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Editorial

Agrivoltaic: Challenge and Progress

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According to the International Energy Agency (IEA) [1], deploying renewable energy technologies is crucial for achieving the net-zero emissions target by 2050. Moreover, using renewable energy is essential in order to reduce global greenhouse gas emissions and attain the target of limiting global warming to 2 to 4 degrees by 2100 [2]. Among these technologies, solar energy is the most promising renewable energy source. In recent years, photovoltaic (PV) technology has developed rapidly, continuously improving PV efficiency. The electricity generation efficiency of commercial PV modules has increased from about 15% in 2010 to about 23% today [3]. In addition, the production cost of PV modules has significantly decreased, with the price per watt dropping from 5 CNY/watt in 2012 to 1.8 CNY/watt in 2022 [4]. However, two significant bottlenecks hinder the large-scale deployment of PV solar energy in an attempt to replace traditional energy: energy storage and the availability of land for installing PV panels. Although countries such as China and the United States have vast, sparsely populated areas with abundant solar resources, there are technical difficulties and increased costs in transmitting PV electricity to densely populated and industrially developed areas through ultra-high voltage transmission systems. Therefore, using agricultural land for PV installation in densely populated areas is becoming increasingly common. In 2021, the global installed capacity of agricultural PV (APV) reached approximately 14 GWp [5]. APV can help to avoid drought stress and maintain higher soil moisture, thus improving plant growth [6].

Compared to rooftop PV, building PV power plants on farmland has certain advantages, such as the following: a single project can cover a larger area, and the unit cost of electricity generation is lower. In China, ground-mounted PV power plants' per watt cost has been reduced to as low as 4.13 CNY/watt [4] in 2022. The biggest challenge faced by APV is ensuring sufficient crop yield under the PV panels. Theoretically, the shaded area underneath the PV panels receives only 20% of the solar energy during a clear day [7]. This level of solar radiation energy is usually insufficient for most crops, resulting in significant reductions in yield.

However, many people believe that implementing APV may be the wrong course of action; in fact, the solar radiation intensity between 11:00 a.m. and 2:00 p.m. during spring, summer, and autumn is excessively strong and may even harm crop growth in many Northern Hemisphere regions. Photosynthesis increases with increasing light intensity, but when light intensity reaches a certain maximum, light saturation is reached, and photosynthetic efficiency ceases to increase, and it can even decrease even if light intensity rises again. The effect of strong light on photoinhibition is obvious, with the strongest sunlight at midday and a significant decrease in photosynthetic rate in the corresponding C_3 plants, such as soybean and rice [8].

It is worth noting that while sunlight is crucial for robust plant growth, too much sunlight can have the opposite effect. Therefore, using APV may help minimize the damaging effects of excessive solar radiation on crops. By reducing the amount of direct sunlight that reaches plants during the hottest part of the day, farmers can create a more favorable growing environment, which may increase their crop yield. While APV may not

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be a panacea for all agricultural challenges, it is a viable choice for farmers facing high solar radiation levels and seeking to increase their yield. In essence, the core of APV is to manage light while considering the unique conditions of crops, enabling farmers to create a more sustainable and productive cultivation environment and then use excess solar energy for PV electricity generation.

There are already two early solutions to address the problem of insufficient light under PV panels. The first involves using mosaic-structured PV panels that allow some light to pass through [9]. APV using this design has already demonstrated successful crop cultivation, as evidenced by the high yield and quality of different fruits in German PV orchards [5]. However, this approach may not be fit for widespread implementation due to the relatively high cost of these panels, which could double the price of PV electricity generation per watt (assuming a transmittance rate of 50%). The second solution utilizes thin-film solar cell technology, particularly semi-transparent thin-film solar cells such as amorphous silicon and cadmium telluride. PV integration in greenhouses has been extensively studied and documented in the scientific literature. Some publications partly describe using solar panels to cover greenhouse roofs [10,11].

The crop cultivation performance of APV-utilizing cells such as amorphous silicon and cadmium telluride is suboptimal because the light transmission spectrum of thin-film solar cells is not aligned with the range required for crop photosynthesis. Therefore, they have not been widely adopted.

A research team at the University of Science and Technology of China recently proposed two innovative solutions to the challenge of realizing crop photosynthesis and PV power generation on the same farmland. The first solution is Spectrum Splitting and Concentrated APV (SCAPV) [12], which uses spectral splitting to selectively transmit red, blue, and far-red light from sunlight to plants for photosynthesis. The remaining sunlight is concentrated and directly generates electricity for the PV panels. The critical aspect of this solution is to design a cost-effective multi-passband filter that separates sunlight [13,14]. SCAPV represents one of the two main strategies for mitigating the shading problem in APV [15]. The second solution is Even-lighting APV (EAPV) [16,17], which aims to improve the structural design of APV by placing grooved glass plates between two PV panels. These plates allow sunlight to be transmitted and distributed evenly, providing even lighting and sufficient light intensity for plant photosynthesis. The conventional method involves the sunlight hitting the top of the PV panels between the grooved glass plates to generate electricity. These two solutions demonstrate the promise of APV and could revolutionize the way we use solar energy, the application of which could help improve plant and crop growth, quality, and yield [17,18]. Moreover, these two solutions significantly reduced water evaporation [19]. By combining the strengths of solar energy and agriculture, we can create a sustainable and efficient system that meets the growing demand for renewable energy and food production.

Our Special Issue focuses on integrating agriculture and PV, covering light and water management, growing in low-light environments, and maximizing economic benefit from land use. Five papers are presented in this Special Issue. These papers explore the potential benefits of APV in addressing various challenges in agriculture, including food security, economic growth, and energy sustainability. In addition, diverse applications of APV are demonstrated, such as using APV to improve crop yield and quality, reduce water consumption, and minimize land use conflicts.

The first paper, authored by Nakata H and Ogata S [20], discusses the benefits of an APV installation model that is compatible with the regional population and attempts to gain social acceptance by considering the area's unique characteristics. A case study and economic analysis were conducted in rural Japan to demonstrate the potential of APV in improving land use efficiency and stimulating the local economy. The study suggests that APV could generate 215% of the annual electricity demand in the area (equivalent to 17.8 GWh) and produce 108.9% (EUR 47.8 million) of economic ripple effects in the region. These quantifiable and applicable results indicate the enormous potential of APV in addressing food-related issues, as well as economic and energy issues, in rural areas.

The second paper, written by Wagner M et al. [21], found that installing overhead APV on agricultural land has positive ecological outcomes; the study also demonstrated that, under certain conditions, APV can promote the expansion of renewable energy production resources without reducing food production resources.

The third paper, authored by Chae S et al. [22], presents a study analyzing the yield, antioxidant capacity, and secondary metabolites of broccoli in three cultivation periods. This study identified the potential benefits of APV in broccoli cultivation. The results showed that APV could produce green broccoli that is preferable to consumers while maintaining yield and antioxidant capacity.

The fourth paper, written by Ali Abaker Omer A et al. [23], includes experimental research on sunlight's ability to partially reduce water evaporation. The study found that, under polymer multilayers, water evaporation could be significantly reduced, and the polymer multilayers could reflect and concentrate most of the sunlight that is not needed for crop cultivation for PV electricity generation. This research provides a promising solution for reducing agricultural water evaporation using low-cost polymer multilayers.

Lastly, the fifth paper, provided by Tao Z et al. [24], presents a study discussing how cultivation and farming techniques can improve crop heat tolerance by regulating ABA. These techniques include adjusting sowing time; applying plant growth regulators and fertilizers; and using irrigation, deep tillage, and heat acclimation.

These five papers highlight the potential benefits of APV in improving land use efficiency, reducing environmental impacts, generating renewable energy, and improving crop quality and yield. They also address critical issues in agriculture, such as water scarcity, climate change, and food and energy security. These papers provide valuable insights into the practical and economic feasibility of APV in promoting sustainable agriculture as well as other technologies. They also indicate the need for further research and development to address the challenges of implementing these solutions and make their implementation easier for farmers. These papers contribute to the ongoing efforts to transform agricultural PV into a more sustainable and resilient technology that meets the growing demands for food and energy while developing green energy, protecting the environment, and supporting local communities.

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