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Review

Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production

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SUMMARY

Harnessing solar energy to renewably produce electricity can contribute to climate mitigation while meeting current energy demands. However, utility-scale photovoltaics are land intensive and can compete with food production. Agrivoltaics, which combines both energy and food production, has the potential to reduce competition for land. However, its benefits remain uncertain. Here, we review the literature to assess how agrivoltaics can provide synergistic benefits across the food-energy-water nexus relative to photovoltaic or agricultural systems in isolation. Overall, agrivoltaics has the potential to enhance the sustainability of agricultural land and the resilience of our food and energy systems while helping meet energy and food demands. However, there are obstacles to be surmounted. Interdisciplinary collaborative research actions to gain a holistic and mechanistic understanding of the ecological, environmental, and socio-economic consequences of agrivoltaics, and to realize how new innovations can unravel the potential of this emerging strategy, are urgently needed.

INTRODUCTION

Meeting rising energy demand in the face of climate change necessitates the widespread scale down of fossil fuel consumption and the efficient optimization of our land and water resources. These goals need to be met while securing food sustainably. Unfortunately, progress on these key elements has been limited. Water and greenhouse gas (GHG) footprints from food and energy sectors are now larger than they have been in recent decades.[1–3] Meanwhile, cropland is expected to continue to expand at a global scale led by rates of crop improvement that are insufficient to meet food demands forecasted by 2050.[4,5] A more integrative approach is critical for the development of sustainable strategies at the nexus of food, energy, and water systems.

Agricultural production—largely for food consumption—takes up to 92% of the global water consumption.[1] Food systems include both crops and grazing lands and occupy over a third of Earth's surface.[6,7] These systems are currently deemed highly vulnerable to climate change, and risk for significant productivity losses for critical commodities is expected to increase up to 19% by the end of the century.[8,9] Modern society builds on an already unsustainable water footprint. Since the 1950s,

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irrigated agriculture has expanded globally by 174%.[10] Globally, four billion people already live under severe water scarcity during at least part of the year, and the necessary intensification of irrigation in currently rainfed regions as the impacts of climate change escalate will further constrain our water supply.[1,11]

The energy industry must reduce fossil fuel combustion while minimizing the use of our freshwater resources. Renewable energy developments have been proposed as key strategic solutions for climate mitigation but some technologies including bioenergy production and high-efficiency thermoelectric power generation rely on high water consumption rates. With a small water footprint, solar energy could supply 30%–50% of global electricity needs with the potential to offset fossil carbon (C) emissions and help meet 2050 climate targets.[12,13] However, conventional, utility-scale solar energy deployment also poses big challenges, as it competes for otherwise natural and agricultural land and may lead to unintended negative outcomes.[14–16] First, the widespread adoption of solar energy may decrease soil organic C (SOC) stocks as vegetation is removed and soil is conditioned for the deployment of solar infrastructure.[17] Second, solar PV deployment could enhance GHG emissions associated with changes in land use, which together with local increases in air temperatures, a process called photovoltaic (PV) heat island effect, could partly offset the climate mitigation potential of this renewable energy source.[18,19] Third, clearing land for solar infrastructure leads to biodiversity losses in otherwise highly diverse grazing lands[20] and nearby managed and natural ecosystems.[21] Finally, although solar is more resilient to climate change than other renewable technologies, warming is expected to reduce the efficiency of solar energy generation by 12% by 2050.[22]

Agrivoltaics (AV), a novel strategy that combines solar PV panels in agricultural land, can reduce the competition for land resources and, with smart decision-making, minimize or even avoid the unintended negative consequences of conventional solar energy deployment. The adoption of AV could also provide synergistic benefits across technological, ecological, environmental, and economic boundaries while enhancing the climate resilience of our energy and food systems. Here, we summarize the state of knowledge and discuss key gaps regarding the potential of AV to sustainably enhance the food-energy-water nexus relative to PV or conventional agriculture systems. We explore this through the lens of the impact of AV on land productivity, GHG emission and C sequestration, physical climate feedbacks, water use, and biodiversity. Furthermore, we analyze the potential impact that technological AV advances, smart land management and plant selection can have to enhance ecological and environmental benefits and resilience of these systems and examine the economic profitability of AV adoption and its potential social acceptance. We find the following: (1) AV can enhance land productivity (by up to 60%) through synergistic increases in energy, plant, and animal production, but a mechanistic understanding of how PV technologies and plant selection affect both food and energy productivity across a wide range of environments—with diverse climate, soil conditions, and management—is lacking. (2) AV can mitigate the PV heat island effect and increase water savings. (3) AV can enhance SOC and biodiversity, but more research is needed to better understand the influence of AV on these key ecosystem metrics and impacts on GHG emissions and biophysical processes, and to represent AV in models for accurate assessments of climatic feedbacks. (4) AV deployment is more costly, but improved productivity, and environmental, and ecological benefits as well as diversified income could increase economic returns above those of PV; however, a framework for evaluating the economics of AV as well as studies on social perception are needed. (5) AV could increase the resilience of our food and energy

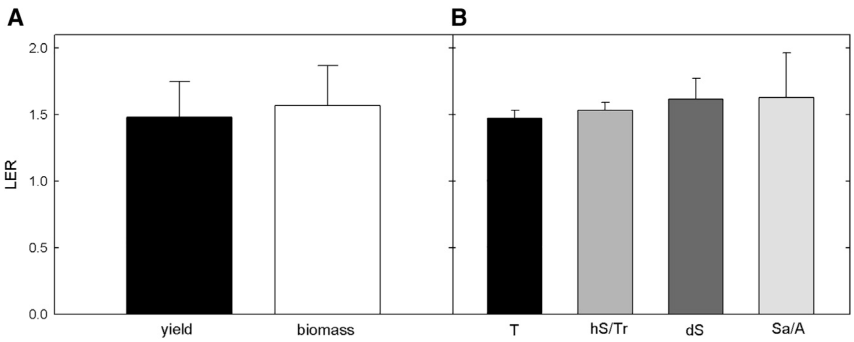

Figure 1. Impact of agrivoltaics (AV) on land equivalent ratio (LER) in agricultural land and within climate category

The LER ratio measures the combined output (yield or biomass production of the crop and electric power production of the PV [photovoltaic] panels; A) per acre relative to a PV system or monoculture or grassland alone. Climate categories (B) considered were temperate (T), tropical and humid sub-tropical (hS/Tr), dry sub-tropical (dS), and semi-arid and arid (Sa/A), and LER values represent the combined yield production of the crop and electric power production of the PV. The AV literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 25 for yield, n = 7 for biomass; Table S1). If LER > 1, the AV system is more effective than the monoculture alone and PV arrays alone for the same land area. Error bars represent uncertainty in reported observations. No significant differences were found for yield LER between climate categories (ANOVA, $p > 0.05$). Due to the paucity of LER data between AV design categories and between plants with diverse photosynthetic pathways (Table S1), we were not able to show how AV design and C3, C4 vs. CAM plants affect yield LER.

systems to climate change (droughts and warming). (6) Strategic management and technological and bioengineering innovations can enhance the benefits of AV compared with PV or agricultural systems alone. We conclude by discussing the challenges and opportunities of AV deployment with the practical aim of understanding which research activities should be prioritized to enhance energy and food production from AV systems while providing climate security.

POTENTIAL TO ENHANCE LAND USE EFFICIENCY BUT UNCERTAIN BENEFITS ACROSS A WIDE RANGE OF ENVIRONMENTS

Evaluating the synergies and trade-offs in achieving maximum PV electrical output and plant productivity is a key research area for AV development. The net impact of AV systems on the efficiency of land use or land productivity can be quantified by the land equivalent ratio[23] (LER) that combines energy and yield production and is defined as follows:

$$LER = \left(\frac{P_{crop\ AV}}{P_{monocrop}}\right) + \left(\frac{Y_{electricity\ AV}}{Y_{electricity\ PV}}\right) \qquad \text{(Equation 1)}$$

where P is plant productivity (i.e., plant yields or biomass) and Y is energy productivity. Plant yield refers to the measurement of the amount of agricultural (food) production harvested per unit of land area, while plant biomass refers to the amount of aboveground plant material per unit of land area. If LER > 1, the AV system is more efficient in terms of productivity than the crop monoculture alone and PV arrays alone for the same land area.

A systematic literature search revealed that AV consistently increased LER (Figure 1A). Yield LER increased to 1.5 $\pm$ 0.3 and plant biomass LER increased to 1.6 $\pm$ 0.3 in AV relative to conventional system (Figure 1A; n = 25 for yield; n = 7 for biomass). The magnitude of these increases varied by plant species and AV

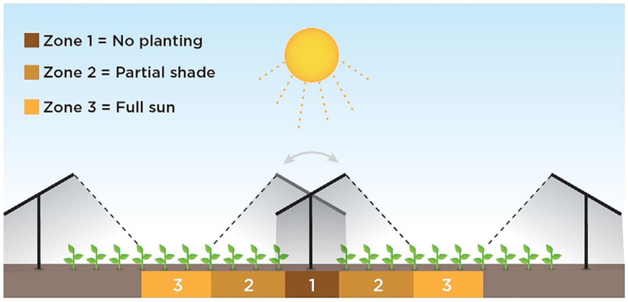

Figure 2. Sun and shading zones in an AV system
In every PV and AV system, there are three "zones": the area directly under a PV panel that receives full shade most or all day and cannot be reasonably farmed with equipment because of the proximity to panel structures (zone 1; no planting), areas that will receive morning (west) or afternoon (east) partial shade (zone 2; partial shade), and areas in between PV rows that will receive full sunlight most of the day, experiencing shade only very early or late in the day (zone 3; full sun).

configuration (Table S1). AV systems with low-density PV arrangements provided in general a smaller LER than high-density arrangements but increased crop and forage yields, underpinning the importance of solar infrastructure design and configuration on plant yields (Table S1).

Yield LER in AV systems varied by climate and most studies concentrated in temperate regions in limited crops and forage plants (Figure 1B; Table S1). Yield LER was slightly higher in AV systems under drier (i.e., arid and semi-arid climates and dry sub-tropical climates) than wetter climates (i.e., wet sub-tropical and temperate climates) (Figure 1B). The slightly higher LER in AV systems under drier climates is likely explained by a combination of factors. These factors include the potential of AV to attenuate the effect of climate extremes such as droughts on plant yields[24] with frequency of these climate events exacerbated in drier climates, as well as prolonged hours of solar irradiance in drier versus wetter climates.[25] Overall, most studies focused on agricultural land in temperate regions with few studies investigating AV systems in tropical, sub-tropical, semi-arid, or arid regions; and, only a few studies reported LER in AV systems consisting of plants with C4 or Crassulacean acid metabolism (CAM) photosynthetic metabolism (Table S1). Taken together, this suggests that knowledge about the impact of AV on LER across a wide range of environments, crop types, and forage species is currently limited.

The physiology of plants, their canopy structure, and environmental variables including light and water availability determine the maximum plant productivity of an AV system. Plants for agricultural purposes are grown in full sun to maximize productivity; however, some species (i.e., shade tolerant) are known to grow better under partial shade. For example, coffee is often grown under shade trees or artificial shade to obtain heavier berries and improve the flavor. Studies investigating how artificial or natural shade (i.e., shading cloths, agroforestry, and intercropping) affect yields are numerous.[26] However, how plants respond to growth under shade netting or in canopy understories may not be indicative of performance in AV systems.[26] In an AV system, shade and sun conditions depend on PV configuration, and they are dynamic and spatially heterogeneous (Figure 2). Traditional PV panels (i.e., opaque and neutral semi-transparent fixed or solar tracking solar panels) generally cause a reduction in solar radiation from 12% to 40%, depending on the density and orientation of the PV modules.[27,28] Therefore, studies focusing on how PV configuration (i.e., design, height, and density of PV panels) and plant selection are necessary to understand under which circumstances AV enhances LER and yields compared with conventional systems.

Although shading might be expected to lower productivity, and does in certain agricultural settings,[29] mounting evidence indicates that AV has the potential to enhance crop and forage yields compared with agricultural systems alone (Table S1). A recent field study[30] showed that yields of shade-intolerant C4 corn grown under low-density PV panels were increased, while those under high density of PV panels were moderately lower. Similarly, yields of several varieties of lettuce, a C3 specialty crop, were found to be equal or even higher when shading was moderate.[31] Alfalfa plants grown under mobile panels showed an average increase of 10% of their biomass compared with conventional system.[32] In semi-arid systems, yields of tomato and chiltepin peppers grown under AV were 2.9- and 2-fold higher compared with traditional agricultural system, respectively, while productivity of jalapeño peppers was similar between systems.[33]

Progress in the field of AV is unveiling mechanisms underlying beneficial yield responses. AV shading can reduce photoinhibition,[34] alleviating decreases in photosynthesis associated with excess light (typically above 33%–50% of full sunlight) that can damage the photosynthetic machinery and reduce light use efficiency (LUE). Furthermore, AV shading can decrease evapotranspiration (ET), enhancing water use efficiency (WUE) and thereby productivity. Recent studies show that the combined effect of shade and lower air turbulence under PV panels not only reduced water evaporation but also increased the leaf boundary layer, trapping air humidity, and reducing vapor pressure (VPD) and water loss through transpiration per unit of C fixed during photosynthesis.[33,35] Therefore, the LUE and WUE of an AV system will largely define plant productivity and yields. Although environmental constraints may prevent an AV system from reaching its maximum productivity, plants growing in AV systems will likely be more resilient to forecasted climate change, particularly to continued or severe drought events, compared with plants grown in conventional agricultural systems.

In AV systems that are more productive than conventional agricultural systems, whether AV deployment will enhance yields either by reduced photoinhibition, increased plant WUE or a combination of both remains uncertain. From a merely physiological standpoint, under equal light, temperature, and water availability conditions, it is likely that the different LUE and WUE of C3 and C4 plants could favor the resilience of one photosynthetic type over the other in AV systems. The CO_2-concentrating mechanism of C4 plants drastically reduces energy losses associated with photorespiration, increasing their LUE and conferring greater resilience at high radiation to C4 relative to C3 species.[36] This CO_2-concentrating mechanism along with the higher CO_2 affinity of PEP carboxylase (a key enzyme of the C4 photosynthetic machinery) improves the efficiency of C fixation in C4 plants with limited stomatal conductance, increasing their WUE particularly under water stress.[37,38] Therefore, we hypothesize that AV systems may yield greater benefits in C3 than C4 dominated AV systems as lower excess light and ET may compensate for the limited resilience of C3 plants to light and water stress. Future studies gaining mechanistic understanding of how C3 and C4 plants across a range of climate and soil conditions respond to AV are necessary to determine the maximum productivity these systems can achieve.

Although the inherent LUE and WUE characteristics of plants will largely define their productivity and yields, improving these parameters, either by bioengineering or management advances, are promising strategies to optimize productivity in AV systems.[39] Progress in the field of bioengineering and management is auspicious in the context of AV systems. Expanding the photosynthetic light spectrum, reducing chlorophyll content of leaves and modifying canopy architecture have shown success in improving LUE.[39,40] Decreasing stomatal density, increasing sensitivity of stomata to water-stress-related hormones, and expanding the root system also have the potential to enhance leaf WUE.[41,42] Certain management practices could further enhance WUE of plants in AV systems. For instance, crop residue management, intercropping, or cover cropping can decrease soil water evaporation, enhancing WUE.[38]

In addition to environmental conditions and intrinsic plant physiology, changes in temperature under panels could also affect plant yields. Studies investigating this topic are scarce.[26,43,44] Many studies have shown that AV can yield warmer nighttime air or crop temperatures, cooler air or crop daytime temperatures, and overall cooler soils, whereas few others demonstrated that air temperature was warmer or remained unaffected in AV systems compared with a conventional system. How AV deployment affects temperature and whether this could lead to positive impacts on productivity remains an active area of research because of the important role of temperature in regulating yields and nutritional quality, and the tight connection between temperature and soil water availability.[45]

Although most crops and forage species are C3 and C4 plants, the theoretical photosynthetic efficiency of CAM plants can be similar or even higher than C4 plants in water scarce conditions typical of arid regions.[46] This is because leaf WUE of CAM plants is higher than that C3 and C4 plants as they open their stomata nocturnally when temperatures are cooler significantly reducing water losses through transpiration.[38] In fact, the greater WUE of some CAM species, including *Agave* and *Opuntia*, results in theoretical yield potentials that are 147% greater than those observed in C4 species under arid conditions.[46] Regardless of these yield potentials, particularly in arid and semi-arid climates, the benefits of AV on LER of plants with CAM metabolism are yet to be explored and detailed understanding of underlying mechanisms is still lacking (Table S1).

In addition to enhancing plant productivity, AV systems can enhance animal production in grazing lands, which provide some of the greatest extensions for the potential deployment of AV.[47] A major challenge for the livestock industry is to minimize animal production losses caused by heat stress.[48] Furthermore, adaptation of livestock to changes in climate is imperative as days under heat stress conditions are predicted to increase by 9-fold by the end of the century, which could cause global livestock industry losses between U.S. $15 and $40 billion annually.[49] Empirical research on AV grazing lands, albeit scarce, showed that AV can benefit domestic livestock production as PV panels provide shade for animals, decreasing livestock water consumption and heat stress.[50–52] Furthermore, there is also evidence that shading can reduce heat stress in livestock confined in feedlots[53] and thus the targeted deployment of elevated PV panels[54] could reduce radiant heat loads and improve animal welfare in this agricultural setting as well.

UNDERSTANDING IMPACT ON C SEQUESTRATION, GHG EMISSIONS, ENERGY AND WATER FLUXES, AND EFFECT ON REGIONAL CLIMATE

The impact of AV on C sequestration is highly uncertain.[55,56] Recent studies suggest that prior land use is a key predictor of the impact of AV on C sequestration with transitions from native to AV systems having a detrimental impact on C sequestration,

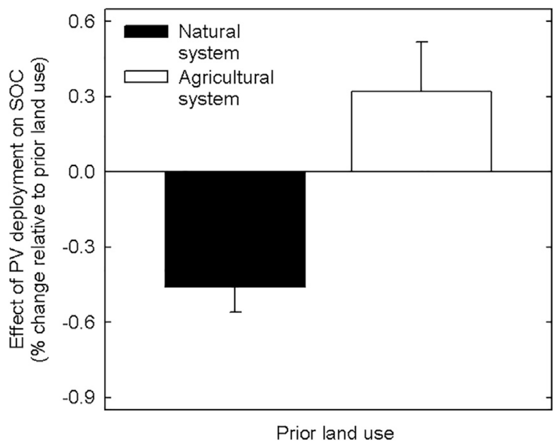

Figure 3. Impact of photovoltaics management on soil organic carbon (SOC) of ecosystems
Prior land use is defined as either natural system or agricultural system. The literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 6; Table S2). The percentage change refers to the relative increase or decrease of SOC in PV system versus prior land use. Error bars represent uncertainty in reported observations.

and transitions from agricultural systems with low SOC content to AV systems promoting SOC accrual (Figure 3; Table S2). The potential benefits of AV on C sequestration will not solely be influenced by prior land use but also by vegetation and soil type and the microenvironment developed beneath the PV structures. Compared with PV system alone, in which vegetation is often removed or kept low,[57] and relative to an agricultural system alone, increases in plant productivity (Table S1) in optimized AV systems could lead to enhanced C sequestration. While the suppressing effect of shade on plant root:shoot ratio could decrease SOC accrual rates in AV systems, this response is reportedly modest or negligible,[58,59] and we do not anticipate changes in C allocation to be a strong determinant of C sequestration in AV systems. In addition to C inputs, AV could increase soil nitrogen (N) availability potentially promoting plant and microbial growth. The N content in leaves, stems, and roots of spinach and basil in AV systems was 10%–68% higher,[60] indicating potential enhanced soil N content relative to traditional agriculture. Lower C/N ratios of plant-derived organic inputs favor microbial C use efficiency and SOC stabilization, which could accelerate the soil C accrual rate of AV systems.[61,62]

Changes in microenvironment and vegetation following AV deployment could also affect non-CO_2 GHG emissions. In the absence of studies focusing on this topic, we hypothesize that enhanced C and N inputs along with increased soil wetness under PV panels will likely stimulate N_2O and CH_4 production relative to PV and conventional agricultural systems.[57] Compared with agricultural systems alone, this impact, however, could be partly or fully offset by temperature constraints of the microbial activity with shade-induced soil cooling under PV structures.[33,35,60,63] Nonetheless, and despite a potential stimulation of non-CO_2 GHG emissions, large GHG savings from solar-displaced fossil emissions reduces the climate cost of AV well below that of conventional agriculture[64] and provides an opportunity for climate mitigation through either reduced or negative GHG emission rates. Solar energy technology innovations (Table 1) as well as the combination of AV with emerging land use management practices that reduce non-CO_2 GHG emissions could minimize potential limitations of the overall climate benefit of AV compared with PV alone. These innovative practices include soil amendments such as biochar or the application of pulverized silicate-rich rocks (i.e., enhanced weathering), two negative emission

Table 1. Technological advances in AV systems across diverse environments and advantages and productivity benefits (land equivalent ratio) over conventional systems

Technological advance	System type	Climate (Country)	Advantage over conventional PV system	Productivity benefit	Reference
Modifying spatial PV density and height					
	Wheat, Poplars and cereals	Temperate (France)	Increasing row spacing vs height of the PV module	Increase in LER between 1.35 and 1.73	Dupraz, Dupraz et al.[23,65]
Use of sun-tracking systems					
	Row and horticultural crops[a]	Temperate (France, Germany, Pakistan, Italy) Semi-arid (California, Texas)	Reducing the spatial heterogeneity of sunlight and soil wetness caused by the solar array structure, enhancing solar radiation over the canopy and the harvestable sunlight by PV panels with customized tracking schemes.	Increase in LER up to 2 due to both enhanced biomass and electricity productivity	Amaducci, Imran, Riaz, Perna, Valle et al.[27,66–69]
Improving solar panel construction					
Using bifacial vertical/horizontal PV array	Lettuce, turnip, corn	Temperate (Pakistan, France)	Reducing light and soil wetness heterogeneity caused by solar structure Reducing soiling loss Enhancing ecosystem albedo Easing the mobility of large-scale combine-harvesters and other farming equipment	Increase in LER up to 2.3	Riaz, Imran, Riaz, Zohdi et al.[67,70–72]
Using checkered pattern PV panels with transparent areas between solar cells	NA	NA	Enhancing light availability for plants under the panels	Potential to enhance LER	[73]
Using checkered pattern PV panels with sun-tracking, bifacial vertical PV arrays and dual-axis tracking scheme	NA	NA	Further enhancing light and soil moisture availability for plant growth due to combining bifacial checked vertical arrays with transparent areas between solar cells Further enhancing ecosystem albedo and reducing soiling loss Easing the mobility of large-scale combine-harvesters and other farming equipment	Potential to enhance LER	[73]
Novel PV materials optimized for AV applications					
Semitransparent organic solar cell (ST-OSC) filter based greenhouse	Red leaf lettuce		Distinct transmission characteristics over the photosynthetically active radiation (PAR) spectrum (400–700 nm), resulting in similar yield and nutrient content compared to the reference	Potential to enhance LER	[74]
Multi-component bulk heterojunction (BHJ) based semitransparent organic PVs (STOPVs)	Mung bean sprout		Enhancing plant light absorption enhances plant growth (24.7%) while achieving high energy PV conversion efficiencies (13.08%)	Potential to enhance LER	[75]
IR absorbing organic semiconductor based STOPVs	Mung bean		Utilizing infrared light spectrum for electricity generation and the penetrated visible light for photosynthesis, enhancing the average visible transmittance over 30% and the PV power conversion efficiency by 10.02%	Potential to enhance LER	[76]
Organic π-conjugated molecules based STOPVs	Algae	NA	Directing PAR while enabling PV panels to absorb long-wavelength radiation for electricity generation, and improving the photosynthesis efficiency of algae as well as total power generation	Potential to enhance LER	[77]

(*Continued on next page*)

Table 1. *Continued*

Technological advance	System type	Climate (Country)	Advantage over conventional PV system	Productivity benefit	Reference
Tinted semi-transparent PVs (STPVs)	Basil, spinach	Temperate (Italy)	Enhancing overall plant and power generation productivity and achieving a ~2.5% and ~35% financial gross gain	Increase in LER between 1.025 and 1.35	[60]
Triphenylamine dye-sensitized solar cells (DSSCs)			Delivering almost 85% external quantum efficiency in the blue and green light spectral region and 55% transparency in the red light spectrum, potentially enhancing plant growth by ~35%	Potential to enhance LER	[78]
Metal/oxide multilayers transparent electrode (PSCs)			Improving the light transmittance by 60% in the wavelength range of 540–760 nm versus regular PVs	Potential to enhance LER	[79]
Perylene red dye-based luminescent solar concentrators (LSC)	Tomato, banana, mango, lemon, fig fruits		Better fruit quality	Potential to enhance LER	El-Bashir, Chen et al.[80,81]
a-Si/a-Ge solar cells	Algae		Enhancing algae growth at a lab scale with flexible spectral (transmission and absorption) tuning based on a Fabry-Perot-type metal/oxide/metal/oxide (MOMO) reflector	Potential to enhance LER	[82]
Multilayer polymer film (MPF) based spectral-splitting concentrator AV	Potato, lettuce		Achieving a maximum PV power conversion efficiency of 9.9%, an increase in plant biomass of 13% and a decrease in plant heat dissipation of ~50%	Potential to enhance LER	[83]
Dichroic materials or the application of commercially available polymeric dichroic mirrors to coat PV panels	NA	NA	Directing photosynthetically active radiation (PAR) while enabling PV panels to absorb long-wavelength (infrared) radiation for electricity generation potentially enhancing both plant and power generation	Potential to enhance LER	Gençer, Ulavi, Charalambous, Ilic, Imenes, Yu et al.,[84–89]

Conventional systems are defined here as fixed-tilt panel array and opaque PV systems. Agroecosystem type, climate, and country where the technology was deployed/tested are also shown. Land equivalent ratio (LER) is defined as the combined output of yield, biomass production, and electric power production per acre relative to conventional solar PV systems or agricultural land. Spatial PV array density refers to the ratio between the row spacing and height of a PV module. Panel orientation is generally classified into two categories, namely east/west (E/W) and north/south (N/S) facing, where the tilt angle of the panel is used as a detailed indictor. A traditional fixed-tilt panel array is generally oriented in the N/S direction, while a bifacial vertical PV array is oriented E/W. The literature search was conducted using Science Citation Index Expanded (SCIE) database from Clarivate Web of Science (WoS). The search resulted in 160 studies, of which 50 matched the selection criteria, especially for PV technology development and optimization in AV research area. Markers: N/A under ecosystem type/climate or country refers to either modeling or experimental studies in which LER values were not provided (i.e., only electricity or plant productivity was provided) or studies in which the PV technology was not tested in an AV setting.

[a]Includes lettuce, turnip, corn, tomato, cucumber, celery, cabbage, potato as crop types.

technologies, with proven capacity to decrease N_2O and CH_4 fluxes.[56] In this context, future research will be crucial to help elucidate under which circumstances AV is most beneficial in terms of climate mitigation potential.

The impact of AV on water and near-surface energy fluxes will be tied to background climate. Areas receiving greater solar radiation are subject to higher rates of water loss[90] whereas areas with less vegetation will experience more sensible heat (i.e., heat absorption with no change in phase; Figure 4). Although we tend to think about these geographical patterns at regional scales, these spatial differences can also exist within a single ecosystem. For example, within a forest ecosystem, the shade of a tree's canopy leads to reduced incoming energy to the soil surface, yielding lower evaporation rates in that understory space. In fact, this is a driving principle for the practice of agroforestry.[91] Similarly, within an AV system, both evaporation and plant transpiration can be reduced in areas that receive even partial shade from overhead solar PV panels.[33,35,92] Importantly, both processes also absorb heat energy from the air in the transition from a liquid to a gas (water vapor), a process called latent heat flux.[93] When vegetation is removed for some forms of PV installation, there is an unintentional shift in the "energy balance" of that ecosystem from one of a mosaic of sensible and latent heat fluxes toward greater sensible heat flux, which therefore raises ambient temperatures within a PV array. Growing concern over this "PV heat island effect" identified within solar arrays where vegetation has been cleared for construction[18,94,95] has led to some reluctance to the implementation of solar technologies at scale. Nearly half of proposed energy projects have been delayed or abandoned because of similar local concerns, representing a significant barrier to PV adoption. However, re-introduction of this cooling feature of water loss from plants and soils has been intentionally used within urban systems to reduce ambient air temperatures and, similarly, could be a primary driver to mitigate the heat island effect in AV systems.

Beyond reassuring public concern over increasing local air temperatures, AV could enhance the climate resilience of our energy systems as AV increases the energy production efficiency of PV panels. The solar cell temperature is a function of the local microclimate on the basis of principles of thermal energy conservation.[47] Previous work has shown that four primary microclimatic parameters—insolation, air temperature, wind speed, and relative humidity—play a key role in regulating the thermal balance of the PV array, thus affecting the PV energy conversion efficiency.[47] In the thermal energy balance, solar insolation acts as the radiative heat source, air temperature and wind speed determine the potential convective heat transfer performance of the PV panel surface, and relative humidity (i.e., the amount of water vapor) regulates the long wave radiation budget. Field tests conducted recently[33] showed that the temperature of AV panels can be $\sim 8.9 \pm 0.2^\circ C$ cooler compared with PV arrays in conventional solar farms, displaying a 3% increase in power generation during the growing months (May to July) in Tucson, Arizona. Others have demonstrated that crops cultivated beneath PV arrays can reduce the local air temperature due to plant transpiration, thereby reducing panel temperatures by up to $10^\circ C$ and increasing the solar PV efficiency by $\sim$0.5%–1%.[30,96–102] Although this benefit has been repeatedly documented in AV systems, a critical gap in AV research is quantifying this potential impact on increased energy production (and economic returns) across a broader climatic gradient and understory crop selection.

Although AV enhances LER and has other potential environmental benefits, a rigorous assessment of the impacts of AV on biogeochemical and biophysical processes at regional scale and feedback on climate is still lacking. Given the large spatial heterogeneity in climatic, edaphic, and management conditions,

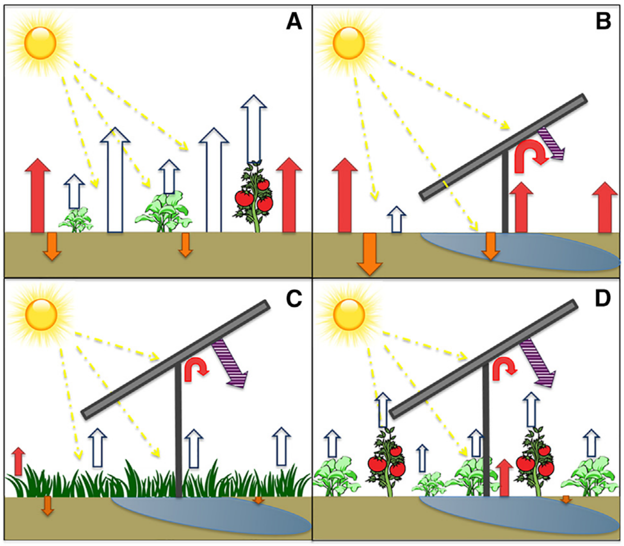

Figure 4. Energy fluxes in AV and conventional systems

Latent heat (evapotranspiration; empty arrows), sensible heat (red arrows), soil heat storage (orange arrows), and energy transferred through energy production (purple broken arrows) in an agricultural system alone (A), solar PV system alone (B), and an AV cropland (C) and grassland (D).

food-energy-water outcomes of AV will likely vary with local conditions. This implies that we urgently need a modeling framework that (1) encompasses knowledge of biogeochemical and biophysical mechanisms underlying ecosystem responses and the impacts of AV on the food-energy-water nexus and (2) incorporates various sources of geospatial information of climate, soil, crop, and management factors for robust regional assessments. Furthermore, the deployment of PV panels at scale can induce significant feedback to regional weather and climate as recently demonstrated using model simulations focusing on ground-mounted PV panels deployed in the desert area.[103,104] Compared with PV panels deployed in the desert, AV systems may trigger a much more complex feedback to the climate system through different pathways, such as enhanced surface roughness, reduced albedo, and changes in ET and in C uptake.[33,35,105,106] This suggests that a full appraisal of the potential impacts of AV on gas, water, and energy exchanges between the land surface and the atmospheric boundary layer is critical to anticipate feedbacks on regional weather and climate, and hence to the evaluation of the suitability of scaling up AV systems in a changing environment. Within this context, the spatial variability in the responses of agricultural land to AV adoption along with the potential impacts of AV on regional weather and climate could be assessed using land surface models coupled with regional climate models such as the Community Land Model (CLM) and Community Earth System Model (CESM)[107,108] once AV is properly represented in those models. To ensure the robustness of regional assessments, ground observations at local AV sites, ideally covering different environmental and management conditions, should be used to parameterize, calibrate, and validate these models before upscaling insights from site-level observations to a regional scale.

TOWARD OPTIMIZING AV DESIGN TO MAXIMIZE THE POTENTIAL BENEFITS

In addition to plant selection, the design of PV technologies plays a prominent role in mitigating the trade-offs between solar energy production and plant productivity to maximize LER (Table 1). Optimizing LER can be accomplished through multiple AV designs. AV designs that modify spatial PV array density and panel orientation can optimize LER as shown in wheat, poplar, and cereals AV systems, to name just a few; in these studies, a 2-fold increase in spatial PV array density resulted in an enhanced LER between 1.35 and 1.75, although in general increasing PV density tends to decrease plant productivity[23,65] (Table 1). The irradiance transmission and shading pattern can also be regulated by optimizing solar panel design parameters to maximize LER. These technologies include sun-tracking schemes, bifacial PVs, and checkered patterns (Table 1) that often decrease shading patterns in AV systems and enhance power generation without diminishing agricultural output (Table 1). Furthermore, these systems often enhance the spatial homogeneity of soil wetness under the panels resulting in increases in yields and in decreases in soiling loss compared with conventional systems (Table 1).

Single-axis sun-tracking systems and East/West tracking configurations can almost double LER compared with fixed-tilt systems,[66] and solar tracking schemes can be customized according to crop requirements to provide enough solar radiation for optimal plant growth while ensuring more sunlight is harvested by the PV arrays.[67] Bifacial PVs, particularly those with vertical schemes, can also enhance plant yields under the panels, particularly of shade-tolerant crops as they increase light homogeneity, decrease soil erosion and facilitate harvest and seeding farming operations (Table 1). Combining PV technologies can also result in interesting benefits in the context of AV systems. For instance, checkered PV patterns with transparent areas between solar cells combined with a dual tracking scheme decreased the impact of shading on plant growth compared with conventional PV systems.[73] Research on the application of these technologies is emerging and the benefits associated are starting to be realized. However, many unknowns remain including which technologies will deliver more benefits depending on ecosystem type across geographical gradients with distinct radiation and soil wetness patterns.

Until recently, PVs have been implemented mainly using opaque and neutral semi-transparent solar panels,[109–111] which have low capacity for regulating solar radiation reaching the plant canopy.[110,112,113] Given that plants generally use a relatively small and specific portion of the solar spectrum, called photosynthetic active radiation (PAR; wavelengths between 400 and 700 nm),[114] PV materials allowing PAR wavelength to fully reach the plant canopy could substantially enhance plant productivity in AV systems while maintaining or even enhancing energy production as these panels absorb the rest of the incoming radiation that is not readily used by plant photosynthesis.[115–117] In this context, the integration of spectrally selective PV technologies into agricultural settings becomes of great interest.[70,118] These innovative technologies include semi-transparent PVs (STOPVs),[76,117,119–122] dye-sensitized solar cells (DSSCs),[78,113,123–125] perovskite cells (PSCs),[79,126–128] luminescent solar concentrators (LSCs),[80,129] amorphous silicon/amorphous germanium (a-Si/a-Ge) solar cells,[60,82,130–135] and spectral-splitting concentrator AV (SCAPV)[83,136–139] (Table 1).

Although most studies have focused on understanding how new spectrally selective PV technologies affect both plant and power generation at the lab or greenhouse scales,[74,76–80,82] recent investigations in the context of AV farms are emerging.[60,83] This is the case of SCAPVs, which can be implemented using low-cost components and are capable of transmitting photons within the PAR wavelength for photosynthesis while reflecting the remaining spectrum for electricity generation. A recent study showed that this technology increased plant biomass by 13% of lettuce and potato plants by enhancing their photosynthetic efficiency and photoprotection. The remaining light spectrum, that also included photons usually dissipated as heat, were reflected for electricity generation, resulting in PV power conversion efficiency of 9.9%, which is close to simulated ideal efficiency.[83]

Applying these spectrally selective PV technologies in AV settings arguably holds potential, but these technologies also present some challenges. Challenges include the low average transmittance of solar cells and inflexible spectral tuning capabilities of the PVs. Once these technological challenges are overcome, combined research on spectrally selective PV panels with an array of crop and forage species in diverse environments and on power generation, economic profitability, and scalability are granted given the tremendous potential of these technologies to optimize LER in AV systems.

Despite the need for water to clean solar panels in PV systems, solar energy has lower water footprint than other renewable energy technologies (i.e., hydroelectric, bioenergy). Dust accumulation on PV panels represents electricity losses anywhere from 5% to 35% at an annual scale.[140] In an AV system, rainfall as well as water used for cleaning the panels can be used on site for plant irrigation. Furthermore, new technological advances consisting of using nighttime radiative cooling from solar panels, through emissivity engineering, are being developed and used for water harvesting.[141] In addition, anti-soiling transparent coatings present another technological opportunity to limit dust accumulation as well as frost, snow, and ice management.[142,143] These water harvesting and anti-fouling approaches represent an important strategy to improve rainfed AV systems and increase plant and energy productivity sustainably.

POTENTIAL TO IMPROVE BIODIVERSITY

The large-scale deployment of solar farms, particularly if they are developed on native ecosystems, often reduces biodiversity.[20,144] However, strategic deployment of PV systems can potentially lead to improved biodiversity. In arid and semi-arid systems, damage during construction and the ongoing operation of conventional solar systems can reduce the cover of native plants and promote the proliferation of invasive species.[145] However, strategic management in arid regions can enhance biodiversity, and shading by PV panels can increase floral abundance and delay flowering time, benefiting late season pollinators.[146,147]

In more temperate, rainfed agricultural areas, intensive agriculture focuses on monocultures or simple rotations of two species with greatly diminished biodiversity. On more marginal areas in these regions, restoration of native vegetation or planting pollinator friendly species under PV panels can greatly enhance pollination services. In a modeling exercise, a 3-fold increase in pollinator supply in an AV grassland as well as 65% and 19% increases in SOC and water retention, respectively, relative to conventional grassland was predicted.[148] The beneficial effect of AV systems with native vegetation can extend well beyond the actual facility, and pollinator-dependent crop species (e.g., soybean, alfalfa, cotton, almonds, citrus) at considerable distance from solar installations would enjoy enhanced pollination services.[149] Although it is becoming more evident that smart decision making in AV systems in arid and temperate degraded rainfed agricultural systems could enhance biodiversity and pollination services, the potential of AV to enhance these services in other climates and land uses is largely unknown and requires further research.[150,151]

UNDERSTANDING VARIATIONS IN PROFITABILITY AND DETERMINANTS OF WILLINGNESS TO ADOPT AV TECHNOLOGY

The profitability of AVs is expected to play an important role in farmers' decisions to adopt them. Conceptually, the profitability of AV will depend on several factors related to both agricultural and energy production. On the agricultural side, profitability is primarily driven by returns from agricultural production, including both livestock and crops. On the solar energy side, the key elements include the capital (e.g., elevated panels, farming equipment, labor) and operational (e.g., fuel, fertilizer, tilling) costs of the system, the amount of solar electricity production, the price of electricity and revenue generated, as well as any renewable energy credits, investment tax credits, and other subsidies for solar energy development.[152]

AV systems involve a significant upfront capital cost and a long-term investment horizon integrating production risks. As AV systems require a long-term commitment of land, the opportunity cost of the land—potential gain from other alternatives when one alternative is chosen—is an important consideration. Selecting the appropriate discount rate (i.e., rate of interest applied to future cash flows of an investment to calculate its present value) is also an important factor in the assessment of anticipated revenue from AV, given that benefits occur in the future. A high discount rate leads to a smaller net present value (NPV), which reflects the net benefits of a solar system over its lifetime, and to a higher levelized cost of electricity (LCOE) production, which reflects the net cost of electricity generation over the lifetime of a solar system.

LER, which increases to >1 on average in AV systems compared with agricultural or PV systems alone (Figure 1), is an important measure of the total land productivity of these systems. However, other economic factors, such as the relative prices of crops and electricity, may drive declines in the profitability of AV despite greater LER (Figure 1). Thus, LER alone is not sufficient to induce AV adoption by farmers. Compared with PV or conventional agriculture alone, the adoption of AV will depend on its impact on the net returns to land, combining returns from both agricultural production and the sale of electricity.[152] In addition, farmers also care about the riskiness of the returns, and while electricity prices remain relatively constant, agricultural prices have the potential to fluctuate. Therefore, AV can reduce the riskiness of the returns to land by diversifying the sources of income and may appeal to risk-averse farmers.[92,153]

Few studies have examined the profitability—costs and benefits—of AV systems compared with agriculture or solar-only options (Table 2; n = 15). Overall, although these studies demonstrate clear benefits for some crops under solar panels in some locations, generalizable findings on the conditions under which AV is more profitable with major food and forage crops across diverse locations are still lacking. Furthermore, results showed that benefit and cost estimates varied widely and were highly uncertain (Table 2; n = 15).

The large variation and uncertainty in profitability estimates in the field of AV (Table 2) is explained by several factors. First, most analyses were small-scale site-specific case studies focused on a few selected crops in a single location. Second, studies used simple techno-economic analysis and were focused on estimating payback periods instead of the NPV (i.e., net benefits of a solar system over its lifetime) to determine adoption.[28,161,165] From an economic standpoint, comparing the payback time of AV system versus conventional agriculture or PV alone, rather than using NPV, may not be sufficient. The payback period is an insufficient calculation that reveals when AV systems breakeven, but it does not reflect the profits over the life of the investment. Finally, several studies deployed models based on assumptions yet to be validated by data from actual AV farms without consideration of the spatial variability in AV benefits, costs, and risks. Future studies focusing on

Table 2. Studies investigating the economics of AV systems

Country (region)	System type	Methods	Impact on crop yield	AV profits vs. crops only option	AV profits vs. solar-only option	Carbon reduction impacts	Reference
Italy (northern Italy)	maize and sorghum production	life cycle assessment	+	+	–	+	Agostini et al.[153]
Germany (Heggelbach)	vegetables and cereal farms	simulation techno-economics	– (40.3% for cereals)	+	–	x	Feuerbacher et al.[152]
Spain (Seville)	irrigated crops (potato, tomatoes)	simulation techno-economics	–	+	–	x	Moreda et al.[154]
Colombia	cassava production	techno-economic analysis	+	+	–	+	Guerrero Hernández et al.[155]
Niger	cash crops (tomato, melon, lettuce)	surveys techno-economics.	– (−20%)	+	+	+ (4.01 T/year)	Neupane Bhandari et al.[156]
U.S.	corn production	techno-economic analysis	x	+	+	+	Proctor et al.[157]
China	vegetables (lettuce, broccoli, etc.)	field experiments	+/−5% (lettuce), +23% (artichoke)	+ (5.14%)	x	x	Schindele et al.[158]
Germany (Heggelbach)	potato and wheat production	field trials techno-economics	–	+/–	+/–	x	Schindele et al.[159]
India (north Gujarati State)	vegetables (okra, ginger, gourd, etc.).	field trials benefit-cost analysis	+	+ (98%)	+	+ (4,000 T/year)	Patel et al.[99]
India (Maharashtra)	grape production farms	simulation model	0	+ (93.6%)	+	x	Malu et al.[160]
China (Shandong Province)	agricultural greenhouses (vegetables)	surveys return on investment	+	+ (9.76%–13.03%)	+	+ (68.77–211.60 T/year)	Li et al.[161]
Western India	tomato production	field experiment LCOE	+	+ (30%–35%)	+	x	Roy et al.[162]
U.S. (Michigan)	lettuce production	simulation model	−10% (half density) −32% (full density)	+ (82.5%)	+	x	Dinesh et al.[163]
Spain (southeastern)	greenhouse tomatoes	field experiment.	0 (9.8% shading)	+ (€639/year)	x	x	Ureña-Sánchez et al.[164]

Studies have used the levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and payback period analyses. The literature search was conducted using the Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science, Scopus, Springer Link, Taylor & Francis, and Google Scholar. The search yielded 100 studies, of which 15 matched the selection criteria. Symbol "+" indicates increase, while "−" indicates decrease in yield profits or C impacts, X denotes information not available for a given parameter.

comprehensive economic analyses for AV systems across various environments and ecosystems, as well as scale, are critical to understand under which circumstances AV deployment is more profitable.[28] The economic benefits that farmers obtain from AV deployment are diverse. AV systems can reduce land-use competition while increasing incomes in rural areas.[148,160,166] They can generate a diversified income stream from agricultural and electricity sales as "joint products," which can be greater than income from one commodity alone.[92] The combined crop and energy output from an AV system with a half-density panel distribution increased land productivity by up to 70% in alfalfa, cotton, and barley compared with crops alone.[28] Similarly, a recent study found a more than 30% increase in profits for farms deploying AV systems for lettuce production in Kansas City compared with crops alone.[167] Also, a 30% increase in profits was reported in lettuce AV systems compared with farms with conventional agriculture only.[163]

To date, most analyses focused on estimating revenue and costs in producing crop outputs and electricity at a single location, without consideration of the heterogeneity in the costs, benefits, and risks, and diversification benefits of AVs and the role and design of policy incentives to induce adoption (Table 2). For PV systems, the level of profits usually increases with the density of the PV panels. However, several studies indicate that the combined income obtained from plant yields and electricity generation can exceed that of a single land use option, particularly when shade-tolerant plant species are considered.[99,160,163] This highlights the trade-offs between crop yield and electricity generation, as the benefits of AV originate primarily from electricity generation, and suggests the important role that thoughtful plant selection and technological advances have to increase both energy and plant yields, and hence economic benefits in the field of AV.

Current cost estimates for AV vary widely and are generally higher than conventional PV systems (Table 2).[26,92,168] This can be attributed to cost-increasing factors (such as additional equipment and labor) outweighing cost-saving factors such as land management costs. Another key factor bearing on AV's feasibility is the cost of potentially elevating the PV panels. A recent study[169] showed that the structural costs of AVs were higher than those of a conventional PV system. AV costs depend on the technology used and the type of land and crops where PV panels are deployed. In this context, an economic study in AV systems in Germany[159] concluded that while the operational costs were similar to those of PV, the overall capital costs for installation were 30% higher for AV systems. Another study[162] examining the initial investment by separating the total costs into engineering procurement cost and land costs in India found that the capital cost was approximately 98% of the total cost (or U.S. $1.3 million per megawatt), and the average land cost was less than 2% of the total cost (U.S. $5,000 per acre), whereas the annual operation cost was 0.12% of the capital cost.[162] Taken together, although these results imply substantial upfront capital costs, the payback period was reduced by two years relative to the PV alone option when the revenue from agricultural production was added to that from electricity generation. Another fascinating insight comes from calculating the LCOE values (i.e., the net cost of electricity generation over the lifetime of a solar system). The LCOE for AV farms was 38% higher than that of a traditional, ground-mounted solar PV installation in Germany, with the respective values being U.S. $0.0992/kWh and U.S. $0.0721/kWh, respectively.[159]

Although other factors including the economic and environmental risks associated with AV adoption will affect its deployment, few studies have examined this topic. Economic risks are likely lower for solar energy than other energy sources because solar power is more resilient to sharp declines in energy production than oil and gas. Solar leases are long-term contracts, typically lasting 25 years, with fixed rental payments instead of royalties, reducing landowners' economic risk.[170] Compared with solar leases, royalties come with unpredictable costs of on-farm oil and gas developments that are deducted from the landowners' payments.[171] Fuel prices are also a major source of revenue variability.[172] Furthermore, oil and gas leases can present serious environmental risks for farmers. They can increase traffic and noise pollution and demand for local water resources, potentially resulting in water and soil contamination and reduced land productivity.[173] Although some risk is associated with long-term agreements, the fixed payment structure and predictable life cycle costs for solar can help farmers by providing a steady income source.[174]

AV can offer farmers environmental benefits and lower economic risks than oil and gas leases while still providing a reliable additional source of income. AV systems can help reduce risk in the case of low crop prices by adding revenue from electricity production.[92] The income from solar leasing often exceeds the income generated by crop yields.[175] In the context of the wider economy, AV can serve as a risk mitigation measure against market shocks while helping meet the energy demands of several farm operations.[153,174] Several studies indicate that AV systems could reduce on-farm water use per unit of output, increase energy cost savings (through solar self-consumption) and help offset GHG emissions by generating clean energy relative to solar energy alone.[161,176] AV could bring significant C emission reductions through environmentally friendly electricity generation. A recent study showed that C emissions were reduced by 12% on AV systems compared with traditional agriculture.[177] Reductions in C emissions were calculated on the basis of a fixed emission factor by assuming PV electricity replaced grid electricity (Table 2). At the ecosystem scale, AV systems can also provide ecosystem services such as improvement in soil moisture, C sequestration, and pollination services relative to PV systems alone, but this has not been accounted for in the costs and benefits of AV in the literature.[149]

Extensive social acceptability studies are also needed to address public perception issues.[176,178,179] Although AV delivers clear benefits, farmers might be reluctant to adopt the technology because of the perceived constraints on future farming activities and the risk for a yield loss. Several studies argue that economic consideration of a PV/AV energy system, interpreted as a favorable cost-benefit calculation made by the landowner, was the strongest predictor of adoption.[64,178–180] In this context, public policy mechanisms aimed at recovering the economic investment in renewable energies[159,181] as well as mechanisms that help AV farms reduce risk and secure electricity sales for long-term economic gain, such as the power purchase agreement price adopted by the Agua Caliente solar project, the largest PV power plant in Arizona, could help drive the adoption of AV.[28]

OUTLOOK AND FUTURE DIRECTIONS

Meeting rising energy and food demands will only be possible with strategies that maximize productivity along with a coordinated effort to reduce the use of fossil fuels. This goal needs to be achieved while enhancing the ecological and environmental benefits from agricultural systems, optimizing the use of land and water resources and ensuring profitability and social acceptance. Compared with either conventional agricultural system or PV alone, the colocation of PV panels within agricultural systems has the potential to enhance plant yields and animal and energy production per unit of land while enhancing the resilience of our food and energy systems.

With strategic management, and thoughtful selection of plant species and PV design and technologies, AV can yield other ecological benefits including enhancing biodiversity and promoting water savings compared with conventional systems.

The use of AV deployment for renewable energy has the potential to help mitigate climate change as we shift away from fossil combustion. AV deployment could enhance C sequestration compared with conventional systems and minimize the heat island effect associated with PV deployment while increasing the efficiency of energy generation. However, AV could also enhance the emission of non-CO_2 GHG, decreasing the overall potential of AV to mitigate climate change compared with PV alone. In this context, combining AV with management strategies that decrease non-CO_2 emissions (e.g., biochar and enhanced weathering) will be promising solutions to enhance AV overall potential for climate change mitigation. Compared with conventional agriculture, AV provides an opportunity for climate mitigation given the large GHG savings from solar-displaced fossil emissions.

Although AV has the potential to enhance benefits compared with either PV or agricultural systems alone, there are critical gaps in knowledge. A deep mechanistic understanding of the impacts of AV on energy, plant and animal production, and biogeochemical and biophysical processes as well as biodiversity across a wide range of environments, soil types, and plant species is urgently needed. Accurate representation of AV in models and life cycle analysis is also needed for robust spatial extrapolations and to assess the overall climate mitigation potential of this emerging technology. Strategic management as well as technological and bioengineering innovations will play a major role in enhancing benefits from AV systems, and improved knowledge of how they affect LER as well as additional benefits could dramatically accelerate its adoption. Improved information about economic profitability of AV deployment across geographically diverse agricultural systems to determine profitability for landowners and farmers as well as social acceptance will also be crucial to ensure farmer adoptability. Furthermore, a better understanding of landowners, farmers, and other key stakeholders' constraints to the wider adoption of AV is required. We urge the scientific community to work across disciplines for a holistic assessment of the sustainability of AV to fully realize the potential of this promising strategy.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2023.101518.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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Cell Reports Physical Science, Volume *4*

Supplemental information

Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production

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Table S1. Impact of agrivoltaics (AV) on Land Equivalent Ratio (LER) and crop/forage relative yield in agricultural land under different agricultural settings (i.e. plant photosynthetic type, ecosystem and AV design). The LER ratio measures the combined output (yield or biomass production of the crop and electric power production of the PV – photovoltaic – panels) per acre relative to a PV system or monoculture or grassland alone. LER is calculated as follows (Dupraz et al. 2011): LER = ($Y_{\text{crop AV}}/Y_{\text{monocrop}} + Y_{\text{electricity AV}}/Y_{\text{electricty PV}}$), where $Y_{\text{crop AV}}$ is the total dry matter or grain yield of an AV system, Y_{monocrop} is yield of a crop-alone field, $Y_{\text{electricity AV}}$ and $Y_{\text{electricty PV}}$ is the electrical production obtained under an AV system and a PV plant. If LER > 1, the AV system is more effective than the crop monoculture alone and PV arrays alone for the same land area. Typically, mixed cropping systems have LERs between 1.0 and 1.3, while agroforestry systems have LERs between 1.1 and 1.5. The literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science. The search criteria included searching for LER in AV systems with no restriction on ecosystem type in the AV system, publication date and climate region. The search resulted in 48 studies, of which 10 matched the selection criteria. Letters under climate refer to climate region (temperate, T; tropical, Tr; humid sub-tropical, hS, dry sub-tropical:dS; semi-arid, Sa; and, arid, A). *Forage relative yield was calculated considering differences in forage biomass and nitrogen content between the AV and the conventional system. †LER yield was calculated from yield observations and assuming 1% annual increase in electricity generation as reported in Barron-Gafford et al. (2019).

Ecosystem	Climate	Country	AV design	Plant metabolism	LER yield	LER biomass	Crop/Forage relative yield	Reference
Alfalfa	T	France	Hybrid mobile/stilt PV panels	C3	-	1.53	1.10	(Edouard et al., 2023)
Grazed grassland	T	USA	PV panels oriented east-west, and tilted south at an 18° angle	C3	2.0	1.74	1.15*	(Andrew et al. 2021)
Lettuce	hS	China	Even-lighting PV system	C3	1.64	-		(Zheng et al. 2021)
Lettuce, cabbage, tomato, mint, okra	Sa	Niger	PV panels with shading	C3	1.13	-	-	(Neupane Bhandari et al. 2021)
Lettuce, cabbage,	Sa	Niger	PV panel configured to minimize shading	C3	1.33	-	-	(Neupane Bhandari et al. 2021)

tomato, mint, okra								
Sugar beetroot, lettuce	T	Russia	PV configuration with 3.2m spacing between PV arrays and 4m distance above the crop field	C3	1.7	-	-	(Kostik et al. 2020)
Sugar beetroot, lettuce	T	Russia	PV configuration with 6.4m spacing between PV arrays and 4m distance above the crop field	C3	1.45	-	-	(Kostik et al. 2020)
Chiltein pepper	Sa	USA	3.3-m raised solar PV panel array, facing south	C3	2.97†	-	2.87	(Barron-Gafford et al. 2019)
Jalapeño pepper	Sa	USA	3.3-m raised solar PV panel array, facing south	C3	0.85†	-	0.75	(Barron-Gafford et al. 2019)
Tomato	Sa	USA	3.3-m raised solar PV panel array, facing south	C3	2.13†	-	2.03	(Barron-Gafford et al. 2019)
Rainfed maize	hS	Japan	Sun-tracking PV units Low panel density	C4	1.57	-	1.06	(Sekiyama and Nagashima 2019)
Rainfed maize	hS	Japan	Stilt PV units High panel density	C4	1.39	-	0.96	(Sekiyama and Nagashima 2019)
Rainfed maize	dS	Italy	Sun-tracking PV units High panel density	C4	1.31	1.28	1.02	(Amaducci et al. 2018)
Rainfed maize	dS	Italy	Stilt PV units High panel density	C4	1.31	1.23	1.08	(Amaducci et al. 2018)
Rainfed maize	dS	Italy	Sun-tracking PV units Low panel density	C4	2.05	2.02	1.04	(Amaducci et al. 2018)

Rainfed maize	dS	Italy	Stilt PV units Low panel density	C4	1.79	1.74	1.08	(Amaducci et al. 2018)
Lettuce	T	France	Sun-tracking PV units	C3	1.31	-	0.80	(Elamri et al. 2018)
Lettuce	T	France	Controlled tracking PV units	C3	1.08	-	0.77	(Elamri et al. 2018)
Lettuce	T	France	Stilt PV units Low panel density	C3	1.23	-	0.72	(Elamri et al. 2018)
Lettuce var. Kiribati	T	France	Stilt PV units Low panel density	C3	1.32	-	0.78	(Valle et al. 2017)
Lettuce var. Kiribati	T	France	Sun-tracking PV units	C3	1.59	-	0.81	(Valle et al. 2017)
Lettuce var. Kiribati	T	France	Controlled tracking PV units	C3	1.25	-	0.79	(Valle et al. 2017)
Lettuce var. Madelona	T	France	Stilt PV units Low panel density	C3	1.21	-	0.66	(Valle et al. 2017)
Lettuce var. Madelona	T	France	Sun-tracking PV units	C3	1.55	-	0.76	(Valle et al. 2017)
Lettuce var. Madelona	T	France	Controlled tracking PV units	C3	1.23	-	0.79	(Valle et al. 2017)
Rape, rye, oats	T	Germany	South-east and south-west PV panels orientation to increase solar radiation received by the crops	C3	1.67	-	-	(Beck et al. 2012)
Potatoes, salad, spinach	T	Germany	South-east and south-west PV panels orientation to increase	C3	1.85	-	-	(Beck et al. 2012)

			solar radiation received by the crops					
Wheat	T	France	Stilt PV units High panel density	C3	1.35	1.32	0.92	(Dupraz et al. 2011)
Wheat	T	France	Stilt PV units Low panel density	C3	1.73	1.64	0.81	(Dupraz et al. 2011)

Table S2. Impact of Photovoltaics management on Soil Organic Carbon (SOC) of ecosystems with prior land use being either native and semi-native systems or agricultural ecosystems. The literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 6). The search criteria included searching for Soil Organic Carbon (SOC) and Net Ecosystem CO_2 Exchange or Productivity (NEE, NEP) and solar park, photovoltaic system or agrivoltaic system with no restriction on publication date and climate region. The search resulted in 13 studies, of which 3 matched the selection criteria for a total of 6 SOC observations. Letters under climate refer to climate region ('T', temperate). We did not find publications reporting NEE or NEP. The % change refers to the relative increase or decrease of SOC in PV system versus prior land use.

Land transition from native/agricultural system							
Climate region	Country	Prior land use	Soil type	SOC		% Change	Source
				Control	PV system		
T	USA	Native grassland	Paleosols	3.1 %	2.1 %	-0.34	(Choi et al. 2020)
T	France	Native shrubland	Fine calcareous silty clay soil	4.1 %	1.6 %	-0.61	(Lambert et al. 2021)
T	France	Native shrubland and abandoned vineyard (5 years after abandonment)	Fine calcareous silty clay soil	2.8 %	1.6 %	-0.42	(Lambert et al. 2021)
T	France	abandoned vineyard (5 years after abandonment)	Fine calcareous silty clay soil	1.5 %	1.6 %	0.1	(Lambert et al. 2021)
T	USA	Row crop	Mollisol	129.3 Mg C ha^{-1}	78.3 Mg C ha^{-1}	0.65	(Walston et al. 2021)
T	USA	Row crop	Mollisol	95.7 Mg C ha^{-1}	78.3 Mg C ha^{-1}	0.22	(Walston et al. 2021)

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