DOE

MARKET RESEARCH STUDY

AGRIVOLTAICS

August 2022

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1.0 Introduction

The Solar Energy Technologies Office (SETO)'s mission is to accelerate the advancement and deployment of solar technology in support of an equitable transition to a decarbonized energy system by 2050, starting with a decarbonized power sector by 2035. Research areas of particular interest to SETO include solar photovoltaics (PV), solar PV combined with agriculture (agrivoltaics) and concentrating solar power (CSP) plants.

The co-location of solar energy and agriculture has the potential to provide benefits to farmers, rural communities, and the solar industry. SETO is exploring this potential through projects such as the **Foundational Agrivoltaic Research for Megawatt Scale (FARMS)** funding opportunity that examines how agrivoltaics can be scaled to provide new economic opportunities for farmers, rural communities, and the solar industry.[1] Another program, the **Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE)** program, managed by the National Renewable Energy Laboratory (NREL), seeks to improve the mutual benefits of solar, agriculture, and native landscapes. Currently, there are 22 projects across the U.S. which bring together a wide array of researchers, farmers, and industry partners.[2]

This report focuses on agrivoltaics, highlighting the benefits and numerous designs that these systems take both within the U.S. and globally. Also explored are restraints to market adoption as well as market gaps.

2.0 Agrivoltaics

Agrivoltaics is increasingly viewed as a solution to concerns over the land demands of solar energy. According to the "Solar Futures Study," considerable land will be needed. *"At the highest deployment level in 2050, ground-based solar technologies will require a land area equivalent to 0.5% of the contiguous U.S. surface area, and this requirement could be met using less than 10% of potentially suitable disturbed lands, thus avoiding conflicts with high-value lands in current use."* The study notes that, "solar installations will affect local communities, ecosystems, and agricultural areas." Ground-mounted solar is projected to require about 5.7 million acres by 2035 (0.3%), increasing to as much as 10 million acres in 2050 (0.5%). The report suggests agrivoltaics as a potential solution to land constraints.

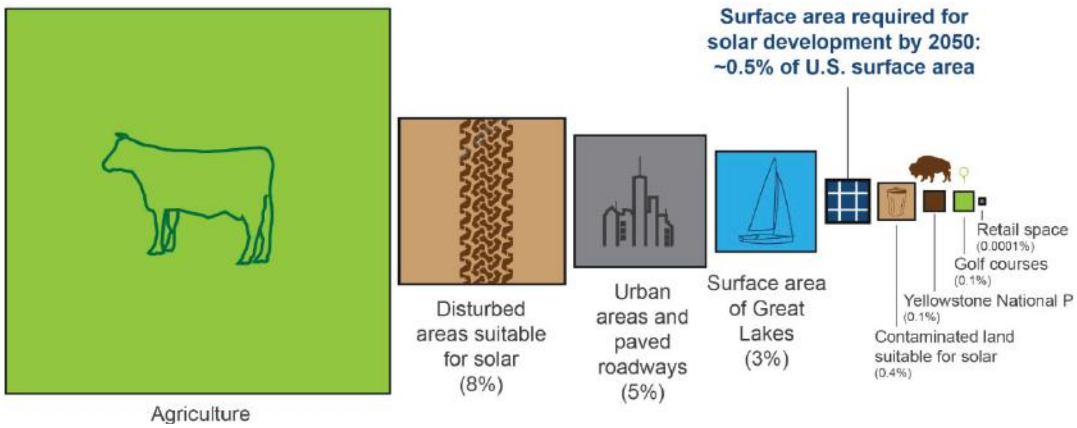

Figure 1: Maximum land use required for solar in 2050 in the *Solar Futures* scenarios
Source: National Renewable Energy Laboratory (September 2021)[3]

2.1 Definition

Agrivoltaics allows the simultaneous use of land for both agriculture and photovoltaic power generation. Crops, animal grazing, and electricity can be harvested on the same land. Other terms commonly used as synonyms include *agriphotovoltaics*,[4] *agrovoltaics*,[5] *agrisolar*,[6] or *dual use solar*.[7] Agrivoltaic systems can be classified in many ways. One classification method is based on application – such as crop + solar PV or livestock + solar PV.

Another classification method is based on the type of system used: open or closed (see figure below). An example of a closed agrivoltaics systems is a solar PV greenhouse, where PV modules are placed on the roof. By contrast, open systems are placed in an open area between or above livestock or crops. According to a National Renewable Energy Laboratory (NREL) study, the U.S. capacity for solar PV + grazing sites is estimated to be over 100 MW. The most common type of solar PV + grazing site involves sheep grazing; however, grazing with other livestock, such as cattle or rabbits, exists as well.[8]

Crop agrivoltaics systems can further be classified by type of farming:

1. **Field crop farming:** Field crop farming refers to production of the typical field crops including, wheat, potatoes, rice, etc.[9] These crops are grown annually and in most countries are highly mechanized.
2. **Orchard / horticulture farming:** Fruit (such as apples, pears, berries, grapes), vegetables or nut-producing trees/shrubs which are planted are generally row-based layout. These crops already require some protection against extreme weather conditions by hail/shade nets, plastic covers.
3.

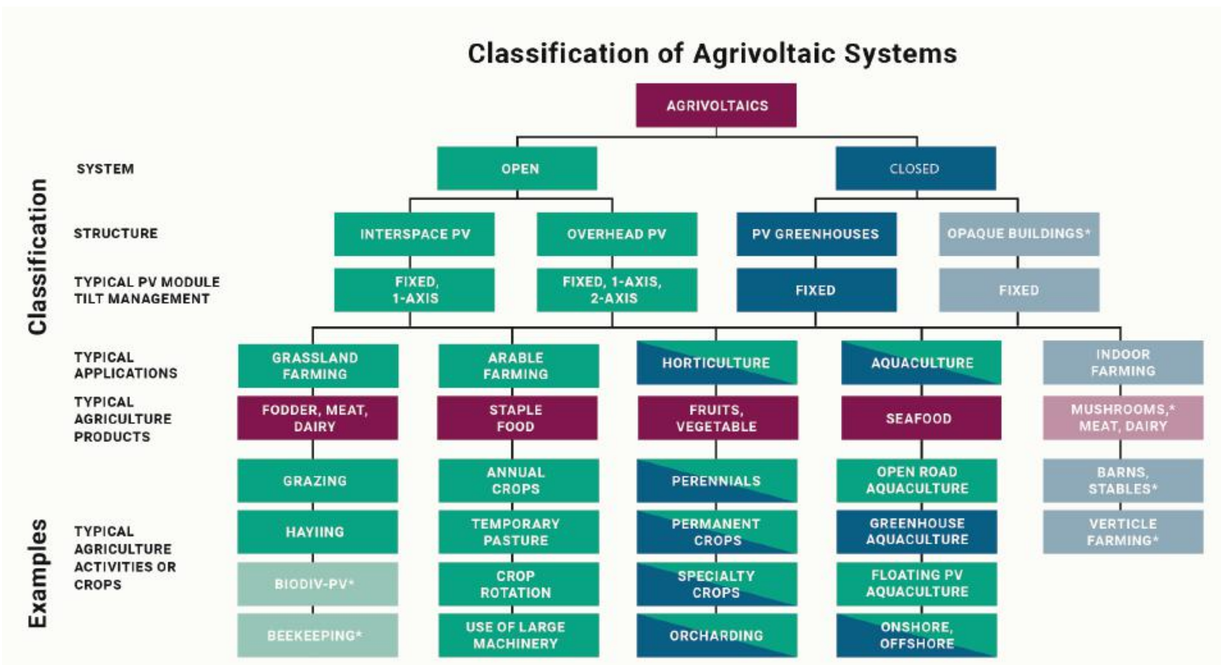

Figure 2: Agrivoltaics systems

Source: Adapted from Max Trommsdorff (May 13, 2021)[10]

Agrivoltaics is available in many different configurations. In the following example, fixed support systems are used to elevate the solar panels above the crops. This allows farm machinery access to the crops.[11]

Figure 3: Agrivoltaics with raspberries
Source: *PV Europe*. (April 4, 2022).[12]

Agrivoltaics also applies to greenhouses where semi-transparent modules can be used as roofs to expose plants to a certain part of the solar spectrum to improve yield such as those provided by Soliculture. Using the solar panels as a "roof" over the plants protects crops from harsh weather such as snow or hail and prevents excess evapotranspiration, reducing irrigation requirements in the process.[13]

In China, solar greenhouses cover up to 1.96 million hectares or 30% of the total horticultural area.

Greenhouse agrivoltaics is common in China. The article "Reinventing the Greenhouse" published in 2015 by the *Low Tech Magazine* reports that 800,000 hectares of passive solar greenhouses had been installed in China during the last decades.[14] In 2021, solar greenhouses in China covered up to 1.96 million hectares or 30% of the total horticultural areas in China. The most popular vegetables grown in the solar greenhouses include cucumbers, melons, tomatoes, eggplants, peppers, strawberries, and leafy vegetables.[15]

Figure 4: Greenhouse agrivoltaics
Source: University of Arizona[16]

PV modules offering shelter and shade for animals are also considered agrivoltaics. This is sometimes referred to as *solar panels*. With livestock such as sheep, the shade provided by elevated solar panels can be beneficial and reduce the amount of water the sheep require. Some research has also been conducted to test effectiveness with cattle, rabbits,[17] and chickens.[18] No data were found regarding the number of agrisolar grazing sites installed globally.

Figure 5: Agrivoltaics offering shelter
Source: Sandra Enkhardt (October 7, 2020)[19]

Another agrivoltaic application involves protecting grazing areas and farmland by using solar panels as fences. Closed rangevoltaic systems, another concept, refers to the "enclosed" area where livestock are placed, acting as a replacement for agricultural fences. A vertical bifacial system can be used for this application.[20] The Next2Sun agrivoltaics project located in Donaueschingen-Aasen (Germany) is an example of vertically-mounted panels. The Next2Sun 4.1 MW solar project spans approximately 14 hectares. It was built with ~11,000 n-type PERT bifacial solar modules, vertically installed on 5,800 racks.[21]

Rangevoltaics refers to an enclosed area where agrivoltaic systems, vertically placed, act as a replacement for agricultural fences.

Next2Sun's panels have also been used in projects in Japan. In April 2022, it was reported that Japan's Institute for Sustainable Energy Policies and the Japanese engineering contractor Ryoeng Co., Ltd., built an agrivoltaics system with a vertical design in Nihonmatsu City. Heterojunction modules and mounting systems were provided by German companies, Luxor Solar and Next2Sun, respectively. The distance between the panel rows ranges from 8 meters to 10 meters. The agricultural surface within the rows can be utilized by local livestock farmers as pasture.[22]

Figure 6: Bifacial solar modules fence for livestock enclosure

Source: Next2Sun[23]

Agrivoltaics is also being explored for growing taller crops such as hops. In, France, Q-Energy is testing an agrivoltaics system that consists of two mounting units with 52 bifacial PV modules for growing hops, which can grow up to 8 meters in height.[24]

Figure 7: Agrivoltaics for hop growth
Source: Peter Moore (July 2022)[25]

Agrivoltaics can also be installed to create pollinator habitats that attract pollinators such as butterflies and bees, or agrisolar beekeeping.[26] The most widely deployed form of dual-use PV in the United States is pollinator agrivoltaics. According to an NREL study, pollinator agrivoltaics systems are already utilized in more than 1 GW of U.S. PV installations.[27]

Pollinator agrivoltaics is already utilized in more than 1 GW of U.S. PV installations.

Figure 8: Agrivoltaics farm to attract pollinators such as honeybees, bumble bees, and butterflies.
Source: NREL Image Gallery[28]

While the co-location of solar PV installations and agriculture has been a concept for decades, the use of agrivoltaics systems has remained largely a niche technology within the solar sector.[29] The dual-use PV industry is still behind the PV industry at large. Approximately 2.8 GW of solar and crop dual-use installations exist globally, with most of the capacity located in China, Japan, South Korea,[30] and Europe.[31]

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2.2 Benefits

In the research article entitled, "Driving and restraining forces for the implementation of the Agrophotovoltaics system technology – A system dynamics analysis," Daniel Ketzer and Peter Schlyter conclude that, "A key finding is that successful APV [Agrophotovoltaics] projects would require stakeholder involvement to achieve greater local acceptance. When it comes to production on agricultural land, APV systems may drive the land use efficiency to up to 186 percent when the PV-panels serve for protection against heat stress. On the other hand, altered precipitation patterns and impacts on agricultural cultivation and, especially, the landscape caused by the technical system, may restrain the application of APV."[32]

Agrivoltaics has close links to precision farming, which improves productivity through the use of technologies such as AI, sensors and yield monitoring.

The global agrivoltaics market is expected to increase in the coming years due to an increase in the global population, decarbonization efforts, limited availability of land for cultivation coupled with rising energy demands.[33] Agrivoltaics encourages photovoltaic self-consumption, since the energy needs of farms can easily be met with the electricity generated. Agrivoltaics also has close links with precision farming, which improves productivity through the use of technologies such as artificial intelligence, sensors, and yield monitoring technologies.[34] Other benefits include the creation of dual-revenue streams, the high suitability for areas with land use constraints, the creation of a beneficial microclimate and a potential reduction in operation and maintenance costs.[35]

Dual-revenue Streams for Farmers

Agrivoltaic systems allow farmers to continue to utilize the land below the panels for either grazing livestock or growing and cultivating a variety of crops while generating electricity at the same time. As such, these systems produce a dual-revenue stream.[36] Agrivoltaics has been carried out for berries, grapes, and orchard crops like apples, and is well suited for shade-tolerant crops such as cauliflower or cabbage.[37] Researchers from the University of Arizona determined that growing crops in the shade from solar panels can yield two or three times more fruit and vegetables than conventional agriculture setups.[38]

Researchers from the University of Arizona maintain that crops grown in shade provided by solar panels can yield two to three time more fruit and vegetables. than conventional farming.

Dual-revenue streams for farmers is especially notable in the case of South Korea and Japan,[39]

> In Japan and Korea, for example, policymakers intended to ensure that as many farmers and technicians benefit from APV [agrophotovoltaics] as possible. In Japan, the original purpose of APV implementation was to counteract the exodus from rural areas and farmers' surrendering of their businesses because of income deficits due to contaminated agricultural crop yields following the Fukushima catastrophe. In Korea, policymakers aim to establish an APV pension scheme by considering the demographic change in an aging farming sector, with many farmers retiring in coming years, thereby suffering from reduced income and buying power as their agricultural land lies fallow. Solar dual-use will at least enable retired farmers to benefit from the additional income generated by selling solar electricity, while the cropland beneath APV installations remains preserved for potential agricultural use in the future.

Creates Beneficial Microclimate

Agrivoltaics benefits include shade, reduced heat damage to crops, and increased water availability for crops by capturing fog moisture. Several research studies have shown that the co-location of plants underneath solar panels creates a beneficial microclimate for both the solar modules and crops.[40, 41] Researchers have found that solar PV can create a cooler environment[42] improving panel performance, while the increased shade can improve water-use efficiency, soil moisture content, and crop yields. For example, within the study cherry tomato production doubled in the agrivoltaics system and water-use efficiency for the crop was 65% greater than normal growing conditions.[43]

The shade from solar panels can also provide protection from the sun and heat for both agricultural workers as well as livestock and protect crops against extreme weather events such as hailstorms.[44] Occupational Safety and Health Administration (OSHA) requires shade structures to be put up on days when temperatures reach 80°F.[45] Agrivoltaics providing shade can protect outdoor workers from heat injury.

Land Use Constrained by Governments and Local Authorities

The dual use of the land for both solar power and agriculture is well suited for areas in which land use is constrained by governments and local authorities. A Michigan Technological University study published in May 2021 found that the co-location of solar and agriculture can increase local support for solar projects in areas where project developments could be perceived as a threat to agricultural practices. Results showed 81.8% of respondents would be more likely to support solar development in their community if it combined the production of both energy and agriculture.[46]

Local communities appear to be more in favor of solar when the production of energy and agriculture are combined.

Reduced Operation and Maintenance Costs

Furthermore, there are other lower-tier potential agrivoltaics benefits such as lower operation and maintenance costs for solar reduced by utilizing land for both solar power projects and livestock grazing. Grazing animals such as sheep have proven to be effective at reducing the need for mowing vegetation and using pesticides to keep vegetation maintained around solar arrays. Below are some examples:[47]

1. Agricultural uses such as grazing sheep can reduce landscaping costs and win project acceptance. For example, it has been reported that Tampa Electric pays a per-acre range of $250 - $750 for sheep to graze at its solar sites, which represents a 75% cost savings over traditional mowing. Tampa Electric also voluntarily spent extra money on putting down a nearly 3-foot predator barrier along the ground at the edge of the 7-foot fence to keep out coyotes, foxes, and raccoons.
2. See example from Cornell University

[Click to see video]

3. Enel Green Power began grazing sheep as a pilot on its 150 MW Aurora project in Minnesota in 2018 and moved to a full-on operations and maintenance program, with more than 4,000 sheep now grazing nearly 400 total acres across six sites. Enel has seen decrease in fire risk and mower-damage risk.
4. Nexamp owns and operates more than 150 solar sites across the U.S. and has seen an average of 19% cost savings across the sites it grazes saving "tens of thousands of dollars" annually.

Importance of Pollinators in Agriculture

In addition to honey bees, certain native bees, of which there are approximately 4,000 species in the United States, and other organisms contribute to agricultural pollination.[48] According to the U.S. Department of Agriculture (USDA), three-fourths of the world's flowering plants and about 35 percent of the world's food crops depend on animal pollinators to reproduce. In addition, "pollinators are facing a variety of stressors in the United States. The health of these organisms is of great importance to the U.S. agriculture, food security, and the Nation's overall economy. Pollination services add tens of billions of dollars to the value of agricultural crops annually."[49] Honey bees are the source of various products and services sold in several markets. The total annual value of U.S. honey bee products is an additional $700 million.[50] Some of the major U.S. crops pollinated by honey bees and other pollinators include almonds, non-citrus fruits, berries, melons, and squash. For example, bees alone support 45% of crop pollination in Massachusetts. Managed honey bees are commonly used as a way to pollinate crops. Improved pollinator habitats can increase the presence of native pollinators on vegetable, fruit, and grain farmland.[51]

Improve crop yields and crop quality

Agrivoltaics systems can improve crop yields and crop quality by optimizing shading and reducing evapotranspiration of plants, through innovations in or semi-transparent modules and trackers, which are available from many non-U.S. companies such as Sun'Agri,[52] the Agrovoltaico[53] system by Rem Tec, bifacial modules, and transparent Agri-PV panels such as those from BayWa.[54] For example, plastic covers used to grow strawberries and raspberries are being replaced with transparent PV panel modules from the Swiss startup Insolight and Indian manufacturer Saatvik Solar has developed bifacial PV modules with 21.12% efficiency and 545 W of peak power output.[55] In one vineyard agrivoltaics system field test in France, Sun'Agri concluded that water demand was reduced by 12% - 34% for the PV-sheltered vines due to a reduction in evapotranspiration. Another benefit was an increase in the aromatic profile of the grapes which was improved in the agrivoltaics set up, with 13% more anthocyanins – red pigments – and 9% - 14% more acidity.[56]

Innovations in semi-transparent modules and trackers can optimize shading and reduce evapotranspiration of plants - improving crop yields and quality.

Added Benefit of Hydrogen Production

Mobile solar PV panels are also being developed by several companies, which are touted to have additional benefits. In April 2022, a Dutch consortium made up of Npk Design, L'orèl Consultancy and LTO Noord reported successful development of a mobile agrivoltaics system (called the H2arvester) that claims to improve soil quality and biodiversity of agricultural fields. The system includes 168 solar panels and an irrigation system that can also provide water to the surrounding area. The system could also be combined with an electrolyzer to produce hydrogen, which could then be used as a green fuel for agricultural applications. Residual heat coming from hydrogen generation may also be used to dry crops, such as oats, grass, and alfalfa. The H2arvester is positioned by the company as "an 'extra crop' in the rotary cultivation of arable farmers and tulip bulb growers. Also, for dairy farmers, with whom the H2arvester solar cars 'rotate' with the outdoor grazing and/or move over ditches, this literally means double use of agricultural land and extra income is generated, with a maximum land occupation of 10% per hectare."[57]

Mobile solar PV panels such as the H2arvester can be combined with electrolyzers to produce hydrogen.

Figure 9: The mobile agrivoltaics array
Source: Emiliano Bellini (April 21, 2022)[58]

Potential for Rural Electric Vehicle Charging

Agrivoltaics presents an opportunity to improve electric vehicles' charging infrastructure in rural areas where electrical infrastructure tends to be weaker.[59] Rural areas may not have the requisite grid transmission infrastructure to support EV charging stations, and agrivoltaics would shift energy production to the point of use. Drivers could anticipate access to charging stations at the great majority of highway access points.[60]

Agrivoltaics presents an opportunity to improve the electric vehicle charging infrastructure in rural areas.

Figure 10: Solar-powered electric vehicle mulching on a farm
Click to see video

3.0 Agrivoltaics Technologies

Currently, the technology for agrivoltaics is the same as for traditional ground-mounted solar PV. However, the requirements for the technical components and supports need to be reconfigured for agrivoltaics application.

3.1 Solar Panel Designs Optimized for Agrivoltaics

Agrivoltaics use the same modules used in traditional ground-mounted installations. Fundamentally, all types of solar modules can be used in agrivoltaics systems. Modules with wafer-based silicon solar cells account for about 95 percent of the global PV market. However, there are efforts underway to design modules specific to agrivoltaics. Examples are provided below.

3.1.1 Artificial Intelligence and Software

Some monitoring systems utilize artificial intelligence (AI) to control the tilt of the solar panels to protect the crops. These systems require complex software models that take factors like crop growth phases and the weather into account. An example of the use of artificial intelligence is Sun’Agri’s viticulture agrivoltaics system, which was installed in Piolenc (Hérault region, France) as part of a program to test how agrivoltaics perform in specific crop cultures. Described as a “dynamic agrivoltaics system,” the 280 panels used have a generation capacity of 84 kW, were placed at a height of 4.2m, and can be moved in real time using an AI algorithm. “The algorithm is said to be able to determine the ideal tilt of the panels according to the sunshine and water requirements of viticulture, growth model of the crop, soil quality and weather conditions.”[61]

Sun'Agri agrivoltaism on vines Tresserre

Figure 11: Sun’Agri’s viticulture agrivoltaics system

Click to see video

The French companies Ombrea and RES are partnering to develop PV shade systems for agrivoltaics projects equipped with artificial intelligence technologies to make them react to unfavorable weather conditions.

Figure 12: intelligent shade systems for agrivoltaics
Source: Joël Spaes (November 16, 2020)[62]

French startup Ombrea[63] has developed a system powered by artificial intelligence to protect crops from extreme heat, drought, hail, and frost. The solar panel-based remote panel retracts in order to modulate light and shadow based on data collected through sensors on-site.

Figure 13: Mobile solar PV panels
Source: Catherine Rollet (December 5, 2019)[64]

3.1.2 Materials – Transparent Polymers

Solar panels are being developed using semi-transparent polymers that allow the wavelengths of sunlight needed for photosynthesis to pass through and absorb the rest to generate energy. Semi-transparent modules are available commercially. For instance, Soliculture's (Scotts Valley, CA) LUMO greenhouse technology. In 2020, the German company BayWa and and its Dutch subsidiary GroenLeven BV designed special monocrystalline solar panels for five pilot agrivoltaics projects in the Netherlands. The companies did not use "standard PV modules for the project, as such products are considered unsuitable in an efficient agrivoltaics project." Weather-resistant 260 W glass-glass panels with different transparency levels were beta tested with five different types of crops: blueberries, red currants, raspberries, strawberries, and blackberries. In addition, mounting systems were also designed specifically to dissipate heat in a way that benefits plants.[65]

Solar panels can be developed using semi-transparent polymers that allow the wavelengths of sunlight needed for photosynthesis to pass through.

In February 2022, Slovenia-based solar panel manufacturer Bisol launched a series of transparent solar modules specifically for agrivoltaics projects or solar carports. Bisol Lumina is designed with a matrix and has bigger gaps between solar cells and 30% transparency rate, which makes it suitable for agrivoltaics projects.[66] The modules come in two sizes, small and large: [67]

- Small module - 1,770×1,050x35mm, weighs in 20.5kg, and is built with 84 half-cut monocrystalline PERC bifacial cells with a size of 166x166mm.
- Large module - 2,110×1,050x40mm, a weight of 24.5kg, and is fabricated with 96 half-cut cells. Its front efficiency is 13.5% and the open-circuit voltage and short-circuit current are 32.9V and 11.2A, respectively.

Electrical Specifications @ STC (AM1.5, 1,000 W/m^2, 25 °C):

Module Type		BBO 300					
Number of Cells		96					
Cell Matrix		6 x 8 + 6 x 8					
Transparent Area	m^2	0.73					
	%	33					
		Front	Bifacial Gain				
Light Source	%	100	5	10	20	30	40
Nominal Power	P_{MPP} [W]	300	315	330	360	390	420
Short Circuit Current	I_{SC} [A]	11.2	11.8	12.4	13.5	14.6	15.7
Open Circuit Voltage	V_{OC} [V]	32.9	32.9	32.9	32.9	32.9	32.9
MPP Current	I_{MPP} [A]	10.7	11.2	11.8	12.8	13.9	15.0
MPP Voltage	V_{MPP} [V]	28.1	28.1	28.1	28.1	28.1	28.1
Module Efficiency	η_M [%]	13.5	14.2	14.9	16.3	17.6	19.0
Power Output Tolerance		±3 %					
Maximum Reverse Current		20 A					
Protection Class		Class II					

Figure 14: BISOL Lumina
Source: Bisol[68]

Swiss solar tech startup Insolight has developed modules based on the THEIA technology (Translucency and High Efficiency in Agrivoltaics). "Insolagrin is more than a simple solar installation. It's also a new tool for farmers, with dynamic adjustment of the light to optimize crops' growth over seasons and changing climate. The module measures 1,141 mm x 595 mm x 50 mm and weighs in at 15 kg. The open-circuit voltage is 44.8 V and the short-circuit current is 3.0 A. Its frame is made of anodized aluminum alloy and its junction box has an IP 67 rating. The panel can be used with operating temperatures between -40°C and 85°C. The power temperature coefficient is -0.32% per degree Celsius. Modules were deployed at a large-scale agrivoltaics pilot facility in Valais, Switzerland."[69]

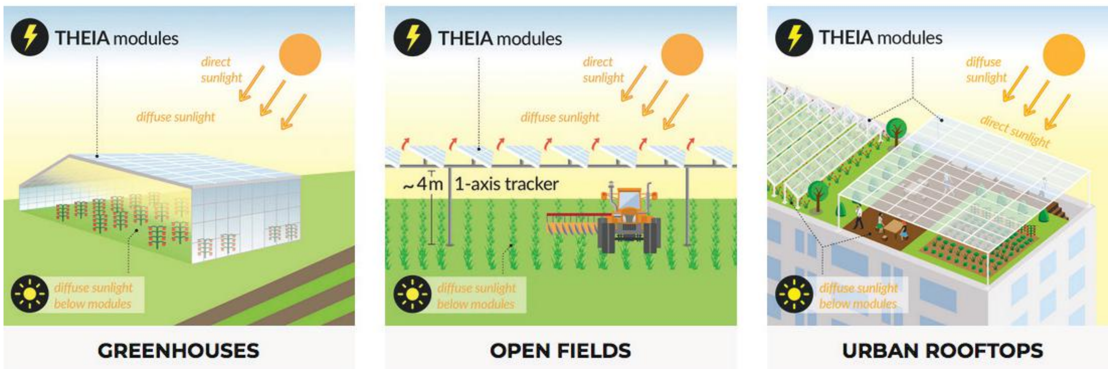


Figure 15: Solar modules are based on the THEIA technology
Source: Insolight[70]

Vietnam-based Irex (the PV module production unit of Vietnamese group SolarBK) introduced a glass-glass solar panel. The Irex Agri-PV glass-glass panel has a power output of 265 W and a power conversion efficiency of 18.1%. It is fabricated with 48 bifacial monocrystalline cells measuring 158.75 mm x 158.75 mm x 2 mm, with tempered glass featuring an anti-reflective coating.[71]

3.2 Mounting Structures and Designs Optimized for Agrivoltaics

The type of mounting structure must be adapted to the specific agricultural application and its respective needs. Agrivoltaics PV modules are typically installed at a greater height than traditional PV. In addition, to ensure that plants get sufficient light and precipitation, the spacing between the module rows is typically larger as compared to conventional ground-mounted photovoltaic systems. The system has to be carefully designed to ensure that it does not meddle with agricultural activities such as harvesting or reduce crop yield.

Researchers from the University of Science and Technology of China have developed a special design for agrivoltaics projects that, compared to other approaches, claims to reduce the shading effect of the PV installation and improve crops' light environment and the crop growth process, yield, and quality.[72]

Figure 16: University of Science and Technology of China
Source: Emiliano Bellini (August 2021) [73]

The Even-lighting Agrivoltaic System (EAS) is a novel design methodology utilizing metal brackets as mounting structures, conventional solar panels, and a grooved glass plate placed between the solar panels. The latter occupies an area that is one-third of the light-receiving area of the entire system.[74]

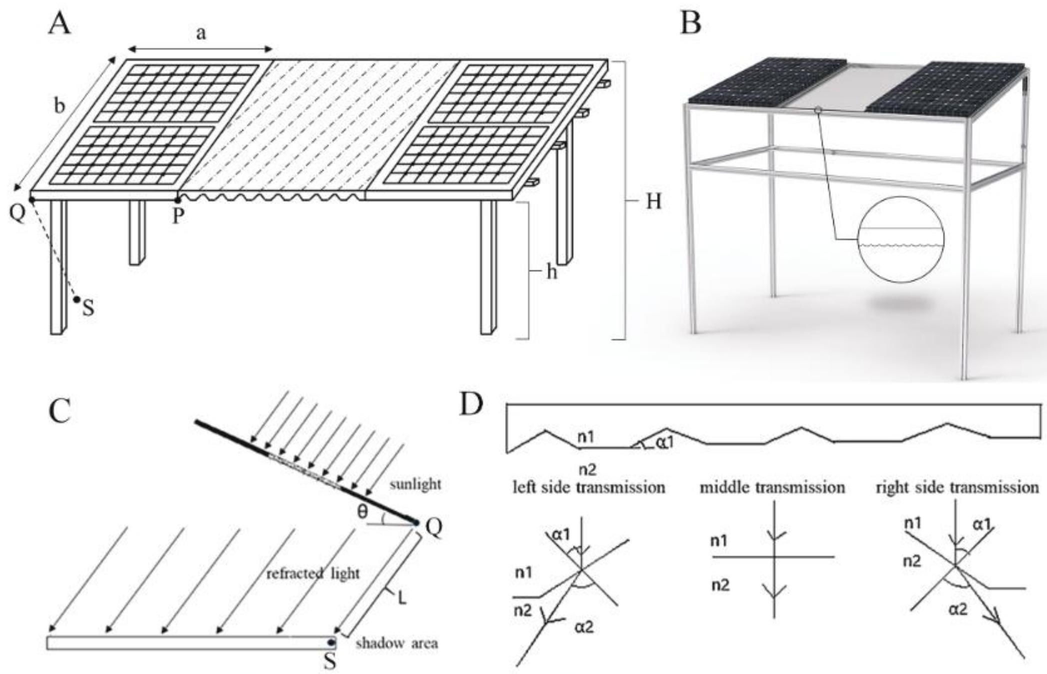


Fig 1. The structure of the EAS (A). The rendered output diagram of EAS structure (B). The side view of the EAS (C). The structure of the grooved glass plate (D).

Figure 17: 'Even-lighting Agrivoltaics System'
Source: Zheng J. et al (2021) [75]

Many companies are also designing mounting systems for agrivoltaics. Many Chinese manufacturers market agrivoltaics mounting systems. For instance, Mibet is marketing a mounting structure for agrivoltaics projects that can be applied to different crops. The structure is claimed to ensure different light transmittance levels and enable several PV system layouts in order to meet the needs for different crop growth.[76]

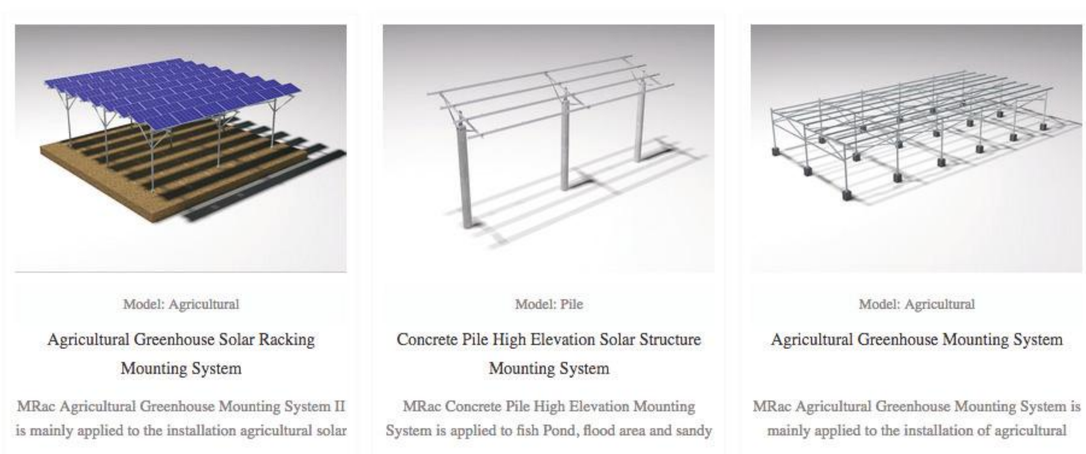


Figure 17: MRac Agriculture PV System
Source: Mibet Energy[77]

Belgium-based, voestalpine Sadef AG markets the FlexAgri Fruit system that serves several purposes. It is a canopy structure, supported by steel profiles and covers the fruit trees to offer ultimate protection and to serve as a mounting structure for solar panels. voestalpine Sadef has developed a steel structure to support the bifacial solar panels that are put in a field or a meadow. The farmer has enough space between the FlexAgri Vertical to mow or maneuver other heavy agriculture machinery.[78]

Figure 18: FlexAgri Fruit solar PV system
Source: voestalpine Sadef AG[79]

3.3 Tracker Designs Optimized for Agrivoltaics

Several companies have developed new tracking systems specifically for agrivoltaics, including:

1. Suspended solar rackin
2. Solar racking/mounting for greenhouse integration
3. Solar integration with livestock feeding structures

Solar FlexRack (Youngstown, OH), a vendor of PV mounting and solar tracker solutions, supplied its TDP solar trackers to Jack's Solar Garden, a 1.2 MW solar farm project located in Boulder County, Colorado.[80] Solar FlexRack offers custom-designed, fixed tilt ground mount and single-axis solar tracker systems.[81]

Figure 19: Solar FlexRack on Solar Mounting and Tracking Competitive Pricing
Click to see video

In 2020 Axial Structural Solutions, a racking systems manufacturer based in Spain, introduced Agritracker, a new type of solar tracker designed specifically for agrivoltaics installations. It adapts to sloping terrains and accommodates crops with different light requirements being planted beneath one installation (grapevine, fruit trees and vegetables, for example). The system can be adapted to various ground conditions and gradients. Modules can be installed at a height of up to 6.8 meters. The tracker supports up to 96 modules per motor, and independent rows of up to 32 modules, split into four groups of eight panels each.[82]

Figure 20: Axial AgriTracker
Source: Axial Structural Solutions[83]

Mechatron Solar (Stockton, CA) is an international commercial and industrial solar project developer that manufactures its own unique, patented dual-axis photovoltaic trackers. In July 2021 the company added the M16KD model, designed for agrivoltaics applications.

The mount features extra spacing between vertical panel stacks to permit light to pass through to crops beneath the structure:[84]

> The M16KD tracker, designed for agricultural installations, features a platform table that is eight panels wide and 10 panels high, with the addition of 10 inches spacing between the vertical panel stacks, which permits more light to reach crops beneath the tracker. The tracker yields solar power of up to 33.6KW using 420W modules. The lower edge of the panel platform moves between 4 feet and 14 feet off the ground, and the upper edge of the panel table moves between 29 feet and 14 feet off the ground.

4.0 Agrivoltaics Worldwide

Data from the German research group Fraunhofer Institute for Solar Energy Systems (ISE) shows that installed agrivoltaics has increased in capacity from 5 MW in 2012 to approximately 2.9 GW in 2018, and to more than 14 GW in 2021, with national funding programs in Japan, China, France, the United States, and South Korea. The report, "*Agrivoltaics: Opportunities for Agriculture and the Energy Transition—A Guideline for Germany*,"[85] estimates the total installed agrivoltaics capacity globally has grown to over 2.8 GW in 2020, from around 5 MW in 2012. Most of it is in China with about 1.9 GW capacity as of 2020. In 2021, Fraunhofer ISE reported the installed capacity was 14 GW compared to 1 TW of installed solar capacity worldwide.[86] Fraunhofer ISE reported China had the largest share in 2021 with an installed system capacity with 1,900 MW, of which 700 MW PV capacity is installed over goji berries grown at the edge of the Gobi Desert. Agrivoltaics is well known in European and Asian countries. Most notable is Japan, where nearly 2,000 agrivoltaics installations currently generate more than 200 MW of electricity and provide cover for more than 120 kinds of crops.[87]

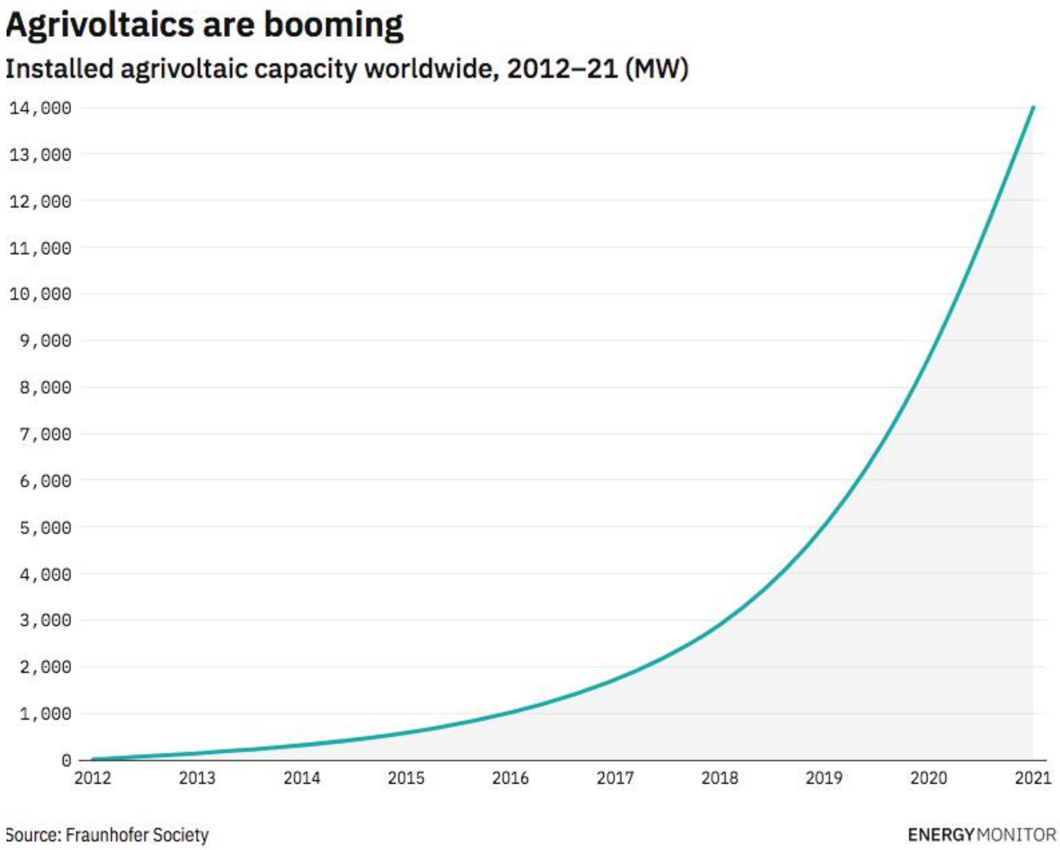


Figure 21: Agrivoltaics global installed capacity
Source: Nick Ferris (January 2022)[88]

4.1 Agrivoltaics Demand

The global agrivoltaics market is expected to reach the market valuation of 36,317.4 megawatts by 2027, expanding at a reasonable CAGR of 45% between the six years spanning 2021-2027.[89] Another market consulting firm, Fitch Solutions Country Risk & Industry Research expects agrivoltaics systems to gain traction globally over the coming years, with total installed capacity set to exceed 10 GW+ by 2030. According to Fitch Solutions Country Risk & Industry Research, the major market driver is the benefits of the co-location of solar power projects and agriculture. These benefits include the creation of dual-revenue streams, the high suitability for areas with land use constraints, the creation of a beneficial microclimate and a potential reduction in operation and maintenance costs.[90]

Consultancy firm Frost & Sullivan forecasts a total of $2 billion will be invested in solar PV through 2030, with half going to utility-scale projects and the rest going to commercial, industrial, and residential PV systems. The decline in costs for solar-generated power over the last ten years is expected to continue through 2030. In tandem, technology costs will also continue to decline although costs will decrease more slowly during 2020-2030 than the last decade (2010-2020). Innovations in solar are also occurring in siting and location of the solar panels. The land scarcity, country-level carbon neutrality targets, and falling prices will all contribute to the growth. Innovations in siting examples include:[91]

The deployment of rooftop solar PV systems has increased significantly in recent years. Rooftop solar PV market is expected to reach $124.36 Billion by 2028, growing at a CAGR of 6.01% between 2021 and 2028.[92]

1. Floating solar is promising, representing ~1% of global solar demand in 2021.[93] The market, estimated at 1.6 thousand MW in 2021, is projected to reach 4.8 thousand MW by 2026. China will dominate floating solar installations over the next five years, followed by India and South Korea.[94]
2. Interest in agrivoltaics is rising.[95]

4.2 Agrivoltaics in the United States

In the United States, agrivoltaics is slowly progressing via research at national labs, universities, private companies, and farmers. For example:

1. University of Massachusetts Amherst researchers are studying the effects of co-locating solar energy panels and agriculture operations at up to eight different farms across the state. This research will help farmers and communities make informed decisions about solar.[96]
2. Cornell University researchers are looking at the benefits of pollinator-friendly plantings on solar farms. One goal is to see if wildflower plantings on solar sites can increase pollinator populations. Another is to see if wildflower plantings on solar farms encourage pollinators to visit crop flowers. Other Cornell research is looking at how sheep grazing may influence pollinator habitat and sequestration of soil carbon.[97]

Table 1: Agrivoltaics Farms in the United States

Farm/Location	Details
Jack's Solar Garden (Boulder County, Colorado)	Jack's Solar Garden, a 1.2-MW solar farm in Boulder County, Colorado.[98] Jack's Solar Garden, a 1.2-MW solar farm in Boulder County, Colorado, is unique in that it represents the largest agrivoltaics research project in the United States and encompasses all four types of vegetation at a single site. Jack's Solar Garden produces enough energy to power about 300 homes and has more than fifty residential subscribers, five commercial subscribers, as well as the City of Boulder and Boulder County as subscribers. Additionally, forty types of plants, such as blackberries, herbs, and tomatoes, will be sowed under the solar arrays, and 3,000 trees, shrubs and other pollinator-friendly plants have been planted around the solar arrays.[99]
Solinator Garden (City of Fort Collins, CO)	In 2019, the City of Fort Collins, Namasté Solar, and Solaris Energy partnered to create a 1MW pollinator friendly solar installation. Solaris Energy, Namaste Solar integrated the 2,700 solar panels with a pollinator garden, promoting agriculture, birds, bees, and renewable energy, all on one site. The 1 MW of generating capacity is equal to the amount of energy used to power over 250 homes annually. Namasté Solar used Solar FlexRack's single-axis TDP Solar Trackers due to their versatility, as they enabled Namasté Solar to easily and efficiently install two-thirds of the solar panels 6 ft high and one-third of the solar panels 8 ft high.[100]
Crescent Run Farm, Skowhegan in Maine	Skowhegan in Maine, sheep owned by Michael Dennett of Crescent Run Farm in Jefferson have started munching under the 10,500 panels at a solar farm developed by ReVision Energy that supplies power for a handful of municipal buildings and a public school. ReVision Energy installed solar for sheep grazing at Crescent Run Farm. The 4 mW 10,500 panels making up the solar project provides energy to the municipal buildings in Topsham, Rangeley, Dover-Foxcroft, Rockland, and Vassalboro, as well as the Vassalboro Community School.[101]
Sun-Raised Farms, North Carolina	The solar developer, 02 emc, has integrated solar PV with sheep grazing at six of their ten solar installations in North Carolina.[102]

While a lot of research is underway, various demonstration sites around the country are seeking to address questions such as the long-term impact of solar energy infrastructure on soil quality, and suitable crops, etc.[103] The DOE SETO office and U.S. Department of Agriculture are funding agrivoltaics programs. SETO is working to better understand the economic, ecological, and performance impacts of agrivoltaics. For example:

1. SETO funded a project led by the University of Illinois to investigate solar co-located with pollinator plantings at large-scale installations, with teams of researchers working at seven separate sites in the Midwest.[104]
2. As part of the Innovative InSPIRE project, researchers from Argonne National Laboratory are counting bees' visits at pollinator-friendly vegetation grown underneath or near solar panels.

3. In May 2022, SETO announced the FARMS funding opportunity, which will fund projects that study how to scale up agrivoltaics, including pollinator habitat, and maximize the combined value to solar energy, pollinators, and agriculture.[105]

DOE is also supporting solar development and agriculture with their InSPIRE program. This program is managed by the National Renewable Energy Laboratory (NREL). It seeks to improve the mutual benefits of solar, agriculture, and native landscapes. There are more than twenty projects sites across the United States. These bring together a wide array of researchers, farmers, and industry partners.[106]

The U.S. Department of Agriculture, through National Institute of Food and Agriculture (NIFA) is also investing in the development of agrivoltaics. In September 2021, NIFA (a division of the USDA) awarded the University of Illinois a $10 million grant (2021-2025) for "Sustainably Co-locating Agricultural and Photovoltaic Electricity Systems" (SCAPES). SCAPES seeks to study agrivoltaics in a variety of land types and climate scenarios (Illinois, Colorado, Arizona). Three existing solar farms — Solar Farm 2.0 at Illinois, Jack's Solar Garden at Colorado State University, and the Agrivoltaics Learning Lab at the University of Arizona will be used in the study.[107]

Some states are making progress with respect to legislation. Examples are discussed below.

State of New Jersey

In June 2021, the Dual-use Solar Act was passed in New Jersey. This act set up a pilot program "to enable a limited number of farmers to have agrivoltaics systems on their property while the technology is being tested, observed and refined."[108] The New Jersey Agricultural Experiment Station was allocated $2M in the 2022 state budget specifically for building research and demonstration agrivoltaics systems on their research farms. These systems will allow for detailed experimentation and engineering that would not be possible in a commercial setting.[109]

State of Massachusetts

In 2018, the Massachusetts Department of Energy Resources established the Solar Massachusetts Renewable Target (SMART) program, which regulates incentives associated with new solar PV development. Agrivoltaics is included in the SMART program. The state of Massachusetts recognizes that "it is expected that in most cases individual crop yield (lbs./acre) or electricity output (kWh/acre) will be lower in dual-use systems than it would be if either activity was carried out alone, but that the combined value of crops and electricity produced will be equal to or higher than single-use of the land for production of crops or electricity alone."[110]

The Massachusetts Department of Energy Resources established the Solar Massachusetts Renewable Target (SMART) program which regulates incentives associated with new solar PV development.

Below is information on SMART:

SMART Program system parameters required for dual-use arrays:

- System Size: The capacity (rated electricity production) of the system must be no more than 2 MW AC.
- Height: The lowest edge of the panel must be at least 8 feet above the ground for a fixed tilt panel system, or 10 feet at horizontal position for tracking systems.
- Shading: During the growing season, the maximum sunlight reduction due to shading from the panels on any square foot of land under the dual-use system may be no more than 50%.
- Agricultural use: The system should be designed to optimize a balance between electrical generation and agricultural production, and the land must be under continuous agricultural production over the 20-year SMART program period.

Compensation
Specific kinds of dual-use systems are known as "Agricultural Solar Tariff Generation Units" (ASTGUs), and can qualify for financial incentives under the SMART program.

Qualifying solar PV systems receive a base compensation rate of $0.14-$0.26 per kilowatt-hour (kWh) of electricity produced, depending on the size of the system and the local electricity utility (e.g., National Grid, Eversource). As solar facilities are approved to participate in the SMART program and solar capacity is added to the electricity grid, this base rate declines at a rate of 4% per capacity block. Dual-use systems qualifying as Agricultural Solar Tariff Generation Units receive an additional $0.06 per kWh.

Annual Reporting Requirements
Owners and managers of ASTGUs must submit annual reports in order to maintain their SMART status detailing:

- Productivity of crop or herd: Including pounds harvested or grazed, herd size growth and/or success of the crop, as applicable, and actual productivity relative to expectations.
- Crop management: Any observable differences in necessary crop treatment relative to solely agricultural systems, including irrigation, soil amendments, disease and weed management, etc.
- Potential changes for future years: Including revised crop or grazing plans.

4.3 Global Overview

Agrivoltaics has benefited from government support programs worldwide. After Japan launched the first supporting scheme on agrivoltaics in 2012, other countries like China, South Korea, France, and Germany followed. The number of countries supporting agrivoltaics may increase in the future. This section discuses global agrivoltaics along with policies in select countries that are intended to grow this sector.

4.3.1. China

In an effort to maintain food security, in June 2022 it was reported the Chinese government plans to bar solar developers from building solar PV on farmland. A draft of the document as reported in the media would disallow solar development on forests and cultivated areas but allowed in special cases such as land used for farming equipment or buildings. It also encourages development of unused land.[111]

Driven by government support, agrivoltaics greenhouses flourish in China, growing tea, grapes, a wide variety of vegetables, and various types of mushrooms. The estimate is for more than 10 GW in the next few years and most of the agrivoltaics projects installed in China are BIPV in combination with plastic tunnel greenhouses with standard solar modules. Development to date has been driven largely by government support, permitting and financing can be obtained quickly.[112] An example of Chinese companies involved with agrivoltaics is publicly listed NESI, with Raysolar (a solar PV module maker that specializes in BIPV) a part of the NESI group of companies.

"Since 2016, Huawei and Baofeng Group have jointly built large PV power plants over the goji plantations. The solar panels have cut evaporation from the soil by 30–40% and increased vegetation coverage by 86% in just a few years."

China, the world's top solar panel producer, is home to the biggest agrivoltaics system: a project covering 20 million square meters of land in the desert in Ningxia. The agrivoltaics system was installed by the Baofeng Group, with Huawei supplying the inverters.[113]

Of the 2.8-gigawatt agrivoltaics systems installed globally, China had roughly 1.9 gigawatt of capacity as of 2020. Solar greenhouses have also played a vital role in China's agriculture. Solar greenhouses are widely used in the regions north of the Huai River and the Beijing area, where greenhouse usage has greatly reduced energy demand and carbon dioxide emissions. "New innovations in greenhouse design are allowing growers to produce more varieties of vegetables, even during long winter months."[114]

4.3.2 France

France remains interested in agrivoltaics. In France, several companies have emerged with the support of national government (such as Total, Sun'Agri, Ombrea). Large-scale energy procurements are seeing agrivoltaics projects with sophisticated crop plans (e.g., vineyards, orchards). Below are examples of French companies targeting agrovoltaics.

Total is exploring agrivoltaics through its group company **Total Quadran**. Total Quadran offers solutions from the production of photovoltaic cells to ground-based solar power plants and roof-mounted photovoltaic solutions. The company has a partnership with Agrosolutions (InVivo Group), a national union of agricultural cooperatives in France. Total Quadran is supplying PV solutions such as sun-shades, windbreaks, panels mounted on trackers, and conventional self-consumption installations. Agricultural land spread on 200 hectares has been identified for the solar PV installations. They will establish a research and development unit to explore and define economic models, identify challenges and solutions.[115]

In May 2021, French-owned state utility EDF Renewables and Cero Generation, a UK solar developer, acquired Green Lighthouse Development, a solar developer that specializes in agrivoltaics and has 2.4 GW of agrivoltaics systems capacity under development in France.[116] In May 2022, Cero Generation closed on a 48-MW agrivoltaics solar project in Lazio, Italy.[117] This is Cero's second large-scale agrivoltaics installation in Italy, in addition to another 70 MW agrivoltaics facility in the Province of Latina. Cero Generation, the company has more than 1.5 GW of solar PV projects under development in Italy.[118]

In March 2021, another French renewable energy company Voltalia installed an agrivoltaics project with 3 MW capacity in France with €700,000 funding contributed mostly by the community. It has a 20-year power sales agreement. "The solar panels are deployed 4.5 meters high using **dynamic trackers** that allows the passage of agricultural machinery while protecting vegetable crops from the heat optimizing agricultural production."[119]

Another French company Sun'Agri is targeting three high value-added agricultural sectors: viticulture, arboriculture, and vegetable farming for its agrivoltaics system. Sun'Agri provides the farmers with technical and administrative support as well as investors if they do not wish to make the investment themselves.[120] Sun'Agri works primarily with the RGreen Invest.[121] It also has agreements with Engie[122] and Boralex.[123] Sun'Agri has 37 agrovaltaics projects planned through 2023 mainly for vines and fruit trees. According to the company, the biggest hurdle that takes the longest time is obtaining building permits issued by the municipality.[124] In November 2020, RGreen Invest and Sun'Agri announced they will deploy solar panels for 300 agricultural farms in France to help farmers improve yield and deal with climate change. The project, called Cultivons Demain covers between 1,500 to 2,000 hectares of land.[125]

The French government is encouraging the development of large-scale agrivoltaics through competitive contracts.

The French government is encouraging the development of large-scale agrivoltaics through competitive contracts. France's most recent auction awarded 40 MW of agrivoltaics projects as part of its innovative PV award. Seven of those projects are agrivoltaics contracts awarded to Sun'Agri, ranging from 575 kW to 3 MW.[126] In addition, the French Environment and Energy Management Agency (ADEME) has defined new standards for agrivoltaics published on its website. The documents provide a definition of "agrivoltaics," along with a guide for the classification criteria.[127]

4.3.3 Germany

Agrivoltaics systems are specified in the legal framework in Germany.[128] The main driver for Germany's commitment is the 2021 amendment to the German Renewable Energy Act that went into effect in January 2021, which scheduled 50 MW bids with a combination of onshore wind, solar PV, biomass and/or power storage devices. Agrivoltaics and floating PV solutions can also participate in the bids.

In Germany, the Fraunhofer Institute has been conducting agrivoltaics crop trials since

2014 (winter wheat, celery, potatoes, grass clover).[129] For example, in 2021, BayWa r.e. and the Fraunhofer Institute for Solar Energy Systems ISE, along with other research partners set up an agrivoltaics system for research purposes in Gelsdorf, Rhineland-Palatinate. Eight different apple varieties are to be used to explore several research questions during this project, which is planned to run for five years. The project first compares apple production at the same location under four different crop protection systems: Foil roofing (blocks rain), hail protection nets (does not block rain), APV with permanent, light-permeable PV modules (blocks rain), and tracking PV modules (blocks rain if necessary).[130]

The main driver for Germany's commitment is the 2021 amendment to the German Renewable Energy Act that went into effect in January 2021.

German companies are also involved in agrivoltaics. For instance, in March 2021, tracking systems supplier Ideematec, Inc. received a supply order for customized tracking systems for 100 MW of agrivoltaics projects in France. Ideematec markets the Ideematec Horizon L:TEC® product forms the basis of the Ideematec Agri-PV system. For this project, the company modified and optimized the Horizon L:TEC® tracker model by adjusting the axis heights of the tracker and maximizing the rotation angle for the module to +/- 70 degrees, allowing the trackers to operate synergistically with agricultural equipment. Ideematec also designed an Agri-PV-specific control and agronomic-orientated monitoring system to improve crop production, land quality, and address specific needs of each Agri-PV project site.[131]

Another German company, BayWa r.e. (parent company BayWa Group) is a leading global renewable energy developer, service provider, distributor and energy solutions provider, and is actively shaping agrivoltaics. BayWa r.e aims to develop 250 MWp Agri-PV by 2025.[132] In March 2021, BayWa r.e. completed a 1.2 MW agrivoltaics project in the Netherlands. More agrivoltaics projects are set to roll out for pears, apples, and other fruits, with a combined capacity of 35 MW by 2022, all in Europe.[133]

German energy group Steag GmbH is another player in agrivoltaics. In March 2021, Steag GmbH announced it will build three solar parks with 244 MW combined capacity in Italy's Apulia (aka Puglia) region for an unidentified "renowned investor" on land that produces mainly olives but also almonds, figs, and tomatoes.[134]

4.3.4 Italy

In June 2022 it was reported that Italy's Ministry of Ecological Transition published the "Guidelines for the Design, Construction and Operation of Agrovoltaic Plants." The purpose of the guidelines is to clarify the minimum characteristics and requirements a photovoltaic system must have in order to be considered "Agrovoltaic." The guidelines open up incentives (yet to be determined) for agrovoltaics. The guidelines specify various activities considered agrivoltaics: agricultural cultivation, floriculture or livestock grazing, maintaining a significant percentage with respect to the "continuity" of the activity that was practiced prior to the installation of the agrovoltaics plant. A requirement is that at least 70% of the surface area is dedicated to agricultural activity. They distinguish two types of systems:[135]

1. Agrovoltaics systems that can, at a minimum, ensure an interaction between energy production and agricultural production; and
2. Advanced agrivoltaics systems, which are also eligible for incentives.

Italy's Ministry of Ecological Transition published the "Guidelines for the Design, Construction and Operation of Agrovoltaic Plants."

In April 2021, Italy's government made public the country's national Recovery and Resilience Plan, which outlines planned investments and reforms. Within the plan, €1.1 B of the nearly €6 B in renewables funding is set to go towards the development of agrivoltaics systems, with the government aiming to deploy 2 GW of agrivoltaics capacity over the coming years. "The investment will target the implementation of hybrid agriculture-energy production systems that do not compromise the use of land dedicated to agriculture but contribute to the environmental and economic sustainability of the farms."[136]

Italy plans to invest €1.1 B ($1.2 B) in agrivoltaics to create about 2 GW of capacity. In January 2021, Italy's Enel Green Power announced it was exploring the potential of solar PV complementing local farming practices through demonstration plants in Spain, Italy, and Greece. Enel Green Power launched experimental projects in Europe to evaluate best conditions for PV and agricultural activities to co-exist. Data collected from these projects in Greece, Spain, and Italy will be compiled in an Atlas to support future decisions on using best farming solutions for solar project sites. [137]

4.3.5 Japan

Revitalizing the use of abandoned farmland is a prime interest in the agricultural policy in Japan.[138] Agrivoltaics development in Japan took off after the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities ("Feed-in Tariffs (FIT) Act").[139] Two directives from the Ministry of Agriculture, Forestry and Fisheries, one in March 2013 and another in May 2018, institutionalized agrivoltaics and promoted its development. The second amendment of feed-in tariff Law in June 2020, enforced in April 2022, further paved the way for agrivoltaics in Japan. Agrivoltaics is expected play an important role to revitalize Japanese agriculture including reclamation of devastated or abandoned farmland as being included in the above-mentioned policies. If all abandoned farmlands were converted to agrivoltaics farms, 280 GW of electricity could be produced.[140]

For farmers to operate solar panels over crops and get credit, the Japanese **legislation requires farmers to maintain agricultural production above 80%** of what they produced before the panels were installed. In June 2020, the second amendment to the FIT Act added preferential treatment to agrivoltaics to encourage its further development: [141]

> There are three "regional use requirements:" (1) self-consumption rate must be at least 30%, (2) there must be a way to confirm the actual self-consumption, and (3) generated electricity must be usable during a disaster (a PCS or inverter with at least 10 kW operational capacity should be self-operatable without external power supply to provide

at least 1.5 kW output during disaster). For agrivoltaics, however, the first requirement of compulsory self-consumption is waived if all the following three conditions are fulfilled: (1) its capacity is within 10 to 50 kW, (2) it already obtained a farmland conversion permit for 10 years, and (3) it is agrivoltaics.

Agrivoltaics development in Japan took off after the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities ("Feed-in Tariffs (FIT) Act").

In Japan, it was reported the Japanese authorities released guidelines for the development of agrivoltaics projects and effectively excluded installations that do not host crops or livestock in the planning phase. Enough examples in Japan and the necessary data for verification could not be collected. Agrivoltaics projects must not exceed 9 meters in height due to building regulations. Projects that use trackers or are installed on barns and horticultural greenhouses are excluded. **The reasoning is that enough examples in Japan and the necessary data for verification could not be collected**. A rebate covering 50% of a project's costs is also available.[142]

Agrivoltaics emerged in 2004 and has now grown to encompass 2,000+ projects nationwide covering 120+ crops. There are 1,992 agrivoltaics farms (560 hectares) that exist throughout Japan. Most agrivoltaics in Japan is small-scale less than 0.1 hectares. It is estimated that total power generated by agrivoltaics is 500,000 to 600,000 MWh or 0.8% of the total power generated by photovoltaics in Japan in 2019.[143] There were 200 MW of grid-connected agrivoltaics projects in operation in Japan by the end of September 2021.[144] Over 120 crops are grown in agrivoltaics in Japan. The top ten most popular crops include mioga ginger, Sakaki or Japanese cleyera, paddy rice, shiitake mushrooms, and blueberries, fuki or butterbur, tea, green onions, pasture grass, and pumpkins. Paddy rice is ranked as the third most popular crop in agrivoltaics not necessarily because it agronomically fits to agrivoltaics but mainly because it is a major crop grown in Japan.[145]

It has been documented farmers are benefiting financially from co-location. In one example, one farmer was making an additional ¥24 million ($187,000) in revenue per year, eight times more than the maximum ¥3 million generated from his produce alone.[146]

In Serbia, the Ministry of Agriculture, Forestry and Water Management in Serbia announced €20 million for agricultural projects in the country by selecting projects through three separate calls under a 3-year joint initiative with the World Bank.

4.3.6 Serbia

In May 2021, the Ministry of Agriculture, Forestry and Water Management in Serbia announced €20 million for agricultural projects in the country by selecting projects through three separate calls under a 3-year joint initiative with the World Bank. Projects under the first call will support projects that produce fruits, vegetables, grapes and flowers. The total value of the project titled Serbia Competitive Agriculture Project (SCAP) is €38 million. Among renewables, adding solar PV technology to agricultural projects also qualifies for these grants.[147]

Agrosolar Kula is one of those agrivoltaics projects, worth €340M and planned. The project will be implemented by the Italian renewable energy company Fintel Energia, together with its partner company MK Group. The annual planned production of green energy of the project is about 832 gigawatt hours, which will meet the needs of about 200 thousand Serbian households.[148]

4.3.7 South Korea

South Korea has targeted 10 gigawatt of agrivoltaics capacity by 2030 under its Renewable Energy 2030 plan. It appears that **South Korea agrivoltaics appears to be policy driven**,[149]

> Policymakers in Korea have designed their APV implementation regulation in such a way that projects are executed by farmers in cooperation with local technicians such as mechanics and electricians, thereby ensuring a decentralized, equal distribution of APV. With a market size goal of 10 GWp and an intended APV project size of 100 kWp, 100,000 APV projects are set to be implemented in Korea by 2030.

South Korean companies have expressed an interest in agrivoltaics. For instance, Hanwha's Q Cells Division was selected by the South Korean government as a partner in the Agrivoltaic System Standardization Project, which included Yeungnam University in the role of consortium lead, and a small Korean company. Hanwha Q Cells will conduct research to develop advanced agrivoltaics systems for Korean rice paddies, farm fields, and orchards. Hanwha Q Cells is heavily investing in research and development for the next generation of solar power technologies and products, including tandem cells. The company is currently seeking to invest KRW 1.5 trillion ($1.2 billion) into research and manufacturing facilities by 2025.[150]

In June 2021, BASF and JS Power Co., Ltd., a company specializing in project development of renewable energy and photovoltaic application, entered a strategic Memorandum of Understanding agreement to jointly promote the usage of BASF Boldur poles for the facility structure of agrivoltaics power generation projects in Korea. Under the agreement, both companies will cooperate in developing 100 megawatts of agrivoltaics projects in Korea within three years and enhance the cooperation in technology, commerce, marketing, and business models.[151]

4.3.8 Spain

Although Spain does not have a policy for agrovoltaics, Spanish utilities such as Endesa[152] and its renewable subsidiary Enel Green Power España (EGPE) are developing projects with standardized crop plans (e.g., red peppers, broccoli, artichokes, thyme, pitayas, sage, oregano, rosemary, lavender, coriander, broccoli, cauliflower etc.)[153]

5.0 Barriers and Challenges

Agrivoltaics has very high potential, but still has multiple hurdles to overcome. Factors such as crop yield reduction, subpar PV system performance, and high installation costs make farmers look the other way.[154] Higher upfront costs, complex non-standard project designs, a lack of regulations and zoning for dual-use systems in most markets and the need to change farming logistics on the dual-use land have limited their installation to a handful of markets such as China, Japan, South Korea, France, and the United States. [155]

The question of how the research plots can be scaled up has not been addressed.

5.1 Can Small Research Plots be Scaled Up?

One concern, which partly pertains to cost, is the question of whether results at small research plots can be scaled up and if so how. For example, a 10-acre, 2 MW farm in Maine[156] was developed by BlueWave, along with Navisun, a solar power producer that owns and operates distributed and small utility-scale solar projects. The project combines solar and agriculture by positioning solar panels above the existing wild blueberry farm field.[157] Jack's Solar Garden is a 1.2-MW, five-acre community solar farm and is the largest agrivoltaics research project in the United States. The solar project was designed and built by Namasté Solar.[158] Other research projects are being undertaken at universities. However, in the literature review, the question of how the research plots can be scaled up has not been addressed.

5.1.1 Cost

The biggest concern is the capital cost of agrivoltaics, which may make it unattractive to PV developers and farmers. Researchers in Germany have stated that agrivoltaics projects are still considerably more expensive than ground-mounted PV plants, as detailed in their report (which is in German and not translated in English).[159] The estimated costs include:

> A reference project, an 850-kW ground-mounted plant with an average total cost of €572/kW and a required investment of €486,200/hectare. The estimated costs for a vertical agrivoltaics project with a capacity of 345.8 kW is €688/kW and the required investment is €237,760/hectare. For an agrivoltaics system with elevated modules and a capacity of 650 kW, the total cost was estimated at €1,234/kW and the total investment at €802,100/hectare.

The researchers found that agrivoltaics developers may incur higher costs during the approval process or due to design constraints. Furthermore, the use of special components such as modules, mounting systems, and trackers may significantly increase a project's cost, especially if vertical plants are planned or the modules must be elevated to let the agricultural machinery operate underneath. Specifically:[160]

1. The substantial difference in costs between agrivoltaics and ground-mounted solar results from higher tracker system costs. Agrivoltaics projects also face more system design constraints as they have to deal with subsoil conditions and are strictly dependent on the chosen type of agricultural use.
2. Agrivoltaics project developers may also incur higher costs during the approval process. These include the identification of the location, soil and environmental reports, development plans, and legal fees of different kinds.
3. Vertically erected agrivoltaics projects are usually built with bifacial panels with

a high degree of bifaciality and a west-east orientation. The additional costs of these panels, however, do not justify the disproportionately higher costs. Special mounting structures are not produced on a mass scale, which also increase a project's costs. The increase in costs is estimated from €220 to €250/kW for the modules and from €75 up to €200/kW for the racks.

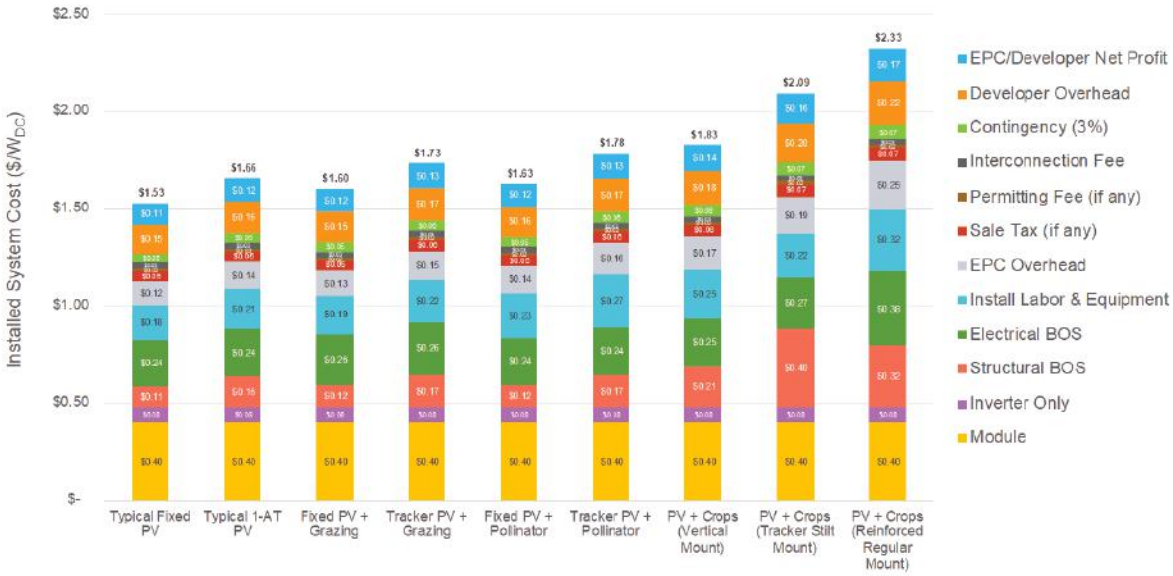
4. For agrivoltaics systems installed at a high distance from the ground, which is necessary to let the agricultural machinery operate under the solar panels, the costs are even higher compared to conventional solar plants. The scientists estimated a total cost of €400/kW for the entire plant construction including the foundations. Mounting systems are expected to cost between €130 and €220/kW, while the cost of highly transparent modules may rise to up to €330/kW. Site preparation and component deployment costs between €250 to €350/kW.
5. Agrivoltaics installations relying on trackers may be much more expensive, as the tracking system may have to be placed at a height of up to six meters.

Agrivoltaics project developers may also incur higher costs during the approval process. These include the identification of the location, soil and environmental reports, development plans, and legal fees of different kinds.

In addition, the cost of agrivoltaics is considerably more than traditional mounted PV with respect to mounting. "The skyrocketing cost of steel has a direct effect on agrivoltaics' emphasis on raising the panels 10 to 14 feet."[161]

In the report, "Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops," National Renewable Energy Laboratory researchers Kelsey Horowitz, Vignesh Ramasamy, Jordan Macknick and Robert Margolis[162] estimated an installed cost premium of $\$0.07/W_{DC}$ to $\$0.80/W_{DC}$ for dual-use PV systems over conventional ground-mounted PV systems installed over bare ground. The researchers found the highest premiums were for PV + crop use cases because of the use of modified PV support structures. In all cases, site investigation costs are higher because of the additional effort needed to plan and design for these more complex installations and to coordinate across additional stakeholders (e.g., farmers).

The figure below shows the U.S. installed costs for their benchmark systems. As seen from the figure, "dual-use PV scenarios have a higher installed capital cost than scenarios with typical PV and a conventional structure installed over bare ground. The **smallest price premium is associated with PV + grazing systems, which can use conventional PV structures and do not require as much site preparation or seeding**, as is the case with pollinator-friendly PV. However, the PV + grazing results shown here are for sheep grazing, which is currently more common; cattle grazing scenarios are expected to be more expensive because of the need to elevate the panels and, in some cases, reinforce the system structure."[163]



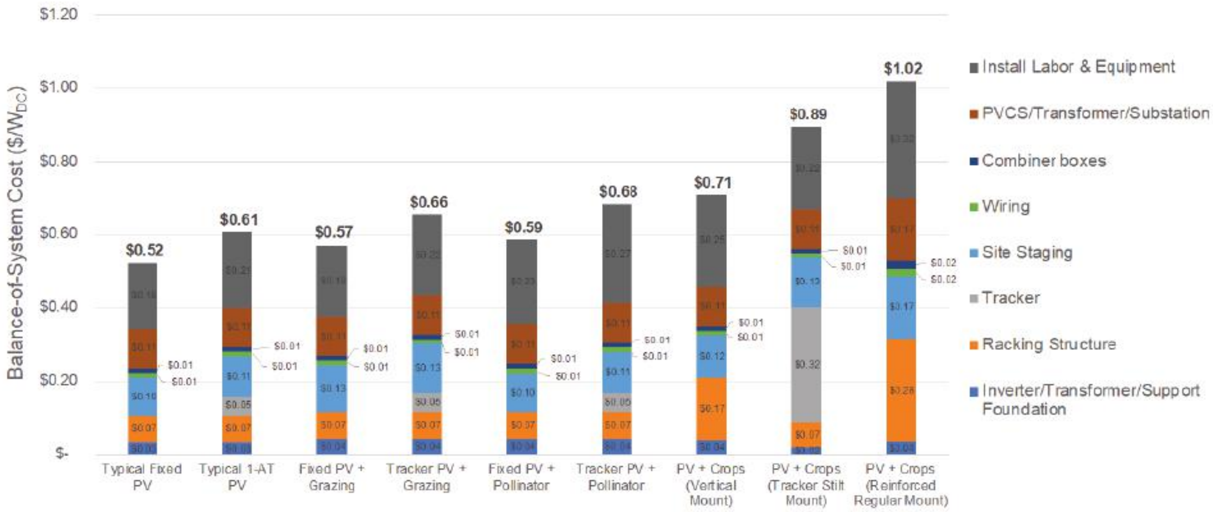
PV installed system costs for each dual-use scenario with benchmark assumptions for a PV system with 500 kW rated power

Costs are based on a simple average of modeled costs in Oregon, Arizona, Michigan, Massachusetts, New York, Connecticut, California, and Illinois—states that currently have one or more types of dual-use PV systems installed.

Figure 22: Installed System Costs for Dual-use Scenario for a 500 kW Rated Power PV System

Source: Kelsey Horowitz, Vignesh Ramasamy, et al. (2020)[164]

The next figure provides a breakdown of balance of system (BOS) costs. "Differences in the cost of the racking structures are also important among the PV + crop scenarios; however, much of the racking structure in the stilt-mount case is included under the 'tracker' cost category. The elevated, reinforced regular mount PV + crop systems need more pounds of steel than the typical systems, PV + grazing, or PV + pollinator habitat systems because of their panel elevations and atypical support structures."



BOS cost breakdown for each dual-use scenario with benchmark assumptions and a PV system with 500-kW rated power

Costs are based on a simple average of modeled costs in Oregon, Arizona, Michigan, Massachusetts, New York, Connecticut, California, and Illinois—states that currently have one or more types of dual-use PV systems installed. Site staging costs include items such as access roads, fencing, temporary office space, and module storage boxes. PVSC = PV Combining Switchgear.

Figure 23: BOS Cost Breakdown for Dual-use Scenario for a 500 kW Rated Power PV System

Source: Kelsey Horowitz, Vignesh Ramasamy, et al. (2020)[165]

5.3 Social Acceptance

Opposition from local governments and residents is common tip solar projects.

Opposition from local governments[166] and residents is common with solar projects. An example is BlueWave, an agrivoltaics developer that was one of several defendants named in a suit over a proposed plan for agrivoltaics in Northfield, Massachusetts. A state court ruled that the neighbor had standing to challenge the proposed development. Some chapters of the Audubon nonprofit environmental organization have been vocal about the technology's potential effect on wildlife. [167]

The opportunities and barriers for agrivoltaics in the United States are described in the paper "Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of Agrivoltaics," published in *Energy Research & Social Science* by Alexis Pascaris and other researchers from the Michigan Technological University and the Department of Energy's Sandia National Laboratories. The study conducted fourteen interviews with people who self-identified as solar developers, solar performance engineers, and energy policy experts, ten of whom had some experience with agrivoltaics, with most of that experience involving passive grazing or pollinator-friendly planting systems. The study made several findings:

Complexity, Risk, Safety, Liability
Solar industry professionals in this study view agrivoltaics projects as complex and requiring extra effort to actualize, including added layers of intricacy in system design and increased coordination with stakeholders. Concerns of complexity range from the technical details of accommodating a dual use under the solar array, the impact, of say, non- optimal tilt angles on electrical production, and other considerations such as balancing stakeholder interests, all of which encumber project development.

Further, participants also raised concerns around risk, safety, and liability, which represent notable market barriers to the realization of agrivoltaics projects. Both developers and engineers were thoughtful about the logistics of hosting a farmer on an electrical site.

Economic Profitability
Participants lamented the constraint economics pose on project fulfillment, explaining that a development has to "pencil financially" in order to be realized. Some participants expressed doubts that investors would finance an agrivoltaics project because dual use has the potential to compound risks and uncertainties. Similarly, participants stated concerns about the costs associated with the increased coordination required to actualize a dual-revenue stream.

Retaining Agricultural Interests
The importance of local communities in determining the success of a solar development is a major theme in the interview results. Participants spoke from experience as they described instances in which their development pursuits were halted by localized community resistance.

Socio-political Acceptance
Community acceptance implies the existence of local zoning bylaws that are favorable of solar development, indicating that socio-political acceptance is embedded within the community dimension of social acceptance of agrivoltaics. Absent of supportive local policy, participants expect agrivoltaics development to encounter challenges.

According to their findings, solar developers and agricultural industry professionals are thinking about very different issues regarding the opportunities and barriers associated with agrivoltaics. "The different opportunities and barriers raised by these two different groups of actors highlight the potential for complex interactions in Agrivoltaics decision making," the paper notes. "If actors come to the table with divergence in their motivations, their concerns, and what they view as the opportunities and barriers, it may be more difficult for them to work together and ensure that each group has their needs and priorities addressed."[168]

In the research article titled, "Driving and restraining forces for the implementation of the Agrophotovoltaics system technology – A system dynamics analysis," Daniel Ketzer and Peter Schlyter et al. concluded that, "system design factors and operator modes are amongst the criteria that may influence the local acceptance in society, farmers' motivation for APV and economic factors for the market launch of APV."[169] The researchers make the following recommendations:

Besides the technical issues, the series of causal loop diagrams (CLDs) illustrate the **importance and influence of local acceptance, planning frameworks and local knowledge as driving and restricting factors for the technology**. Bringing stakeholders', citizens' and experts' perspectives into a system design allows for identifying the need for improvement in the technology and shape the required political framework.

Even though the basic relationships may be transferrable, some of the key driving forces and feedbacks need to be specifically assessed depending on local site conditions and crop type. Hence, this CLD-based representation underlines the need for a locally adapted framework, as the implementation of the APV-technology would lead to different outcomes in different regions. The strong dynamics between the systems and the partly large influence of an alteration of single factors might initially appear too complex to be solved. This is why leverage points need to be identified for which acceptance criteria for a sustainable framework could be developed. In order to provide detailed analyses, **a decision support tool needs to be implemented supporting a wide array of stakeholders based on a quantitative model and relying on yield data, radiation data etc. and could easily be developed, if data is available**.

5.4 Approval Process and Design Constraints

Agrivoltaics developers may incur higher costs than traditional PV during the approval process or due to design constraints.

Agrivoltaics projects are more expensive than ground-mounted PV plants. Agrivoltaics developers may incur higher costs than traditional PV during the approval process or due to design constraints. Furthermore, the use of special components "such as modules, mounting systems and trackers may significantly increase a project's cost, especially if vertical plants are planned or the modules must be elevated to let the agricultural machinery operate underneath."[170] In addition, very few module manufacturers market modules of a suitable size and efficiency for agrivoltaics systems. The PV modules, for example, should be lightweight as they are elevated. The modules and structures also need to be designed in such a way that shadows cast on the ground are optimized for the crops.[171]

5.5 Technical Barriers

One important technical barrier is the availability of solar panels, modules, and structures that are appropriate for agrivoltaics projects.

5.5.1 Lack of Data on Agrivoltaics Crop and Animal Production

Although agrivoltaics systems are increasingly being installed globally, there is very little scientific research examining their impact on agronomic parameters such as crop performance and crop yields:[172]

> Altered microclimate conditions in an APV [agrivoltaics] cultivation system may trigger several effects on crop yield and quality of the harvestable products. However, there are no data available for a large number of crop species. Moreover, as the results mainly stem from netting and agroforestry experiments, there are limits to their transferability to APV systems. This emphasizes the need for distinct investigations for crop cultivation under APV. Nevertheless, the most prevalent change affecting plant cultivation will be the restricted light availability, which will most likely lead to yield losses in the majority

of cultivated crops. The extent of the losses will very much depend on the local climatic conditions, particularly solar radiation, and the technical implementation of the APV system.

Mounting structures for agrivoltaics systems are taller than those of standard PV systems to accommodate crops and require special fixtures to place them on the ground; they cannot use a lot of concrete as that impacts arable land negatively.

The agrivoltaics system has to be carefully designed to ensure that it does not interfere with agricultural activities such as harvesting or reduce crop yield. Since food production is the top priority, the PV system used in agrivoltaics is usually suboptimal, as it is oriented in the same direction as the farm and is tilted to shade the crops properly rather than solely focused on energy production. Agrivoltaics systems usually reduce crop yields compared to an open field due to uneven shading, and module spacing is crucial to minimize damage. Moreover, mounting structures for agrivoltaics systems are taller than those of standard PV systems to accommodate crops and require special fixtures to place them on the ground; they cannot use a lot of concrete as that impacts arable land negatively.

Similarly, there is a paucity of information on the impact of solar panels on pasture and animal production. Solar panels in agrivoltaics systems can provide cool microclimate for grazing livestock, promoting animal welfare by providing shelter from sun, wind, and predators. One study found that spring lamb growth and liveweight production per hectare from open and solar pastures demonstrated that agrivoltaics systems would not decrease the production value and potential of the land.[173]

5.5.2 Technical Crop Management

Agrivoltaics systems impose several requirements on crop production and its technical management, creating all sorts of issues, as noted by one study: [174]

> First of all, the mounting structure needs to be adjusted to the requirements of the agricultural machinery used. As already mentioned, the PV panels have to be raised to an adjusted overhead clearance to permit conventional agricultural machines to pass. For cereal cropping with its large combined harvesters in particular, a clearance of at least 4–5 m is required. To prevent the loss of utilizable land, the distance between the pillars needs to be suitable for planting distances and working widths of the machinery. Our APV [agrivoltaics] field trial showed that driving machinery underneath the APV facility and the arrangement of driving lanes require some experience and the driver's increased attention to prevent damage to the facility. In addition, the working width needs to be adjusted to the distance between the stilts. Given the fast development of autonomous driving and precision-farming applications, we expect these restrictions to be of minor importance for future large-scale arable farming. However, a certain loss of production areas between the stilts that are difficult to reach by agricultural machinery is inevitable and should be considered when predicting impacts on agricultural yields.

One study mentioned the PV structure itself is a constraint, with reference to workers being authorized to work at a certain height (in the U.S., the Occupational Safety and Health Administration has jurisdiction over this):[175]

The structure supporting the panels is a constraint for the farmer. Once it is implemented, he cannot change the dimension of his agricultural machines because the design of the PV plant is based on the dimensions of the machines used. Farming around metal poles is more difficult. The system of irrigation also needs to be adapted. The use of some chemical products has to be controlled to ensure they cannot damage the metal structure or the panels. The elevation of panels is also a constraint for the operation and maintenance of the solar farm. **Maintenance personnel must be authorized to work at heights.** The exploitation of the agricultural and solar farm is much more complicated when an agrivoltaics system is implemented and it requires adaptation of cropping practices.

5.5.3 Longtime Effect of Agricultural Activities on PV Modules

The effect of dust spread by products, components, and fertilizers employed in agricultural activities to ensure crop production could impact the reliability and durability of PV module materials, in addition to impacting the power output of the system. Studies documenting PV module longevity could not be identified.

5.6 Legislation

The absence of incentives is another major impediment that makes farmers ignore agrivoltaics. Existing policies do not specify standards that explain the dual use of land, leading authorities to dismiss agrivoltaics systems. This gives rise to permitting issues, and there are no incentives to sell electricity to the grid (e.g., via feed-in tariffs) that traditional solar enjoys.[176]

One of the main challenges hindering development of agrivoltaics in the U.S. is the absence of regulatory frameworks to support the development of agrivoltaics projects. Agrivoltaics systems have no specific incentives as compared to traditional ground mounted solar systems.

One of the main challenges hindering development of agrivoltaics in the U.S. is the absence of regulatory frameworks to support the development of agrivoltaics projects. Agrivoltaics systems have no specific incentives as compared to traditional ground mounted solar systems. Few states specifically address the overlap between siting renewables and the effect on agricultural lands, most merely require that siting or permitting authorities.[177] Some states are moving in this direction, one example is New Jersey:

Rutgers Agrivoltaics Program[178]

The State of New Jersey has set a very aggressive goal for 100% renewable energy by 2050. According to the 2019 Energy Master Plan, this will require 32,000 megawatts of installed photovoltaic electricity. Successfully meeting the 2050 goal will likely require utilizing both developed and currently undeveloped land (including farmland) for photovoltaic infrastructure.

In June 2021, the New Jersey Legislature passed the Dual-use Solar Act, which establishes the Dual-Use Solar Energy Pilot Program for unpreserved farmland. This program will

> enable a limited number of farmers to have agrivoltaics systems on their property while the technology is being tested, observed and refined. Dual-use solar energy (also called Agrivoltaics) offers the potential to both create sustainable renewable energy and keep the precious farmland below it productive and profitable. Until recently, very little agriculture could be done on land with solar panels because of the difficulty in using farm equipment around them and the substantial shading that occurs from the panels. Properly designed agrivoltaics systems have the potential to be built high enough that they allow for farm equipment operation below and also relatively uniform ground-level illumination resulting in lower impact on crop productivity.

Specific recommendations include:[179]

> Based on the analysis results, a comprehensive legal framework for Agrivoltaics should arguably include a combination of federal and state energy financing mechanisms coupled with favorable state and local land use policies. Specifically, a state-level feed-in tariff and local government allowances for mixed land use between solar and agriculture will be the key features of an enabling legal framework.

5.6 Other Non-technical Barriers

There are other additional barriers to agrivoltaics, discussed below.

Finding Willing Farmers
The challenge with grazing is not the technical aspects of the agrivoltaics itself but a "challenge to scaling up is finding local shepherds. It's more that the [grazing] industry needs to catch up and generate interest among other people who want to get into it."[180]

Keeping Predators Away in Agrivoltaics Grazing
A classic ranching challenge with grazers is successfully keeping predators away, especially in the western United States. Tucson Electric Power ran into this problem at this agrivoltaics pilot:[181]

> Tucson Electric Power brought 30 sheep to one of its own sites in 2018. They lasted one year. At the Red Horse site, there was one Great Pyrenees dog for every 30 sheep. Tucson Electric Power's site involved an easement with Pima County, as well as a battery storage device that needed access. Dogs created too much of a liability, but without them, coyotes kept getting to the lambs. Both the shepherd and the utility broke even for the year, but discontinued the grazing there. "As much as we wanted to get dogs there, people needed access regularly. It was too much of a [safety] risk."
>
> Tucson Electric Power is building a 100-acre, 15 MW solar site that the utility will own outright when it comes online in the next few years. Grazing livestock there is a five-year plan at this point.

6.0 CONCLUSION

Agrivoltaics which allows for the simultaneous use of land for both agriculture and photovoltaic power generation is increasingly viewed as a possible solution to the land demands of ground-mounted solar used strictly for power generation purposes. This report provides insight into the wide variety of configurations that are currently used in agrivoltaics and the benefits garnered when used with livestock, in fruit and vegetable production and for pollinators. The agrivoltaics advances that are being made due to the use of artificial intelligence, transparent polymers, mounting structures and racking systems are also discussed.

The United States is lagging behind Europe and the Asia-Pacific region in the adoption of agrivoltaics. China has the largest installed base and is the home of the biggest agrivoltaics system: a project covering 20 million square meters of land in the desert in Ningxia. An introduction to the agrivoltaics initiatives in China, France, Germany, Italy and other countries is provided, as well as an overview of various demonstration sites in the U.S. The report concludes with a discussion of the barriers and challenges to be addressed.

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