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Study on the feasibility of agrivoltaics in the Kansai region of Japan †

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Abstract: As the climate crisis intensifies, the urgency for sustainable, agroecological farming practices has never been greater. This study explores the potential of agrivoltaic system (AVS) to meet these needs efficiently. Utilizing geographic information systems for quantitative analysis, the research assesses electricity generation, agricultural output, job creation, and economic impact of implementing AVS in Japan's Kansai region. The study identifies a generation ample potentials, including up to 14,041 GWh/year of electricity generation, suggesting that AVS could be instrumental in shaping effective policies for both decarbonization and food security.

Keywords: agrivoltaics; geographic information system; decarbonizing agriculture

1. Introduction

The escalating climate crisis makes decarbonizing all sectors, including agriculture. Approximately 30% of global greenhouse gas emissions originate from agriculture, necessitating immediate measures for its decarbonization[1]. To tackle this, the agrivoltaic system (AVS), which allows for both farming and solar power generation on one land tract, has gained much interest. The agrivoltaic concept was originally introduced in 1982 by Goetzberger and Zastrow, affiliated with Germany's Fraunhofer Institute for Solar Energy Systems ISE[2]. In Japan, an AVS support program was initiated in 2013, and as of 2021, a cumulative total of 3474 AVSs had been approved for establishment[3].

AVS offers multiple benefits rooted in agroecology[4,5]. As an example, AVS protect the ground and plants from direct sunlight and increase water use efficiency. Furthermore, the revenue generated by AVS has the effect of diversifying farmers' incomes. This diversification provides farmers with opportunities for economic independence and value-adding to their products. In addition, AVS encourages farmers to reclaim farmland by increasing the profitability of abandoned farmland with unfavorable agricultural conditions. This process preserves above- and below-ground biodiversity. AVS-based synergies can practically implement agroecology principles.

On the other hand, certain instances of AVS diverge from the foundational principles of agroecology. For example, in Japan, there are more than 100 instances where agricultural yields, influenced by AVS, fall below 20% of the region's average agricultural output[6]. Among various reasons contributing to these problematic cases is an inappropriate balance between power generation and agriculture. In particular, there are cases where solar power generation has been excessively prioritized—by installing too many solar panels, for instance— to the point that it interferes with agriculture, and agriculture has been relegated to a perfunctory role, known as "pseudo-farming. Appropriate system design is essential to prevent such instances.

Against this backdrop, the objective of this research is to assess the viability of introducing AVS in a manner that maintains a balanced relationship between agricultural and

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power generation activities. Moreover, it aims to acquire an in-depth understanding of the prevailing conditions in the region under study. The results of this research will present policy makers with critical insights into the current status of agroecology in the region, thereby aiding in appropriate system design and the formulation of effective policies.

2. Methods

2.1. Study area

For the geographical focus of this research, the Kansai region of Japan serves as the study area. Situated in the southern central part of the country, this region encompasses seven prefectures and 227 municipalities. As of 2020, the total population amounts to 22,311,695, spread over an area of 33,125.70 km^2[7]. The region is home to Japan's second-largest industrial zone, the Hanshin Industrial Region, where manufacturing predominates[8].

2.2. Scenario development and analysys

This study undertakes a quantitative evaluation of the prospects for introducing AVS. The target areas for this deployment are circumscribed to reclaimable idle farmland, a choice influenced by considerations of food and energy security. Moreover, farmlands that are severely degraded—such as those converted into forest lands—are excluded from the project's scope. The estimated cost for rehabilitating idle, yet minimally devastated, farmland ranges between 15,000 and 18,000 euros per hectare[9]. Although the introduction of AVS to severely devastated farmland would have a greater potential, the cost of rehabilitating farmland would be too high and difficult to commercialize, so it is not included in the scope of this study.

We limit the land area occupation ratio (LAOR) of the AVSs to be introduced to 35%. The LAOR is "the ratio between the area of the modules and the area of land that they occupy"[10]. The value of 35% is a level that does not interfere with agricultural production for many crop species grown in Japan[11]. For the system architecture, a rattan-shelf open-field-type AVS is selected.

The study employs soybean as the chosen crop, owing to its versatility in serving as food, livestock feed, and a meat substitute. Given that Japan's self-sufficiency rate for soybeans languishes at merely 6-7%, the production of this crop is considered to bolster national food security[12].

Finally, two distinct scenarios inform the estimation of idle farmland distribution. The Full Coverage Scenario (FC) contemplates the installation of AVS across all reclaimable idle farmlands, whereas the Priority Coverage Scenario (PC) restricts AVS implementation to areas that are identified as being particularly conducive for AVS deployment based on the FC Scenario.

In this study, to accurately estimate the distribution of revitalizable idle agricultural land, this study employed Agricultural Land Polygon Data and the High-Resolution Land Use and Land Cover Map of Japan (HRLULC). The former is published by Japan's Ministry of Agriculture, Forestry and Fisheries (MAFF) and was developed through the interpretation of satellite imagery to capture the footprints of potential agricultural land[13]. This data allows for high-precision, parcel-by-parcel identification of farmland while excluding non-cropland and severely devastated farmland. To further refine the target area by excluding currently used farmland, HRLULC data from the Japan Aerospace Exploration Agency (JAXA) was utilized. This machine-classified data comprises 12 categories, such as paddy fields, croplands, and grasslands, based on average usage from 2018 to 2020. The data is resolved to a mesh size (1 / 12,000) degree × (1 / 12,000) degree, corresponding to an approximate 10 m × 10 m, with an overall accuracy reported at 88.85%[14].

To mitigate disaster risk, the selection of target areas was further constrained. Specifically, areas vulnerable to landslides and flooding, as delineated in Table 1, were excluded, as were lands requiring ecosystem conservation. In the PC scenario, AVS introduction is confined to farmlands with high suitability for AVS, based on slope and aspect indicators. Farmlands intersecting with areas identified in the lower part of Table 1 are solely excluded from the PC scenario.

Table 1. High-risk areas excluded from this study's consideration.

Scenarios	High risk areas
Both scenarios	Sediment disaster alert areas
	steep slope failure hazard areas
	Flood disaster alert areas
	Areas with steep slopes (20 or more degrees)
	Natural parks
	Landscape districts
	Wildlife protection areas
Only PC scenario	Areas with moderate slopes (10-20 degrees)
	Areas with northern maximum slope directions

Source: Compiled from [15,16].

In addition, a non-installed area was established 5 m inward from the boundary of each agricultural field based on a survey by the Japanese Ministry of the Environment (MOE). This non-installed area is established to avoid shadowing of the AVS structures on adjacent land and to maintain operational efficiency. In addition, based on the MOE survey, parcels with an area of less than 16 m^2 after exclusion were excluded from the survey.

Following the mapping of idle farmland, the impact of AVS installation was quantified. Power generation was estimated utilizing solar radiation and temperature data from Japan's New Energy and Industrial Technology Development Organization (NEDO)[18]. Agricultural yields were assessed at 80% of the per-area soybean harvest in each prefecture, premised on the use of conventional farming methods[19]. This 80% threshold serves as the minimum yield required for the ongoing approval under Japan's AVS support program, constituting a conservative assumption[20]. Prior research indicates that even at 73-75% solar transmittance, 85-92% of control yields were achieved, justifying this as a prudent assumption[11].

Economic and employment impacts were also analyzed. Ripple effects within each prefecture were assessed using the economic ripple effect analysis tool published by the MOE[21]. The economic impact in the power generation sector is predicated on electricity sales through the feed-in tariff system. In agriculture, ripple effects were calculated using the average bid price of Japanese soybeans in 2022 (70.5€/60kg)[22].

The employment creation effects were estimated for the power generation and agricultural sectors. For the power generation sector, an employment coefficient per GWh of electricity generated per year was used. This employment factor takes into account direct and indirect employment in both the construction and operation and maintenance phases[24]. In the agricultural sector, the detected idle farmland area was multiplied by the average number of agricultural workers per area in each province[25].

3. Results and Discussion

3.1. Full coverage scenario

The results of FC scenario analysis are summarized in Table 2. The highest estimated annual power generation in the first year reaches 3953.59 GWh in Mie, compared to a low of 708.42 GWh in Osaka. In Wakayama, the data suggests that nearly 30% of annual electricity consumption could be sourced from photovoltaic power generation. Furthermore, the implementation of AVS could potentially create employment opportunities ranging from 2,653.88 person-years in Nara to 12,803.41 person-years in Mie. The majority of regional economic ripple effects are attributable to the power generation sector, with impacts varying from 0.14% of the Gross Regional Product (GRP) in Osaka to 3.51% in Mie at the construction stage.

Table 2. Results of the full coverage scenario analysis.

Indicators of performance	Unit	Mie	Shiga	Kyoto	Osaka	Hyogo	Nara	Waka-yama	Total
Idle cropland area	km^2	39.59	22.73	14.67	7.45	37.29	8.16	17.09	33125.97
The rate of idle cropland area to total area	%	0.69	0.57	0.32	0.39	0.44	0.22	0.36	0.44
System capacity	MWac	3353.59	1872.26	1190.38	615.19	3096.18	669.76	1419.09	12216.43
Annual electricity generation (1^{st} year)	GWh	3954.12	2104.31	1271.87	708.42	3575.55	749.55	1677.67	14041.49
The rate of electricity generated compared to consumption[1]	%	21.4	18.5	8.0	1.3	10.7	11.9	28.2	9.6
Food production (soybeans)	t	234.40	278.20	100.91	42.29	253.55	61.34	120.31	1091.00
Job creation (Construction)	Person-years	6761.55	3598.38	2174.9	1211.39	6114.19	1281.73	2868.82	24010.95
Job creation (O&M)	Person-years	4468.16	2377.88	1437.21	800.51	4040.37	846.99	1895.77	15866.88
Job creation (Agriculture)	Person-years	1573.70	743.42	883.08	652.97	2146.89	525.16	1648.32	8173.54
Economic ripple effects (Construction)	EUR 1M	4811.75	2656.85	1766.44	943.09	4581.82	999.90	2027.28	17787.14
Economic ripple effects (O&M, 1^{st} year)	EUR 1M	507.79	279.49	188.86	101.02	487.04	108.38	215.5	1888.08
Economic ripple effects (Agriculture)	EUR 1M-years	0.33	0.38	0.14	0.06	0.36	0.09	0.17	1.54
Nominal gross regional product[2]	EUR 1M	58,683	50,067	78,177	299,810	161,916	28,485	27,262	704,400

[1] .FY2021 electricity consumptions[26], [2] .FY2019 nominal gross regional product[27].

3.2. Priority coverage scenario

In PC scenario, the potential assessment is limited to areas with high potential for AVS installation, so the scale of installation is smaller. Actually, as shown in Table 3, the area of idle farmland diminishes substantially: 3.41 km^2 in Osaka compared to 16.97 km^2 in Mie under FC scenario. The most marked reduction occurs in Shiga, where the area decreases from 22.73 km^2 in FC scenario to just 7.11 km^2—a 68.7% reduction. Conversely, both Mie and Wakayama still demonstrate the potential to cover about 10% of their annual electricity consumption through solar power, even within the constraints of PC scenario.

3.3. Discussion

Focusing on the Kansai region of Japan, this study suggests that the implementation of AVS serves as an effective means for achieving agroecological principles. Under both the FC and PC scenarios, the reclamation of idle cropland encompasses an area ranging from 59 to 147 km^2. This reclamation provides multiple benefits, including enhanced food and energy security, ecosystem preservation, and increased resilience in agricultural operations. Policymakers should consider leveraging these benefits while mitigating inappropriate land use by operators pursuing short-term economic gains. Immediate tasks for achieving this may include disseminating best practices, providing financial incentives, or strictly regulating problematic practices.

Table 3. Results of the priority coverage scenario analysis.

Indicators of performance	Unit	Mie	Shiga	Kyoto	Osaka	Hyogo	Nara	Waka-yama	Total
Idle cropland area	km²	16.97	7.11	5.48	3.41	16.41	3.82	6.20	59.39
The percentage of idle cropland area to total area	%	0.29	0.18	0.12	0.18	0.20	0.10	0.13	0.18
System capacity	MWac	1436.35	584.48	444.36	282.22	1361.58	313.12	515.42	4937.54
Annual electricity generation (1st year)	GWh	1689.39	651.26	474.04	325.07	1569.14	350.00	610.54	5669.44
The rate of electricity generated compared to consumption	%	9.1	5.7	3.0	0.6	4.7	5.6	10.3	3.9
Food production (soybeans)	t	100.48	87.03	37.69	19.38	111.56	28.70	43.62	428.46
Job creation (Construction)	Person-years	2888.86	1113.65	810.62	555.88	2683.23	598.50	1044.02	9694.74
Job creation (O&M)	Person-years	1909.01	735.92	535.67	367.33	1773.13	395.50	689.91	6406.47
Job creation (Agriculture)	Person-years	674.59	232.56	329.86	299.32	944.59	245.67	597.59	3324.18
Economic ripple effects (Construction)	EUR 1M	2060.78	829.39	659.39	432.65	2014.87	467.45	736.27	7200.81
Economic ripple effects (O&M, 1st year)	EUR 1M	219.85	88.27	70.71	46.38	214.78	50.91	78.93	769.82
Economic ripple effects (Agriculture)	EUR 1M-years	0.14	0.12	0.05	0.03	0.16	0.04	0.06	0.61
Nominal gross regional product	EUR 1M	58,683	50,067	78,177	299,810	161,916	28,485	27,262	704,400

Additionally, one key aspect that is underexplored in this study relates to the diversity of agriculture and AVS practices. The current research focuses primarily on soybean cultivation, using both rattan-shelf AVS and conventional farming methods. However, from an agroecological standpoint, the incorporation of more complex agricultural systems—such as variety mixtures and crop-livestock integration—is warranted. In the domain of power generation, a diverse range of systems exists, including vertical bifacial setups, PV greenhouse systems, and spectrally selective solar modules. Although these advanced systems are not explored in this study, their integration could offer synergistic advantages within an agroecological framework.

4. Conclusions

AVS is an effective tool for achieving agroecological principles. Our study shows 59-147 km² of idle cropland in Japan's Kansai region. AVS on these lands could produce 5669-14041 GWh of power and 428-1091 tons of soybeans yearly. This effort could create jobs and economic revenue from construction to maintenance. These findings underscore the considerable contributions that AVS can make to agroecology, which is critical information for policymakers. Utilizing this data could aid in developing policies for effective agroecology.

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