Bill Pedersen
Brooks Lamb

AGRIVOLTAICS

PRODUCING SOLAR ENERGY WHILE PROTECTING FARMLAND

contents

EXECUTIVE SUMMARY

Agrivoltaics is a solar market subsegment that co-locates solar energy production and agricultural operations. Combining these practices into one space creates an efficient and sustainable land use system that benefits farmers, solar developers, rural communities, and the earth itself. This emerging form of renewable energy blends complementary land uses and eliminates the false "food or energy" dichotomy that has traditionally dominated discussions about solar-agricultural land use. People often feel forced to choose between fuel *or* farming, climate *or* conservation, energy *or* rural economies. But with thoughtful planning, communities can simultaneously expand and strengthen solar infrastructure while conserving farmland, generating ecological benefits, and supporting rural places.

Relying on combined solar and agricultural knowledge from the authors, *Agrivoltaics: Producing Solar Energy While Protecting Farmland* introduces agrivoltaics and highlights the various agricultural, environmental, ecological, and economic benefits that these systems can generate. The report, which is written for a broad audience, also examines how communities, solar developers, local leaders, and policy makers can effectively promote, support, and regulate agrivoltaic systems.

BILL PEDERSEN is an experienced solar development professional with over five years of experience developing solar projects, primarily in the American Northeast.

BROOKS LAMB works with American Farmland Trust to conserve farmland, promote environmentally sound farming practices, help farmers remain viable, and advance equity in agriculture. While his efforts are national, much of his work focus on the American South.

INTRODUCTION

CLIMATE CHANGE NECESSITATES SOLAR ENERGY DEPLOYMENT

Massive amounts of renewable energy infrastructure must be built to mitigate the worst impacts of anthropogenic climate change.[1] In 2019, over 80 percent of America's energy was derived from fossil fuel resources (36 percent oil, 33 percent natural gas, 13 percent coal), which are leading contributors to climate change.[2] While American solar has averaged 42 percent annual growth between 2010 and 2020,[3] it is still a relatively small portion of the nation's energy portfolio. Solar deployment must be accelerated to meet the Biden Administration's goal of achieving 50-52 percent economy-wide greenhouse gas emissions by 2030 and to help contain temperature increases to 1.5°C.[4]

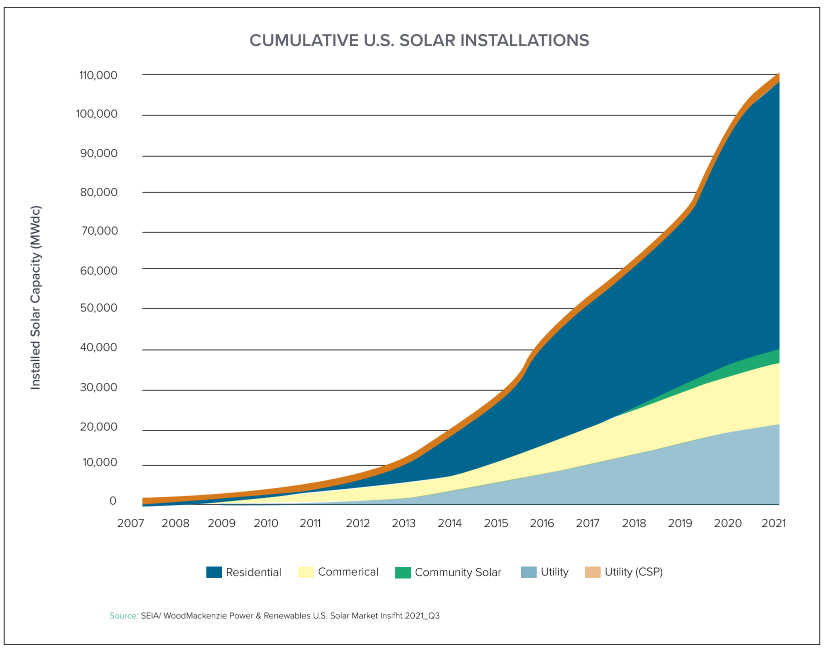


Figure 1: Solar energy is growing in the United States.
Photo source – *Solar Energy Industries Association,* Solar Industry Research Data

1 Brad Plumer and Henry Fountain. "A Hotter Future Is Certain, Climate Panel Warns. But How Hot Is Up to Us." *The New York Times.* August 9, 2021. https://www.nytimes.com/2021/08/09/climate/climate-change-report-ipcc-un.html.

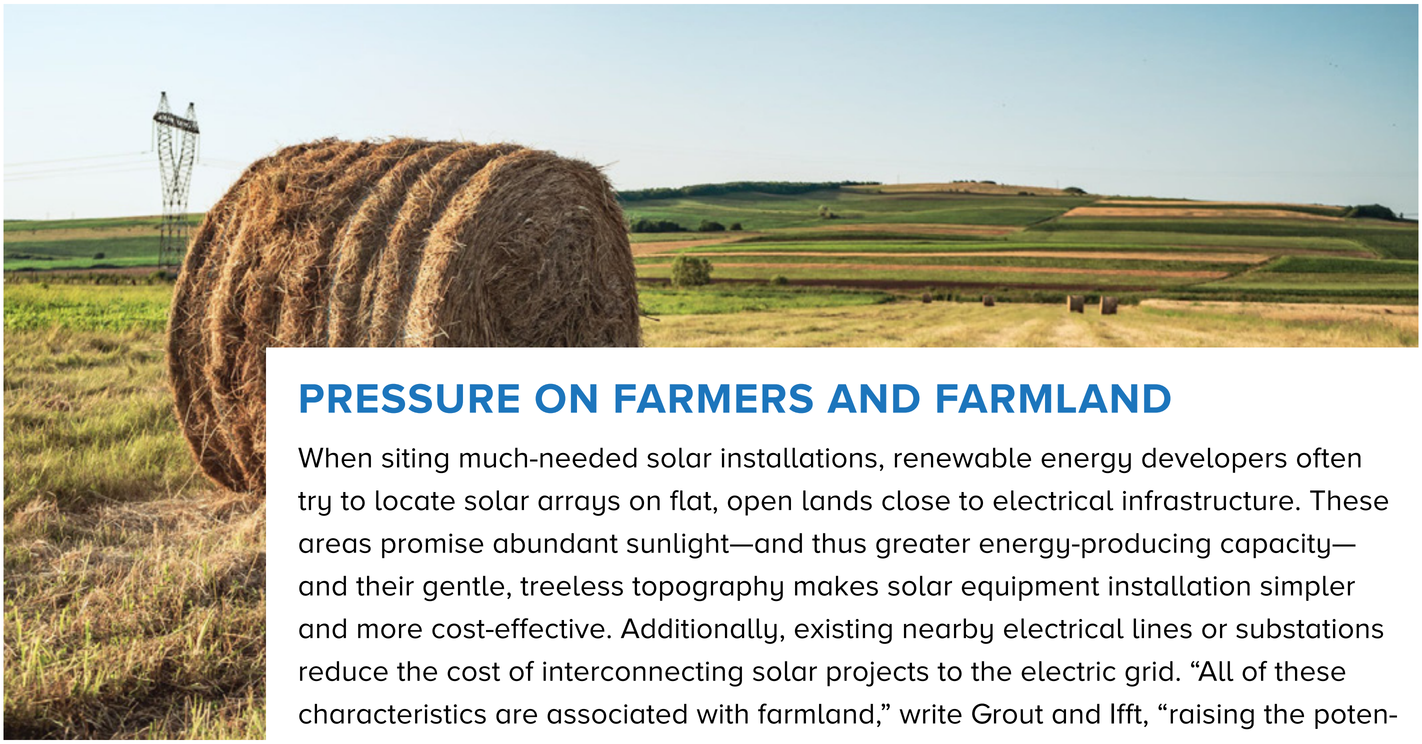
2 International Energy Agency (IEA). "United States - Countries & Regions." September 13, 2019. https://www.iea.org/countries/united-states.

3 Solar Energy Industries Association (SEIA). "Solar Industry Research Data." Accessed May 17, 2021. https://www.seia.org/solar-industry-research-data.

4 The White House. "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." April 22, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

Economic forces are also propelling solar growth as utility-scale solar has developed into the cheapest form of electricity in many parts of the country.[5] Increasing numbers of corporations and government entities are turning to solar to reduce electricity costs and provide environmental benefits. Due to combined climatic and economic forces, American solar is projected to expand over 500 percent by 2030.[6]

Most of solar energy's recent growth stems from large, ground mounted solar farms rather than rooftop arrays. Because these massive systems can power anywhere from hundreds to tens of thousands of households with a single project, they are projected to play a prominent role in solar's continued expansion. It is doubtful that rooftop solar alone can provide enough clean energy to meet America's ambitious climate objectives in the timescale necessitated by the climate crisis.



PRESSURE ON FARMERS AND FARMLAND

When siting much-needed solar installations, renewable energy developers often try to locate solar arrays on flat, open lands close to electrical infrastructure. These areas promise abundant sunlight—and thus greater energy-producing capacity—and their gentle, treeless topography makes solar equipment installation simpler and more cost-effective. Additionally, existing nearby electrical lines or substations reduce the cost of interconnecting solar projects to the electric grid. "All of these characteristics are associated with farmland," write Grout and Ifft, "raising the potential for conflict between farmland preservation and the transition to renewable energy. Indeed, prime farmland"—which is agricultural land with the best soils and highest productive capacity—"may be particularly attractive for solar development."[7] Unfortunately, solar developers' desire for these ideal open landscapes close to

5 Davinder Singh. "Levelized Cost of Energy and of Storage." *Lazard*. Accessed May 17, 2021. https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020.

6 Silicon Ranch. "Silicon Ranch Launches Regenerative Energy." Accessed May 17, 2021. https://www.siliconranch.com/silicon-ranch-launches-regenerative-energy/.

7 Travis Grout and Jennifer Ifft. "Approaches to Balancing Solar Expansion and Farmland Preservation: A Comparison across Selected States." EB 2018-04. Charles H. Dyson School of Applied Economics and Management – Cornell University. May 2018. https://www.farmlandinfo.org/wp-content/uploads/sites/2/2020/09/Cornell-Dyson-eb1804.pdf.

existing infrastructure often leads to the erasure of productive-yet-vulnerable agricultural lands.[8] In the northeastern United States where solar development is booming, for example, “The solar companies have figured out that open farmland is the easiest to convert,” explained Henry Talmage, who leads Connecticut’s Farm Bureau.[9] This is especially true because farmland in rural communities tends to be less expensive than open space in suburban or urban areas. When combined with suburban sprawl and haphazard large-lot rural development—both of which led to the permanent loss or fragmentation of over 11 million acres of American agricultural land between 2001–2016, according to a report from American Farmland Trust[10]—aggressive solar siting on farmland is a worrisome trend across the nation.

Figure 2: Land adjacent to this dairy farm east of Ithaca, New York was converted to solar arrays.
Photo source – Cornell University

8 Rebecca Hernandez, Madison Hoffacker, Michelle Murphy-Mariscal, Grace Wu, and Michael Allen. “Solar energy development impacts on land cover change and protected areas.” *Proceedings of the National Academy of Sciences* 112, no. 44 (2015): 13582; Sanderine Nonhebel. “Renewable energy and food supply: Will there be enough land?” *Renewable and Sustainable Energy Reviews* 9, no. 2 (2005): 191-201.

9 Gregory Hladky. “State Encouraging Solar Development at Expense of Farmland.” Hartford Courant (Hartford, CT), August 1, 2016. https://www.courant.com/business/hc-solar-versus-farmland-20160801-story.html.

10 American Farmland Trust. Julia Freedgood, Mitch Hunter, Jennifer Dempsey, and Ann Sorensen. *Farms Under Threat: The State of the States*. Washington, D.C. 2020: 3.

In addition to encroaching solar, residential, and commercial/industrial development, America's farms and farmers grapple with other challenges, including razor-thin economic margins and an aging farmer population.[11] Further, many farmers and rural communities are harmed by policies and economic structures that value large-scale industrial agriculture over small and mid-sized farms. The "get big or get out" mentality that has plagued American agriculture for decades is still dominant, enabling a small percentage of farmers and companies to amplify their wealth while the majority struggles.[12] These compounding challenges help explain why so many farmers have sold their land out of agricultural production—whether to solar developers or real estate interests—in recent years.

POTENTIAL SOLUTION: AGRIVOLTAICS

The narrative above reveals a tension between two pressing issues, forcing citizens and leaders to wrestle with difficult questions. Should solar energy production be amplified to create a more sustainable energy source, lower greenhouse gas emissions, and stem anthropogenic climate change at the expense of farmland? Or should communities conserve irreplaceable agricultural landscapes, which supply the world with food and fiber, sustain rural economies, and provide innumerable environmental services by excluding renewable energy?

Society will increasingly have to wrestle with these questions as agricultural land loss and the climate crisis intensify. Barron-Gafford et al. write in *Nature Sustainability*—one of the world's leading environmental journals—that "a key challenge to building resilience under a changing and uncertain climate is maintaining and improving both energy and food production security. Such efforts are hampered, in part, by conventional understanding of land use that asserts an inherent 'zero-sum-game' of competition between some forms of renewable energy—particularly solar PV installations—and agricultural food production."[13] When both practices are desperately needed, which do we choose?

11 Citing data from the most recent Census of Agriculture, the National Agricultural Statistics Service states, "The average age of all U.S. farm producers in 2017 was 57.5 years, up 1.2 years from 2012, continuing a long-term trend of aging in the U.S. producer population" (USDA – NASS 2019).

12 Jonathan R. McFadden and Robert A. Hoppe. "The Evolving Distribution of Payments from Commodity, Conservation, and Federal Crop Insurance Programs, Economic Information Bulletin Number 184." U.S. Department of Agriculture, Economic Research Service. November 2017. Alana Semuels. "'They're Trying to Wipe Us Off the Map.' Small American Farmers Are Nearing Extinction." *Time Magazine*. November 27, 2019. https://time.com/5736789/small-american-farmers-debt-crisis-extinction/. Marty Strange. *Family Farming: A New Economic Vision*. Second Edition. Lincoln, NE: University of Nebraska Press, 2008.

13 Greg Barron-Gafford, Mitchell Pavao-Zuckerman, Rebecca Minor, Leland Sutter, Isaiah Barnett-Moreno, Daniel T. Blackett, Moses Thompson, Kirk Dimond, Andrea Gerlak, Gary Nabhan, and Jordan Macknick. "Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands." *Nature Sustainability* 2 (2019): 848.

Thankfully, the difficult dichotomy presented by this either-or mentality is, at least in some ways, deceptive. Society does not have to choose between fuel *or* farming, climate *or* conservation, energy *or* rural economies. With thoughtful planning, communities can simultaneously expand and strengthen solar infrastructure while conserving farmland and supporting rural places. Agrivoltaics—the combination of agricultural production and photovoltaic solar panels on the same land area—offers a sustainable, equitable, and productive path forward.

There are few "win-win" solutions in the environmental field. Most of the time, progress requires making significant sacrifices. Agrivoltaics is not a perfect land use system, nor is it appropriate in all settings. However, when designed and used carefully, it approaches the kind of synergistic solution that is often elusive but desperately needed to secure a healthier future for people, places, and the planet.[14]

14 The National Renewable Energy Laboratory echoes this sentiment. In a 2019 publication, they wrote: "The co-location of PV (photovoltaic) and agriculture could offer win-win outcomes across many sectors, increasing crop production, reducing water loss, and improving the efficiency of PV arrays." For more, see this site.

HOW DO AGRIVOLTAIC SYSTEMS WORK?

Agrivoltaic systems elevate ground mount solar arrays so that people, equipment, and animals can traverse underneath the arrays for crop and livestock cultivation. A variety of crops have been grown under raised solar panels, including kale, peppers, swiss chard, broccoli, celery, winter wheat, clover, potatoes, and more.[15] While many crops are selected for their shade-tolerant characteristics, non-shade-tolerant species—such as tomatoes—have also been utilized.

Farmers and solar developers are also increasingly grazing animals under solar systems. Solar owners typically mow under panels as part of standard array maintenance. Using animal grazing instead of mowing equipment for vegetation management produces the same outcome in a more environmentally friendly manner, all while maintaining agricultural production. The vast majority of agrivoltaic grazing operations use sheep, as they are generally docile animals that do not try to eat the electrical components or disturb the modules.[16] However, some farms—such as Maple Ridge Meats in Vermont—have successfully placed cattle under elevated systems.[17] Interest in grazing cattle in agrivoltaic systems is growing in pockets across the nation.

15 Many of these crops have been grown on the University of Massachusetts experiment farm in South Deerfield. The authors visited this farm during the research process for this paper. For more specific information on potato production, see this article.

16 Dr. Stephen Herbert of the University of Massachusetts spoke specifically to this issue (Herbert interview 2021).

17 Bill Opalka. "Renewable Energy Growing among Vermont's Animals and Crops." *Energy News Network*. February 11, 2019. https://energynews.us/2019/02/05/renewable-energy-growing-among-vermonts-animals-and-crops/.

Figure 3: Agrivoltaics operation at the University of Massachusetts' South Deerfield experiment farm. Photo by authors.

Figure 4: Crops growing under panels at the South Deerfield experiment farm.
Photo source—CleanTechnica

While many conventional ground mounted solar arrays have the lower edge of their solar modules just a few feet off the ground, agrivoltaic systems may lift their modules up to ten or twelve feet in the air. Depending on the regulations and the crops, grasses, or livestock raised under the arrays, modules may be installed close together or spaced over four feet apart. Spacing designs allow varying amounts of sunlight to reach the ground to meet agricultural goals. For enhanced stability, agrivoltaic systems often need deeper foundations and may require reinforced materials to compensate for the elevated racking system, which could be subjected to higher wind loads than traditional systems. Improved sturdiness also helps handle contact from large livestock, like cattle.

Agrivoltaic systems can benefit ecosystems in addition to preserving agricultural operations. There is a growing movement in the solar industry to include pollinator-friendly vegetation—such as wildflowers—and local seed mixes in solar arrays. Almost all ground mount solar projects, including agrivoltaic projects, will include areas with unused grasses or non-crop producing vegetation. Seeding these areas with a diverse array of native, drought-resistant, perennial plants that support local insect populations can enhance biodiversity, prevent erosion, improve soil health, and sequester carbon. Sustainable operational practices, such as ecologically friendly mowing and irrigation, and deliberate land use requirements can also support ecosystem vitality.

Figure 5: Sheep grazing in an agrivoltaic system.
Photo source—Silicon Ranch

WHAT BENEFITS DO AGRIVOLTAICS OFFER?

Agrivoltaic systems can enhance land productivity by enabling multiple land uses in the same area. Admittedly, agrivoltaics produce less energy than a denser conventional solar farm. Similarly, shading from dual-use systems may reduce crop production relative to an unshaded farm. However, overall land use efficiency increases with a co-located system. For example, German researchers have suggested that crop production of an agrivoltaic system would be roughly 80 percent of a standard farm. Similarly, an agrivoltaic array would produce approximately 80 percent of the electricity of a typical ground mounted solar system. When agricultural production is combined with solar production, it results in 160 percent overall output for the land area.[18]

18 For more on this German study, see this article.

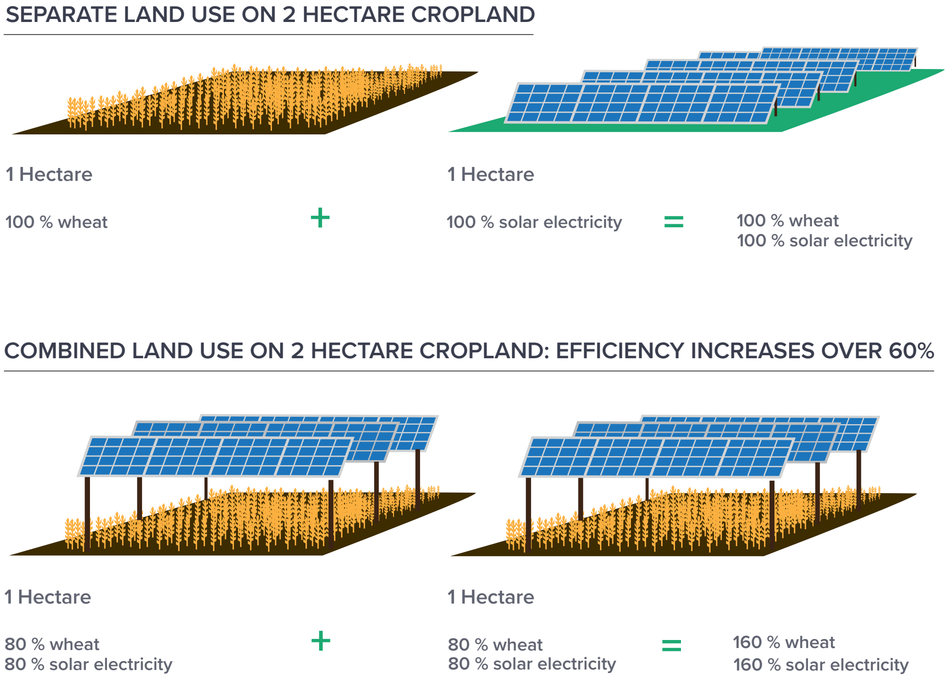


Figure 6: Product visualization under agrivoltaic systems.
Photo source—[Fraunhofer Institute for Solar Energy Systems]

In addition to generating clean energy while enabling continued agricultural production, these arrays can also provide economic and ecosystem service benefits. If implemented properly, agrivoltaics can simultaneously generate clean energy, support local food production, conserve threatened farmland, boost the health of rural economies and communities, produce pollinator habitats, revitalize ecosystem health, and capture and store carbon in the soil.

CLEAN ENERGY BENEFITS

Agrivoltaics can expand renewable energy production while respecting communities' rural culture and keeping land in agricultural production. Solar energy production must grow rapidly to mitigate greenhouse gas emissions and meet increasingly bold climate targets. Dual-use systems can expand the potential land areas available for solar. Some landowners and communities may be unwilling to support solar development if it necessitated the end of agricultural operations. Agrivoltaic systems that enable continued agricultural production thus unlock new lands that were previously inaccessible for clean energy deployment.

While agrivoltaic systems are less dense and generate less electricity than conventional arrays, elevating modules will increase system efficiencies and counteract some production loss. Solar generation is negatively correlated with temperature because warmer temperatures decrease voltage.[19] Lifting solar modules further off the ground cools them, reducing electrical losses and boosting efficiency. According to a recent study by the National Renewable Energy Laboratory (NREL), "Agrivoltaic PV (photovoltaic) panels were cooler during daytime hours compared to the traditional panel array by approximately 9°C, allowing for better performance."[20] Additionally, there is the potential to reduce long-term solar operations costs by implementing alternative maintenance practices. If a farmer mows under the panels—or if sheep or cattle eat the grasses—solar developers may save time and money on maintenance.

ECONOMIC BENEFITS

In addition to agrivoltaics' energy and environmental advantages, this land use system offers promising economic benefits for farmers and rural communities. When a farmer chooses to lease her land to a solar developer for an agrivoltaics array, she receives lease payments from the solar company. Although it is difficult to say exactly how much a farmer will earn from this arrangement—compensation depends on the size of an array, the geographic location of an installation, the expected amount of energy that will be produced, local electricity prices, and more—a farmer can potentially earn tens of thousands of dollars per year. Lease payments can be especially lucrative in states where interest in agrivoltaics is growing and supportive policy measures are emerging.

For small and mid-sized farmers struggling to maintain their operations in the face of increasing consolidation in the agricultural community, these solar lease payments could be a saving grace. Having a reliable income source is especially useful given the variable returns farmers receive for their products—whether livestock or crops—each year. Steady payments could very well mean the difference between having enough income to make an annual farm payment or being forced to sell a farm out of agricultural production.

Payments from solar companies for agrivoltaics arrays could also enable smaller-scale farmers to focus more on their agricultural operations. In the United States, a surprising percentage of farmers must rely on off-farm income

19 Renvu. "How Temperature Affects Solar Panel Efficiency." Accessed May 17, 2021. https://www.renvu.com/Learn/How-Temperature-Affects-Solar-Panel-Efficiency.

20 National Renewable Energy Lab (NREL). "Benefits of Agrivoltaics Across the Food-Energy-Water Nexus." September 11, 2019. https://www.nrel.gov/news/program/2019/benefits-of-agrivoltaics-across-the-food-energy-water-nexus.html.


to support their farms and families. According to Bunge and Newman of the *Wall Street Journal*, "Most U.S. farm households can't solely rely on farm income, turning what was once a way of life into a part-time job. On average," they continue, "82 percent of U.S. farm household income is expected to come from off-farm work this year [2018], up from 53 percent in 1960, according to the U.S. Department of Agriculture." [21]

According to estimates from the USDA's Economic Research Service, that percentage has increased in recent years. This need for off-farm income leaves many farmers waking up early to complete chores, working a full day in a non-agricultural vocation, and then returning to more farm work at night. It is an exhausting process, one that strains physical, mental, and emotional health.[22]

Obviously, these types of lease payments would help farm families themselves. However, evidence also shows that, by helping keep these farmers afloat and perhaps even enabling them to prosper, entire rural communities will benefit. Research indicates that when small and mid-sized farmers succeed, they tend to support localized economies more than people who live in suburban bedroom communities.[23] In other words, these farmers and their families help small businesses and other local institutions flourish. When combined with other factors—such as the reduced costs of providing community services in areas characterized by farmland versus areas dominated by alternative uses like urban sprawl[24]—the community-wide economic benefits of supporting farmers through measures like agrivoltaic lease payments are readily apparent.

21 Jacob Bunge and Jesse Newman. "To Stay on the Land, American Farmers Add Extra Jobs." *Wall Street Journal*. February 25, 2018. https://www.wsj.com/articles/to-stay-on-the-land-american-farmers-add-extra-jobs-1519582071.

22 In part because of these strains, data shows that farmer suicides have drastically increased. Suicide rates among farmers are higher now than at the peak of the early 1980s farming crisis. For more on this heartbreaking phenomenon, see Semuels (2019) and this 2018 article from *Successful Farming*.

23 David Brown and Kai Schafft. Rural People & Communities in the 21st Century: Resilience and Transformation. Malden, MA: Polity Press, 2011; Charles Tolbert, Michael Irwin, Thomas Lyson, and Alfred Nucci. "Civic Community in Small-Town America: How Civic Welfare is Influenced by Local Capitalism and Civic Engagement." Rural Sociology 67, no. 1 (2002): 90-113.

24 Over 30 years and through more than 150 studies, American Farmland Trust has shown that "working lands generate more public revenues than they receive back in public services" when compared with other land uses, like residential development (AFT 2016: 6).

Dual-use agrivoltaic projects have also enabled the creation of local, specialized agricultural-solar businesses. For example, companies such as Solar Shepherd[25] and organizations such as the American Solar Grazing Association[26] have emerged to help farmers earn extra revenue by grazing animals under solar projects. There is also a nascent network of companies and consultants designed to help farmers adopt agrivoltaics.

AGRICULTURAL BENEFITS

Beyond the aforementioned energy, environmental, and economic justifications for advancing agrivoltaics, there are also agricultural reasons for embracing this system. In particular—and flying in the face of popular assumptions—agrivoltaic systems have been shown to maintain or even increase overall agricultural production and the performance of certain crops, grasses, and livestock.

Generally, it is assumed that because solar panels in agrivoltaic systems reduce the amount of sunlight that reaches the ground, agricultural production will suffer. At times, this anticipated reduction in production does occur. But in many other cases, studies have shown that yields can remain the same or improve under well-designed solar arrays. Dr. Stephen Herbert, who was interviewed for this project, speaks to the production impact of certain vegetable crops in agrivoltaic systems. A national expert in this field and a leader of the University of Massachusetts—Amherst's South Deerfield experiment farm, Herbert explains that—when solar panels are appropriately spaced—yields of some vegetables, such as cherry tomatoes, kale, swiss chard, turnips, and potatoes, remain at 90-95 percent of their typical productive capacity.[27] This data should inspire confidence in farmers who are interested in practicing agrivoltaics through localized vegetable production.

Similar results are shown for grass growth in pastures. These findings bode well for grazing livestock or growing hay. For example, researchers from Oregon State University studied grass production under an agrivoltaic system and concluded that growth was as or more abundant under panels than in an open field control group. In some instances, the study found that 90 percent *more* biomass was grown in areas under panels. "These net benefits were largely achieved through an increased water use

25 For more information about Solar Shepherd, see their website (solarshepherd.com).
26 To learn about the ASGA, visit their web page (solargrazing.org).
27 "Interview with Dr. Stephen Herbert." University of Massachusetts Crop and Animal Research and Education Farm – South Deerfield, Massachusetts. April 30, 2021.

efficiency in the shaded areas of the field which left water stored in the soil column available throughout the entire observation period," researchers note.[28] Another recent study affirms this thinking, saying that "although shade reduces the light interception potential of crops, a higher soil moisture achieved by the installation of photovoltaics can be a more water efficient farming, leading to a significant increase in late season biomass of forages."[29] In other words, moderate shading from spaced panels facilitates more water retention in soil, which can help boost forage and fodder growth.

Livestock such as sheep and cattle benefit from enhanced grass growth under solar panels. They can also enjoy the shade directly, especially during scorching summer months. Recent research on a dairy farm that incorporated agrivoltaics into its operation shows that the panels can help livestock. Citing complex statistical data, Sharpe et al. write that "agrivoltaics incorporated into pasture dairy systems may reduce the intensity of heat stress in dairy cows and increase wellbeing of cows and the efficiency of land use."[30] Greater wellbeing is intrinsically valuable, and it can lead to increased milk production. Through complementary research on sheep, Andrew et al. mention similar findings. "Solar panels in agrivoltaic systems can provide cool microclimates for grazing livestock," they write, "promoting animal welfare by providing shelter from sun and wind."[31] Similar results have been seen across other studies, highlighting the benefits of agrivoltaics for livestock farmers and the animals themselves.

28 Elnaz Hassanpour Adeh, John Selker, and Chad W. Higgins. "Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency." *Public Library of Science (PLOS) One* 13, no. 11 (2018): 13.

29 Alyssa Andrew, Chad Higgins, Mary Smallman, Maggie Graham, and Serkan Ates. "Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System." *Frontiers in Sustainable Food Systems 5* (2021): 2.

30 K.T. Sharpe, B.J. Heins, E.S. Buchanan, and M.H. Reese. "Evaluation of solar photovoltaic systems to shade cows in a pasture-based dairy herd." *Journal of Dairy Science* 104, no. 3 (2021): 2794.

31 Andrew et al. "Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System." 2.

Figure 7: Cattle grazing under solar array at University of Minnesota's West Central Research and Outreach Center in Morris, Minnesota. Photo source—Share et al. 2021

While much of the research into agricultural production under solar panels is novel, it has roots in the established agroforestry field. Agroforestry is a land use system that intentionally integrates trees into crop fields and pastures, seeking to achieve production through both elements. Whether through alley cropping (i.e. growing crops between rows of trees), silvopasture (i.e. grazing livestock under intentionally-managed trees), or other methods, agroforestry is a well-studied dual land use system. Significantly, some of the same advantages for crop growth, grass abundance, and livestock performance reported in agrivoltaic systems have been identified in agroforestry systems for decades. This long-term trend in a comparable dual-use system emphasizes that—even though agrivoltaics is a new movement—it is anchored in effective, productive, and sustainable traditions.

ECOLOGICAL BENEFITS

Solar companies are becoming significant landholders (or lessors) and will soon manage millions of acres globally.[32] Incorporating effective conservation practices into agrivoltaics and all solar projects can yield important ecological benefits. Opportunities for solar projects to help restore natural ecosystems include supporting pollinator populations, utilizing local, drought-resistant vegetation, and incorporating wildlife-friendly designs.

POLLINATOR PLANTINGS

America is experiencing an alarming collapse of pollinator and insect populations, which are critical to ecosystem health. The Center for Biological Diversity reports that over 700 bee species are in decline, and hundreds are at risk of extinction. These population contractions are largely the result of habitat loss and overzealous pesticide use.[33] Bees and other pollinators are vitally important as 75 percent of the world's flowering plants and 35 percent of the world's food crops depend on pollinators.[34]

Figure 8: Pollinators planted under panels. Photo source—Solar Power World

32 Silicon Ranch. "Silicon Ranch Launches Regenerative Energy." Accessed May 17, 2021. https://www.siliconranch.com/silicon-ranch-launches-regenerative-energy/.

33 Justin Worland. "Bee Populations Decline Due to Pesticides, Habitat Loss." *Time*. March 2, 2017. https://time.com/4688417/north-american-bee-population-extinction/.

34 NexAmp. "The Buzz on Pollinator Friendly Solar." *Solar Energy Solutions*. November 25, 2018. https://www.nexamp.com/blog/the-buzz-on-pollinator-friendly-solar.

Many states, including Massachusetts and Minnesota, are encouraging or requiring the inclusion of pollinator habitats in all solar projects.[35] Specialized seed mixes have been developed to facilitate the inclusion of pollinator-friendly plantings in solar projects. For example, Ernst Pollinator Service, the American Solar Grazing Association, and Cornell University Extension teamed up to develop "Fuzz and Buzz" seed mix, a combination of soft grasses, clover, and flower species to support pollinator communities.[36] When planted along the edges of fields containing arrays, these pollinator practices coexist well with agriculture and augment agrivoltaic arrays.

Municipalities should consider including pollinator planting requirements for all ground mount solar projects, not only agrivoltaic projects. For more on the importance and benefits of pollinator-friendly solar developments, see Siegner et al.'s report, [Maximizing Land Use Benefits from Utility-Scale Solar: A Cost-Benefit Analysis of Pollinator-Friendly Solar in Minnesota](), *which was published by the Center for Business and the Environment at Yale in December 2019.*

UTILIZE NATIVE AND DROUGHT-RESISTANT NONFLOWERING PLANTS

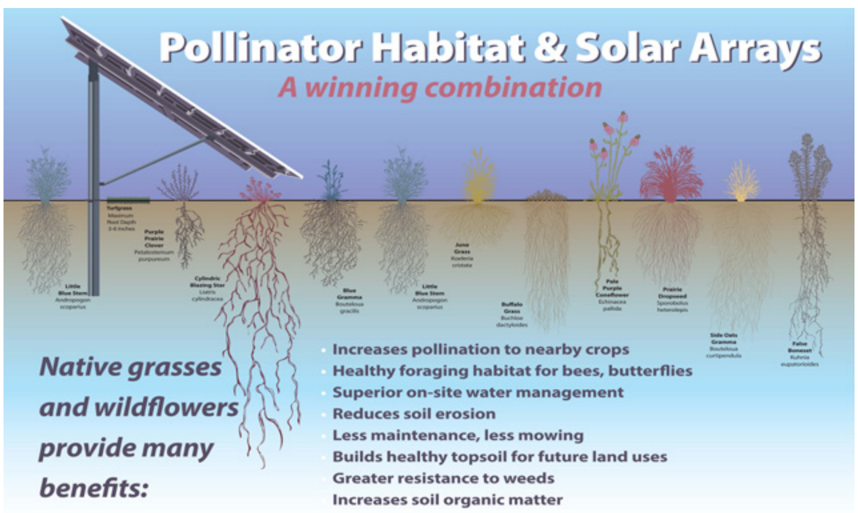


Figure 9: The benefits of native grasses and wildflowers incorporated into agrivoltaic and solar arrays are clear. Photo source—[PV Magazine]()

35 Dunbar, Elizabeth. "Solar Energy Finds Ways to Help Soil, Pollinators." *MPR News*. June 20, 2019. https://www.mprnews.org/story/2019/06/20/pollinatorfriendly-solar-energy-becomes-the-norm-in-minnesota.

36 Clean Energy Resource Teams. "Grazing Livestock and Growing Pollinator-Friendly Plants Add Value to Solar Farms." Accessed May 17, 2021. https://www.cleanenergyresourceteams.org/grazing-livestock-and-growing-pollinator-friendly-plants-add-value-solar-farms.

Solar projects can support critical biological processes by utilizing native grasses and vegetation in addition to pollinator-friendly plantings. Soil is the foundation of most ecosystems. Native grasses with deep root systems can revitalize soils while providing beneficial ecosystem services. Grasses with deep root systems sequester significantly more carbon dioxide than turfgrass and function as an important nature-based climate solution.[37] Native grasses can also increase soil organic matter, which improves soil health and helps to build topsoil.

Additionally, native grasses provide superior on-site water management, which reduces irrigation requirements and soil erosion. Since these grasses are adapted to local conditions, they often require fewer pesticides and fertilizers—particularly if they are being grazed by livestock, who return nutrients to the soil via waste—and do not need to be mowed as frequently as turfgrass. Incorporating native grasses into agrivoltaics and conventional solar projects can minimize negative ecosystem impacts by reducing water consumption, stormwater runoff, pesticide and fertilizer use, and mowing activities.

Municipalities should consider including native planting requirements for all ground mount solar projects, not only agrivoltaic projects.


37 John Fitzgerald Weaver. "Solar-Powered Pollinators for Less than a Penny a Watt." *PV Magazine* USA. April 6, 2019. https://pv-magazine-usa.com/2019/04/05/solar-powered-pollinators-for-less-than-a-penny-a-watt/.

WILDLIFE HABITATS

Solar projects can support local wildlife populations by incorporating amenities such as birdhouses and bat boxes. In fact, some solar projects have even become certified as official National Wildlife Federation Wildlife Habitat, such as NexAmp's Rutland, Massachusetts, array.[38] Solar projects should also be designed and constructed in manners that reduce negative impacts. Solar developers should consult with local biologists to ensure that their projects do not significantly harm wildlife populations. Additionally, construction activities, particularly any tree clearing, should be avoided during critical breeding or nesting periods. All security fences should include a six-to-twelve-inch gap at their base to enable animal movement and minimize habitat fragmentation. These practices can be easily integrated into an agrivoltaic system without negatively affecting solar or agricultural production.

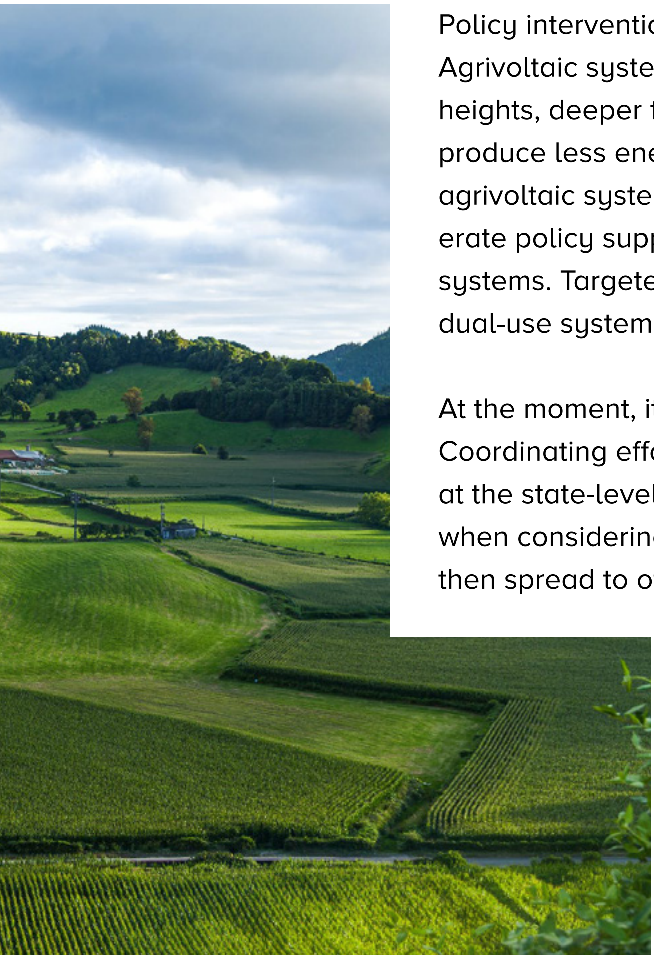
Municipalities should consider including wildlife requirements for all ground mount solar projects, not only agrivoltaic projects.

If solar companies develop into leading conservationists that embrace good stewardship and treat the land as a biological asset rather than a resource to be exploited, they can increase biodiversity and enhance overall ecosystem functions at an enormous scale.

Figure 10: With proper steps, solar arrays can benefit wildlife.
Photo source—NexAmp Twitter

38 NexAmp. Post to Twitter. April 7, 2020 at 4:04 p.m. https://twitter.com/Nexamp/status/1247616307383750657.

HOW CAN COMMUNITIES ENCOURAGE AGRIVOLTAICS ADOPTION?



Policy interventions are needed to enable widespread agrivoltaics adoption. Agrivoltaic systems cost more to build than traditional arrays due to their greater heights, deeper foundations, and potentially reinforced materials. Additionally, they produce less energy than conventional ground mount solar systems. Therefore, agrivoltaic systems are unlikely to proliferate at a meaningful scale without deliberate policy support to improve their financial competitiveness with traditional solar systems. Targeted incentives and support mechanisms can be crafted to promote dual-use systems and unlock their unique and much-needed benefits.

At the moment, it is challenging to pursue these incentives on the national level. Coordinating efforts across state lines is difficult, and most energy policy is crafted at the state-level. For these reasons, it is prudent to concentrate on individual states when considering strategic policy action. These recommended best practices can then spread to other jurisdictions across the country.

Currently, many view Massachusetts as the leading state in the nation for agrivoltaics. The state's preeminence is due in large part to groundbreaking research at the University of Massachusetts and a deliberate Agricultural Solar Tariff Generation Units (ASTGU) incentive program. This incentive program is the result of a collaboration between the Massachusetts Department of Energy Resources (DOER) and the Massachusetts Department of Agricultural Resources (MDAR), as well as an extensive stakeholder outreach process.[39]

The ASTGU program created a significant financial incentive for qualifying dual-use arrays that helps to counteract higher construction costs and electricity production reductions. The dual-use incentive program is incorporated within the broader Solar Massachusetts Renewable Target (SMART) program and is designed to "support diverse installation types and sizes that provide unique benefits."[40] SMART's dual-use guideline can be found here: Guideline Regarding the Definition of Agricultural Solar Tariff Generation Units. A specific Agricultural Solar Tariff Generation Unit financial adder, which is pictured below, was incorporated into the SMART program to support agrivoltaic proliferation.

GENERATION UNIT TYPE	ADDER VALUE
Building Mounted Solar Tariff Generation Unit	$0.02
Floating Solar Tariff Generation Unit	$0.03
Solar Tariff Generation Unit on a Brownfield	$0.03
Solar Tariff Generation Unit on an Eligable Landfill	$0.04
Canopy Solar Tariff Generation Unit	$0.06
Agriculture Solar Tariff Generation Unit	$0.06

Figure 11: Additional value is given to agrivoltaic arrays in Massachusetts,
Table source: Massachusetts Department of Energy Resources

39 Massachusetts Department of Energy Resources and Department of Agricultural Resources. "Guidelines Regarding the Definition of Agricultural Solar Tariff Generation Units." April 26, 2018. https://www.mass.gov/doc/agricultural-solar-tariff-generation-units-guideline-final/.

40 Ibid.

ACTION ON THE LOCAL LEVEL

Although much of the policy innovation occurs at the state level in places like Massachusetts, local land use planners can play an essential role in encouraging the development of agrivoltaic systems by crafting regulations to govern these projects. Rules and ordinances can include a combination of regulatory incentives, penalties, and prohibitions to ensure responsible solar development on agricultural land. Best practices include drafting a statement of purpose communicating support for responsible dual-use solar. Guidelines should also indicate which zoning districts or overlay districts are suitable for agrivoltaics, differentiate dual-use systems from conventional solar arrays, prohibit activities that meaningfully limit future agricultural production, and restrict construction on high-quality agricultural soils. These types of all-important measures are best implemented on the local level, where place-based knowledge can be harnessed.

Agrivoltaic regulations should be as consistent as possible across different towns and counties. All standards should reference and conform to any state guidance documents to the greatest extent possible. Land use regulators should share best practices to ensure that Planning Boards and Zoning Boards of Appeal have the tools to effectively evaluate and regulate these innovative projects. Additionally, standardizing land use entitlement will make it easier and more affordable for solar developers and farmers to deploy these beneficial projects. Bespoke land use applications, which require agrivoltaic proponents to play by different rules in different jurisdictions, should be eliminated wherever possible.

Exhibit A includes suggestions for a model agricultural solar zoning bylaw. While this is not a comprehensive list, these recommendations can help land use planners evaluate and regulate agrivoltaic systems. These elements of a model regulation are designed to complement the model solar zoning laws that states such as Massachusetts and New York have already developed. These nitty-gritty regulatory suggestions can help local leaders and planners advance agrivoltaics in their communities. When widely adopted, standardized local zoning would facilitate more agrivoltaics interest from the solar development community, improve the understanding of farmers and community members, and simplify land use governance for regulators.

Planners and community members interested in advancing agrivoltaics may also benefit from the following resources.

- Massachusetts Executive Office of Energy and Environmental Affairs: Model Zoning for the Regulation of Solar Energy Systems
- New York State Research Development Authority: Model Solar Energy Local Law
- New York State Department of Agriculture and Markets: Guidelines for Solar Energy Projects – Construction Mitigation for Agricultural Lands
- University of Massachusetts Clean Energy Extension-Dual Use: Agriculture and Solar Photovoltaics Fact Sheet
- Massachusetts Department of Energy Resources and Department of Agricultural Resources – Guideline Regarding the Definition of Agricultural Solar Tariff Generation Units
- American Farmland Trust-Smart Solar Siting Principles and Examples of Land Use Laws that Support Renewable Energy While Protecting Farmland

ADDITIONAL RESEARCH

Although the benefits of agrivoltaics are clear, further research could help make this land use practice even more effective and beneficial. For example, social science research that explores the concerns and interests of farmers, land use leaders, and solar developers would help in making these policy efforts even more impactful. In particular, semi-structured interviews, focus groups, and surveys that investigate this topic would yield fruitful insights and help agrivoltaics advocates make this system more commonplace. This research should be conducted across counties, states, and regions to document both local and national trends.

In addition to social science studies, more work could be done to better understand agrivoltaic systems' energy production profiles and installation economics. Throughout diverse geographic settings, roughly how much energy is produced per acre with varying panel spacing and tilts? How could construction costs be lowered to facilitate greater dual-use adoption while still maintaining the highest safety and quality standards? Addressing these sorts of questions—along with agriculturally-based questions about soil health, crop and livestock production capacity, water use, and more—could be a boon to agrivoltaics in America.

CONCLUSION

As demonstrated throughout this paper, agrivoltaics is a promising system that combines energy, ecological, economic, and agricultural benefits into a common land area. Although it is still a burgeoning movement, this dual-use system offers hope on many fronts. As the climate and land consumption crises become more and more pressing and intertwined, society must turn to approaches like agrivoltaics to ensure sustained progress.

Despite agrivoltaics' diverse and definitive benefits, current rules and regulations will not facilitate meaningful adoption of these systems, at least not at a scale that promises to make a significant impact. Solar developers and farmers need encouragement to pursue this sort of novel initiative. Otherwise, potential risks distract from rewards, and agrivoltaic systems may struggle to achieve financial feasibility. Without reforming existing laws and enacting new regulations, agrivoltaics may languish as a limited land use instead of becoming a well-known and widespread practice.

States can certainly encourage action by developing or supporting the creation of agrivoltaic support mechanisms. Following the lead of exemplars like Massachusetts, other states across the nation can develop targeted policy interventions to spur agrivoltaics forward. But without the cooperation of local land use leaders and elected officials, as well as advocacy from invested community members, agrivoltaics cannot reach its full potential. By creating an even playing field for solar developers and farmers and encouraging sustainable, smart, and equitable practices, local leaders can promote a proliferation of agrivoltaic systems. Policy makers' consideration and support of agrivoltaics could propel a synergistic solution into enhanced existence, securing a brighter and more productive future.

EXHIBIT A: SUGGESTIONS FOR AGRIVOLTAIC LAND USE REGULATION

STATEMENT OF PURPOSE

American Farmland Trust recommends including a statement of purpose regarding dual-use solar systems in opening lines of land use regulations. These statements help reinforce overarching goals and set the tone for subsequent regulatory elements. For example:

> *Town of Farmington, New York—The goal is to: "enhance agricultural viability and preserve productive agricultural land resources and provide public utilities that meet present needs and anticipate future needs of residents; and … support green economy innovations; and support NYS's energy goals."*[41]

DUAL-USE CONSIDERATIONS

Agrivoltaic systems should be designed to enable continued use of the land for agriculture. Dual-use solar systems should "optimize a balance between the generation of electricity and the agricultural productive capacity of the soils beneath."[42]

PERMISSIBLE ZONING DISTRICTS

Land use regulators should communicate where communities want agrivoltaic systems to be built. Zoning bylaws should clearly state which districts or zoning overlay

41 American Farmland Trust, "Smart Solar Siting Principles and Examples of Land Use Laws that Support Renewable Energy while Protecting Farmland," https://s30428.pcdn.co/wp-content/uploads/2019/05/AFT-Smart-Solar-Siting-Principles-and-Examples-of-Local-Solar-Laws-that-Protect-Farmland.pdf.

42 Massachusetts Department of Energy Resources and Department of Agricultural Resources, "Guideline Regarding the Definition of Agricultural Solar Tariff Generation Units," April 26, 2018, https://www.mass.gov/doc/agricultural-solar-tariff-generation-units-guideline-final/download.

districts allow agrivoltaic systems. Towns should consider developing regulatory incentives to encourage the development of dual-use solar systems instead of conventional solar arrays. For example, dual-use systems may be allowed with a Site Plan Review instead of a Special Permit, eliminating some of the red tape that can hinder the advancement of these sorts of projects. Similarly, more favorable density or setback requirements could be developed for solar projects that allow for continued agricultural production.

RETAIN AGRICULTURAL USE TAXATION

Farms that adopt agrivoltaics arrays are still farms, so they should continue to recieve agricultural tax benefits. State and local governments often recognize the significant burden that high property tax rates can place on farmers, so they grant relief to land areas that are actively used for agricultural purposes. This financial assistance is intended to help promote and sustain agricultural economies and conserve farmland, which provides important ecological and environmental benefits. Rather than change the taxation classification to a higher “commercial” rate, farms that implement agrivoltaic systems—especially smaller systems that interconnect to the local electrical distribution network—should retain their agricultural taxation status.

DEFINE PRODUCTIVE FARMLAND

Solar installations that negatively impact agricultural production should be discouraged on the most productive farmland. Land use regulations should identify superior soil types to ensure that projects are sited in appropriate locations. Land use regulators have frequently leveraged U.S. Department of Agriculture soil designations when crafting solar regulations. Local land use officials could identify soils that qualify as:

- Prime Farmland Soils
- Prime Farmland Soils (if drained)
- Soils of Statewide Importance
- Unique Soils
- Farmland of Unique Importance

Regulators and officials could then encourage developers and farmers to locate solar arrays in areas with lower-quality soils. In instances where agrivoltaics are installed in areas with a substantial percentage of high-quality soils, local leaders could require farmers to submit a viability plan explaining how these areas will continue to generate significant agricultural production.

REGULATE SOLAR FOR FARM CONSUMPTION

Most ground mount solar projects export their power to the grid because they produce more electricity than a household could use. However, some smaller systems are designed to service on-site energy needs. Many communities have found it advantageous to develop separate regulations for projects intended for on-farm energy usage. Below is an example designating solar for farm use as "small scale" instead of "large scale":

> *Town of Copake, New York: "A solar energy system located on a farm operation as defined in S301 (11) of NYSDAM law and located in an agricultural district which primarily serves the needs of the farm and produces up to 110% of farm's needs shall be deemed a small-scale solar energy system."*[43]

CONFORM TO STATE RULES AND REGULATIONS

Local ordinances should conform to state-level rules, wherever possible, to leverage best practices and increase the standardization of the land use entitlement process. For example, projects in New York should reference the New York State Department of Agriculture and Markets *Guidelines for Solar Energy Projects — Construction Mitigation for Agricultural Lands*. An example is below:

> *Town of Goshen, New York: Installation on farms shall abide by rules, standards and regulations established by NYSDAM. The construction and installation of any energy system shall be designed to minimize any adverse impacts on the productivity of the soil and the farm operation.*[44]

ACCESS ROADS

Access roads should be constructed along the periphery of agricultural operations, wherever possible, and should minimize their impact on agricultural lands. Access roads should be no wider than local emergency access requirements to mitigate their effects on agricultural land. All access roads should allow for farm equipment and livestock crossing while maintaining the original surface drainage patterns. Further, access roads should be built of permeable materials, such as gravel, as opposed to impervious surfaces like concrete or asphalt. Impervious surfaces could negatively affect water filtration and absorption from rain and snow.

43 American Farmland Trust, "Smart Solar Siting Principles and Examples of Land Use Laws that Support Renewable Energy while Protecting Farmland," https://s30428.pcdn.co/wp-content/uploads/2019/05/AFT-Smart-Solar-Siting-Principles-and-Examples-of-Local-Solar-Laws-that-Protect-Farmland.pdf.

44 Ibid.

DECOMMISSIONING

Solar developers must present towns with a bond or financial surety to cover decommissioning costs at the end of the array's life. The form of the surety must be agreeable to the town's counsel. The surety amount must cover the cost of returning the site to a pre-development state. The decommissioning surety should include the cost for removing any energy storage system, if applicable. Among other responsibilities, the developer should remove all equipment (including underground conduit), restore the surface grade and soil, and revegetate and restore soil areas with native seed mixes. These measures allow landowners to easily return given areas to full-scale agricultural production or, if desired, other uses. The following excerpt addresses decommissions:

> *Town of Goshen, New York: "Must restore the land to the condition which existed before construction, including an adequate layer of topsoil where existing topsoil has been removed or eroded…"*[45]

Nonprofits or governmental agencies could consider purchasing conservation easements on land that has been decommissioned in order to continue conserving open space. Further, landowners could consider applying for funding from entities like the Natural Resources Conservation Service to implement more conservation practices on decommissioned land. Relevant programs could include NRCS's Conservation Stewardship Program or Conservation Reserve Program.

VISUAL SCREENING

Solar projects should provide a visual screen to minimize viewshed impacts. The screening mechanism can be composed of short, coniferous trees or a wooden fence. Tree plantings in particular could yield useful benefits, including wildlife habitat, agricultural windbreaks, and carbon sequestration. Solar developers and farmers will be responsible for maintaining the health of any vegetative plantings. Projects that do not have any abutters or that can leverage a preexisting visual barrier can apply for an exception to screening requirements.

TOPSOIL SEGMENTATION

During construction, stripped topsoil should be stockpiled and kept separate from other excavated material. This nonrenewable resource can be repurposed after construction or used for site restoration. If there is not an immediately apparent use for the stockpiled topsoil, it should be spread evenly in adjacent agricultural areas.

45 Ibid.

MITIGATE WILDLIFE IMPACTS

Any fence surrounding an agrivoltaic project should include a six to twelve-inch gap at its base to allow small animals to travel under it. Additionally, towns should consider including requirements for wildlife support structures such as birdhouses and bat boxes to accompany solar projects.

**This requirement should apply to all ground mount solar projects, not only agrivoltaic systems.*

VEGETATION

Municipalities should require native, drought-resistant vegetation in any nonagricultural portions of agrivoltaic sites, such as along access roads, by fences, or between visual screens. Additionally, regulators should consider requiring the inclusion of pollinator-friendly vegetative plantings.

**Any native and pollinator-friendly requirements should apply to all ground mount solar projects, not only agrivoltaic systems.*

An example of a town requiring pollinator plantings is below:

> *Town of Shawangunk, New York: "Non-invasive, native ground cover under and between the rows of solar panels shall be low-maintenance, drought-resistant, non-fertilizer-dependent and, where required by the Planning Board, shall be pollinator-friendly to provide habitat for bees."*[46]

46 Ibid.

REFERENCES

American Farmland Trust. "Cost of Community Services Studies." September 2016. https://farmlandinfo.org/publications/cost-of-community-services-studies/.

American Farmland Trust. "Smart Solar Siting Principles and Examples of Land Use Laws that Support Renewable Energy while Protecting Farmland." https://s30428.pcdn.co/wp-content/uploads/2019/05/AFT-Smart-Solar-Siting-Principles-and-Examples-of-Local-Solar-Laws-that-Protect-Farmland.pdf.

American Farmland Trust. Julia Freedgood, Mitch Hunter, Jennifer Dempsey, and Ann Sorensen. *Farms Under Threat: The State of the States*. Washington, D.C. 2020.

Andrew, Alyssa, Chad Higgins, Mary Smallman, Maggie Graham, and Serkan Ates. "Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System." *Frontiers in Sustainable Food Systems* 5 (2021): 1-12.

Barron-Gafford, Greg, Mitchell Pavao-Zuckerman, Rebecca Minor, Leland Sutter, Isaiah Barnett-Moreno, Daniel T. Blackett, Moses Thompson, Kirk Dimond, Andrea Gerlak, Gary Nabhan, and Jordan Macknick. "Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands." *Nature Sustainability* 2 (2019): 848-855.

Bunge, Jacob and Jesse Newman. "To Stay on the Land, American Farmers Add Extra Jobs." *Wall Street Journal*. February 25, 2018. https://www.wsj.com/articles/to-stay-on-the-land-american-farmers-add-extra-jobs-1519582071.

Brown, David and Kai Schafft. *Rural People & Communities in the 21st Century: Resilience and Transformation*. Malden, MA: Polity Press, 2011.

Center for Agriculture, Food, and the Environment—University of Massachusetts. "Pollinator-Friendly Solar PV for Massachusetts." February 8, 2021. https://ag.umass.edu/clean-energy/services/pollinator-friendly-solar-pv-for-massachusetts.

Clean Energy Resource Teams. "Grazing Livestock and Growing Pollinator-Friendly Plants Add Value to Solar Farms." Accessed May 17, 2021. https://www.cleanenergyresourceteams.org/grazing-livestock-and-growing-pollinator-friendly-plants-add-value-solar-farms.

Dunbar, Elizabeth. "Solar Energy Finds Ways to Help Soil, Pollinators." MPR News. June 20, 2019. https://www.mprnews.org/story/2019/06/20/pollinatorfriendly-solar-energy-becomes-the-norm-in-minnesota.

Grout, Travis and Jennifer Ifft. "Approaches to Balancing Solar Expansion and Farmland Preservation: A Comparison across Selected States." EB 2018-04. Charles H. Dyson School of Applied Economics and Management—Cornell University. May 2018. https://www.farmlandinfo.org/wp-content/uploads/sites/2/2020/09/Cornell-Dyson-eb1804.pdf.

Hassanpour Adeh, Elnaz, John Selker, and Chad W. Higgins. "Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency." *Public Library of Science (PLOS) One* 13, no. 11 (2018): 1-15.

Herbert interview. "Interview with Dr. Stephen Herbert." University of Massachusetts Crop and Animal Research and Education Farm—South Deerfield, Massachusetts. April 30, 2021.

Hernandez, Rebecca, Madison Hoffacker, Michelle Murphy-Mariscal, Grace Wu, and Michael Allen. "Solar energy development impacts on land cover change and protected areas." *Proceedings of the National Academy of Sciences* 112, no. 44 (2015): 13579-13584.

Hladky, Gregory. "State Encouraging Solar Development at Expense of Farmland." Hartford Courant (Hartford, CT), August 1, 2016. https://www.courant.com/business/hc-solar-versus-farm-land-20160801-story.html.

International Energy Agency (IEA). "United States - Countries & Regions." September 13, 2019. https://www.iea.org/countries/united-states.

Massachusetts Department of Energy Resources and Department of Agricultural Resources. "Guidelines Regarding the Definition of Agricultural Solar Tariff Generation Units." April 26, 2018. https://www.mass.gov/doc/agricultural-solar-tariff-generation-units-guideline-final/.

McFadden, Jonathan R. and Robert A. Hoppe. "The Evolving Distribution of Payments from Commodity, Conservation, and Federal Crop Insurance Programs, Economic Information Bulletin Number 184." U.S. Department of Agriculture, Economic Research Service. November 2017.

National Renewable Energy Lab (NREL). "Benefits of Agrivoltaics Across the Food-Energy-Water Nexus." September 11, 2019. https://www.nrel.gov/news/program/2019/benefits-of-agrivoltaics-across-the-food-energy-water-nexus.html.

NexAmp. Post to Twitter. April 7, 2020 at 4:04 p.m. https://twitter.com/Nexamp/status/1247616307383750657.

NexAmp. "The Buzz on Pollinator Friendly Solar." Solar Energy Solutions. November 25, 2018. https://www.nexamp.com/blog/the-buzz-on-pollinator-friendly-solar.

Nonhebel, Sanderine. "Renewable energy and food supply: Will there be enough land?" R*enewable and Sustainable Energy Reviews 9*, no. 2 (2005): 191-201.

Opalka, Bill. "Renewable Energy Growing among Vermont's Animals and Crops." Energy News Network. February 11, 2019. https://energynews.us/2019/02/05/renewable-energy-growing-among-vermonts-animals-and-crops/.

Plumer, Brad and Henry Fountain. "A Hotter Future Is Certain, Climate Panel Warns. But How Hot Is Up to Us." *The New York Times*. August 9, 2021. https://www.nytimes.com/2021/08/09/climate/climate-change-report-ipcc-un.html.

Renvu. "How Temperature Affects Solar Panel Efficiency." Accessed May 17, 2021. https://www.renvu.com/Learn/How-Temperature-Affects-Solar-Panel-Efficiency.

Seigner, Katie, Scott Wentzell, Maria Urrutia, Whitney Mann, and Hallie Kennan. "Maximizing Land Use Benefits From Utility-Scale Solar: A Cost-Benefit Analysis of Pollinator- Friendly Solar in Minnesota."

Yale Center for Business and the Environment. December 2019. https://cbey.yale.edu/research/maximizing-land-use-benefits-from-utility-scale-solar.

Semuels, Alana. "'They're Trying to Wipe Us Off the Map.' Small American Farmers Are Nearing Extinction." *Time Magazine*. November 27, 2019. https://time.com/5736789/small-american-farmers-debt-crisis-extinction/.

Sharpe, K.T., B.J. Heins, E.S. Buchanan, and M.H. Reese. "Evaluation of solar photovoltaic systems to shade cows in a pasture-based dairy herd." *Journal of Dairy Science* 104, no. 3 (2021): 2794-2806.

Silicon Ranch. "Silicon Ranch Launches Regenerative Energy." Accessed May 17, 2021. https://www.siliconranch.com/silicon-ranch-launches-regenerative-energy/.

Singh, Davinder. "Levelized Cost of Energy and of Storage." Lazard. Accessed May 17, 2021. https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020.

Solar Energy Industries Association (SEIA). "Solar Industry Research Data." Accessed May 17, 2021. https://www.seia.org/solar-industry-research-data.

Strange, Marty. *Family Farming: A New Economic Vision*. Second Edition. Lincoln, NE: University of Nebraska Press, 2008.

"Successful Farming Special: Farmer Suicides Today vs. 1980s Farms Crisis." *Successful Farming*. April 30, 2018. https://www.agriculture.com/family/health-safety/sf-special-farmer-suicides-today-vs-1980s-farm-crisis.

Tolbert, Charles, Michael Irwin, Thomas Lyson, and Alfred Nucci. "Civic Community in Small-Town America: How Civic Welfare is Influenced by Local Capitalism and Civic Engagement." *Rural Sociology* 67, no. 1 (2002): 90-113.

Weaver, John Fitzgerald. "Solar-Powered Pollinators for Less than a Penny a Watt." PV magazine USA. April 6, 2019. *https://pv-magazine-usa.com/2019/04/05/solar-powered-pollinators-for-less-than-a-penny-a-watt/*.

Worland, Justin. "Bee Populations Decline Due to Pesticides, Habitat Loss." *Time*. March 2, 2017. https://time.com/4688417/north-american-bee-population-extinction/.

United States Department of Agriculture (USDA)—National Agricultural Statistics Service. "2017 Census of Agriculture Highlights: Farm Producers." April 2019.

White House, The. "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." April 22, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

ACKNOWLEDGEMENTS

The authors would like to thank the many people who supported and contributed to this paper. First, we offer a special thank you to Professor Marjorie Shansky, who encouraged us to pursue our agrivoltaic interests in her Land Use Law and Environmental Planning course at Yale School of the Environment. Professor Shansky's guidance, questions, and feedback played an important role in shaping this report. We are grateful for her ongoing support. Additionally, we would like to thank Dr. Stephen Herbert and the University of Massachusetts Crop and Animal Research and Education Farm team for allowing us to visit their incredible facility and teaching us about their groundbreaking research on agrivoltaics.

We would also like to thank the many family members and friends who took time out of their busy lives to discuss dual-use solar. From planned phone calls and classroom discussions to impromptu conversations around fire pits, we appreciate their advice and encouragement.

Finally, we want to thank Heather Fitzgerald, Stuart DeCew, and the entire Yale Center for Business and the Environment ("CBEY") team for supporting this paper and enabling us to reach a broad audience.