Agrivoltaics

Merging Solar Energy and Agricultural Production

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DOVETAIL PARTNERS

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EXECUTIVE SUMMARY

As the U.S. continues efforts to transform its energy to renewable sources, solar power is growing in importance. The Department of Energy estimates that solar could provide 40% of U.S. electricity by 2035. However, accomplishing this goal could require as much as 5.7 million acres of land (and another 4.6 million acres by 2050),[1] setting up a potential conflict with agricultural production. A new approach to solar development may provide a solution. Dubbed *agrivoltaics* or simply *AV*, the concept is to combine solar energy and food production. While colocation of energy and agriculture tends to result in lower production of both agricultural crops and solar energy than when land is dedicated solely to production of one or the other, combined production offers the potential for optimization of land use, reducing competition for land, and greater income and market diversity for landowners.

The concept of agrivoltaics (AV) is currently in an early development stage. Within the U.S. as of early 2024 AV systems ranged in size from 660MW to 0.01MW.[2] About 70% were demonstration projects with capacities of 5MW or less.[3] The majority involve installation of solar panels on land used for livestock grazing or land dedicated to native grasses and/or pollinator habitat. However, research has shown possibilities for much wider application of agrivoltaics including in conjunction with vegetable production, other crops that don't require irrigation or use of large machinery, and aquaculture. It also appears that agrivoltaics could help to alleviate some of the negative impacts of a warming climate by offering protection to crops and animals, conserving water, and improving solar panel performance.

This report examines the potential of agrivoltaics, research findings, early experiences, and challenges to widespread development. Throughout the report the terms solar panel and photovoltaic (PV) panel are used interchangeably.

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1 For reference, 5 million acres is about the size of the state of New Jersey.
2 To put 5MW into perspective, as a national average 1MW is sufficient to power 172 homes, a number that ranges from 100 to 260 across various U.S. regions and local electricity demand (Solar Energy Industries Association 2024).
3 Maguire (2024)

Agrivoltaics – Prospects and Constraints

Agrivoltaics was introduced in 1980 by the German-based Fraunhofer Institute (27). Germany has been a pioneer in the development of solar energy and renewable energy in general (18). In 1980 the country also had (and continues to have) a high population density, with 8.8 times more inhabitants per square mile than the U.S. Scientists there recognized the concurrent challenges posed by growing demand for food and energy – both in Germany and globally, increasing importance of solar energy development, and the possibility of reducing competition for land by combining agricultural and energy production.

The potential for competition for land between agricultural and alternative energy interests has been examined in the U.S. context with findings that suggest this to be a relatively trivial issue here. For instance, the U.S. Department of Energy, Solar Futures Study (28) estimated that domestic solar capacity of 1,600 GW_{ac} would be needed by 2050 to achieve a zero-carbon grid capable of serving current and anticipated electrical demand. About twice that capacity would be needed to decarbonize the entire U.S. energy system. But as challenging as that may be, the estimated land area required for solar deployment by 2050 (~10.3 million acres) amounts to only about 1% of the total area now used for agricultural purposes in the U.S. But while land area does not pose a constraint to solar development overall in the U.S., competition for land between agricultural and solar interests can be an issue near major population centers and in arid regions viewed as ideal for intensive solar development.. Further, there are other apparent advantages of agrivoltaics that warrant a closer look.

Regarding the advantages of agrivoltaics, ongoing research has led to identification of a myriad of potential benefits, particularly in highly populated and/or high temperature environments:

- Optimization of land use
- Less competition for land
- Reduction of soil temperature
    - benefit to crops
    - reduction of water demand, soil moisture loss, and stress on water table
    - increased efficiency of solar arrays in high heat environments
- Reduction of heat stress in livestock
- Opportunity for expansion of pollinator habitat
- Diversification of farm income sources and possibly greater farm income

While there is some reason for optimism regarding the potential for significant adoption of agrivoltaics, the benefits of this emerging strategy remain uncertain (6). In virtually all configurations of agrivoltaics, agricultural output is lower than if land is dedicated to agriculture alone. The same is true of solar energy production.

Constraints to agriculture from co-location of crops and solar collectors include:

- Shading that can significantly reduce yields of many types of crops
- Incompatibility with large-scale agricultural equipment
- High costs of site preparation and other aspects of solar array installation
- The need for locating large scale solar installations near transmission lines (4).

LOOKING DEEPER

Source: Tobi Kellner/Wikimedia Commons

Source: USDA

Source: PV Magazine

AV Design and Location Fundamentals

Agricultural production and power generation are typically greatest when land is solely dedicated to one use or the other. However, combining the two functions on the same site increases the efficiency of land use by optimizing the distribution of sunlight between agricultural production and power generation.

There is considerable potential for AV, and solar energy production in general, across the U.S. However, due to location limitations, utility-scale solar energy generation facilities will not be evenly distributed across the landscape. One requirement is that generation sites be located near transmission corridors or substations (4).

Most of the future development of AV (between now and mid-century) will likely be in the form of projects developed specifically for AV as this offers the greatest opportunity for achieving optimal results. There is also interest in conversion of existing solar arrays into AV operations (11).

One type of AV design involves moderate to wide spacing between rows of PV panels to facilitate crop or forage growth in the open spaces. Another approach involves installation of solar panels on elevated platforms 6 feet or more above ground allowing for livestock grazing and, if needed, of sufficient height to accommodate the operation of mechanized equipment beneath the structure. Both types can incorporate use of light filtering solar panels that provide partial shade and further apportion sunlight between agricultural and energy production. Another AV design strategy makes use of vertically installed solar panels. Vertical installation is a lower cost strategy that largely eliminates issues with machinery movement, cleaning of panels, and other concerns. The downside of vertical installation is that energy production is significantly lower than when panels are more strategically oriented to maximize solar exposure (19).

Impacts of AV on Agricultural Production

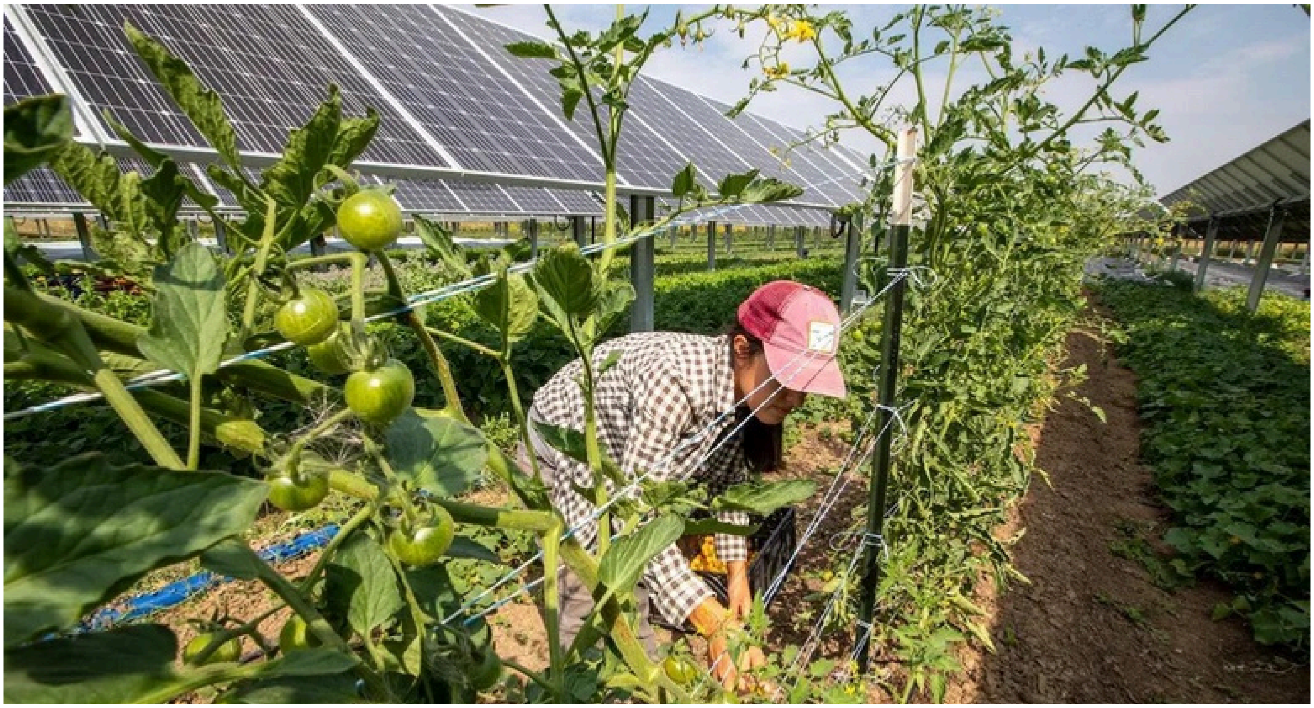
Shading and Crop Yields

Almost all plants are characterized as either C3 or C4 (see sidebar) as defined by the efficiency with which they process carbon dioxide in the process of photosynthesis. About 95% of plants in the world are of the C3 type, including most agricultural crops (including wheat, oats, rice, cotton, sunflower), many vegetables, and most trees. These plants have limited resilience to heat and water stress. C4 plants, that include corn, sugarcane, and sorghum, limit photorespiration in the growth process, and have greater light and water use efficiency and tolerance to extreme heat conditions (6, 19).

Standard PV panels can substantially reduce the amount of solar radiation received by crops, with the resulting shading serving to reduce both light intensity and duration and moisture loss from soils. These more shaded conditions are most likely to benefit C3 plants. However, studies have generally found that shading reduces plant productivity (6), and often substantially. Several studies reported yield reductions of 3% to 62% for more than 80% of tested crops (19). In corn, a C4 crop, 50% shading from PV panels was found to result in reduction of virtually every measure of corn growth and grain yield. Nonetheless, experiments with spatial array and orientation of solar panels have shown substantial increases in land use efficiency with wheat, cereal, and other types of crops (6).

Definition of C3 & C4:
Photosynthesis is the process that plants use to turn light, carbon dioxide, and water into sugars that fuel plant growth. The majority of plant species use C3 photosynthesis, in which the first carbon compound produced contains three carbon atoms. Some plants have evolved another form of photosynthesis to help reduce energy and water losses in hot, dry environments. In C4 photosynthesis, a four-carbon compound is produced, and a unique leaf anatomy structure allows plants to retain water and continue fixing carbon. Examples of C3 plants include cowpea, cassava, soybean, and rice. Examples of C4 plants include maize, sugarcane, and sorghum.

Source:https://ripe.illinois.edu/blog/difference-between-C3-and-C4-plants



Source: NREL

Shading is obviously a significant issue affecting the viability of AV. There may, however, be a solution. Further research into the shading issue has revealed that reducing exposure to 33%–50% of full sunlight through partial shading can increase light use efficiency, water use efficiency (WUE), and crop yields (6). An interesting avenue of AV research is focused on the possibility of filtering the spectra of light that reaches PV panels. This work is based on the knowledge that plants utilize only about half of the solar radiation that they are exposed to. Photosynthesis is driven by the longer, less energy intensive wavelengths of solar radiation that constitute the visible light spectrum (400 – 700 nm). By designing PV panels such that only this portion of solar radiation can penetrate the panels and reach the plants below (while the rest of the shorter wavelength energy intensive spectra is absorbed at the panel surface) could substantially enhance plant growth while having little or no impact on the energy conversion capacity of PV arrays (6, 14, 19).

The production of opaque PV panels with light filtering capacity is already a reality. However, creating high efficiency PV surfaces that reliably filter light by specific wavelengths at price points similar to conventional PV panels is a challenge. Opacity is a significant issue in that even modest reduction of exposure to the critical wavelengths can reduce plant growth and yields (22). Work in this area is ongoing.

A few types of food and forage plants benefit from partial shading in the form of greater yields even when traditional PV panels make up a solar array. Benefit is most likely to be realized in hotter, drier climates. Beneficial results of AV have been found with shade-tolerant C3 corn, alfalfa, several varieties of lettuce, other vegetables and fruits (6), and strawberries (36). One study of vegetable production in a semi-arid region found yields of tomatoes to be 2.9 times greater under an AV system compared to traditional agriculture. Yields of several kinds of peppers ranged from 2 times greater to no difference in a PV system, again compared to traditional practice.

Soil and Moisture

Shading from PV panels commonly reduces soil temperature under the solar array while at the same time reducing water evaporation. A study in the UK (19) found that shading from solar panels markedly lowered average soil temperatures; summer soil temps were 3.5°C to 7.6°C (6.3-13.7°F) cooler, and on average 5.2°C (9.4°F) cooler, below a solar array than soil with no panel coverage. Other studies have documented more modest, but consistently cooler ground temperatures beneath solar arrays than in areas without coverage (19). The cooling effect of shading yields more than the direct benefit of blocking some of the incoming radiation. Shading of vegetation also reduces evaporation and plant transpiration which conserves plant energy and water (6).

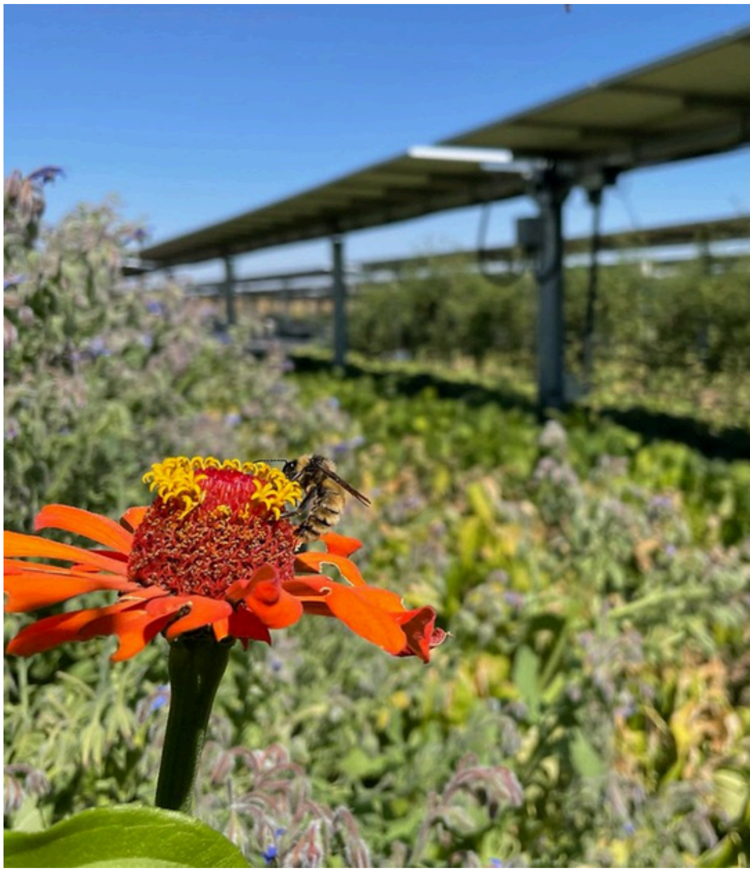
Modeling of water consumption under AV systems in the arid Southwestern U.S. showed the extent of water evaporation losses to be closely correlated with PV array coverage and corresponding shading; findings were consistent for all locations examined (35). Reduction of evaporation losses of up to 30% have been documented under solar arrays (21). In an Oregon study (1) it was found that areas under PV panels were far more (328% more) water efficient in comparison to uncovered areas. The result was that the volume of late season biomass under the panels was 90% greater. Another study, in which modeling was done of different land use scenarios under solar arrays in the U.S. Midwest, found increases in sediment and water retention of over 95% and 19%, respectively on AV sites compared to pre-solar agricultural land use (34).

Observations stemming from several studies are cautionary regarding potential water savings. One study found that shading-related water savings came at the expense of crop yields, with a near 1:1 ratio of water savings to yield loss in some cases (35). Based on observations involving standard and not opaque PV panels, the results of this study suggest clear limits to shading benefits. Another study (21) found that solar panels, that are virtually always angled relative to the ground, can redistribute rainfall so as to create alternating wet and dry zones that can be disadvantageous to plant growth and yield.

Because water runoff patterns are influenced by solar energy site configuration and ground coverage (or lack of coverage), sometimes with unfavorable results, regulations in many localities require installation of runoff capture systems and drainable basins similar to those required for parking lots and other impervious surfaces (7). In view of the documented water absorption and erosion protection provided by vegetated sites, AV developers may avoid costly investment in water runoff mitigation measures.

Pollinator Promotion

Pollinators are critical to over a third of global food production (31) with 87 of the principal food crops globally dependent upon pollinators for seed production (4). Consequently, the significant drop in pollinator numbers in recent years is of great concern (4, 16). Habitat loss has been identified as a major factor in pollinator decline (4). This is an area in which AV may be particularly valuable. An earlier cited study, wherein modeling was done of different land use scenarios under solar arrays in the U.S. Midwest, indicated a 3-fold increase in pollinator numbers in an AV grassland (34).



Source: www.energy.gov

The greatest benefit to insect pollinated crops comes when pollinator habitat is located within one-half mile of the crop (32). Recognizing the importance of proximity of pollinator habitat to crops, a joint study of Argonne National Laboratory and the National Renewable Energy Laboratory (34) examined existing and planned utility-scale solar facilities located in agricultural areas, with a focus on potential benefit from conservation of these solar facilities to pollinator-friendly sites. Using an effective distance of 1.5 km (0.6 miles), the study identified 1,350 square miles (864,000 acres) of agricultural land that could benefit from such conversion, with little impact on solar energy production.

Animal Agriculture and AV

There is considerable potential for application of AV in conjunction with grazing livestock. With heat stress for animals expected to grow as the climate continues to warm, shading provided by elevated PV panels is seen as an important benefit in livestock production. The number of days of extreme heat stress in all major domesticated animal species (cattle, sheep, goats, poultry, and pigs) is expected to increase significantly in this century (6, 24, 30).

Relatively few studies of benefits to animal agriculture with AV have been conducted, though findings to date suggest significant benefit with this form of agriculture. For example, an ISO-compliant life cycle assessment of sheep-based agrivoltaic systems found AV to be twice as land-use efficient as providing sheep and PV services separately. The study also indicated a reduction in global warming potential of 3.9% as compared to conventional PV and sheep grazing separately. Study authors noted that shifting sheep to PV farms in comparison to grazing alone would reduce CO2 equivalent emissions per year from sheep raising equivalent to removal of 117,000 average automobiles from the nation’s highways. Moreover, calculations showed that by shifting the current national 5.2 million domestic sheep to AV systems the U.S. could expand utility scale PV by a factor of four (8). A cautionary finding in an Oregon study (2) was that forage production in fully shaded areas under panels was 38% lower than in open pasture, although the quality of forage production in shaded areas was higher.

Another study (32) concluded that rising ruminants, and particularly sheep, is highly compatible with AV since very little modification of typical solar arrays is needed to accommodate sheep grazing beneath or between the PV panels with the exception that wiring and electrical boxes require extra protection. It was further observed that the grazing activity can reduce costs of ground cover management under the arrays. It was observed that in addition to other advantages provided by PV arrays, their co-location with grazing animals promotes animal welfare by helping to reduce heat stress and provide protection from other forms of extreme weather, both of which are expected to increase with climate change.

Several studies have been conducted of milk and beef production in AV systems vs traditional cattle farming operations. One (13) examined productivity and grazing behavior of heat-stressed Holstein cows in a pasture-based automatic milking system. A subset of the cows studied were bearing young for the first time. Heat stress in the study was defined by a temperature-humidity index ≥68 (where temperature was in ˚C). A linear relationship was found between THI[4] and milk yield, with decreases of approximately 0.18 kg (0.4 pounds) for each THI increment in those cattle bearing young for the first time, and 0.4 kg (0.9 pounds) in the others. Another study, however, found no difference in milk production between cattle grazing in open pasture and those in an AV system, although the open-pastured cattle exhibited signs of stress viewed as likely to adversely impact animal welfare and milk yield (20).

Source: www.agproud.com

A study that did not consider AV, but which modeled potential impacts of heat stress on cattle (24) led to prediction of substantial heat stress loss in the value of both milk and beef production globally by the end of the century, with greatest impacts in the tropics and subtropics. An earlier study by the same team (25) concluded that climate change would seriously challenge the ability to raise livestock by traditional means in the decades ahead. Both findings suggest that AV may play an increasingly important role in animal agriculture in the future. As with sheep, wires and electrical boxes need extra protection. Solar support structures also need to be taller (15).

Aquaculture

One form of animal agriculture for which clearly positive effects of AV have been shown is solar photovoltaic-aquaculture or aquavoltaic ecology. Sometimes referred to simply as aquavoltaics (9), it is the application of AV to fish farming. Raising fish is an energy intensive enterprise, requiring power to drive oxygenation equipment, periodic distribution of fish food, and artificial lighting (9,17). Installation of PV panels above fish tanks or ponds provides shade, cools the water, and reduces surface evaporation rates while also generating power needed for system operation (17).

Application of aquavoltaics to fish farming appears to offer considerable potential for shifting fish farms to off-the-grid operations, with benefits both to operators and society in general (5, 9, 10, 17). Assessment of benefits that could accrue to wide application in the U.S. found that, based on the national average value of solar flux and the aquaculture surface areas in use in 2016, the adoption of aquavoltaics could provide a power output equivalent to 10.3% of total U.S. energy consumption in 2016 (17).

4 In dairy milk production TH1 refers to a type of T helper cell in the cow's immune system that helps fight pathogens, combat infections, and maintain health. A strong TH1 response is beneficial for dairy cows.

AV and Energy

Although solar panel coverage and electricity production is lower in AV systems than in dedicated solar energy installations, AV can boost the efficiency of power production and reduce regulatory requirements. The energy benefits of AV systems over traditional solar energy installations include:

- heat island effects of PV arrays are moderated.
- the likelihood of erosion from stormwater runoff is reduced.
- PV panels are cooled by the presence of understory vegetation, thereby increasing efficiency of power production.[5]

As with any significant investment, careful planning of AV installations is critically important. Among factors to be considered are regulatory requirements, site layout, needs for solar array structure foundations, needed height of PV arrays, selection of solar technology, and the need for periodic PV panel cleaning (7). Investment requirements for AV have been found to vary considerably and to generally be higher than for construction of typical solar farms. One study in Germany found capital costs to be about 30% greater for AV systems than for conventional solar, with operational costs showing a similar increase. Economic assessments of AV assume useful lives of PV panels to be 25-30 years, and those of support structures to be 60 years (6, 33).

Land Use Efficiency

A metric that is used to describe land use efficiency in an AV system is the *Land Equivalent Ratio* or LER. Introduced by a team of German scientists (26). LER is calculated by:

$$\text{LER} = \frac{\text{Yield}_x\ (\text{dual})}{\text{Yield}_x\ (\text{mono})} + \frac{\text{Yield}_y\ (\text{dual})}{\text{Yield}_y\ (\text{mono})} - 8.3\%$$

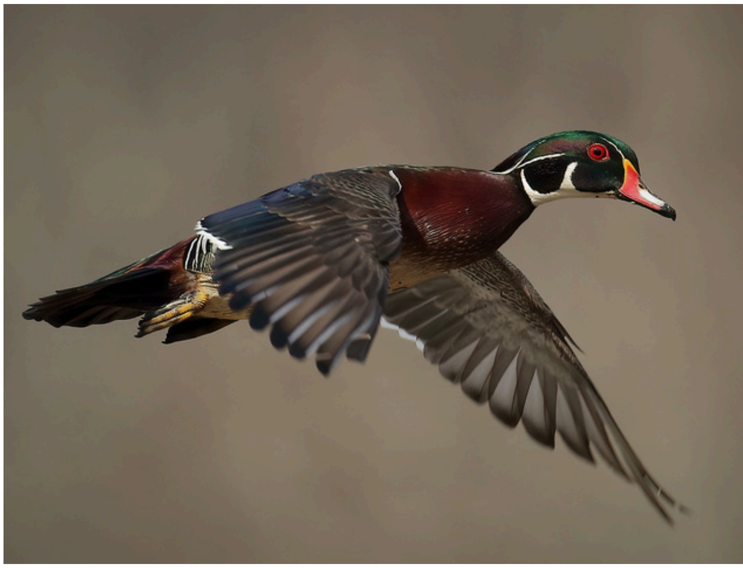
Where Yield_x is crop production and Yield_y is energy production.
The – 8.3% factor accounts for land surface area occupied by the PV support structure.

A comprehensive review of AV studies (19) found reported increases in land use efficiency of 35 to 73%. Modeling of AV in the U.S. Southwest (Arizona, California, and Colorado) found higher LER for all locations and AV configurations considered as compared to conventional systems. Calculated LER values were greater than 1.0 even with low PV panel coverage, indicating benefit from even minimal adoption of AV (35).

No definitive studies of investment returns from AV systems have been published. However, a comprehensive guide to AV systems design, installation, and financing in the German context available online (27).

5 Solar panels lose from 0.1 to 0.5% efficiency with every 1℃ (every 1.8℉) above 25℃ (77℉). Studies have consistently shown the temperature of solar panels in AV installations to be 9-10℃ cooler compared to conventional solar farms (6). In Arizona this translated to a 3% increase in power generation during the growing months (3).

Impacts on Wildlife/Biodiversity



Not considered in the LER metric are factors beyond land productivity. One of these is potential impact to wildlife and biodiversity. Specific concerns include habitat loss, fragmentation, degradation (particularly in areas of known habitat for rare and endangered species), bird collision risks, an associated “lake effect”,[6] and disruption of animal movement patterns. These concerns are associated with solar installations in general and also apply to AV systems.

Risks of habitat loss are seen as especially great in the U.S. desert Southwest. The area is viewed as prime real estate for solar farms but contains vegetation communities and rare plants that are difficult to replace or restore if destroyed or damaged. With regard to bird collision risks, concerns are primarily focused on waterfowl that may either see a large extent of reflective panels as a water body and attempt to dive into it, as well as birds that may be attracted to water and lack the capacity to take off from land. There is also a collision risk when panels are mounted vertically (29).

The risk to disruption of animal movement patterns is for the most part due to the likelihood of concentrated solar development along transmission line corridors. Removal of vegetation over large areas can threaten habitats that animals and insects rely on. The creation of extensive infrastructure is seen as a potential barrier to free movement across extensive solar energy collection sites (23).

Because of these concerns many states now have voluntary best practices guidelines for solar farm siting. Most include wildlife considerations and species-specific information to assist developers in planning and implementation. As reported by the U.S. Department of Energy, some project planners use guidance developed for use in wind energy development in the absence of solar-specific information (29). Also now available is a map developed by The Nature Conservancy to guide renewable energy siting.

6 The "lake effect" is a hypothesis that solar panels can attract birds and other wildlife by mimicking the visual cues of water bodies.

SUMMARY

Agrivoltaics (AV) involves blending solar energy and agricultural production on the same plot of land. Adoption of AV has potential application to crop production, expansion of pollinator habitat, animal agriculture (and particularly sheep), and aquaculture. AV provides an opportunity for diversifying farm outputs and income while optimizing land use. Potential benefits to energy producers include the possibility of less resistance from communities and agricultural interests to new solar array siting and beneficial effects of solar panel cooling linked to AV.

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