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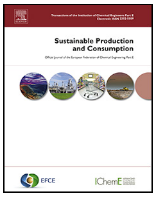

Perspective Article

Current status of agrivoltaic systems and their benefits to energy, food, environment, economy, and society

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ABSTRACT

The rate of solar power generation is increasing globally at a significant increase in the net electricity demand, leading to competition for agricultural lands and forest invasion. Agrivoltaic systems, which integrate photovoltaic (PV) systems with crop production, are potential solutions to this situation. Currently, there are two types of agrivoltaic systems:

1) systems involving agricultural activities on available land in pre-existing PV facilities, and 2) systems intentionally designed and installed for the co-production of agricultural crops and PV power. Agrivoltaic systems can boost electricity generation efficiency and capacity, as well as the land equivalent ratio. They also generate revenue for farmers and entrepreneurs through the sale of electricity and crops. Therefore, these systems have the potential to sustain energy, food, the environment, the economy, and society. Despite the numerous advantages of both types of agrivoltaic systems, few studies on utilizing the available land area under existing ground-mounted PV systems for agricultural crop production have been conducted. Moreover, with several conventional solar power plant projects currently underway around the world, an expanding trend is anticipated. As a result, this article offers practical advice for agrivoltaic systems on how to implement an agricultural area under ground-mounted PV power systems without agricultural pre-plans. These systems are useful for policymaking and optimizing land use efficiency in terms of energy production, food supply, environmental impact, local economy, and sustainable societies.

1. Introduction

Solar energy is the cleanest and most abundant renewable energy source because it is converted into electricity via photovoltaic (PV) systems (Kumpanalaisatit et al., 2022). According to International Energy Agency Photovoltaic Power Systems Program (2021), the global PV power plant capacity at the end of 2020 will exceed 760 GW. According to Jäger-Waldau (2018) research, global PV power plant capacity increased by approximately 34.21 % from 2018. Additionally, the top three global PV markets (China, Europe, and the United States) had installed cumulative PV capacities of 48.2 GW, 19.6 GW, and 19.2 GW, respectively. PV power plants account for 94.20 % of ground-mounted PV power plants, with the remainder made up of solar roof tops (5.58 %; Europe, 2018) and solar floating panels (0.22 %; Gamarra and Ronk, 2019). The total required land area for ground-mounted PV power plants is 2201.890 ha (Ong et al., 2013). Thailand, for example, has a PV capacity of 1558 MW, with projects under construction totaling 1261 MW, for a total capacity of 2819 MW (Chimres and Wongwises, 2016). Currently, 9020 ha of land has been set aside for PVs (Ong et al., 2013).

According to the global trend of ground-mounted PV power generation plants, the demand for solar power plant land construction will increase, resulting in increased competition for agricultural lands and forest invasion, affecting food security and national forest resources (Evans et al., 2022). To address the aforementioned issues, agrivoltaic systems were proposed. These could promote PV system land use and achieve a future tradeoff between producing food and energy. Agrivoltaic system deployment has grown dramatically in recent years, with a global installed capacity of 2.8 GW by 2020, up from 5 MW in 2012 (Gorjian et al., 2022). There are two recommendations for agrivoltaic system implementation: 1) systems involving agricultural activities on available

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land in pre-existing PV facilities, and 2) systems intentionally designed and installed for the co-production of agricultural crops and PV power.

According to research conducted between 1982 and 2022, PV panel land use focuses on installing PV panel systems with agricultural plans. Land can be valued by designing and installing PV panels in such a way that plants can capture enough sunlight while minimizing associated problems. However, considering the environment under PV panels, installing fixed PV systems to generate only electricity is insufficient for plant cultivation (Katsikogiannis et al., 2022). Thus, few studies on land use under PV panels that are fixed to generate only electricity have been conducted. Therefore, with regard to agrivoltaic systems, land use development under PV panels of these fixed PV systems is recommended. The problem of solar power generation encroaching on farmland and forest areas has been studied, and solutions have been proposed to use the space under the solar panels for systems that generate only electricity. However, the proposed solutions have yet to be widely adopted. Therefore, the advantages of implementing solar power plants in agriculture are significant.

This paper discusses agrivoltaic systems, the advantages of land use, and the efficiency of solar power generation including agrivoltaic systems' effects on energy, food, the environment, the economy, and society. Furthermore, we offer recommendations for future research on how to integrate agricultural activities into pre-existing PV panels by utilizing available land to benefit from the agrivoltaic concept synergistically.

2. Agrivoltaic ideas

Goetzberger and Zastrow (1982) developed an agrovoltaic system, also known as an agrophotovoltaic system (Jo et al., 2022), for co-production in 1982 (i.e., PV systems with plant production). PV panels were installed 2 m above ground, with 6 m between individual PV arrays. This configuration allowed sufficient solar radiation penetration under the PV panels for plant growth. In 2004, Japan developed an agrivoltaic system prototype made up of multiple systems, known as solar sharing. The prototype was transferred and improved until Japan had over 1000 agrivoltaic system sites (Toledo and Scognamiglio, 2021). The term “agrivoltaic system” was first used in 2011 by Dupraz et al. (2011). Before installing PV systems, Dupraz developed a model to predict crop yields under PV panels and estimate the electricity generated compared to that of a plant production system for agricultural planning. Producing plants under PV panels has been shown to increase land productivity by 35 %–73 %. In addition, an appropriate PV system design and installation, in conjunction with planting, is required to maximize the benefit of co-producing agricultural crops and electricity. The accrual land productivity could increase by 60 %–70 %.

Co-production has received significant global research attention. For example, de la Torre et al. (2022) designed, installed, and analyzed a horizontal tracker PV system tracking/backtracking technique between rows of olive groves in hedges up to 3.0 m tall and 1.5 m wide. The crop would not shade the solar panels because there was a space between the collectors. The land equivalent ratio (LER) for an agrivoltaic system in this study can range between 28.9 % and 47.2 %. Katsikogiannis et al. (2022) used a multi-scale modeling technique to establish the best topology for a medium-to-large-scale fixed bifacial agrivoltaic array to be compatible with several different climates and blueberry cultivation. The E-W wing topology created the most effective shading schedule and the most predictable microclimate. Modules were redesigned to feature wider cell spacing and a spread cover to optimize photosynthesis under shading. When compared to conventional and separate food and energy production, an E-W wing topology enhanced yield potential by 50 % while reduced electrical output by 33 %.

3. Agrivoltaic systems

Agrivoltaic systems can be categorized into two types depending on how the systems are planned. The first system type is one in which the agricultural component is not pre-planned during designing and constructing the PV infrastructure, but rather crops are grown on available land areas beneath the PV panels. The second type is a well-organized system which is purposefully designed to co-produce agricultural products and photovoltaic power. This allows the mutual benefit between agriculture and photovoltaics to maximize the land use efficiency.

3.1. Land use under pre-existing fixed PV panels

Land use under pre-existing fixed PV panels refers to exploiting agricultural activities performed and incorporated into existing fixed PV systems in order to utilize the available and unexploited area surrounding the solar farm. Land use is categorized into three types: planting under PV panels, planting between PV panels, and PV installations with animal farming (see Table 1).

3.1.1. Planting under PV panels

Owing to limited sunlight intensities, agricultural planting under PV panels of fixed PV systems without agricultural pre-plans (see Fig. 1) has not been widely performed (Katsikogiannis et al., 2022). Several crops, however, such as lettuce, sweet potatoes, eggplants, soybeans, and peanuts, thrive in shady or low-light environments (Wolff and Coltman, 1990). Kumpanalaisatit et al. (2019) investigated land use under PV panels by building a pond, planting chilis and grass, and monitoring sunlight intensity, air temperature, PV panel temperature, electric current, and voltage. The pond and chili plants produced optimal electricity generation of 1.6 kW. This discovery implied that planting under PV panels of fixed PV systems without agricultural pre-plans potentially produce adequate yields.

3.1.2. Planting between PV arrays

Planting in the gaps between PV panels in each array (see Fig. 2) is a type of co-production with fewer plants, due to the small spaces between PV panels in each array in comparison to the land area under the PV panels (Evans et al., 2022). Furthermore, the reduced walking space between the PV arrays has an impact on electrical operation. The amount of sunlight exposure in this scenario, however, is similar to that in conventional agriculture. Therefore, studies have been conducted to develop suitable methods for land use between PV arrays without interfering with electrical operation and achieving significant plant production. For example, Ravi et al. (2016), installed a water system on PV panels to remove dust and dirt. The used water was then poured into the aloe vera plots between the PV panels, ensuring that the water was used efficiently. Besides that, Malu et al. (2017) studied the effectiveness of PVs and their feasibility in grape production in India. The efficiency and economic returns have been estimated. When compared with conventional grape farming, the economic value of PV-equipped vineyards increased by a factor of more than 15. Further to that, if grape farms nationwide had PV systems, up to 16,000 GWh of electricity could be generated, sufficient for electricity demand of a population over 15 million people.

3.1.3. PVs with animal farming

PVs can be used in conjunction with aquaculture or terrestrial animal farming (see Fig. 3). Pringle et al. (2017) examined PVs with aquatic animals by installing a PV system in the water of a culture pond. This system accelerated fish growth rate and increased the PV system's efficiency by 30 %, which was attributed to a decrease in temperature under the PV panels caused by water evaporation from the pond. This finding agreed with the observations made by Rajvikram and Leoponraj (2018), who studied the efficiency of electricity generation by coating PV panels with aluminum oxide and tantalum pentoxide. Lowering the temperature underneath the PV panels enhanced their efficiency.

PVs have been implemented with two types of livestock farming, i.e., terrestrial animals and livestock in greenhouses, in addition to aquatic animals. Maia et al. (2020) investigated land use for livestock

Table 1
Agricultural land use under PV panels of fixed PV systems without agricultural plans.

Year	Pattern	Condition			Results and discussion	References
		Panel installation	Type of plant/animal	Variable(s)		
2015	Under PV panel	Fixed	Java tea	Internal rate of return (IRR), net present value (NPV)	IRR of 15.74 %, discount rate greater than 3.36 %, and NPV of 2068 USD were obtained. Planting Java tea under PV panels was discovered to be economically feasible.	Othman et al. (2015)
2016	Between PV array	Fixed	*Aloe vera*	Co-production	PV aloe vera planting has been proven to be economically feasible, allowing communities to generate rural electric power and promoting economic growth. Furthermore, the use of wastewater (from the PV panels cleaning) on aloe vera was the most beneficial use of water.	Ravi et al. (2016)
2017	Between PV array	Fixed	Grape	Efficiency of PVs, feasibility in relation to production	The economic value of PVs-equipped vineyards increased by a factor greater than 15 compared with conventional grape farming. Up to 16,000 GWh of electricity could be generated if grape farms nationwide installed PV systems.	Malu et al. (2017)
2017	Under PV panel	Floating	Fish	Floating PV system	This system increased the fish growth rate and the efficiency of electricity generation by 30 %, which can be attributed to the reduction in the temperature under the PV panels caused by water evaporating from the pond.	Pringle et al. (2017)
2019	Under PV panel	Fixed	Chilis	Power output	Since the developed pond was based on the same principle as installing the PV panel on water, planting chilis and developing the culture pond generated more electricity than the control group. Regular watering was performed for the planting of chilis; as a result, the air temperature and PV panel temperature decreased as the amount of electricity generated increased.	Kumpanalaisatit et al. (2019)
2020	Under PV panel, Between PV array	Fixed	Sheep	Power output, CO_2 emission	PVs with sheep cultures generated up to 5.2 kWh of electricity and reduced greenhouse gas (GHG) emissions by 2.8 tons/year. The PV systems cut costs by 698 USD/year, demonstrating long-term economic feasibility. Despite the lack of sheep sales within a year, the data revealed that agriculturists' costs were diminished.	Maia et al. (2020)
2022	Under PV panel	Fixed	Bok choy	Power output Cultivating crops	The PV system with Bok choy (*Brassica rapa* subsp. chinensis L.) produced 2.28 kW of solar power and 1.50 kg of crops. Crop cultivation under solar panels lowered the module temperature to less than 0.18 °C, increasing voltage and power generation by 0.09 %.	Kumpanalaisatit et al. (2022)

under PV panels in one study of PVs with terrestrial animals. The authors demonstrated that under solar radiation of more than 800 W/m^2, sheep spent 70 % of their time under the panels. Consequently, the PV systems generated up to 5.19 MWh of electricity while reducing GHG emissions by 2.77 tons/year.

3.2. Land use under PV panels planned for agrivoltaic system installation

The environment for growing is difficult to control, particularly sunlight, for agricultural land use under PV panels of fixed PV systems without agricultural plans (Gorjian et al., 2022). Therefore, another concept for obtaining acceptable conditions prior to co-production has emerged. The solar panels for this agrivoltaic system are designed and installed on stilts to raise the panels to a suitable height above an open field, thereby meeting the sunlight demand for the plants growing under the panels. Additionally, if the solar panel is installed high enough, farming machinery can access the crops (Evans et al., 2022) (see Table 2).

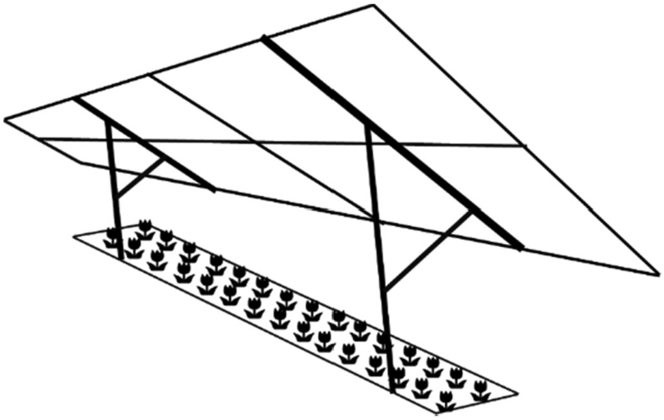

Fig. 1. Planting under PV panels.

Valle et al. (2016) used solar tracking and fixed systems to grow lettuce under PV panels. Because those planted in solar tracking systems received enough sunlight, the dry masses of lettuce produced by solar tracking systems and conventional agriculture were comparable. Marrou et al. (2013a) used co-production to estimate plant growth rates. The experiment was divided into three methods: planting under regular exposure to sunlight, planting under PV panels with 50 % spacing of a regular PV panel installation (half density), and planting under regular PV panel installation (full density) (see Fig. 4). Three types of seasonal plants were cultivated: lettuce, cucumbers, and wheat. The growth rates were the same as those under half-density conditions. The daily air temperatures and relative humidity of the plots under the PV panels and those with regular sunlight exposure were the same. However, when compared to regular sunlight exposure, the soil temperature under the PV panels was reduced. Therefore, agriculturists could potentially transform conventional agriculture into co-production.

To achieve efficient cultivation, however, suitable plants for the environment under the PV panels should be selected. Marrou et al. (2013b) researched co-production by planting under PV panels at half density and full density. The total yields of lettuce planted under PV panels were the same as those planted under regular sunlight exposure. In relation to the morphological characteristics and physiological responses of a low-light space, despite the different leaf area distributions, the space and size of the leaves increased.

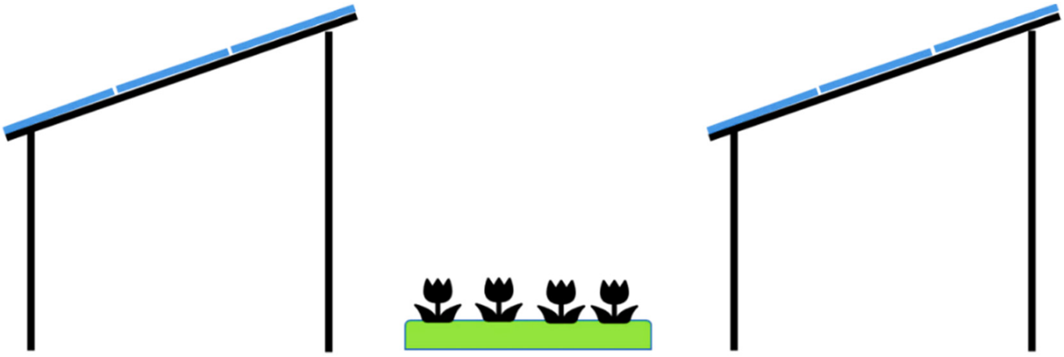

Fig. 2. Planting between PV arrays.

In this section, the design and installation of solar panels for agrivoltaic systems are evaluated with various distances between the solar panels and ground. In addition, the planning and position of solar panels on greenhouse rooftops are discussed (Evans et al., 2022). Installing a PV system on a greenhouse rooftop (see Fig. 5) is a form of co-production that involves the application of PVs to control the sunlight intensity, temperature, and humidity in the greenhouses. In one study, Colantoni et al. (2018) investigated the effect of the solar radiation distribution in greenhouses on the growth of iberises and petunias. Flexible and fixed PV panels were both installed on 20 % of the rooftop space. The growth rates of both plants in the greenhouses and controlled plots were not statistically different when compared with the non-PV greenhouse, although the decrease in solar radiation intensity differed between the greenhouses.

Further, Aroca-Delgado et al. (2019) studied the impacts of shade from the flexible solar cells on rooftops in terms of the morphological characteristics, yield, and quality of tomatoes. The results were compared to those of tomatoes planted in conventional greenhouses. At 193 days, the morphological characteristics and yields of the planted tomatoes in the PV greenhouses and the controlled plots were not statistically different. The total soluble solids of the tomatoes planted in the PV greenhouse were 0.3 brix higher than those in the controlled plots. This finding was consistent with the observations made by Ezzaeri et al. (2018), who investigated the effects of PV panel installation on 10 % of the greenhouse rooftop space on the weather and yields of planted tomatoes. The increases in the diameters of the trees and the number of tomatoes per tree were not statistically different. Nonetheless, when considering the yields after harvest, the yields of tomatoes planted in the PV greenhouse and controlled plots were 260 kg and 245 kg, respectively. The yields harvested in the non-PV greenhouse were lower than those in the PV greenhouse due to the invasion of caterpillars that consumed the tomato leaves.

Cossu et al. (2014) studied the solar radiation distribution, temperature variation, and humidity in a PV greenhouse. PV panels were installed on 50 % of the rooftop space with a capacity of 68 kWp. The PV panels installed on the greenhouse rooftop reduced the intensity of solar radiation by 64 %. Solar radiation was found to be more intense on the greenhouse sidewalls and less intense towards the center of the span. In winter, however, the solar intensity did not differ significantly between the plant rows. Consequently, the solar radiation distribution study identified the most suitable plants and the design of co-production PV greenhouses. Furthermore, Trypanagnostopoulos et al. (2017) installed PV panels on greenhouse rooftops in two configurations: solar tracking and fixed system. Plant growth was monitored and compared to that of conventional greenhouses. The plants in the PV greenhouses grew as efficiently as those in the non-PV greenhouses, and the PV panels generated 50.8 kWh/m^2 of power. Moreover, the solar tracking system with PV panels installed on the greenhouse rooftops generated more electricity than the fixed system, given that the electricity obtained was sufficient for internal environment control via sensors (Evans et al., 2022).

4. Solar power generation efficiencies of agrivoltaic systems

By lowering the temperature of the solar panels, the efficiency of solar power generation can be increased (Roy and Ghosh, 2017). There are several methods for increasing efficiency, including coating the tops of PV panels with aluminum oxide and tantalum pentoxide (Rajvikram and Leoponraj, 2018), chilling the PV panels with ice (Peng et al., 2017), and cooling with water (Deephang and Suphan, 2018). These methods have the potential to reduce panel temperature by 2.9 °C–5 °C while increasing PV panel efficiency by 14 %–47 %. Although these methods can improve the efficiency of solar panels, when applied to actual work, they cannot increase land use. Agrivoltaic systems should respond effectively to both the ability to increase solar panel efficiency and the ability to expand land utilization. The temperature of the solar panels could be reduced by using agricultural humidity, evaporation from agricultural activities, and plant transpiration. Teng

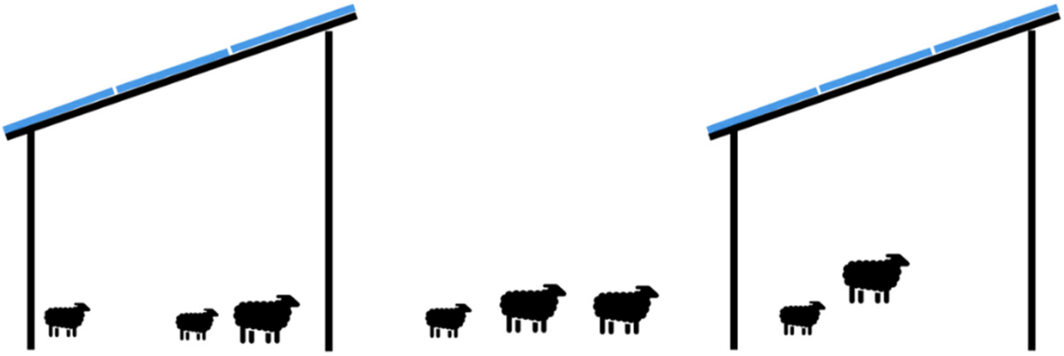

Fig. 3. PVs with animal farming.

Table 2
Land use under the PV panels planned for agrivoltaic system installation.

Year	Conditions			Results and discussion	References
	Panel installation	Type of plant/animal	Variable(s)		
2010	–	–	Solar energy applications for agriculture	Solar energy could be used in agriculture in a range of methods. It reduces air pollution while lowering costs and increasing self-reliance. It could also be used to generate electricity for direct use in agricultural lands, yield processing, greenhouses, or livestock buildings.	Peng et al. (2017)
2012	Fixed	Salad vegetables	Shading	Conventional PV panel installation with panels aligned to the south cast a shadow throughout the day. Hence, this orientation was unsuitable for planting. To resolve this issue, the panels should be oriented southeast or southwest.	Beck et al. (2012)
2012	Greenhouse	Onions	12 % PV on greenhouse	Zigzag PV panel installation for 12 % of the rooftop space allowed solar radiation to reach the ground. Thus, the fresh and accumulated dry masses of onions were higher than those in the greenhouse with single-array PV panels.	Kadowaki et al. (2012)
2013	Fixed	Lettuce, cucumbers, wheat	Full density, half density, full sun	Because half-density PV panels were used, the growth rates were the same. The plants under the panels received adequate light, and their growth was unaffected.	Marrou et al. (2013a)
2013	Fixed	Lettuce	Full density, half density, full sun	The total yields were the same as those planting under regular exposure to sunlight owing to sufficient sunlight and the efficiency of photosynthesis.	Marrou et al. (2013b)
2013	Fixed	Cattle farming	Simulation	The PV systems connecting to the suitable transmission lines of the cattle farm were at a capacity of 50 kW due to the most suitable current net cost. Furthermore, the system used solar power and electricity at rates of 58 % and 42 %, respectively.	Maammeur et al. (2013)
2014	Greenhouse	Tomatoes	50 % PV on greenhouse	The PV panel installation on the greenhouse rooftop with 50 % spacing reduced solar radiation by 60 % when compared with the non-PV greenhouse. Moreover, the yields were reduced. Solar power, on the other hand, generated a substantial profit.	Cossu et al. (2014)
2016	–	–	Solar energy applications for greenhouse	Solar energy could be used in greenhouses for cooling, heating, lighting, and irrigation. Consequently, harnessing renewable energy for food production in agricultural greenhouses is currently humanity's greatest major challenge. Further experiments and studies on this technology are required to support agricultural greenhouses and the utilization of solar energy. Simultaneously, the government should provide significantly more opportunities and energy policies to promote this technology.	Hassanien et al. (2016)
2016	Fixed, tracking	Lettuce	Full density, half density, half density-solar tracking, full sun	The dry mass of plants under the PV panels was 1 g less than those under regular exposure to sunlight, with a land equivalent ratio (LER) of 1.67. Thus, the land utilization increased by 67 % from that with electricity generation and plant production.	Valle et al. (2016)
2017	Greenhouse	–	Types of greenhouses	The PV greenhouse increased the annual return by 9 %–20 % compared with conventional greenhouses. The payback period was 4–8 years, given that PV panel installation could use electricity in the greenhouse and could increase income.	Li et al. (2017)
2017	Fixed	–	Shading	Plants for cultivation between PV arrays should be selected based on light requirements and plant height due to the limited light intensity of the space between arrays.	Santra et al. (2017)
2017	Fixed	–	19 % and 59 % PV module density	Co-production could reduce land-use conflicts between the energy and agricultural sectors because these sectors could implement production on the same land area with appropriate spacing between PV panels.	Elborg (2017)
2017	–	–	–	Agrivoltaic systems have the potential to reduce land-use conflicts, increase economic benefits to agriculturists, and reduce GHG emissions. However, additional theoretical and practical research is required to improve solar power generation yields and efficiency.	Xue (2017)
2018	Greenhouse	Iberises, petunias	20 % of PV, 20 % of PV tracking	The diameters of the trees and the flowers of the iberises and petunias grew at the same rate. Although the installation of PV panels on 20 % of the rooftop space reduced the intensity of solar radiation for planting, the light was still adequate for the plants.	Colantoni et al. (2018)
2018	Greenhouse	Tomatoes	10 % PV on greenhouse	The growth of the tree diameters and yields per tree were the same. The yields under the PV greenhouse were higher than those of the controlled greenhouse owing to the invasion of caterpillars biting into the tomato leaves in the non-PV greenhouse.	Ezzaeri et al. (2018)
2018	Greenhouse	Tomatoes	PV greenhouse, on-PV greenhouse	Because the non-PV greenhouse used electricity from the electricity authority, the PV greenhouse emitted 37 % fewer GHGs.	Leon and Ishihara (2018)
2018	Greenhouse	Tomatoes	10 % of flexible PV on greenhouse	The morphological characteristics and tomato yields at 193 days in the PV greenhouse and the controlled plot were not statistically different. Despite the fact that only 10 % of the rooftop space was covered with PV panels, the plants received adequate light. Furthermore, their growth was comparable to that of the non-PV greenhouse.	Aroca-Delgado et al. (2018)
2019	–	–	–	Solar power generation could be obtained in conjunction with the planting of rice, corn, soybeans, sesame, vegetables, and cassavas, as well as livestock, fish culture, and shrimp culture. The capacity for electricity generation of 10–16 TWh/year was sufficient, and the generated electricity could be sold to nearby cities. Co-production reduced land-use conflicts, increased agriculturist income, and reduced CO_2 emissions by up to 8–13 tons/year.	Brohm and Khanh (2019)
2019	Greenhouse	–	Solar radiation	The installation of PV panels on the greenhouse rooftop reduced the intensity of solar radiation. However, plant growth was unaffected because photosynthesis efficiency was inadequate at maximum intensity.	Yano and Cossu (2019)
2019	Greenhouse	–	Semi-transparent PV panel	In this case, 20 % of the light could radiate through semi-transparent PV	Peretz et al. (2019)

Table 2 (*continued*)

Year	Conditions			Results and discussion	References
	Panel installation	Type of plant/animal	Variable(s)		
				panels. More light could be radiated with proper spacing. As a result, this panel type is a possible candidate for co-production.	
2019	Fixed	Corns	Low density, high density, full sun	Planting corn under PV panels with 40 % spacing produced 5.6 % higher yields per square meter than regular lands.	Sekiyama and Nagashima (2019)
2019	Fixed	–	Social impact	The agrivoltaic system influenced interested locals positively. Energy and food security, in particular, were provided.	Irie et al. (2019)
2019	Tracking	–	Shading	The solar tracking system was more efficient than a south-oriented PV panels. Furthermore, the maximum amount of electricity was generated with no negative effects on plant production.	Perna et al. (2019)
2019	Fixed	–	–	Farming with solar power generation is an innovation that could achieve a water-energy-food nexus by encouraging agriculturists to use less electricity and sell excess electricity to supplement their income. Groundwater protection is also promoted.	Al-Saidi and Lahham (2019)
2019	Fixed	–	Direction (south and east)	The electricity generation capacities were the same. Yields increased when the density of the PV panels was reduced.	Riaz et al. (2021)
2019	Fixed	–	Agrivoltaic system	Co-production was expected to increase the land equivalent ratio by 30 %.	Mavani et al. (2019)
2020	Fixed & tracking	Lettuce	Solar radiation tracking, non-tracking	The most suitable design for plant growth was panel installation on 50 % of the space as the plants receive sufficient light. Co-production was expected to increase the LER.	Dos Santos (2020)
2020	Fixed	Potatoes	Ground-mounted PV system, agrivoltaic system	The return on tomato production with PVs increased by 15 % compared with that of conventional solar systems.	Schindele et al. (2020)
2020	Fixed	–	Agrivoltaic system, solar power generation, agriculture	Conventional solar power generation emitted more GHGs than that of the agrivoltaic system, given that the agrivoltaic system used 14 %–29 % less water.	Ott et al. (2020)
2020	Fixed	Grapes	Agrivoltaic system	Solar power generation with grape production had no negative effects on the growth or sucrose content.	Cho et al. (2020)
2021	Fixed	Lettuce	Even-lighting agrivoltaic system (EAS)	The EAS exhibited crop yields and quality levels similar to those realized in a natural state, as well as a high LER (average 1.64)	Zheng et al. (2021)
2022	Fixed & greenhouse	–	Type of Semi-transparent PV (STPV) modules	Compared to other STPV modules, crystalline silicon modules are commonly used in agrivoltaic systems due to their low cost, high stability, and high efficiency.	Gorjian et al., 2022
2022	Between PV array	Olive tree	The tracking / backtracking technique for horizontal tracker PV systems	Because there is space between the collectors, the crop would not shade the solar panels. The LER for an agrivoltaic system can increase by 28.9 % to 47.2 %, according to this study.	de la Torre et al. (2022)
2022	Fixed	blueberry	The fixed bifacial agrivoltaic	The E-W wing agrivoltaic topology increased the yield potential by 50 %, while decreasing electrical output by 33 % compared with conventional and separate food and energy production.	Katsikogiannis et al. (2022)
2022	Fixed	Turmeric	The efficiency of system of three different design	For average yearly revenue, LER, and payback period, a 6 kWp agrivoltaic system with a double row array design capacity is the best system, resulting in 2308.9 USD, 1.42, and up to 7.6 years, respectively. Furthermore, under the same land use, the socioeconomic parameters of the revenue, benefit–cost ratio, and price–performance ratio of turmeric were 187.3 USD, 1.86, and 0.75, respectively.	Giri and Mohanty (2022)

et al. (2022) conducted microclimate simulations employing ENVI-met simulations and indicated that between 08.00 a.m. and 6.00 p.m., PV temperatures in the plot with crops below the PV system were 2.83 °C and 0.71 °C lower than without crops on a typical sunny and cloudy day, respectively. The PV efficiency, on a sunny day, increased by 1.13 %–1.42 %, but only by 0.28 %–0.35 % on a cloudy day. When compared to a control system with no crops below, the agrivoltaic system with PV panels generated between 3.05 % and 3.2 % more energy during the day. In actual work, Kumpanalaisatit et al. (2022) discovered that crop cultivation under solar panels can reduce module temperature to less than 0.18 °C, resulting in a 0.09 % gain in voltage and power output.

5. Crop production of agrivoltaic systems

The crop yields of agrivoltaic systems (see Table 3) obtained lower than the control ranged from 3.98 % to 91.30 %. This was due to crop yields being impacted by shading. Shading affects the amount of direct solar irradiation, which effects yield, especially crop weight (Sekiyama and Nagashima, 2019; Tahir and Butt, 2022; Moon and Ku, 2022). Therefore, by reducing the number of solar panels installed on the planted area, the amount of light intensity for the plants grown under the panels could be increased. Despite the use of a low-density PV configuration, Jiang et al. (2022) and Choi et al. (2021) noticed that crop yield was still lower than the control. A solar tracking system could be used to solve this issue. Kirimura et al. (2022) found that even though the solar tracking system was employed to increase the light under the solar panels, it produced lower yields than the control. The growth rates of the solar tracking system, fixed system, and control system were not significantly different. Consequently, while the planting was consistent, the harvest period may vary depending on whether solar panels are present. Although crop yield differed between agrivoltaic systems and open field cultivation, Moon and Ku (2022) discovered no significant difference in crop yield quality. Trypanagnostopoulos et al. (2017), on the other hand, demonstrated that installing a PV system on a greenhouse rooftop resulted in a slightly higher crop yield than the control of approximately 6.88 % because the shading of the solar panels provided a cooler climate than the control.

6. Land equivalence ratio of agrivoltaic systems

Land used for power generation or agriculture could generate a single source of income. Therefore, co-production was required to increase the LER and electricity generation efficiency to increase land-use efficiency. This may reduce future production conflicts between the energy and agricultural sectors. According to the LER analysis results for the co-production systems proposed by Giri and Mohanty (2022), de la Torre et al. (2022), Mavani et al. (2019), Valle et al. (2016), and Dupraz et al. (2011), the LERs of the systems ranged from 1.29 to 1.73.

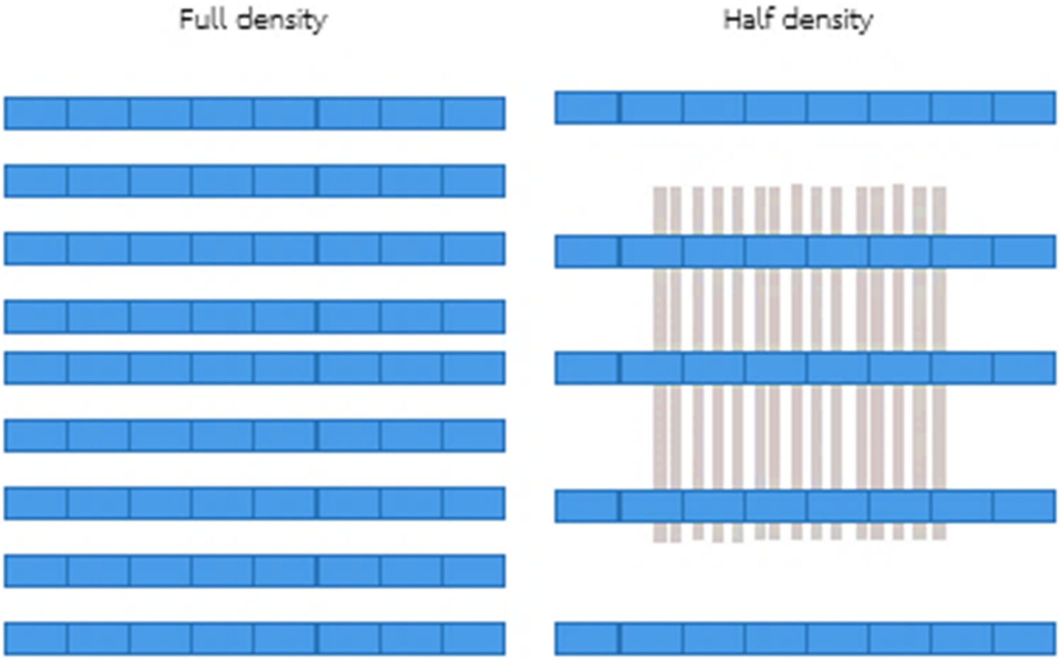

Fig. 4. Top views of the installed agrivoltaic systems.

Co-production could thus increase land use by up to 29 %. There were two recommendations with respect to land use under PV panels of PV systems, i.e., agricultural land use under PV panels of fixed PV systems without agricultural pre-plans and planned PV system installation with agricultural plans. Planting under PV panels could be implemented in three forms, i.e., under PV panels, between PV arrays, and in PV greenhouses. A PV system for livestock farming could be implemented by allowing animals to roam and consume grasses around PV panels. The animals, such as sheep, goats, and cattle, could find shelter in the shade of the panels. This method could also be utilized to raise poultry livestock in PV greenhouses by digging fishponds under PV arrays. A few research studies on ground-mounted PV systems in an agricultural area without agricultural pre-plans have been conducted. As a result, future research should focus on a proposed agrivoltaic system for ground-mounted PV power plants that only supply electricity to stimulate land-use growth.

7. Agrivoltaic systems: relationships among energy, food, environment, economy, and society

The relationships between energy, food, environment, economy, and society were analyzed with respect to agrivoltaic systems (see Fig. 6), The importance of applying agrivoltaic systems to develop the energy and agricultural sectors is demonstrated. A balance between the two sectors and the upcoming sustainable development goals, in particular, could be achieved.

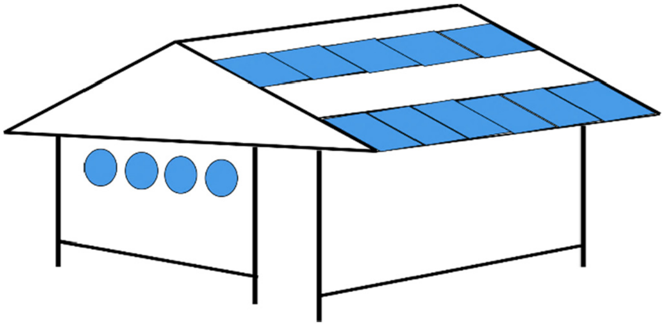

Fig. 5. PV system installed on the greenhouse rooftop.

7.1. Energy impact

Solar power is a renewable energy source that has the possibility of meeting the global electricity demand. Further to that, it is a type of renewable energy that could replace fossil-fueled electricity generation, improving national energy security and self-sufficiency. Moreover, conflicts over land use are likely between the energy and agricultural sectors. Therefore, several types of agrivoltaic systems have been proposed to resolve this issue, as agrivoltaic systems have the potential to enhance the efficiency of solar power generation.

7.2. Food impact

Several countries have policies in place to expedite the construction of solar power plants in response to increased demand for renewable energy, particularly electricity generated by solar energy. The expansion of solar power plants in accordance with each country's policy raises demand for building sites, which may lead to further invasion of agricultural areas. Solar power plant development issues that cause conflict in agricultural areas may lead to food insecurity in many locations (Trommsdorff et al., 2021b; Ketzer, 2020; Dinesh and Pearce, 2016). Thus, by limiting encroachment on agricultural areas, agrivoltaic systems can help to improve food security. Additionally, mutual benefits between solar power generation and agricultural production can be provided. A solar power plant in conjunction with agriculture should be developed to improve food security (Agostini et al., 2021; Chae et al., 2022; Bhandari et al., 2021). Jing et al. (2022a, 2022b), for example, revealed that an urban rooftop agrivoltaic system in Shenzhen city can produce an order of magnitude more lettuce than the local demand. Food security could be promoted by encouraging the expansion of agriculture in conventional power plants, in addition to increasing the number of agricultural areas in tandem with the number of solar power plants. However, factors other than government policy influence the operation's performance, and improving understanding between farmers and power sector owners could help the operation succeed.

Table 3
Crop yields in agrivoltaic systems.

Type of plant/animal	Condition	Agrivoltaic yield (kg/m^2)	Conventional yield (kg/m^2)	Reference
Bok Choy	Under PV panel (Conventional PV system)	0.10	1.15	Kumpanalaisatit et al. (2022)
Lettuce	Under PV panel (High-density configuration in summer)	2.65	4.50	Dinesh and Pearce (2016)
Corn	Under PV panel (High-density configuration)	3.23	3.35	Sekiyama and Nagashima (2019)
Lettuce	Greenhouse	2.18	2.03	Trypanagnostopoulos et al. (2017)
Kiwifruit	Under PV panel (Low-density configuration)	1.66	1.71	Jiang et al. (2022)
Winter cabbage	Under solar panel	0.32	0.35	Moon and Ku (2022)

7.3. Environmental impact

GHG emissions contribute significantly to global warming. Agriculture accounts for approximately 10 %–14 % of the increase in GHG emissions, owing primarily to the energy sector and livestock production (Gołasa et al., 2021). Solar energy is a renewable energy source that has the ability to lower GHG emissions in agriculture. According to previous estimates, 1500 kW ground-mounted PV systems could reduce GHG emissions by 1549 tCO_2e/year (Chaivanich, 2018). By integrating renewable energy sources with agriculture, developing renewable energy can help to reduce agricultural GHG emissions (Gołasa et al., 2021). This concept has been proved by Maia et al. (2020), Cho et al. (2020), and Lytle et al. (2020), who indicated that an agrivoltaic system could reduce GHG emissions more than the control. Moreover, Choi et al. (2021) demonstrated that an agrivoltaic system results in a large offset in GHG emissions when compared to the same-scale diesel power generation or grid supply. According to the Stedman and Higgins (2022) study, integrating an energy generating system with agriculture could reduce GHG emissions, and the electricity generated by the agrivoltaic system could be used to power electric vehicles (EVs). By installing systems along 86 % of Oregon's main rural highways, they showed that an agrivoltaic system could be applied to EV charging stations to facilitate in the transition to EVs. Agrivoltaic system rural charging stations could sustain the equivalent of 673,915 EVs/yr, reducing GHG emissions from vehicle use by 3.1 million $MTCO_2$/yr or 21 %. Additionally, using waste in agrivoltaic activities from basic manufacturing processes and processing that employed raw materials from the agrivoltaic system reduces waste entering the environment and adds value to the waste produced. This activity has the potential to lower GHG emissions while introducing agrivoltaic systems into the Bio-Circular-Green economic model.

7.4. Economic impact

Agrivoltaic systems may generate three income streams for entrepreneurs and agriculturists, i.e., sales of electricity and agricultural products (Hernán and de Arruda, 2021). For example, Thompson et al. (2020) demonstrated that the income from selling electricity with basil and spinach increased the production values by 18 % and 113 %, respectively. Additionally, when compared to electricity production, co-production minimized the payback period by up to 30 %–35 % (Roy and Ghosh, 2017), and the average simple payback period for agrivoltaic systems was between 5 and 8 yrs (Hernán and de Arruda, 2021; Giri and Mohanty, 2022; Jing et al., 2022a, 2022b). Solar electrical energy could be co-generated with livestock farming, in addition to co-producing electricity and agricultural crops. According to Lytle et al. (2020), who proposed an agrivoltaic system design idea based on feeding rabbits, this system could increase overall income by 2.5 %–24 %, as each rabbit has a high value per unit weight.

The detailed economic impact of agrivoltaic systems affects stakeholders upstream, midstream, and downstream. These key stakeholders could offer mutual assistance as a source of income and a higher

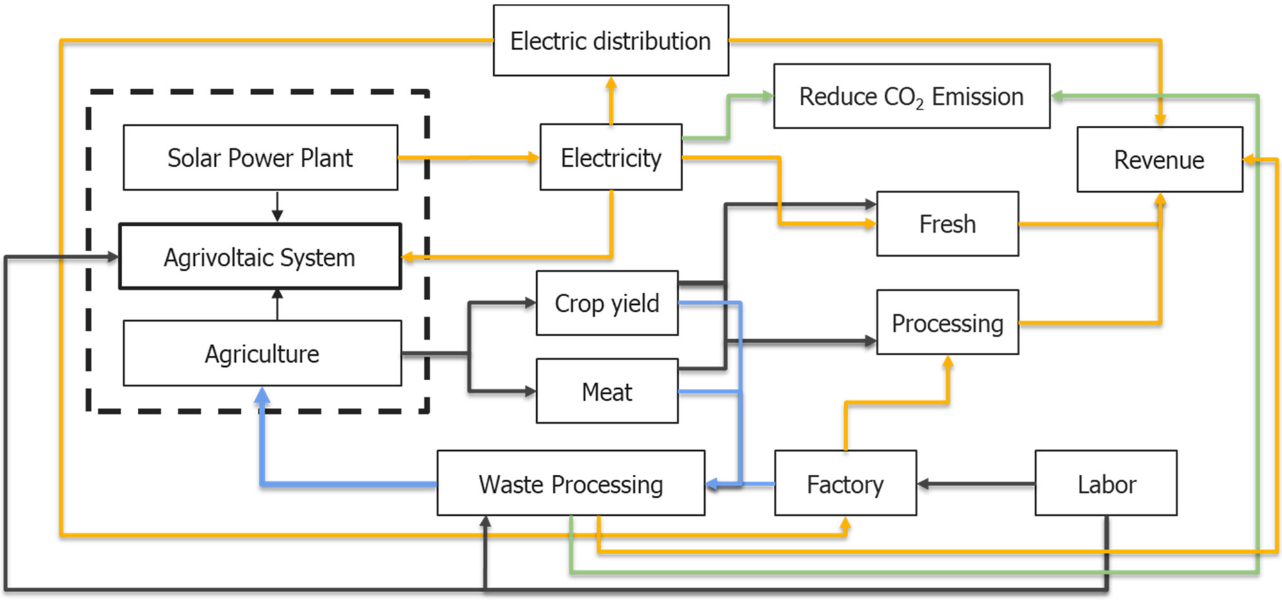

Fig. 6. Relationships between energy, food, environment, economy, and society with respect to agrivoltaic systems.

standard of living, thereby promoting the national economy (Agostini et al., 2021). According to Proctor et al. (2021) research, the photovoltaic components of agrivoltaic system installation alone could provide 117,000 jobs in the United States over a 20-year period, with 40 % of those jobs being in the form of ongoing operation and maintenance. This estimate excludes agricultural employment generation associated with the system.

Upstream stakeholders include entrepreneurs of solar power plants who aim to produce plants with PVs; agriculturists who aim to install PV systems on agricultural lands; solar cell manufacturing and distribution companies; agricultural machinery, tool, and equipment distribution companies; and workers. Agrivoltaic systems provide a cash stream for entrepreneurs and agriculturists (Havrysh et al., 2022; Chae et al., 2022; Bhandari et al., 2021; Zheng et al., 2021; Irie et al., 2019), and they may also minimize the expenses by using the electricity generated on their farms. Using power generated in agricultural areas can help farmers save money on energy (Bhandari et al., 2021). Transitioning from solely farming or solar power generation to agrivoltaic systems, or developing new agrivoltaic systems, may generate revenue for solar cell manufacturers, distributors, and system integrators, as well as agricultural enterprises (Bhandari et al., 2021). Profits from the manufacture, distribution, and installation of solar cells also help to support jobs and pay skilled workers in the installation of solar power generation systems. Furthermore, increased agricultural lands will raise agricultural jobs. Once their agrivoltaic systems have been developed and their carbon sequestration has been assessed, owners can profit by selling carbon credits to other businesses seeking to reduce their greenhouse gas emissions.

Midstream stakeholders include community enterprises, agricultural product processing factories, and related businesses. Agrivoltaic crops can be sold fresh and can also be used as community enterprises or factories in the food industry, generating income and jobs (Bhandari et al., 2021). Electricity purchased directly from the agrivoltaic system by the system owner and food producing operators will generate more cash flow in the economy (Bhandari et al., 2021). However, Trommsdorff et al. (2021a) suggested that electricity selling prices be lower than consumer prices in order to improve economic performance and increase self-consumption. Furthermore, if operators have their own systems and food processing factories, the cost of purchasing raw materials and energy can be reduced by using crops and electricity generated by the systems in their enterprises. According to Trommsdorff et al. (2021a), the local agricultural community used 41 % of the generated electricity (101.2 MWh) in the first year of operation. The potential to increase the proportion of electrical self-consumption, on the contrary, was especially suitable for small systems. Owners will benefit not only from using the agrivoltaic system's output, but they may also cut expenses or generate income by using food processing waste in their agrivoltaic system, transforming it into ready-to-market products, or selling it to other agrivoltaic plots. Agrivoltaic system production and food processing can generate cash flow in linked firms such as agrochemical businesses, packaging businesses, and maintenance businesses during the manufacturing process.

Downstream stakeholders include community members, consumers, restaurants, distribution centers, electricity authorities, suppliers, and the transportation sector. The development of agricultural plots, solar power plants that only generate electricity, or abandoned land for agrivoltaic systems can generate cash for the community by raising employment (Trommsdorff et al., 2021b; Ketzer, 2020). To support more agrivoltaic crops, more community members may be employed in food processing industries. Fresh and processed products from agrivoltaic systems can be supplied directly to customers, restaurants, and distribution centers (Bhandari et al., 2021). A cash flow turnover is also caused by trading. Moreover, product delivery to various locations generates cash and jobs for the transportation sector. Entrepreneurs can earn money by selling power to electricity authorities after generating enough electricity with agrivoltaic systems and other activities (Bhandari et al., 2021). If agrivoltaic systems are installed in areas without electricity or at the end of a transmission line, they can support electrical authorities lower the cost of expanding transmission lines and increasing electricity capacity to those areas. The activities performed at various times will distribute cash to the suppliers.

7.5. Social impact

Agrivoltaic systems have positive effects on the economy and on society for upstream, midstream, and downstream stakeholders. Entrepreneurs can gain managerial abilities and an understanding of other disciplines by developing agricultural plots or solar power plants that focus entirely on generating electricity for agrivoltaic systems (Randle-Boggis et al., 2021; Irie et al., 2019). Moreover, because employees in the system will be trained until they have acquired the necessary skills, entrepreneurs can ensure that employees are competent in their jobs (Trommsdorff et al., 2021b). This action will improve skilled labor in accordance with community needs. In the future, certain employees' abilities and expertise may enable them to advance to become owners of solar power, agricultural, and service businesses, creating numerous career opportunities in the community. The productivity of agrivoltaic systems will provide stability and self-sufficiency in food and energy for areas experiencing food insecurity and/or energy shortages (Agostini et al., 2021; Randle-Boggis et al., 2021; Ketzer, 2020). According to Malu et al. (2017), if a grape-based agrivoltaic system is implemented in rural India in the future, it may provide electricity to the community. The system will improve people's quality of life. As a result, food, and energy security, as well as self-sufficiency, are achieved through the use of the system's products (Irie et al., 2019). Additionally, strong community cooperation is required to improve the system and expand its coverage of the community's space. Moreover, this system has the potential to improve the community's environment. Adopting this method would help reduce greenhouse gas emissions, allowing the community's or entrepreneurs' agricultural operations to transition to a greener economy, providing a long-term impact on the development of excellent health in humans (Agostini et al., 2021; Choi et al., 2021). For example, Proctor et al. (2021) demonstrated that widespread installation of agrivoltaic systems in the United States can result in CO_2 emissions reduction equivalent to eliminating approximately 70,000 cars from the road each year. Furthermore, the system's encouragement of organic agricultural operations will allow customers to lead an environmentally friendly lifestyle and consume non-toxic products.

Agrivoltaic systems foster connections between energy, food, the environment, the economy, and society. In addition, these systems increase electricity generation, ensure energy and food security, reduce GHG emissions, add value to land use, improve access to electricity for agricultural lands or communities with power outages, and expand opportunities at power plants that require co-production. However, these systems' implementation has been limited. System maintenance necessarily requires specific skills that most agriculturists struggle with. Only crops that require low light can be grown due to the limited intensity of solar radiation under PV panels. Therefore, agriculturists should be trained to be highly proficient in the application of PVs to agriculture. Appropriate system designs for various forms of plant production could mitigate future land use conflicts between the agricultural and energy sectors.

8. Future prospects

With the continuous advancement of solar energy production, mathematical models for predicting the effects of planting agricultural crops under PV panels that are solely used for solar power generation would be beneficial in order to shorten the time required prior to practical implementation. For a fixed PV system, such models could facilitate the selection of crops to be cultivated under specific climate conditions. Because agricultural plants require water, the moisture in the air surrounding the PV panel areas may have an effect on the PV structural materials. Thus, a thorough investigation of the corrosion and lifetime characteristics of the materials used in such conditions is required. Moreover, if the land under the PV panels can be used to plan agricultural crops, agrivoltaic systems are expected to provide income to growing local communities and help reduce the likelihood of forest devastation. Finally, appropriate government policies on agrivoltaic systems are critical for obtaining local people's support for solar energy production and use.

9. Conclusion

This paper discussed two recommendations for land use under PV system panels: agricultural land use under PV panels of fixed PV systems without agricultural pre-plans and planned PV system installation with agricultural plans. Consequently, two types of agrivoltaic systems were considered: co-production (planting under PV panels and between PV arrays) and PVs combined with terrestrial and aquatic animal farming. Co-production improved the efficiency and potential of electricity generation, and agrivoltaic systems could promote the use of renewable energy. Furthermore, they could ensure energy and food security, reduce GHG emissions, generate income for entrepreneurs or agriculturists, and raise community employment. Despite the benefits of both types of agrivoltaic systems in terms of energy, food, environment, economy, and society, few studies on ground-mounted PV systems without agricultural pre-plans have been conducted. This approach could reduce agricultural land competition and forest invasion, while also increasing the LER. Further research and implementation of PV systems could benefit the environment by reducing the effects of deforestation through effective land use planning and the steps required by authorities, thereby benefiting agronomic markets.

1) In order to shorten the time required to investigate the effects of cultivating land under fixed solar panels on solar power generation, a mathematical model for predicting agrivoltaic systems should be investigated.
2) Crops suitable for planting under fixed PV systems, along with the crop growth parameters, should be identified.
3) Agrivoltaic systems must water the plants on a daily basis. Material corrosion should be monitored since moisture under the solar panel may affect the plant structure.
4) Appropriate agrivoltaic policies should be implemented to reduce competition for agricultural lands and forest invasion and to also support local people.

Declaration of competing interest

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.

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