AgriVoltaics World Conference 2023
System Accessment and Performance Indicator
https://doi.org/10.52825/agripv.v2i.1019

Published: 23 May 2024

Research on Evaluation Indicators of AgriVoltaics

Liulu Fan[1][https://orcid.org/0000-0001-9707-5583], Xinyu Zhang[1,2][https://orcid.org/0000-0002-6234-6467], Wenjun Liu[2][https://orcid.org/0000-0002-9251-6711], Altyeb Ali Abaker Omer[1][https://orcid.org/0000-0001-9420-9910], and Wen Liu[1][https://orcid.org/0000-0002-4788-3598]

[1] University of Science and Technology of China, China

[2] Xiongan Institute of Innovation, China

Abstract. In recent years, with the popularization of environmental protection concepts and the continuous development of new energy technologies, agrivoltaics has attracted increasing attention and become an important direction of new agricultural development as a new type of agricultural planting method and new energy utilization method. This article classifies ground-based agrivoltaic schemes into three categories according to different management and distributions of solar radiation: intensity management, spectrum management, and time management. The article also details the performance of high-quality schemes proposed by our research team for these three categories. In addition, the article proposes four evaluation indicators for agrivoltaic schemes: land equivalent ratio (LER), return on investment (ROI), water-saving performance, and crop-friendliness, and calculates the performance of different schemes proposed by our research team based on these indicators. Finally, we recommend using these four dimensions to evaluate the performance of agrivoltaic schemes.

Keywords: AgriVoltaics, Classification, Cost Analysis, Evaluation Indicators

Introduction

As global energy demand continues to increase, seeking sustainable and green energy sources has become an urgent issue for countries around the world. According to statistics, in 2021, wind and solar energy accounted for over 10% of global electricity generation for the first time, with solar energy generation increasing by 23% compared to 2020 [1]. According to SolarPower Europe, global photovoltaic (PV) installed capacity will reach 1.3 TW by 2023 [2]. Meanwhile, according to *World Population Prospects 2022* from United Nations Department of Economic and Social Affairs, the global population is expected to reach 8 billion on November 15, 2022 [3]. The increase in solar energy generation requires more land area, while the growing demand for food due to population growth requires that agricultural land area cannot be reduced. AgriVoltaics, as a new type of green energy, successfully combines solar energy with agriculture, providing more possibilities for agricultural production. Therefore, agrivoltaic systems are an excellent technical solution to solve the above problems.

In the development of agrivoltaics, researchers have proposed various solutions. For example, Next2Sun has developed the Next2Sun system, which places solar panels vertically and allows both the front and back of the panels to generate electricity [4]. Some scholars have proposed a mosaic-style agrivoltaic solution, which places solar panels at intervals with transparent glass to achieve uniform lighting below [5,6]. In addition, Elinor P. Thompson et al. and Mark Uchanski et al. have proposed solutions with different semi-transparent modules [7,8]. Overall, researchers have explored various possibilities for agrivoltaic solutions.

Due to the diverse types and characteristics of agrivoltaic schemes, there are differences in their adaptability, economic viability, and ecological sustainability. Therefore, it is necessary to establish a classification standard and evaluation system to conduct scientific, objective, and comprehensive analysis and comparisons of various schemes, providing guidance and reference for the selection, planning, design, and construction of agrivoltaics. Based on the research results of the project team, this article conducts preliminary research and exploration on the classification standards and evaluation indicators of agrivoltaic schemes.

1. Classification

In recent years, agrivoltaics have received widespread attention and rapid development worldwide. Many countries have also included agrivoltaics in their strategic planning of national energy and provided policy support for them, resulting in the emergence of various distinctive agrivoltaic implementation schemes. These schemes can be classified into three categories based on their different methods of managing and distributing solar radiation.

Light intensity management. This type of agrivoltaic scheme mainly redistributes the intensity of sunlight, with a portion used for power generation and the other for crop growth. Different distribution schemes can be used in fields with different lighting environments. In fields with strong light, the area of the photovoltaic panel can be increased to improve power generation capacity while reducing the suppression of crops and the rate of water evaporation by sunlight. If the lighting environment in the field is slightly weaker, the area of the photovoltaic panel can be reduced, focusing on protecting the normal growth of crops.

Spectrum management. This type of agrivoltaic scheme mainly separates the solar spectrum in a reasonable manner, using technical means to allow beneficial spectra for crop growth to pass through while blocking spectra that are detrimental to crop growth and using that energy for power generation. The aim is to achieve precise and efficient distribution and utilization of solar energy.

Time management. This type of agrivoltaic scheme does not regulate solar radiation based on its physical properties but rather redistributes it based on time. A typical example is a single-axis or dual-axis tracking agrivoltaic system, which can choose between shading for power generation or allowing sunlight for crop growth at different times of the day. This time-based selection can be set according to the growth cycle of crops or the daily light intensity, providing the advantage of flexible regulation.

In general, intensity management is more straightforward and does not have a significant impact on the spectrum received by crops. It mainly relies on excellent structural design. Spectral management has strong targeting towards crops and has good planting effects, but the cost of filters is currently high. Time management does not have a significant impact on intensity and spectrum, and its effect mainly depends on the tracking algorithm used for the growth characteristics of different crops.

2. Existing evaluation indicators: LER and ROI

Land equivalent ratio (LER), also known as land use coefficient, refers to the ratio of the return when two or more crops are mixed in the same farmland to the return of each crop when it is cultivated alone, which is suitable for measuring the land use efficiency of agroltaic systems. The LER calculation formula is as follows：

$$LER = \frac{Crop\ Yield_{APV}}{Crop\ Yield_{natural\ state}} + \frac{Electricity_{APV}}{Electricity_{PV\ Station}} \quad (1)$$

Return on Investment (ROI), it is suitable for measuring the economic viability of agrivoltaic systems. Its calculation formula is as follows:

$$ROI = \frac{Annual\ Profit}{Total\ Investment} \times 100\% \qquad (2)$$

3. Three Schemes Proposed by Our Group

Professor Liu Wen's team from the University of Science and Technology of China has proposed targeted solutions for the above-mentioned classifications, namely, Even-lighting Agricultural Photovoltaic System (EAPV), Spectral-Splitting Concentrated Agricultural Photovoltaic System (SCAPV), and Tracking Agricultural Photovoltaic System (TAPV).

3.1 EAPV

EAPV is a scheme that manages and redistributes sunlight based on intensity. In EAPV, a glass plate with grooves is added between two equally sized photovoltaic panels, which is specially designed according to the Fresnel lens theory. This glass plate can scatter some of the sunlight to both sides, evenly illuminating the land below the photovoltaic panels, as shown in Figure 1(a). This method solves the problem of uneven illumination under the mosaic-style agrivoltaics. Moreover, it greatly reduces the cost as it does not require special design like mosaic-style photovoltaic panels. Additionally, the special glass plate is not expensive and reduces the use of photovoltaic panels, which also promotes cost reduction.

The area of the even-lighting plate can be designed to different sizes to achieve different light intensities below it, depending on the crop to be planted. Once constructed, the area of the even-lighting plate is fixed. In our scheme, we make the area of the even-lighting plate one-third of the light-receiving area of the photovoltaic panel. Therefore, $\frac{Electricity_{EAPV}}{Electricity_{PV\ Station}} = 0.67$.

Based on experimental planting results for multiple crops (as shown in Figure 2) [9], the part of $\frac{Crop\ Yield_{EAPV}}{Crop\ Yield_{natural\ state}}$ can reach 0.97. Therefore, the average LER of EAPV can reach 1.64 [9]. Meanwhile, we conducted water evaporation reduction experiments under EAPV for up to 45 days, and the results showed that the cumulative soil water evaporation was reduced by 33% [10].

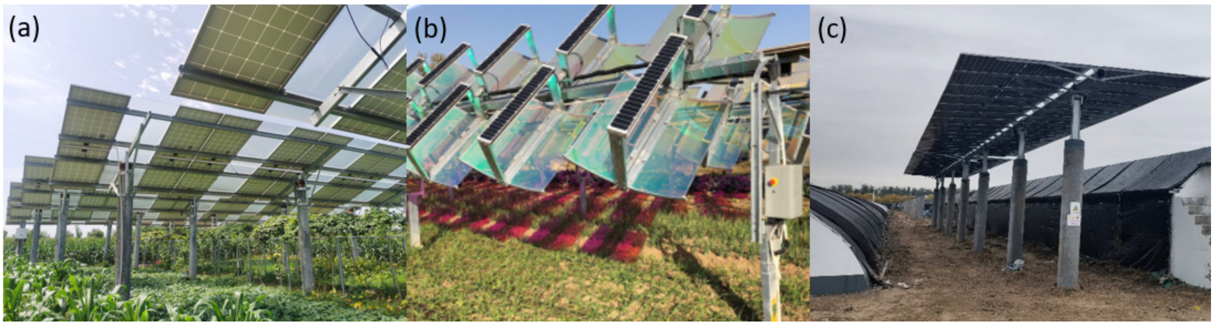

Figure 1. Actual Scene of (a) EAPV; (b) SCAPV; (c) TAPV

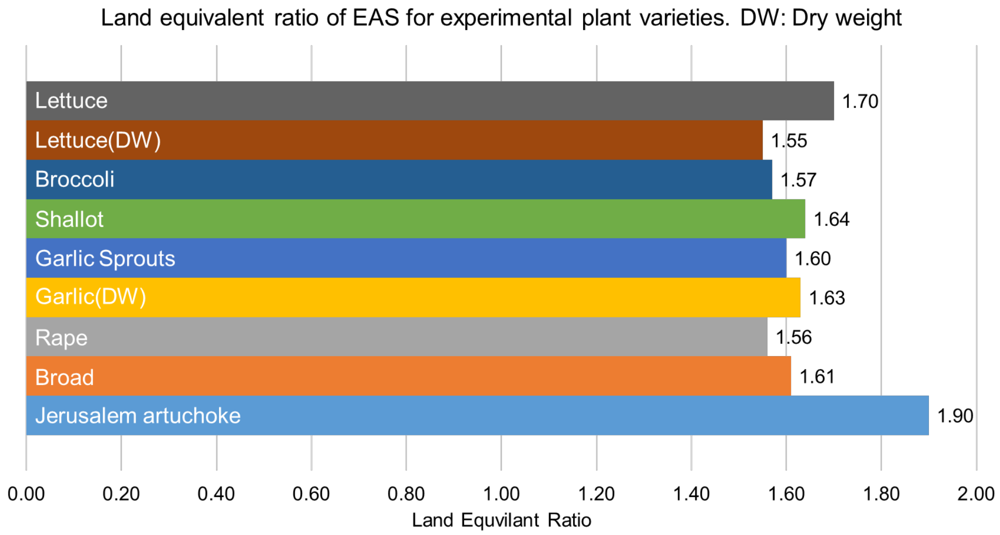

Figure 2. LER of EAPV for different plants

3.2 SCAPV

We propose SCAPV scheme for separating and utilizing solar energy to its fullest potential. SCAPV uses a special film that allows the spectrum of light required for crop growth (primarily red and blue light) to pass through, satisfying the normal growth of crops below. At the same time, it reflects other spectra of sunlight for power generation. To collect energy from the other spectra of sunlight and reduce the shading of the farmland by photovoltaic panels, the film is applied to a curved glass with a certain curvature. The curved design takes into account the angle of incidence of sunlight and concentrates the reflected light onto a smaller, elongated photovoltaic panel. This is shown in Figure 1(b).

According to our previous experiments [11], conventional solar panels can provide about 180 W/m^2, SCAPV currently provides about 90 W/m^2, so the value of $\frac{Electricity_{SCAPV}}{Electricity_{PV\ Station}}$ is 0.5. At the same time, we grew lettuce, cucumber, and water spinach under SCAPV and open air （CK）, and the yield and the LER results are shown in Table 1 [11].

Table 1. and yield of lettuce, cucumber, Water Spinach under SCAPV

Plants	Plants yield (kg) under SCAPV	Plants yield (kg) under open-air (CK)	LER
Lettuce	24.719	19.382	1.775
Cucumber	13.416	10.626	1.763
Water Spinach	5.135	4.615	1.613

$$LER_{Average\ SCAPV} = (LER_{Lettuce} + LER_{Cucumber} + LER_{Water\ spinach}) \times \frac{1}{3} = 1.71 \quad (3)$$

The average LER of SCAPV is about 1.71. In addition, in the water evaporation reduction experiment lasting 45 days, the cumulative water evaporation of soil under SCAPV was reduced by 21%, and the water saving effect was obvious [11].

3.3 TAPV

Experiments are being prepared for TAPV. We place photovoltaic panels in the gaps of greenhouse sheds and use a single-axis tracking scheme, that is, the angle of the photovoltaic panel to the horizontal plane can be adjusted, as shown in Figure 1(c). When the light cannot meet the normal growth of crops, the direction of the photovoltaic panel will be adjusted to be parallel to the direction of sunlight and not block sunlight; when the light exceeds the light value required for the maximum net photosynthesis rate of plants, the photovoltaic panel will rotate to block sunlight and generate electricity fully. Because the installation of photovoltaic panels does not affect crop growth, crop yields are consistent with before. In this TAPV, the area occupied by photovoltaic panels is about 40% of traditional photovoltaic power stations, and the power generation is about 93.6% of traditional photovoltaic power stations. So for the entire system:

$$LER = 1 + 0.4 \times 0.936 = 1.37 \quad (4)$$

Although the LER of TAPV is not very high, the implementation cost of the system is not high because the PV modules used are much reduced compared to traditional photovoltaic power stations and no modification or adjustment of farmland is required.

In the future, we plan to further study the water evaporation of TAPV and the crops suitable for cultivation under this system, and then comprehensively evaluate the practical effect of the scheme.

3.4 Crop-friendliness

The actual light intensity required for photosynthesis in plants is 200 ~ 700 $\mu mol/m^2 \cdot s$ Above 1000 $\mu mol/m^2 \cdot s$, photosynthesis is inefficient [12], and excess sunlight also stimulates plant photoinhibition and photoprotection mechanisms, making plants temporarily dormant and stop growing, forcing most crops into a "lunch break". Therefore, the appropriate reduction of light intensity will not only not affect the growth of crops, but also help increase crop yield and income.

According previous experiments (as shown in Table 2), SCAPV has a more significant yield improvement for ginger and an acceptable yield reduction for other crops. EAPV has less impact on the yield of several crops grown than SCAPV, and has a significant yield increase for tubers such as potatoes, and is not as effective as SCAPV for ginger.

However, as the cost of SCAPV decreases, different spectra can be given to different crops, which will greatly reduce the impact of SCAPV on crop yields and even promote yield increases for most crops.

Table 2. Yield comparison of SCAPV and EAPV

Crop	SCAPV	Open-air	EAPV
Ginger	+10.6%	100%	+6.4%
Potato	/	100%	+15.3%
Broccoli	-9.5%	100%	-5.4%
Garlic	-6%	100%	-4%
Rape	-17%	100%	-11%
Broad bean	-8%	100%	-6%

3.5 Cost and ROI

According to Table 3 the cost of module of 50% MAPV (Mosaic AgriVoltaics with 50% of the total area of power generation) is 3.36 yuan/W, which is higher than other solutions (except SCAPV). The cost of even-lighting glass of EAPV is 0.15 yuan/W, accounting for only 2.8% of the total cost. It will be cheaper in the future. For TAPV, the cost of bracket (single-axis) is 0.65

yuan/W, if dual-axis tracking is used, the cost may be 0.78 yuan/W. At present, the cost of SCAPV's spectral-splitting film is very high, accounting for 70% of the total cost, this cost will be greatly reduced if the technology advances in making spectral-splitting film in the future. In the future, the cost of single- or dual-axis tracking will fall, TAPV and SCAPV have great potential in agrivoltaics.

According to Figure 3, from the perspective of photovoltaics alone, although CAPV (Conventional AgriVoltaics) has the highest ROI, the investment amount of the same area is 40%, 33% and 120% higher than that of 50%MAPV, EAPV and TAPV respectively. The highest ROI for the whole system is EAPV when considering crop returns, due to its low cost and small or even positive impact on agricultural activities. Overall, EAPV remains the most recommended of several options. TAPV has good performance and ROI, but its installed capacity per unit of land is somewhat limited when combined with greenhouse sheds. The impact of SCAP on crops is likely to be minimal, but currently it cannot be rolled out on a large scale due to cost. in the foreseeable future, the cost of filter films will be greatly reduced, which will result in an overall ROI of over 11% for the SCAPV solution.

Table 3. Cost analysis of several agrivoltaic schemes

Schemes (yuan/W)	CAPV	50%MAPV	EAPV	TAPV (single-axis tracking)	SCAPV (dual-axis tracking)	SCAPV (10GW, future)
Bracket (dual-axis or single-axis tracking)	0.24(5%)	0.48(7%)	0.32(6%)	0.65(12%)	0.75(3.3%)	0.45(10%)
Module	2.40(50%)	3.36(49%)	2.40(44%)	2.40(44%)	3.75(17%)	0.85(18%)
Spectral-splitting film	/	/	/	/	16.00(70%)	1.50(32%)
Even-lighting glass	/	/	0.15(2.8%)	/	/	/
Others	2.16	3.01	2.53	2.41	2.21	1.85
Total cost	4.80	6.85	5.40	5.46	22.71	4.65

Note: In Table 3, the percentage in parentheses represents the cost as a percentage of the total cost; the last column shows the cost of SCAPV in the future and at 10GW scale, which is predicted based on market conditions.

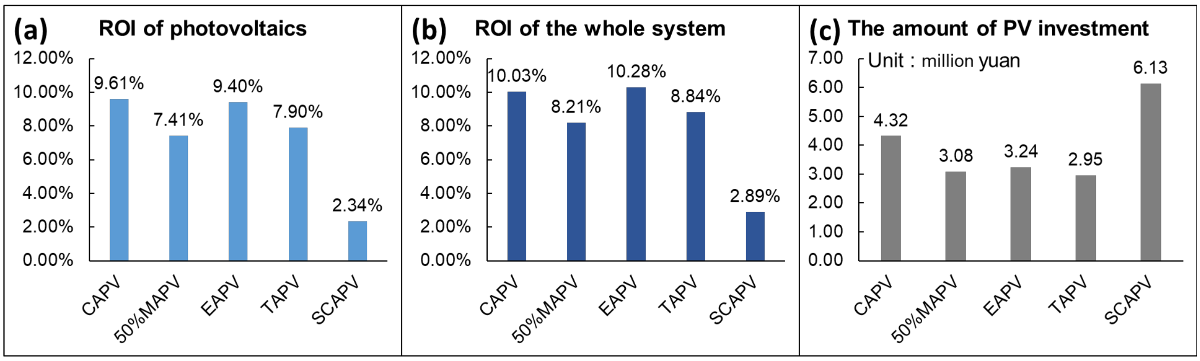

Figure 3. (a) ROI of photovoltaics. The investment and return of crops are not included; (b) ROI of whole system. The investment and return of photovoltaics and crops are all included. (c) The amount of PV investment. Assumptions of Figure 3: suppose the area is 1 hectare; assume that the rent and planting cost per hectare are 30,000 yuan, and potatoes are grown, and different schemes will have an impact on the yield of the crop.

4. Conclusion

The ability of the system to save water is a necessary evaluation indicator. Because it is relatively independent of other indicators, and has important reference significance for geographical location and crop variety selection. For example, EAPV is more water-efficient than SCAPV, so EAPV will have more advantages in arid areas. Crop-friendliness should also be one of the metrics used to evaluate agrivoltaic schemes. EAPV has a relatively high LER and ROI, but since the light under the PV panels is only about 35% of the sunlight, the system may not be suitable for crops that are particularly sun-loving. Through experimentation and analysis, we recommend a comprehensive evaluation of agrivoltaics in the future using LER, ROI, water-saving performance, and crop-friendliness.

5. Outlook

In the face of different agrivoltaic solutions, there is an urgent need to categorize them rationally and create a more comprehensive and accurate agrivoltaic evaluation system. On this basis, the most suitable agrivoltaic solutions for different regions, different climates and different crops can be selected to maximize the value of the agrivoltaic system.

In the context of global implementation of green emission reduction and food security and energy security are concerned, high-quality development of agrivoltaics will play an important role in solar energy supply, solving the problem of global poverty, and greatly enhance the resilience of mankind to face unknown challenges, and the establishment of a perfect evaluation system will provide a solid foundation for the high-quality development of agrivoltaics.

Data availability statement

This study utilized data from cited references as well as actual engineering experience. The data from cited references is the achievement of our research group and can be found through the reference list. The actual engineering experience data supporting the results of this study can be obtained from the corresponding author, Prof. Wen Liu. However, the engineering cost data may fluctuate with the market.

Underlying and related material

There is no other underlying and related material.

Author contributions

Liulu Fan: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing

Xinyu Zhang: Resources, Supervision, Investigation, Writing – review & editing

Wenjun Liu: Resources, Data curation, Investigation, Writing – review & editing

Altyeb Ali Abaker Omer: Resources, Investigation, Writing – review & editing

Wen Liu: Conceptualization, Resources, Supervision, Funding acquisition, Validation, Writing – review & editing

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The study was sponsored by the Fundamental Research Funds for the Central Universities (Grant No. WK5290000003), Students' Innovation and Entrepreneurship Foundation of USTC (Grant No. XY2022G01), Plan for Anhui Major Provincial Science & Technology Project (Grant No. 202203a06020002), and Science & Technology Program of Hebei (Grant No. 22327215D).

Acknowledgement

The author would like to thank Professor Liu Wen and Dr. Zhang Xinyu for their guidance, as well as Altyeb Ali Abaker Omer and other students and colleagues in the laboratory for their strong support and help.

References

1. Ember. (2022). Global Electricity Review 2022. https://ember-climate.org/insights/research/global-electricity-review-2022/
2. SolarPower Europe. (2019). Global Market Outlook for Solar Power 2019-2023. https://www.solarpowereurope.org/wp-content/uploads/2019/05/SolarPower-Europe-Global-Market-Outlook-2019-2023.pdf
3. United Nations, Department of Economic and Social Affairs, Population Division. (2022). World Population Prospects 2022: Summary of Results. https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022
4. Next2Sun GmbH. (n.d.). Next2Sun - The vertical solar power plant. Retrieved from https://next2sun.com/en/
5. B. Willockx, B. Herteleer, and J. Cappelle, "TECHNO-ECONOMIC STUDY OF AGROVOLTAIC SYSTEMS FOCUSING ON ORCHARD CROPS"
6. A. Yano et al., "Shading and electrical features of a photovoltaic array mounted inside the roof of an east–west oriented greenhouse," Biosystems Engineering, vol. 106, no. 4, pp. 367–377, Aug. 2010, doi: 10.1016/j.biosystemseng.2010.04.007.
7. E. P. Thompson et al., "Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland," Adv. Energy Mater., vol. 10, no. 35, p. 2001189, Sep. 2020, doi: 10.1002/aenm.202001189.
8. M. Uchanski, T. Hickey, J. Bousselot, and K. L. Barth, "Characterization of Agrivoltaic Crop Environment Conditions Using Opaque and Thin-Film Semi-Transparent Modules," Energies, vol. 16, no. 7, p. 3012, Mar. 2023, doi: 10.3390/en16073012.
9. J. Zheng et al., "Increasing the comprehensive economic benefits of farmland with Even-lighting Agrivoltaic Systems," PLoS ONE, vol. 16, no. 7, p. e0254482, Jul. 2021, doi: 10.1371/journal.pone.0254482.
10. A. Ali Abaker Omer et al., "Water evaporation reduction by the agrivoltaic systems development," Solar Energy, vol. 247, pp. 13–23, Nov. 2022, doi: 10.1016/j.solener.2022.10.022.
11. W. Liu et al., "A novel agricultural photovoltaic system based on solar spectrum separation," Solar Energy, vol. 162, pp. 84–94, Mar. 2018, doi: 10.1016/j.solener.2017.12.053.

12. Q. Song et al., “Diurnal and Seasonal Variations of Photosynthetic Energy Conversion Efficiency of Field Grown Wheat,” Front. Plant Sci., vol. 13, p. 817654, Feb. 2022, doi: 10.3389/fpls.2022.817654.