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# Critical Analysis of Agrivoltaic Systems: Balancing Energy Production with Agricultural Sustainability

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**ABSTRACT:** An agrivoltaic system (AVS) offers a potential strategy for meeting global demands for renewable energy and sustainability by integrating photovoltaics and agriculture. Many empirical studies have installed facilities and cultivated actual crops, revealing that AVSs improve land use efficiency. However, it is rare for actual end-users and farmsteads to adopt AVSs owing to a lack of standardised models and design criteria. In this study, we conducted a comprehensive AVS design considering agronomic aspects and structural safety along with an analysis of design criteria to promote the dissemination of AVSs. Based on the photovoltaic module arrangement and adjusting installation conditions, various design types were considered to reflect on-site conditions and user preferences. In addition, safety standards for disaster resistance and trade-offs among shading ratio, power generation capacity, and quantity of structural members were analysed. The safety assessment results demonstrated that the column of the AVS structure was vulnerable to wind loads, and the safety standards varied according to the adjusted column spacing. The narrower the column design, the more advantageous the safety and power generation and the more disadvantageous the crop cultivation environment and installation cost. The sequentially mounted type allowed relatively less solar radiation to reach the crop and generated more solar energy. When the modules were mounted at a distance, the structural safety was slightly reduced; however, more solar radiation and economic feasibility were secured. These results will support decision-making regarding AVS designs, help in identifying the sensitivity of crops to shading, and be utilised for the establishment of a standardised AVS model to promote dissemination.

**KEYWORDS:** agrivoltaic, AVS, energy, agricultural, sustainability

## I. INTRODUCTION

We review the various types of AV systems and summarize the potential ecosystem services they may provide. Ecosystem services are the direct and indirect benefits that ecosystems provide to humans (Millennium Ecosystem Assessment, 2005).[1,2,3] There are four broad categories of ecosystem services: provisioning services such as energy and food production, regulating services such as carbon sequestration and erosion control, cultural services such as recreation, and supporting services such as photosynthesis and net primary production. Significant improvements in solar technologies have fueled the continued growth of solar in the global electric sector. The best-known service of photovoltaic systems (including AV systems) is the low-carbon energy production these systems can provide. While in operation, a solar energy facility represents a carbon-free source of electricity [U.S. Department of Energy (DOE), 2021a]. Estimates of projected solar capacity growth suggest up to 22 TW of installed capacity by 2050 globally in a scenario where 100% of the power sector is supplied by renewable energy (Fischer et al., 2020). The associated land area (estimated as about 165 million acres or 67 million ha) is <0.5% of global land mass, but also represents a significant opportunity for AV systems to provide ecosystem services in addition to energy production.

Information on the total global amount of electricity generation from AV systems is lacking but recent estimates suggest there could be >2.8 GW of global electricity generation from AV-cropping systems (Gorjian et al., 2020), corresponding to ~21,000 ac (8,500 ha) using land use assumptions from Heath et al. (2020). There could be far greater global electricity generation from AV systems co-located with native habitat restoration. Despite recent research examining the opportunities for habitat restoration within solar facilities in the U.S. and U.K (for example see Blaydes et al., 2021 and Walston et al., 2021), there is currently little quantitative information on the amount of solar energy development with co-located native habitat restoration activities. In the U.S. state of Minnesota, it is estimated that about 1,400 ac (570 ha) of land operated for solar energy production is co-located with native habitat restoration, representing ~175 MW of electricity production [Minnesota Board of Water and Soil Resources (MN BWSR), 2021].

There is a growing body of evidence suggesting that some AV designs may improve the efficiency of solar PV panels and therefore improve energy production. Temperature has a significant impact on solar PV panel operating efficiency. A 1°C increase in temperature can decrease panel efficiency by 0.6% when temperatures exceed 25°C (Barron-Gafford et al., 2019). During hot summer months when PV panel efficiency is known to plateau and become less productive, AV systems vegetated with cropping systems or native habitat can create cooler microclimates under the PV panels, improving PV panel life and performance (Adeh et al., 2018; Barron-Gafford et al., 2019). In addition, advancements in solar technologies can also act synergistically with AV systems to improve energy efficiency. For example, in AV systems utilizing bifacial PV modules, the undersides of the PV panels [4,5,6] may utilize greater reflectance from vegetation, leading to increased energy production (Rodríguez-Gallegos et al., 2020). In addition, a recent study in Saudi Arabia described how running water through the frame of the PV panel functioned as a heat exchanger improving the efficiency of the PV panel by nearly 10% (Li et al., 2020).

In addition to creating plant-friendly and more PV-efficient cooler microclimates, some AV systems may also lower the net energy requirements for a solar facility by improving the site's water use efficiency for plant irrigation by either (a) repurposing water used for cleaning panels for irrigating plants for agricultural production, and/or (b) reducing evapotranspiration due to shading from the PV panels (Hernandez et al., 2019).

Agrioltaic systems have the potential to not only help meet global decarbonization goals for the electricity grid, but to also do so sustainably by simultaneously achieving other environmental, economic, and social objectives (Hernandez et al., 2019; Proctor et al., 2021; Al Mamun et al., 2020). Solar PV jobs are expected to reach 22.2 million by 2050 (Ram et al., 2020). As agricultural areas are ideal locations for solar energy development, AV developments may benefit rural economies through jobs, tax revenues for local programs, and by providing income diversification for farmers and landowners [Moore et al., 2021; Electric Power Research Institute (EPRI), 2020]. Globally, this may be most positively impactful in rural arid landscapes facing the most urgent needs for sustainable agriculture and energy production and where the benefits of PV shading for crop production and water use efficiency are highest (Parkinson and Hunt, 2020).

#### Agricultural production

A variety of dual use opportunities have emerged to combine AV systems with crop production, livestock grazing (Andrew et al., 2021; Electric Power Research Institute (EPRI), 2020), and other forms of animal husbandry such as beekeeping and rabbit farming (Dolezal et al., 2021; Lytle et al., 2021). Worldwide, farmland is being lost due to conversion to other land uses (Hu et al., 2020) or becoming less productive as a result of climate change (Ortiz-Bobea et al., 2021). These factors place greater pressure to intensify agricultural production on remaining farmland or to convert other natural areas for agricultural purposes. Paradoxically, solar energy development often competes with agriculture for land (Dupraz et al., 2011) and represents one form of land use conversion of former agricultural fields (Walston et al., 2021). [7,8,9]As more land for solar development is needed, there are concerns regarding land use changes from converting agricultural land from food production to energy production. AV-cropping and AV-animal systems may mitigate these concerns by allowing food production to occur at these sites (Marrou et al., 2013; Dinesh and Pierce, 2016; Barron-Gafford et al., 2019; Sekiyama and Nagashima, 2019). In addition, these multifunctional AV systems can be mutually beneficial to both the solar industry and the agricultural communities. For example, AV-cropping and AV-animal systems may reduce operations and maintenance (O&M) costs associated with water needs and vegetation maintenance while also providing land access for agricultural producers (Proctor et al., 2021). AV-habitat systems may also be managed in a manner that reduces O&M costs while also providing pollination services to nearby (offsite) agricultural fields (Walston et al., 2018). Lower O&M costs may have positive economic implications for the solar industry while the land access and habitat restoration may positively impact agricultural communities directly, by providing land for crop production, and indirectly, by providing agricultural services to adjacent offsite fields.

Co-locating crop production with solar energy development has been deployed in different configurations throughout Europe, Asia, Australia, and recently, the United States (Marrou et al., 2013; Elamri et al., 2018; Barron-Gafford et al., 2019; Toledo and Scognamiglio, 2021; Al Mamun et al., 2020). Currently, most AV systems with co-located crop cultivation are planted with high value and hand harvested crops (i.e., lettuces, tomatoes, saffron, kale, broccoli, eggplant, peppers, etc.). A number of AV demonstrations have suggested that crop cultivation at solar facilities may be particularly useful in arid regions where shading by PV panels can improve microclimate conditions, such as temperature and soil moisture, and improve the site's water use efficiency for irrigation (Barron-Gafford et al., 2019; Parkinson and Hunt, 2020). Although the majority of AV systems have focused on crop cultivation at relatively small solar sites (<3 MW) using shade-tolerant specialty crops that can be cultivated manually or with little equipment needs,

emerging research is examining how AV systems can be integrated with more traditional shade-intolerant commercial crops such as corn, soybeans, and wheat. For example, a small-scale experimental field study in Japan suggests that corn production could be achieved at solar PV facilities with raised PV panels (Sekiyama and Nagashima, 2019). While this study is limited in scale and replication, it is suggestive of the potential feasibility of commercial crop production at AV facilities and is being followed by current research in the United States and elsewhere (e.g., U.S. Department of Agriculture SCAPES Study, <https://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=fastlink1.txt&id=anon&pass=&search=R=94424&format=WEBLINK>). In these applications, there may be additional considerations for designing solar systems that could accommodate these traditional cropping systems (i.e., increasing PV panel height and the spacing between rows of PV panels) or altering agricultural operations to facilitate row crop agriculture with solar energy infrastructure (i.e., modifying agricultural equipment [10,11,12] to reduce risk of damage to solar infrastructure). Future research is needed examine the feasibility and cost implications of scaling AV systems to larger, commercial cropping systems.

Several other demonstrations of AV systems have shown that livestock grazing or other forms of animal husbandry can be compatible with solar energy development (Table 1). Livestock such as sheep may be particularly compatible with solar infrastructure due to their relatively small size and docile nature compared to other livestock [Al Mamun et al., 2020; Electric Power Research Institute (EPRI), 2020]. For example, Andrew et al. (2021) found lamb growth and production at a 1.4 MW (2.4 ha) solar facility in Oregon comparable to growth and production on open pastureland, demonstrating that land productivity can be improved through AV systems that co-locate livestock grazing and solar energy development. This could be particularly beneficial for the sheep industry, which has been in decline in the United States (The National Academies, 2008). While concerns have been raised about the compatibility of AV systems and other forms of livestock such as cattle [Electric Power Research Institute (EPRI), 2020], future research may help identify which solar development designs and types of livestock might be most compatible for future AV-grazing systems.

Other recent publications have argued for the utility of AV systems as sites for other forms of animal husbandry such as beekeeping (Armstrong et al., 2021; Dolezal et al., 2021). The utilization of AV systems as apiaries for honey production could have several ecosystem service benefits for honeybees and food production. Honey, a specialty crop in its own right, is valued at over \$300,000,000 USD annually in the United States [United States Department of Agriculture (USDA), 2021], and honey production is reliant upon access to areas with high quantities of nectar availability. Land use changes such as agricultural intensification have led to reductions in land available to support apiaries and resulting declines in the quality and quantity of honey yields (Otto et al., 2016). As solar installations become more common in agricultural settings, there is growing opportunity for these sites to be co-managed with apiaries, which could improve honey yields and the agricultural services provided by managed honeybees (Dolezal et al., 2021). For example, a study across solar facilities in the United Kingdom found that if honeybee hives were installed at all existing solar parks in 2017, the total pollination service benefit to surrounding agricultural production would have been £5.9 million (Armstrong et al., 2021). [13,14,15]

## Biodiversity

Biodiversity provides several ecosystem services critical to human wellbeing, such as assisting in food production, pest control, and the purification of fresh water (Millennium Ecosystem Assessment, 2005). Worldwide, biodiversity is threatened from the loss of native habitat as a result of the expansion of human land uses (Ekroos et al., 2016). In many areas, land conversion associated with agricultural intensification has contributed to the loss of native grassland systems and declines in biodiversity – most notably pollinator populations (Kremen and Ricketts, 2000). In these agricultural landscapes, land management approaches that focus on providing diverse high-quality pollinator habitat may have an important role in safeguarding pollinator populations and the agricultural services they provide.

Recent attention has been placed on the role of AV-habitat systems that integrate native habitat enhancement as a means to conserve biodiversity and restore associated ecosystem services [Walston et al., 2018, 2021; Hernandez et al., 2019; Dolezal et al., 2021; Graham et al., 2021; Electric Power Research Institute (EPRI), 2020]. In these configurations, most of the focus has been placed on the creation and maintenance of pollinator-friendly seed mixes of regionally native grasses, forbs, and other wildflowers, within the solar infrastructure footprint, that attract and support native insect pollinators by providing food sources, refugia, and nesting habitat (“solar-pollinator habitat”; Walston et al., 2018, 2021). The establishment of solar-pollinator habitat could benefit biodiversity and be an important conservation mechanism for some imperiled species (Hernandez et al., 2019). In addition, increased insect abundance and diversity associated with solar-pollinator habitat could restore ecosystem services such as crop pollination and pest

control that may maintain or enhance production on nearby agricultural lands. These potential benefits are inferred by years of field research associating native habitat restoration in agricultural landscapes with increases in pollinator populations and their agricultural services. For example, habitat restoration near agricultural fields can increase insect pollination services and resulting crop yields of fruits such as strawberries and blueberries (Blaauw and Isaacs, 2014; Ganser et al., 2018), and there is additional evidence that habitat restoration around other commercial crop fields, such as soybeans, could improve insect pollination services (Levenson et al., 2020) and provide habitat for natural enemies that feed on crop pests (Gardiner et al., 2009).

While there is an abundance of evidence on the benefits of habitat restoration in agricultural landscapes for biodiversity, the concept of solar-pollinator habitat restoration is still relatively new and there are questions regarding vegetation management, compatibility with solar infrastructure, and ability to achieve certain ecological objectives. Emerging research suggests that in some areas, the partial shading of solar panels can benefit the growth of native vegetation and increase insect diversity (Graham et al., 2021). In addition, modeling studies have demonstrated the important role solar facilities may serve in the conservation of native insects through the establishment of solar-pollinator habitat [16,17,18]

#### Supporting and regulating services

Along with the provisioning services of energy and food production and benefits to biodiversity, AV systems also have the potential to positively influence other ecosystem services, such as the regulation of climate, air quality, water, and soil quality. Solar PV energy is one of the lowest emitting sources of greenhouse gases (GHG) of all electricity generating types [Hernandez et al., 2019; Agostini et al., 2021; U.S. Department of Energy (DOE), 2021a], in large part because carbon-containing fossil fuels are not combusted to produce energy. Analysis of greenhouse gas emissions from solar facilities showed that these systems have life-cycle greenhouse gas emissions from 10 to 50 times lower than fossil-fuel based power (Turconi et al., 2013; Ludin et al., 2018; Bosmans et al., 2021). The range of lifecycle greenhouse gas emissions for solar PV facilities has been found to be most dependent on the panel type, with mono-crystalline silicon panels associated with the largest emissions due to high energy requirements of production (Muteri et al., 2020; Bosmans et al., 2021). Still, more than 99% of solar PV facilities have lifecycle emissions lower than 100 g CO<sub>2</sub> eq/kWh (Bosmans et al., 2021). Creating AV-habitat systems can offset these relatively small greenhouse gas emissions (through vegetative capture of carbon), and improve air quality. As sites of agricultural production or habitat restoration, all types of AV systems can influence flows of other supporting and regulating ecosystem services such as net primary production, soil carbon sequestration, soil stabilization, and water retention. For example, AV systems can be designed to improve the site's water retention potential, as a result of increased shading from vegetation and PV panels that reduces evaporation and plant transpiration (Adeh et al., 2018; Barron-Gafford et al., 2019; Parkinson and Hunt, 2020).

AV-habitat systems co-located with native habitat restoration ("solar-pollinator habitat") can also improve the supporting services of photosynthesis and net primary productivity (Huang et al., 2013) and regulating services of carbon sequestration, water retention, and erosion control. As shading by solar panels may create more favorable microclimates for the growth of native vegetation, the above- and below-ground growth of these onsite plant communities can better stabilize soil and provide greater carbon sequestration potential compared to conventional solar vegetation management practices (e.g., turfgrass) (Walston et al., 2021). Native grasses and forbs typically have deeper root systems than turfgrass (Schenk and Jackson, 2002), and these deeper root systems can facilitate the accumulation of soil organic carbon (Yang et al., 2019), improve soil stabilization to minimize erosion, and reduce water runoff (Schulte et al., 2017). Recent modeling results have demonstrated the potential for AV systems co-located with native habitat restoration to improve the site's carbon sequestration potential and reduce erosion and runoff (Walston et al., 2021). However, empirical evidence on the regulating services of AV systems is sparse and the limited available information suggests it may take several years for some of these service benefits to be realized. For example, soil organic carbon accumulates at former row-crop agricultural fields that have been restored to native prairie grasses at a rate of  $\sim 0.68 \text{ Mg C} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$  (McLauchlan et al., 2006). Therefore, it may take several years for statistically distinguishable changes in soil organic carbon to be detected once habitat restoration activities have started at AV systems. At one solar site in the U.S., for example, the solar site's soil carbon content remained lower than reference soils in a nearby natural area seven years after solar site construction and revegetation (Choi et al., 2020).

## II. DISCUSSION

An agrivoltaic practice is a concept that originated in 1980 [23]. It is defined as a land-use concept that directly integrates solar energy production and agricultural activities, which are practiced under the photovoltaic field installation, both of which are highly dependent on sunlight [28]. Agrivoltaics has several names that vary according to region and application, such as “dual-use”, “co-location”, “agri-PV”, “agri-solar”, “solar sharing”, “pollinator-friendly solar”, etc. [29]. Indeed, it is a symbiotic relationship in which both activities interact directly and benefit from this co-location [30]. This practice leads to synergies by optimizing the potential offered by both production systems [31], especially in agroforestry systems [32].

Agrivoltaic practices can be carried out in different ways depending on the activities carried out by the population in a given area. Agrivoltaic applications represent the combination of energy production with (i) agricultural production in the field or (ii) agricultural production in greenhouses or livestock rearing, or (iii) provision of ecosystem services through vegetation management or (iv) different agricultural practices combined [29]. Agrivoltaic technology has an important role in strengthening the water–energy–food relationship [33], given the increasing future need for energy and food production in the face of population demand [34]. Indeed, one of the constraints on the development of PV systems is the increased competition for land due to high population growth and rising food demand [35]. Although land resources are limited, the need for energy and food is increasing, leading to increased competition for land between the two sectors. In response to this growing competition, agrivoltaics was conceived to keep the two activities in balance [36]. Due to their dual use, agrivoltaics would mitigate competition for space and offers the possibility to install large PV systems, while keeping the land accessible for food production [37]. Thus, agrivoltaics system reduces land constraints concerning the placement of solar PV plants for electricity generation [38]. Moreover, this system has proven to be a particularly effective way to increase land use efficiency [32]. Land use efficiency is determined by the so-called parameter Land Equivalence Ratio (LER). The method of measuring land use in integrated agricultural and electricity production systems was originally derived from the intercropping method applied in the farming sector to increase land yield and total income [39]. The LER is a function of the area of the PV system and the total area needed to meet the agricultural and electricity production of the system [40]. Agrivoltaic systems can increase overall land productivity by 35–73%, thus they avoid using land solely for energy production at the expense of agricultural production [41]. According to Lee et al. [42] and Weselek et al. [31], agrivoltaics can increase land productivity by 60–70%, and for Dinesh and Pearce [38], it can increase the economic value of land by more than 30% by minimizing yield losses due to shading effects through appropriate crop selection. According to Trommsdorff et al. [43], land use efficiency varies depending on time and climate. In 2017, the Land Equivalence Ratio (LER) in Germany indicated an increase in land productivity from 56% to 70%, and this value reached 90% during the dry and hot summer of 2018. Abidin et al. [39] reported that applying agrivoltaics to less than 1% of the world’s cultivated land could offset the global energy demand. Although agrivoltaics may reduce the efficiency of electricity generation or agriculture when viewed in isolation, studies have shown that the synergy between the two activities can lead to increased overall efficiency. For example, the combination of two hectares of land (1 ha of crops and 1 ha of solar panels each considered individually) corresponds to 100% of crops and 100% of solar energy. However, the use of agrivoltaics in two hectares of land corresponds to 160% cultivation and 160% energy (i.e., 80% of crop and 80% of energy in only 1 ha of land) [15,16,17]

## III. RESULTS

Water, energy, and agriculture are the bedrock of modern civilization. And while many technologies have advanced these components separately, few have aimed to address all three components at once. It is time to step back and reimagine their relationship.

This new technology promises to improve food production and reduce water use, while also creating energy and additional revenue. Essentially, the solar panels placed on the same land where crops are grown allow growers to harvest the power of the sun twice.

A recent OSU study estimates that converting just 1% of American farmland to agrivoltaics could meet our national renewable energy targets and save water and create a sustainable long-term food system. It will also create new revenue opportunities for family farms which are currently facing increasing economic challenges, with a 23% increase in bankruptcy filings over the past year.

The solar panels also help plants grow more efficiently by needing less water.

How exactly do solar panels help plants use less water?

See, plants have a limit to how much sun they can actually use. It's called the light saturation point. Once reached, any light beyond that point does not increase photosynthesis or help the plant grow, it only increases the plant's water demand. It simply makes the plant sweat, which in turn makes it more thirsty.

Solar panels can be positioned to allow plants just the right amount of sunlight, and then the excess sunlight can be harvested for electricity—and produce more than they would without crops below them.

That's right. Plants help keep the solar panels cool, which makes them more productive. Our studies have shown that panels positioned above plants produce up to 10% more electricity.

Agrioltaics is a symbiotic relationship where both the solar panels and the crops benefit because they help each other perform better.

The electricity can be used to run the farm with electric tractors and equipment, and to power precision ag technology that helps further reduce water usage. Surplus energy can be stored in battery banks or sent to the grid for consumer use.

It's a win-win-win relationship between the three most foundational elements of modern life: food, water, and energy. Conservation agriculture (CA) consists of a set of management practices to minimize soil structure disturbance, conserve soil water, enhance biodiversity, promote cover crops, and optimize crop rotation all while focusing on improved crop yields (Altieri et al., 2005; Hobbs, 2007), CA principles can be applied universally to all agricultural landscapes or land uses with corresponding practices adapted at a local scale. CA principles can be applied to AV as a novel approach (Conservation-AV) to sustain the resilience of renewable energy and food production security. [18,19]

#### IV. CONCLUSION

Conventional agricultural practices in AV systems may include irrigation, soil fertility, weeds management, and pest control. As conventional agricultural management is based on soil tillage as one of its primary operations, there is evidence of potential negative effects of tillage on soil structure under conventional systems (Islam & Reeder, 2014). Research suggest that tillage can lead to soil compaction and reduced permeability, resulting in an increased runoff, soil erosion, and nutrient losses (Gliessman, 2014; Gomiero, 2016; Lal et al., 2007; Montgomery, 2007; Nearing, 2013). Additionally, tillage has been linked to decreased soil organic matter, which can further reduce soil fertility (Feller et al., 2020; Hassink, 1995; Huggins & Reganold, 2008; Six et al., 2000; West et al., 2002). Due to the harmful effect of tillage, no-till practices are increasingly implemented in agricultural fields (Islam & Reeder, 2014). The effects of tillage under AV systems are unknown. The integration of CAMP (conservation agriculture management practices) into AV presents a promising avenue for addressing the pressing global challenges of climate change, food security, and sustainable land management. The combination of solar PV and food production on the same land through AV offers a unique opportunity to enhance energy and food security while minimizing land-use conflicts. However, the success of AV as a climate mitigation strategy hinges on the adoption of well-characterized CAMP strategies. While challenges and uncertainties remain, the potential benefits of CAMP in AV systems are substantial. These practices, including zero tillage, cover crops, crop rotation, and intercropping, have shown the potential to increase carbon storage, improve soil health, reduce GHG emissions, enhance biodiversity, and optimize resource use. Moreover, they hold promise for improving economic returns at both the individual and societal levels. Yet, the path to implementing CAMP in AV is not without obstacles. Economic considerations, particularly the divergence between social benefits and individual farm-level attractiveness, present challenges to widespread adoption. However, the societal benefits of reduced emissions, enhanced food security, and improved environmental quality could serve as a foundation for incentive programs and policy support. While research and data on CAMP in AV systems are still emerging, the need for further investigation is evident. The integration of these practices paves not only the way for a more resilient and sustainable future but also underscores the importance of policymakers, farmers, researchers, and other stakeholders in realizing the full potential of AV with CAMP. [20]

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