ASPEN GLOBAL CHANGE INSTITUTE ENERGY PROJECT

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How "Agrivoltaics" can provide more benefits than agriculture and solar photovoltaics separately

By Martín Bonzi, Aspen Global Change Institute

Solar photovoltaic (PV) technology plays a key role in transitioning to low-carbon economies thanks to its modularity, decreasing cost, long lifespan, and improving efficiency. However, PV farms compete directly with agricultural farms for land allocation, making innovative solutions for implementing PV while reducing its related land use increasingly relevant to the clean energy transition (Toledo et al., 2021).

One of these solutions, *agrivoltaic systems*, combines solar electricity generation with agricultural production. In recent years, agrivoltaics have been the subject of numerous studies due to their potential benefits in the food-energy-water nexus.

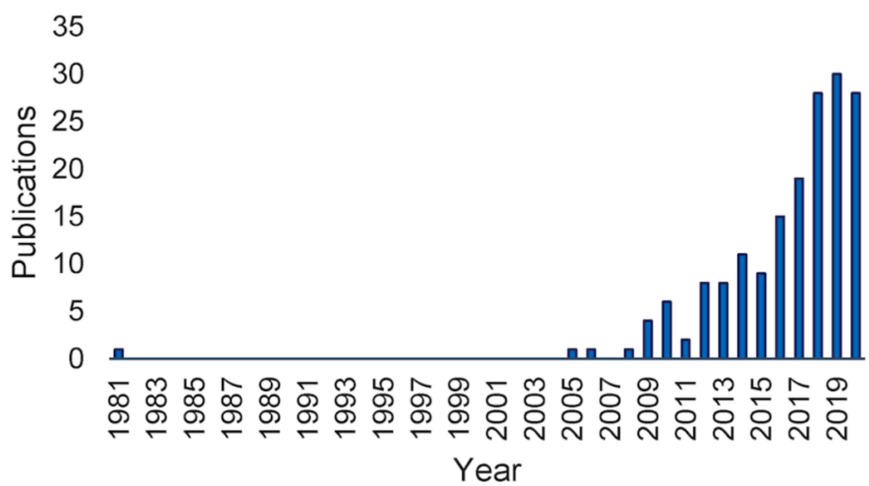

Figure 1. Number of relevant agrivoltaic academic papers published yearly. Source: Toledo et al., 2021.

Researchers around the world are discovering the multiple benefits of agrivoltaic systems, some of which include:

Agrivoltaic systems can improve public support for solar PV development: In a May 2021 paper in SocArXiv (open archive of the social sciences), Pascaris and colleagues reported on a survey of approximately 2,000 respondents in Michigan and Texas. A significant majority of 81 percent indicated they would be more likely to support solar development in their community if it combined energy and agriculture production. Respondents preferred agrivoltaic projects that are designed to provide economic opportunities for farmers and the local community, are located on private property or existing agricultural land, do not threaten local interests, and ensure fair economic benefit distribution. These results indicate an opportunity to deploy agrivoltaic systems in a manner that reflects societal concerns and refines local land use policy to support increased solar development.

Agrivoltaic systems in drylands can simultaneously increase irrigation water conservation, increase renewable energy production, and increase crop production: A study by Barron-Gafford and colleagues compared the food, energy, and water implications of an agrivoltaic system to a traditional agriculture system in Arizona. They found that water-use efficiency and cumulative carbon dioxide uptake was 65 percent greater in the agrivoltaic installation, while fruit production (chiltepin pepper, jalapeño, and cherry tomato) was doubled. The agrivoltaic PV system generated 1 percent more electricity on an annual basis (3 percent increase during summer months) compared to a regular PV system in the same location, due to the cooling effect of plant transpiration on the solar panels.

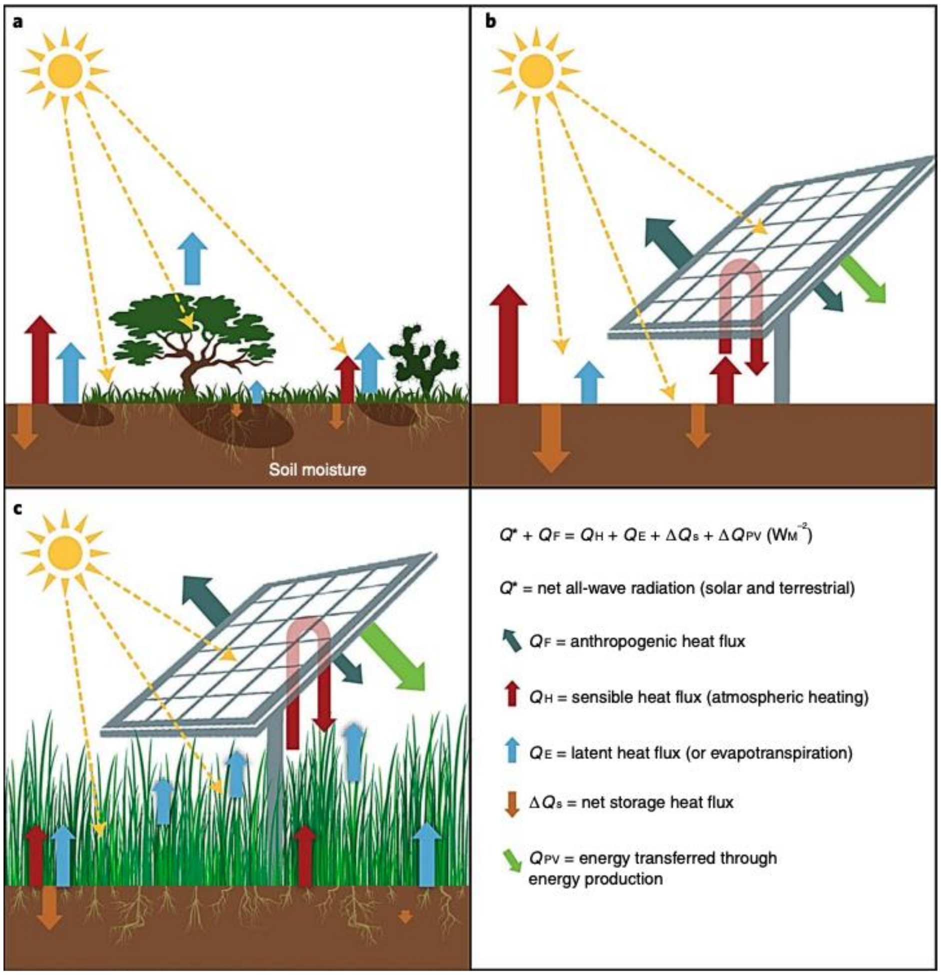

Figure 2. Illustration of changes in midday energy exchange with transitions from natural systems, solar PV arrays and a collocated agrivoltaic system. a,b, Assuming equal rates of incoming energy from the sun (broken yellow arrows), a transition from a vegetated ecosystem (a) to a solar PV installation (b) will significantly alter the energy flux dynamics of the area because of the removal of vegetation, and thus the latent heat fluxes (blue arrows). This leads to greater sensible heat fluxes (red and orange arrows), which yield higher localized temperatures. c, Reintroduction of vegetation, in this case agricultural plants, restores latent heat fluxes and should reduce sensible heat loss to the atmosphere. Energy re-radiation from PV panels (teal arrows) and energy transferred to electricity (green arrows) are also shown. Arrow size and abundance correspond to the magnitude of the effect. Source: Barron-Gafford et al., 2019.

Agrivoltaic systems can support economic development of rural communities in developing countries: A recent study conducted by Choi and collaborators focused on agrivoltaics implementation in rural communities in developing countries. Using Indonesia as a model system, they investigated the land use, energy, greenhouse gas emissions, economic feasibility, and environmental co-benefits associated with off-grid solar PV when combined with high-value crop cultivation. Life-cycle analyses indicate that small-scale agrivoltaic systems are economically viable in certain configurations and can potentially provide co-benefits including rural electrification, retrofitting diesel electricity generation, and providing electricity for local processing of agricultural products. A hypothetical full-density, off-grid solar PV system for a model village in Indonesia showed electricity output almost three times higher than total residential consumption, revealing an opportunity to downscale PV infrastructure by half to lower capital cost, co-locate crops, and support secondary income-generating activities. This economic analysis also found that the 30-year net present cost of electricity from these PV systems is significantly lower than the flat cost of diesel required to generate the equivalent electricity.

Agrivoltaic systems improve land-use efficiency when combined with grazing for sheep: An interesting use of agrivoltaic systems is combining PV installations with animals that graze the pastures growing below and surrounding the PV array. An April 2021 research article by Andrew and colleagues in *Frontiers in Sustainable Food Systems* compared lamb growth and pasture production between solar pastures in agrivoltaic systems and traditional open pastures in Oregon. Over two years, solar pastures produced 38 percent less herbage than open pastures due to low pasture density in fully shaded areas under the solar panels. However, the lower herbage mass available in solar pastures was offset by higher forage quality, resulting in similar spring lamb production to open pastures.

Lambs on solar pastures spent their time predominantly under shade and had similar or lower water intake than those grazing open pastures. Comparable lamb growth in both systems might also have been due to the lambs experiencing less heat stress under shade in solar pastures. Because land-use efficiency and animal welfare were substantially greater in agrivoltaic systems than in single-use systems, the authors concluded that agrivoltaics constitute a sustainable agricultural system, especially as global food and energy requirements continue increasing due to population and economic growth.

Agrivoltaic systems that integrate solar and pasture-based agricultural systems reduce environmental impacts and energy intensity: A recent study in *Cleaner and Responsible Consumption* by Pascaris and colleagues focused on the emissions and energy use of pasture-based agrivoltaic systems integrated with rabbit production. A life-cycle assessment (LCA) quantified the impacts of integrated agrivoltaics compared to conventional practices, including separate rabbit farming and PV production, along with separate rabbit farming and conventional energy production. The pasture-based agrivoltaic system produced the least greenhouse gas emissions and demanded the least amount of fossil energy over 30 years compared to the two other scenarios under study. This shows the potential for agrivoltaic systems to significantly reduce environmental impacts, and demonstrates that integrated solar and pasture-based agricultural systems are superior to conventional practices in terms of their comparatively lower emissions and energy intensity.

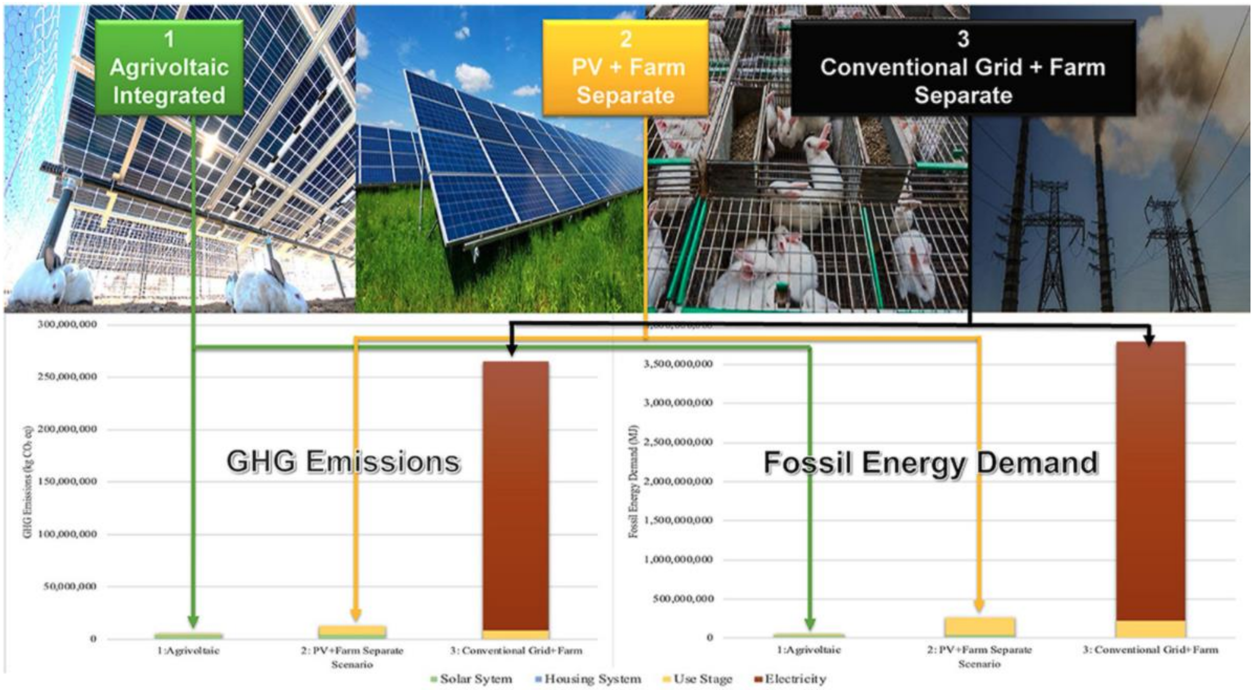

Figure 3. Comparison of greenhouse gas (GHG) emissions and fossil energy demand between an agrivoltaic integrated system, separate rabbit farming and PV production, and separate rabbit farming and conventional energy production. GHG emissions and fossil energy demand are broken down to show solar system, housing system (includes lighting, heating, and water), use stage (conventional rabbit feeding and vegetative maintenance of the PV array—estimated at two mows and six herbicide applications per year), and electricity. Source: Pascaris et al., 2021.

Agrivoltaic systems can restore pollinator habitat: Pollinator habitat can also be configured as part of an agrivoltaic system. According to the National Renewable Energy Laboratory (NREL), pollinator-friendly PV is much more established in the United States than PV plus crop or PV plus grazing applications. Based on data gathered through primary interviews and web searches, NREL estimates more than 1 gigawatt of PV plus pollinator habitat has been installed in the U.S. – though best practices have not been established for seeding, types of soil to use, soil care, herbicide application and vegetation management, erosion control, and other factors.

A report by Graham and colleagues published earlier this year in *Nature Scientific Reports* compared plant composition, bloom timing, and foraging behavior of pollinators after peak bloom on fully and partially shaded plots under solar arrays and on full-sun (control) plots at the Eagle Point Solar Plant in southwestern Oregon (Figure 3). They found that increased floral abundance and delayed bloom timing on the partial-shade plots has the potential to benefit late-season foragers in water-limited ecosystems. Pollinator abundance, diversity, and richness were greater in full-sun and partial-shade plots than in full shade. Pollinator-flower visitation rates did not differ among treatments at this scale.

The study demonstrated that pollinators will use habitat under solar arrays, despite variations in community structure across shade gradients. Given that pollinating insects are a cornerstone of natural and agricultural ecosystems, aiding in the reproduction of 75 percent of flowering plant species and 35 percent of crop species globally, and that habitat for pollinating insects is declining globally as a result of land-use change, these research findings should inform management of solar understories by local farmers and solar developers, as well as the locations agriculture and pollinator-health advocates target for pollinator habitat restoration.

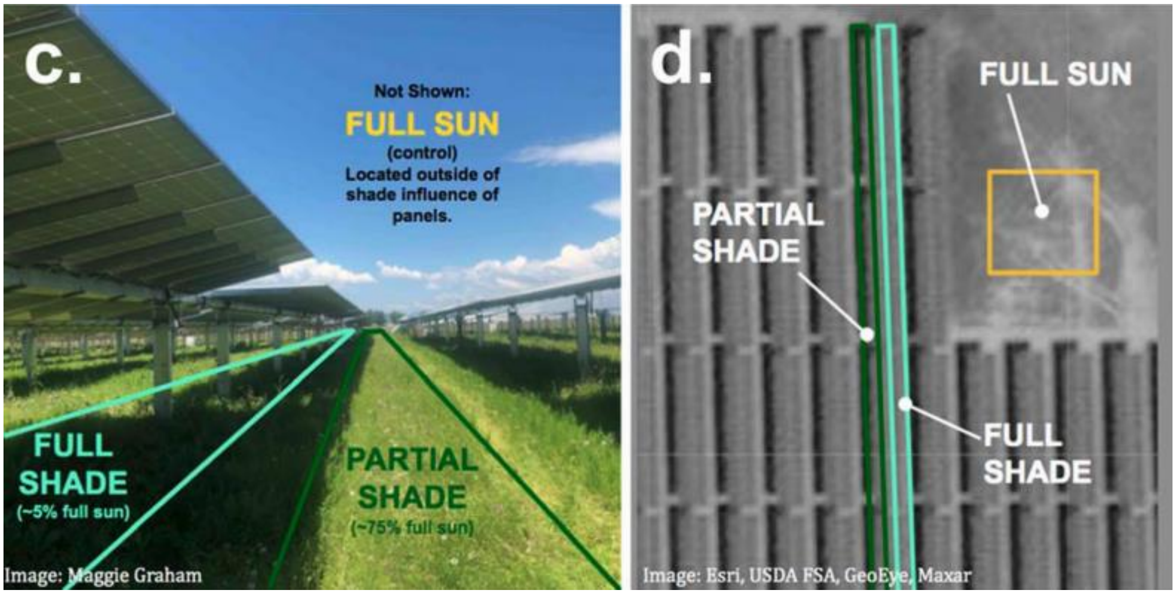

Figure 4. Photo (c) shows a side view of the full shade (~5 percent full sun) and partial shade (~75 percent full sun) plots used in this study. Photo (d) shows the control full sun plots in yellow, partial shade in green, and full shade in turquoise. Source: Graham et al., 2021. Note that the solar array consists of monocrystalline solar panels, which typically have the highest efficiencies and power capacity. Other types of solar panels can allow for more sunlight to go through them, therefore increasing sunlight availability underneath them. A final note is that prior to solar development, this site was used for cattle grazing, which serves as an empirical example of the land-use tensions between agriculture and utility-scale solar PV.

This recent research shows that different agrivoltaic system configurations (PV plus crops, PV plus grazing, and PV plus pollinators) offer multiple benefits to developing and developed societies. Support and guidance on best-practice implementation as well as policy supporting agrivoltaic system development is needed to increase adoption of these systems globally. Moving from land-use competition to cooperation is a sustainable solution to meet increasing land-use, food, water, and energy demands around the world.

Featured Research

Toledo, C.; Scognamiglio, A. Agrivoltaic Systems Design and Assessment: A Critical Review, and a Descriptive Model towards a Sustainable Landscape Vision (Three-Dimensional Agrivoltaic Patterns). Sustainability 2021, 13, 6871. https://doi.org/10.3390/su13126871

Pascaris, A. S., Schelly, C., Rouleau, M., & Pearce, J. M. (2021, May 5). Do Agrivoltaics Improve Public Support for Solar Photovoltaic Development? Survey Says: Yes!. https://doi.org/10.31235/osf.io/efasx

Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L. *et al.* Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat Sustain* **2,** 848–855 (2019). https://doi.org/10.1038/s41893-019-0364-5

Horowitz, Kelsey, Vignesh Ramasamy, Jordan Macknick and Robert Margolis. 2020. Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for GroundMounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77811. https://www.nrel.gov/docs/fy21osti/77811.pdf.

Andrew AC, Higgins CW, Smallman MA, Graham M and Ates S (2021) Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System. Front. Sustain. Food Syst. 5:659175. Doi: 10.3389/fsufs.2021.659175

Alexis S. Pascaris, Rob Handler, Chelsea Schelly, Joshua M. Pearce (2021) Life cycle assessment of pasture-based agrivoltaic systems: Emissions and energy use of integrated rabbit production. Cleaner and Responsible Consumption, Volume 3, 2021, 100030, ISSN 2666-7843, https://doi.org/10.1016/j.clrc.2021.100030.

Graham, M., Ates, S., Melathopoulos, A.P. *et al.* Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Sci Rep* **11,** 7452 (2021). https://doi.org/10.1038/s41598-021-86756-4