from direct sunlight in some areas and seasonal full direct sunlight in other areas. Project A can be considered an experimental plant, which depending on harvest amount and experience is to some extend adjustable by providing more light by manually tilting the solar panels. Even complete disassembly would be feasible at manageable cost in case the requirements of MAFF are not meet during the operation of the plant. For project B, although the growth of shade-loving species is proposed, the permanent shade under the arrays might jeopardize the agricultural crop production with no anticipated adaptability of the photovoltaic construction.

5. Conclusion

Agro-photovoltaic power plants are a promising option to reduce land-use competition of photovoltaic energy generation and food crop production, however the concept is at an early stage of development and performance needs to be monitored closely to evaluate it in the context of sustainability. Since it is difficult to predict the growth of plants under these specific shading conditions (timely variable, direct, diffuse sunlight), adaptability of agro-photovoltaic systems is important to allow for correction and improvement. As shown from this case study, the current legal rules allow for largely different configurations of agro-photovoltaic plant designs which will only be judged in hindsight depending on their harvest yield. To allow for scientific studies and to further the understanding of the concept, it is advisable to require monitoring of micro climate as well as setup of comparison plots for the agricultural crops in installations beyond a certain size. Agro-photovoltaic power plants are a young concept which will require an adaptable learning process to meet the initially set goal for reducing land competition, keeping existing agricultural land in production, and providing income opportunities for rural farmers.

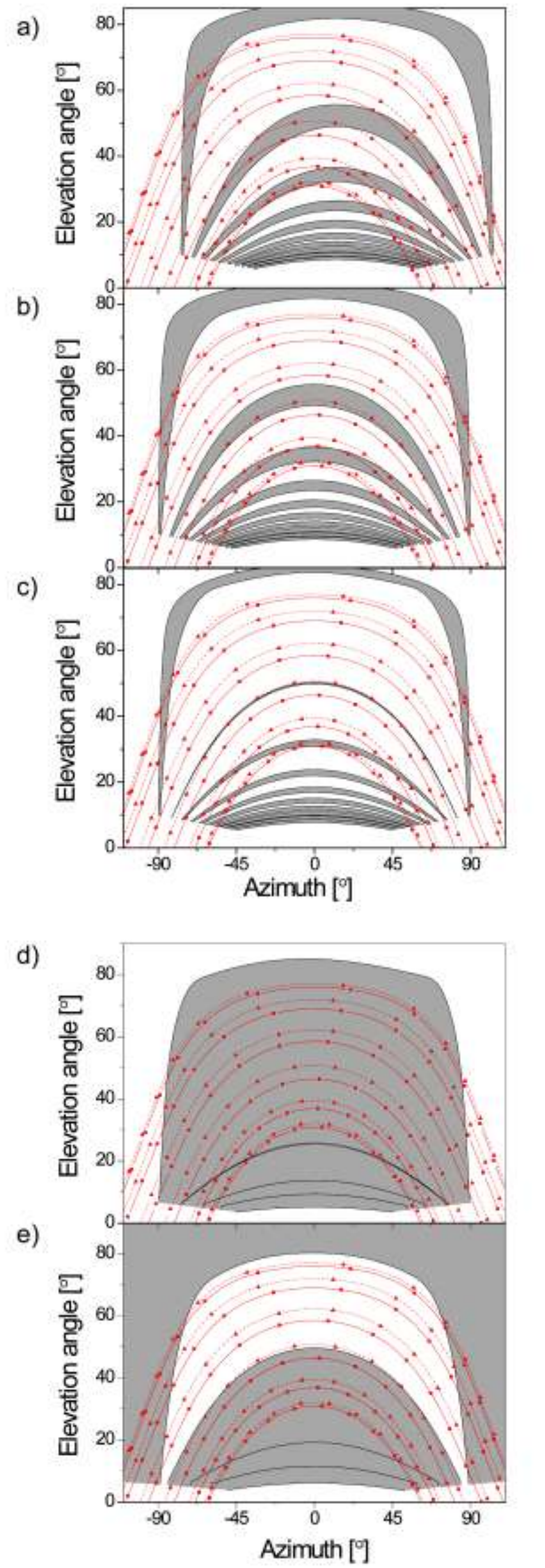

Figure 4: Projection of panel geometry and sun path chart (solid lines January-June, dashed lines July-December) for a) project A oriented 13° off south, panel tilt 36° b) project A, oriented south, panel tilt 36°, c) project A, panel tilt -54°.

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b), c), and d) are projection from observation point P, Q, and R as indicated in Fig. 3 e), respectively

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