Agrivoltaics: An emerging technology for small-scale and urban agriculture

by

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A REPORT

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Abstract

Agrivoltaics is the practice of producing crops or raising livestock under and around photovoltaic solar panels. With land increasingly in demand for both food and energy, agrivoltaic systems can help producers use land more efficiently. This report serves as a guide for farmers and educators exploring agrivoltaics for the use of urban or peri-urban agriculture. Solar power basics, system geometry, and types of arrays are discussed. Practical design including solar resource evaluation, determining spacing and panel configuration, power storage, and maintenance planning are critical for success. Using Kansas-based field experiments as case studies, we compare fixed-tilt, uniaxial tracking, and vertical-bifacial systems to evaluate how each configuration of panels affects crop light levels and site usability. Light characterization data under/around these arrays over a growing season are presented, and the importance of dead zones in agrivoltaics systems are discussed. In the report, worksheets and examples are provided to help guide growers through early design and consultation with licensed professionals. Our findings suggest that agrivoltaics must be site-specific, and are affected by the soil, climate, and farm management priorities at a given operation. Interdisciplinary collaboration and informed decision-making are encouraged to promote safe and efficient agrivoltaics systems that benefit small-scale, urban growers. For local and urban growers, agrivoltaics and co-located production as a farm operations strategy propose an opportunity to strengthen energy independence, improve land efficiency, and drive innovation in local, sustainable agriculture.

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Acknowledgements

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I am deeply grateful to the staff and students of the Olathe Horticulture Research and Extension Center (OHREC). Their daily dedication — from routine fieldwork to the planning and construction of an entirely new horticultural research facility — made this project not only possible, but an exceptional experience throughout. Your commitment, skill, and patience shaped every stage of this work, and years of my life to come.

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Introduction

Underlined words are defined in the 'Key Terms' section at the end of this report.

Land-Use Competition

Figure 1 - Sheep grazing under solar panels at Colorado State University's ARDEC Research Center

Renewable energy production is a "growth industry" in Kansas and worldwide as governments and businesses work to offset the negative impact of climate change and reduce reliance on fossil fuels. Recent estimates have suggested that solar power generation (often referred to as 'photovoltaics') in Kansas will increase by more than 3000% in the next few years (Hack, 2023). The large-scale deployment of solar panels offers a clean energy alternative, but can come at a cost, including using vast tracts of land to develop solar that could otherwise be used for agriculture or other uses. This high demand for two different kinds of land-use poses a significant challenge (King et al., 2024), especially in regions with a strong agricultural history, like Kansas.

Selecting the location where solar systems are installed can be critical to their success. In Kansas, however, many of the most "ideal" sites for solar power generation are already occupied by agriculture (Morris, 2024). Compared to 2000, agriculture globally may lose land area which

accounted for 3-4% percent of food production to urban expansion by 2030—and by then the strategies required to avoid needing even more land than now to produce sufficient food are unlikely to be implemented at the scale or speed to counteract the increase in demand (King et al., 2023). If solar continues to expand according to current projections, it could demand up to another 1% of global cropland, with other renewables factored in. Additionally, solar developers benefit from the availability of relatively flat, accessible land – the same land that farmers prefer. The singular issue of land-cover or land-use (i.e. the desire of neighbors or local governments for an alternative to developing solar nearby) can be enough to slow the permitting process or stop it altogether.

What is "Agrivoltaics"?

Agrivoltaics (APV) is the practice of growing crops and/or livestock on the same land as solar panel arrays (Figure 1). This co-location strategy has the potential to optimize land-use and generate clean energy without sacrificing valuable agricultural production space (Trommsdorf et al., 2022). Agricultural production co-located with photovoltaics can range from simple grass plantings for livestock grazing to intensive, specialty crop production.

Beyond the choice of land-use, the environmental implications of solar power generation regarding wildlife endangerment, habitat loss, water and streams, and more have also caused public concern (Pizzo, 2011). The impact that solar power development has on soil health is debated; different policies can greatly influence how small-scale landowners can implement solar power (Yang, 2025). In Kansas, for instance, solar installations are exempt from property tax for the 10 years after installation, but this exemption can require conditional use permits from county governments (Kansas, 2021). While agrivoltaics is not without its own complexities, co-

locating agriculture and solar power could help provide a middle ground for many of the concerns discussed in this section.

Agrivoltaic Cropping Systems Showing Viability

There are several different cropping systems that have been studied worldwide which included power generation through agrivoltaics. The following examples show the wide diversity of ways in which this concept can be applied.

1. Orchard & Vineyard Applications (Figure 2)

Figure 2 - Workers operating an agrivoltaic orchard setup. Source: Sun'Agri. (2024). Fostering food sovereignty by protecting agricultural production. https://sunagri.fr/consultation-publique-sur-lagrivoltaisme-la-reponse-de-sunagri-et-okwind/

The production of fruit in temperate climates has recently seen the implementation of multiple methods of protection for the crop, such as plastic or colored netting to filter sunlight and precipitation (Livera et al., 2025). Panels are being increasingly introduced to provide similar protection to high-value crops such as fruit. Technology like semi-transparent panels allow for light-modification while still producing electricity. Since crops in orchards can benefit in yield and/or composition from specified shading techniques, the panels may be potentially doubly effective, increasing productivity at a site in both fruit and in electricity generation (Serra et al., 2020).

2. Row-Cropping with V-BF Panels

Currently under development worldwide and especially in central Europe are agrivoltaics applications which are constructed to allow for row-crops. These systems typically utilize vertical, bi-facial panels, The direct, indirect, and interactive effects of these systems are still being determined, but that has not stopped farmers from demonstrating it with multiple different crop species (Figure 3). Mathematical modelling of these systems suggests that they could provide energy and plant-available sunlight at levels comparable to other, more-established configurations, with potential benefits in equipment access and cost savings (Riaz et al., 2019).

Figure 3 – Grain combine and companion tractor harvesting row crops in Germany. Source: Next2Sun. (2024). Vertical Agri-PV for dual land use [Photograph]. https://next2sun.com/en/agripv/

3. Solar Grazing / livestock APV

Perhaps the most "popular" form of agrivoltaics today, solar grazing (Figure 4) gets its popularity from its ease of application. Potential benefits include shade and protection for livestock and vegetation management for the solar operation. Solar grazing is being investigated worldwide as it is suggested to be highly integrative with existing solar installations and have relatively low labor requirements. Seed mixes can be planted that promote livestock cultivation, and stocking rates are adjusted to align with the presence of solar panels (Andrew et al., 2025). Solar grazing has its own setbacks, as well. Farmers interested in this

Figure 4 - Sheep grazing under a fixed photovoltaics array. Source: American Solar Grazing Association. (2025). [Photograph of sheep grazing under solar panels]. Retrieved October 22, 2025, from https://solargrazing.org/recommendations

mode will have to reckon with legal restrictions, zoning requirements, and public reactions in addition to the usual trappings of grazing sheep (American Solar Grazing Association, 2024). However, there are many different consulting firms and partnerships throughout the country like solargrazing.org that are working to make solar grazing more accessible for solar power operators of any scale.

4. Prairie Strips and other conservation planting efforts

Prairie Strips are a technique that have been closely studied by researchers at Iowa State University that show promise in this arena (Schulte et al., 2017). They aim to provide habitat for pollinators, other beneficial insects, and wildlife (Figure 5). Reports in the literature indicate that prairie strips can even improve the crop growth characteristics of cash crops grown nearby or in alternating rows. Solar developers have identified prairie strips as a potential way to increase the environmental-sustainability of solar installations (Moore et al., 2021).

Figure 5 - Iowa State University. (2025). Prairie strip in Tama County, Iowa [Photograph]. Science-Based Trials of Rowcrops Integrated with Prairie Strips. https://www.nrem.iastate.edu/research/STRIPS/content/what-are-prairie-strips

5. Greenhouse APV (Figure 6)

Figure 6 - REGACE. (2025, May 1). Improved sun-tracking greenhouse system [Photograph]. HortiDaily. https://www.hortidaily.com/article/9727925/greece-improved-sun-tracking-greenhouse-system-at-upcoming-general-assembly/

Combining the technologies of controlled environment agriculture (e.g., high tunnels and greenhouses) with agrivoltaics systems is also gaining interest, especially in arid regions like the Mediterranean region, northern Africa, and the Middle East (Younes, 2023). Panels can be located inside or outside greenhouses. Other research approaches to this integration are focused on covering or replacing greenhouse covering with solar panels—using traditional modules, thin-film, semi-transparent, or some other photovoltaic design. There are also numerous applications where semi-transparent or other panels are affixed inside the greenhouse and can be angled to modify the light environment within the greenhouse.

Urban Agriculture

As urban populations grow and available farmland declines, local food production becomes essential to ensuring reliable access to fresh and affordable produce. Urban agriculture has been proposed as a critical way to improve food access in cities. Locally produced food reduces transportation costs, shortens supply chains, and can mitigate the environmental footprint associated with conventional distribution systems (Specht et al., 2014). Moreover, Specht et al. state that decentralized production can strengthen community food security by embedding food sources directly within residential and commercial zones, reducing dependence on external markets and long-distance logistics. However, urban agriculture is not without its challenges. Scalability, income diversification and stabilization, and resource efficiency are all

central issues in developing urban food systems into the 21st century, driving many urban growers to seek ways to further intensify production (Benis & Ferrão, 2018).

The intensive cultivation methods employed in urban agriculture—such as hydroponics, vertical farming, and controlled-environment systems—maximize productivity with constrained space and resources (Beacham et al., 2019). These technologies enable improved production on minimal land area. As cities continue to confront growing competition for land, integrative production techniques like these demonstrate how urban agriculture can reconcile limited space with increasing demand for fresh food. Integration with renewable energy infrastructure could further enhance the sustainability and resilience of these high-efficiency production models (Walston et al., 2022).

In addition to enhancing food availability, urban agriculture contributes to local economic diversification by generating new income sources and employment opportunities across production, marketing, and educational sectors. Small-scale enterprises and cooperative models can transform vacant lots, rooftops, and underutilized public spaces into productive assets that support microenterprise development and workforce participation. Empirical studies demonstrate that urban agriculture stimulates local economies by creating value-added markets and fostering entrepreneurial innovation within food systems (Eigenbrod & Gruda, 2015). When strategically integrated into policy and planning frameworks, urban agriculture initiatives promote economic opportunity and strengthen community resilience by building productive capacity within neighborhoods.

Agrivoltaic Potential in Urban Agriculture

Urban agriculture stands to benefit greatly from developments in agrivoltaics. Metropolitan areas throughout the United States have seen recent interest in improving their

urban food systems, especially in ways that utilize already-scarce land more efficiently. Studies have indicated that an increase in the presence and availability of locally-grown fruits and vegetables can bring about reduced food insecurity and improved health outcomes for the communities in which they are grown (Ilieva, 2022). Effective co-location of production could increase environmental sustainability in previously neglected areas while providing an additional income, making farming in urban areas more economically feasible. Agrivoltaics can thus provide a way to maintain or even improve small- and mid-scale farms' viability without sacrificing valuable land. Income diversification has also been identified as a central issue to small-scale farmers (Yoshida et al., 2019); agrivoltaics systems allow small-scale and urban farmers to integrate additional revenue in their business by selling electricity.

Report Objectives

The goal of this report is to familiarize small- and mid-scale, local and urban farmers with the basics of Agrivoltaics: where/when/how it can work, and who is best-positioned to take advantage of recent advancements in these systems, especially as these advancements apply to horticultural and specialty crops grown in Kansas. More specifically, this report aims to cultivate growers who:

1. Can understand and interpret the most common terms and concepts in agrivoltaics as they currently exist;
2. Are able to make well-informed choices as they start developing their own plans for an agrivoltaics production system;
4. Are able to pursue their own agrivoltaics research with tools and information to understand the needs and potential benefits at their own site; and

5. Understand the importance of: developing a solid plan, determining motivations and realistic expectations, and consulting with licensed, professional engineers and/or electricians.

Some of the best resources available on Agrivoltaics today:

www.agrisolarclearinghouse.org/ ; energy.gov/eere/solar/agrivoltaics-solar-and-agriculture-co-location/

Solar Power and Agrivoltaics

Solar power generally refers to any power system that has the sun as its primary energy source. There are multiple ways to get usable energy from the sun – one of the earliest examples is 'Concentrated Solar Power' (Figure 7), which is essentially a steam turbine that uses mirrors to harness the energy from the sun to heat the water. Among other instances of solar energy are "solar water heaters" which harness the heat from the sun for warming greenhouses and residential and commercial buildings. For the purposes of this report, photovoltaic solar power will be the primary focus.

Figure 7 - Kallerna. (2021, March 25). Gemasolar thermosolar plant 4 [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Gemasolar_Thermosolar_Plant_4.jpg

Photovoltaic ('PV') Systems

'Photovoltaic' solar power generation refers to power systems which utilize solar panels, or 'modules' which are made of two different 'types' of silicon. Essentially, solar panels generate electricity from a chemical reaction that occurs between these two 'types' of silicon when the sun shines on each cell (Solar Energy Technologies Office, 2025). Modules are typically built such that the sun-facing side is about 1 meter by 2 meters (Figure 8). This can

vary widely, but the panels that are used for large-scale power generation are usually this size. Retail sellers provide these panels for a typical cost of $150-400 per panel, depending on panel wattage and other quality parameters (Consumer Reports, 2025). On many panels, the side facing away from the sun can also generate significant amounts of electricity – these are known as bi-facial modules, and they are quite useful in certain array configurations.

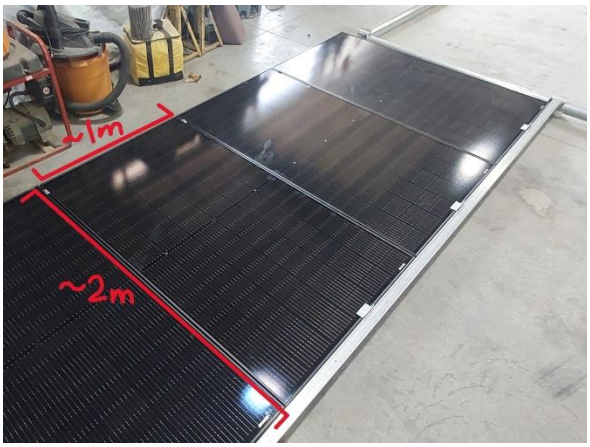

Figure 8 - Solar panels with markup showing approximate dimensions.

Most mono-facial panels have an 'efficiency' of up to 25%, give or take about 4% (Mahim et al., 2024). This means that if the sun illuminates a typical panel with 1000W/m^2 (and typical panels are about 2m^2 in surface area, as discussed above) it should produce around 500W. Bifacial modules produce around the same amount on their sun-facing side, and anywhere from 10-30% as much energy on the opposing side (Ibid.).

Solar Panel/Module Arrangement

Agrivoltaic systems are largely defined by what kind of geometry, or configuration, the array of panels will have (Figure 9). While there are infinite options, especially when one considers agrivoltaics, this report will discuss three common array configurations in depth:

latitude-tilt, uniaxial-tilt/tracking, and vertical-bifacial. Bi-facial panels can be used in any type of array. They capture a significant amount of sunlight on their backside (Mahim et al., 2024), whereas mono-facial modules do not. This allows panels in all three of these configurations to generate 'extra' electricity from ambient light in the field.

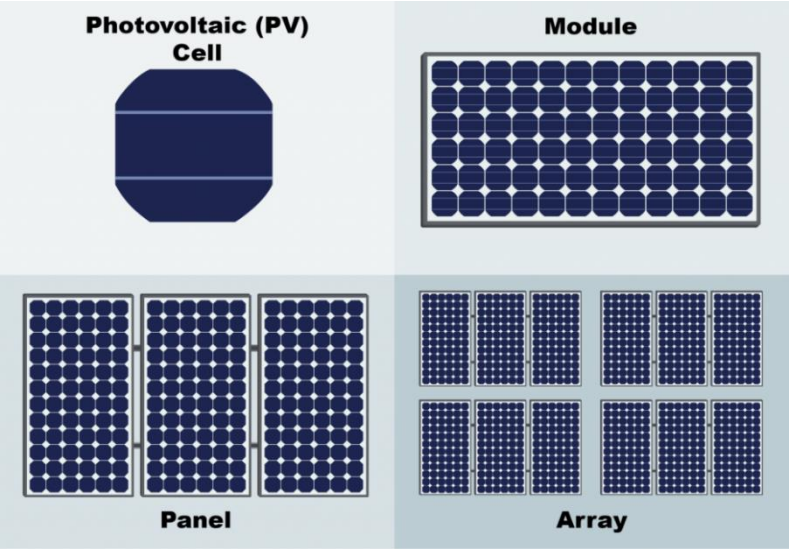

Figure 9 - Florida Solar Energy Center. (2025). Solar energy's constituent parts. University of Central Florida. https://energyresearch.ucf.edu/consumer/solar-technologies/solar-electricity-basics/cells-modules-panels-and-arrays/

1. Latitude-Tilt Fixed Arrays

One of the most common array types are latitude-tilt fixed configurations (Figure 10). Panels are faced south towards the sun and tilted so that they are perpendicular to the **angle of the sun** at certain times. These panels are tilted at approximately the same angle the sun makes with the southern horizon (when built north of the equator) when it crosses the sky. The latitude in Kansas City is about **39ºN**. For latitude-tilt fixed arrays solar installations in this area, one could measure that same angle with the ground. As a result, the large, flat side that catches light for energy will be pointed *directly* at the sun, especially at solar noon, when the sun is highest in the sky.

Figure 10 - Victoria, M. (2023, August 26). Fixed mounting structure in a photovoltaic array [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Fixed_mounting_structure_in_a_photovoltaic_array.jpg

Solar panels have been installed using this configuration in most major installations since the mid-1980s, when the first large-scale installations were being constructed (Tabassum et al., 2021). Latitude-tilt arrays are generally considered the least expensive to build, and highly effective at capturing sunlight for power generation. They are also fairly simple to construct and maintain, making them preferred for many do-it-yourself operators. Up until the 2010s, this style of solar installation comprised the vast majority of installations in the United States.

2. Uniaxial-tilt Tracking Arrays

Uniaxial tracking arrays (Figure 11) are swiftly increasing in popularity as energy companies build larger and larger solar fields across the country for utility-scale power production (Mordor Intelligence, 2025). 'Uniaxial' means the panel arrays move in a row and tilt from side-to-side on a single axis. As the day progresses, the array tracks and follows the movement of the sun in order to keep the panels perpendicular to the incoming rays. In this configuration, long rows of panel arrays are typically oriented north-south. Every panel starts the day facing east. As the sun rises, the panels follow the sun, tilting to be completely horizontal with the ground when the sun is at its peak during solar noon and then following it west, ending up with all panels facing the western horizon by sunset. Overnight, panels slowly reset to face east before the sun rises again, and the pattern repeats. The arrays do not tilt up-and-down to follow the angle of the sun, which changes seasonally and at different latitudes. This also means that land topography is important as panels are parallel to the ground.

Figure 11 - Uniaxial-tilt tracking array outside of Lawrence, KS

Most new, utility-scale solar installations are built with uniaxial-tilt tracking systems. Due to the more complicated racking system, uniaxial-tilt tracking arrays are significantly more expensive and difficult to build and maintain. In spite of this, sun-tracking systems have comprised more than half of the commercial PV generation built in the United States since 2017 (EIA, 2025).

3. Vertical-bifacial Arrays

In this configuration (Figure 12), panels are positioned vertically and perpendicular to the ground, similar to a wall or fence. The array is oriented north-south so that the panels face directly east and/or directly west. Often, bi-facial panels are utilized so that power generation is optimized in the morning and afternoon hours. Solar power production from this configuration peaks *twice* per day when panels are evenly-distributed east & west; this occurs in the morning, when the sun is in the east, and again in the evening, when the sun is in the west (Willockx et al., 2023). During solar noon, when the other two configurations are in peak power production, vertical arrays are likely producing very little solar energy.

Figure 12 - Vertical/Bi-facial arrays at the KSU-OHREC Research Station

In the United States, vertical arrays are relatively new and as-yet uncommon. This system is gaining popularity in places like Germany and Austria, where large, sprawling fields are rare. Vertical arrays take up the least ground-area per panel, and can even be installed on pre-existing

fencing or infrastructure without taking up as much valuable farmland as other configurations (https://next2sun.com/en/agripv/).

All these configurations, with similar modules and other characteristics, can still have different Levelized Costs of Energy (LCOE). According to a 2022 publication from NREL, residential scale, latitude-tilt has an LCOE of about $0.11/kWh, while uniaxial-tilt trackers (at utility scales) cost only approximately $0.04/kWh (Ramasamy et al., 2022). Vertical-bifacial arrays have been demonstrated to have an LCOE of around $0.14/kWh (Gul et al., 2025). The LCOE of a built system, however, will depend on site conditions, equipment quality and upkeep, and other, sometimes unforeseeable factors. Always consult with a licensed engineer and/or electrician before buying or building any solar equipment.

Methods of Co-Location

When looking from above, co-located production can be arranged in a pattern of layers, rows, boxes, or other repeating patterns of production. There are three general categories that most agrivoltaics systems fall into:

Interrow – As seen in (Figure 13), interrow APV setups look much like other farms with alternating rows of crops and solar panels. These arrangements can be utilized across the entirety of a solar production field. Sunlight falls entirely on each row for various times during the course of the day, and rows generally do not shade each other.

Figure 13 - Akmu.cazri. (2017, August 17). Solar Agri Voltaic Farming System [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Solar_Agri_Voltaic_Farming_System.jpg

Shade-Patterned – Shown in an experimental setup in (Figure 14), this is an APV setup wherein solar panels are 'checkered,' or patterned, so that light gets through to the crops below them in a measured, alternating manner. Plants are subject to total-shade and total-sun as the shadows move over and past them. Agrivoltaics systems are also becoming more popular whereby panels are fixed inside of greenhouses both to produce power and provide shade for the crop.

Figure 14 - Afnfan. (2024, May 5). Agrivoltaics case, Sōsa, Japan [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Agrivoltaics-case-sosa-japan.jpg

Semi-Transparent Panels – (Figure 15): These systems are ‘layered’ so that a portion of sunlight is used by each type of production. This creates a semi-shaded effect under the panels, leaving a percentage of sunlight for plants to effectively grow (Bernsten, 2022). Many of the modules that are semi-transparent throughout the entire face are rare and made of experimental chemicals. However, there are ways to achieve a similar shading effect by making PV modules of clear substrate with individual silicon cells separated, allowing light through in diffuse amounts (Figure 6).

Figure 15 - Semi-Transparent panels over alfalfa crops outside Colorado State University's ARDEC Research Station

Effects of Co-Location

The effect of agrivoltaics systems on the productivity of crops and solar panels when patterned in these or other ways are of increasing interest (Ali et al., 2025). Similarly, when considering a new agrivoltaics installation, it will be important to understand the potential economic costs and benefits for the different systems. While the precise effects that certain solar array configurations can have on nearby crops are as yet largely uncertain, there are two major types of co-location’s effects that are important to consider:

1. Direct Effects – include impacts that occur directly to crop productivity, quality and profitability. Similarly, crop production can have direct effects on power generation through shading (Hudelson & Lieth, 2021). How much crop yield (%, lb, or $/acre) is lost

or gained due to being grown among solar panels? Are there factors such as shading, planting density, or others related to cultivation that may reduce the yield or productivity of the space (Ibid.)? Direct effects also include the ways that shade can affect the physiology, color, nutrition, and other aspects of crops when they are grown among solar panels (Khudair et al., 2025). It is important to note that direct effects can also benefit the production in question. For example, in Kansas a small amount of shade and protection from wind could be beneficial for vegetable production.

Figure 16 - Roggero, E. (2021, October 11). Mechanized agricultural processing in agrivoltaic vineyard, Laterza, Taranto, Italy [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Lavorazione_agricola_meccanizzata_in_vigneto_agrovoltaico.jpeg

2. Indirect effects – are oftentimes more difficult to quantify than yield or direct production costs. They can also include interactive effects due to co-located production. Some of these could include: equipment access (Figure 16), shade benefits to laborers, windbreaks, evapotranspiration changes, noise effects, and others.

Most current agrivoltaics research focuses on direct effects on crop yield, but the interactive effects which APV systems present have recently gained more attention. This report will focus briefly on **specific crop types** and APV configurations that have shown viability thus far and any apparent effects that have been reported. It is important to note that any successful

photovoltaic operation will need to have some type of vegetation management plan. In large, utility-scale production facilities, outside contractors are typically hired to maintain vegetation and/or assist with day-to-day maintenance of the operation. When installing any type of solar panel array it is important to consider how vegetation will be managed to prevent shading and keep the operation safe and well-kept.

Agrivoltaics' Future Developments & Trends, as of 2025

People around the world are beginning to explore agrivoltaics in countless ways. Although each site and system remains unique, future developments in APV are likely to be shaped by a handful of emerging, yet still largely untested, technologies. Some of the areas expected to influence APV innovation moving forward include:

Figure 17 - "East-West Array". Image by Jurchen Technology, accessed October 20, 2025, from https://www.jurchen-technology.com/peg-design/. Used under Fair Use rights. No modifications made.

East-West Arrays: **(**Figure 17**)**

- East-west arrays are panels which are fixed-tilt and installed in array-pairs with half tilted to the west and half tilted to the east. This mimics the sun-tracking abilities of uniaxial tracker systems. Plus, these setups have become significantly more economical than tracking systems as solar modules have become more affordable.

- Further reading and resources available from these sources: terraformindustries.wordpress.com/2025/04/29/the-future-of-solar-doesnt-track-the-sun/ ; www.jurchen-technology.com/peg-design/

Perovskites: **(**Figure 18**)**

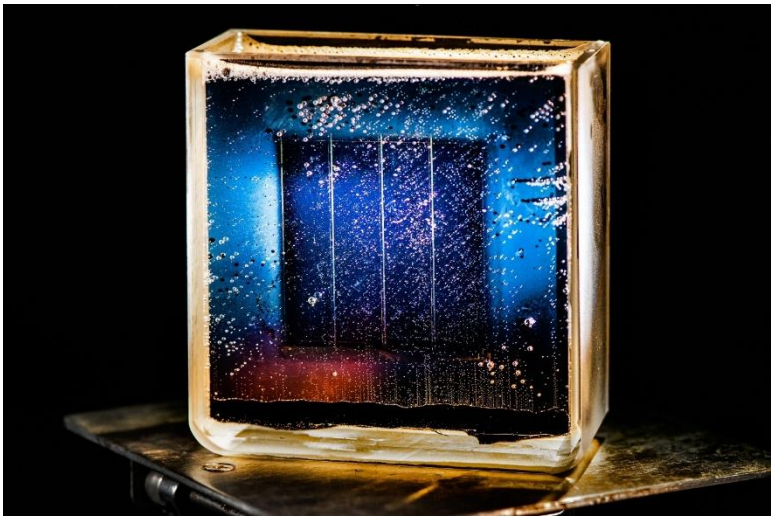

Figure 18 - U.S. Department of Energy. (2019, October 29). Hybrid perovskite solar cell integrated with an electrolyzer [Photograph]. Flickr. https://www.flickr.com/photos/departmentofenergy/48981195407/

- Solar panels made of 'perovskites,' a class of synthetic materials with a crystalline structure, have been shown to have significantly higher efficiencies (>34%) than typical silicon-based panels (~25%). This change in materials allows for the same size and number of panels to produce even more electricity, allowing for lower ground cover ratios.
  - Further reading and resources available: www.nrel.gov/pv/perovskite-solar-cells

Thin-Film Panels: (Figure 19)

- Thin-film products refer to a variety of materials (not just silicon) that perform much in the same way as traditional N-P silicon solar panels. Notably, thin-film panels are much

easier to manipulate and shape, making them especially applicable to greenhouses or other farm buildings. This characteristic also makes them good for applications on top of agricultural, commercial, or marine vehicles.

- Further reading and resources available from these sources: www.nrel.gov/pv/polycrystalline-thin-film-photovoltaics ; solarmagazine.com/solar-panels/thin-film-solar-panels/

Figure 19 - United Solar Ovonic. (2008, July 15). UNI-Solar's thin-film laminate product [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:UNI-Solar%27s_thin-film_laminate_product.jpg

Luminescent Solar Concentration cells (LSCs): (Figure 20)

- LSCs are solar cells, usually made of a block of clear plastic/glass substrate containing quantum dots of a single 'color' which take in light from a broad spectrum – like sunlight – and emit light in a single wavelength, or color. This allows them to operate more efficiently than traditional photovoltaic cells. Dots and cells are 'tuned' together to emit and absorb the same wavelength and maximize the energy efficiency of the cells. Thus, light wavelengths which previously

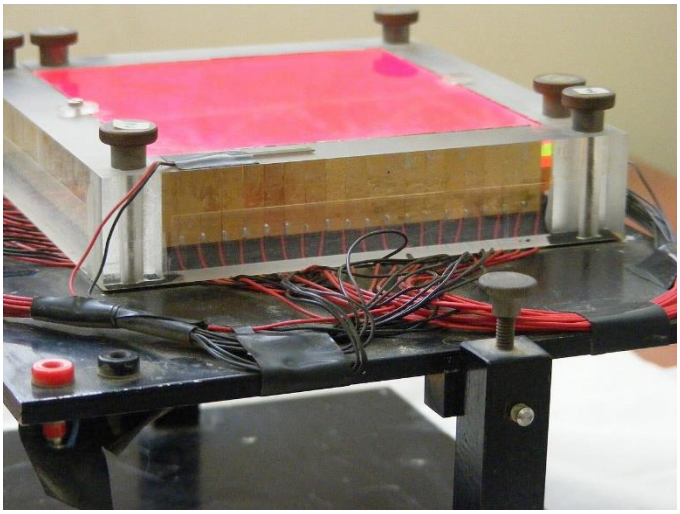

Figure 20 - Levita.lev. (2011, March 15). Working model of luminescent solar concentrator [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Luminescent_solar_concentrator_model.jpg

would have had no effect on the solar panel, or which would have simply heated it and decreased its efficiency, can now be converted to light that the PV cell can easily utilize. Additionally, these LSCs can be constructed in such a way as to still allow some light through, increasing their possible applications as windows or partially-transparent panels.

- Further reading and resources available from these sources: research-hub.nrel.gov/en/publications/design-criteria-for-micro-optical-tandem-luminescent-solar-concen-4 ; www.nobelprize.org/prizes/chemistry/2023/press-release/

Panels as Structural Components – Shelterbelts, Canopies, Fences, etc.

- One of the newer applications of solar technology to agriculture is actually one of the simplest. Panels are usually made of solid material; thus, they break air flow through them, forcing wind to slow down. Recently, some have taken advantage of this property of solar panels to develop a concept known as **solar shelterbelts**. Using the same principles of co-location as other types of APV, solar shelterbelts (Figure 21) exploit previously unused space for solar. Shelterbelts need to be constructed to survive weather, and traditional 1m*2m panels may not make sense in this application. However, modern technologies are bringing about smaller, more-modular panels, and integrating weather-dependent tracking. Researchers have begun successfully implementing a solar shelterbelt system at one site made entirely of a specially

Figure 21 – FARM SHOW Magazine. (2025). [Photograph from "Solar Panels Used As Shelterbelt," Volume 49, Issue 4, p. 4]. FARM SHOW Magazine. https://www.farmshow.com/a_article.php?aid=40414

constructed solar array using these smaller panels (FARM SHOW Magazine, 2025). Beyond shelterbelts, the opaque nature of solar panels makes them viable materials to build **canopies** (Figure 22) over paved parking lots where farm marketing, packing/processing, or storage may occur. This not only provides cover and reduces the heat in the space, it generates electricity like any solar power installation would. Finally, using solar panels as **fencing** (Figure 23) or any other structural component can be made into a synergistic use of land and farm infrastructure.

Figure 22 - Wikideas1. (2024, May 4). Solar canopy in parking lot at Winona State University in Minnesota [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Solar_canopy_Winona_State_02.j

Figure 23 - Next2Sun GmbH. (2024). Solar fence in Adnet [Photograph]. Next2Sun. https://next2sun.com/en/solar-fence/

- Further reading and resources available from these sources: www.farmshow.com/a_article.php?aid=40414 ; www.scenichudson.org/viewfinder/a-fresh-land-use-win-solar-canopies-shading-parking-lots/ ; next2sun.com/en/solar-fence/

The limit on new agrivoltaics technology exists only in the creativity of the practitioner. There will always be a new way to combine old technologies, develop new ones, or even re-

purpose existing ones in a way that sheds new light on agrivoltaics. The role of the landowner is to keep an open and inquisitive ear towards APV innovation.

Check out AgriSolar Clearinghouse for new APV technologies and developments at the link below; especially the very bottom of the page for 'The Latest' in APV news and research: www.agrisolarclearinghouse.org/agrisolar-information/.

Designing and Implementing an Agrivoltaics System

Site-Specific Agrivoltaics

An agrivoltaics system can be tailored to meet the specific power requirements, equipment access needs, business model, and most importantly, the intended goal to co-locate solar panels with agricultural production. A thorough evaluation of the land and its attributes may lead to the conclusion that agrivoltaics is not a suitable option, or that co-location may be better achieved through spatial separation, such as placing panels on one side or the perimeter and crops on the other or within. In some cases, the envisioned agrivoltaics setup may not only be feasible but may also qualify the farm for grant funding or other resources if implemented correctly.

Regardless of the chosen approach, it is essential to design a system that aligns with the unique conditions of the farm, rather than following external trends without critical assessment. The involvement of a licensed engineer or electrician is indispensable to ensure that the system is constructed safely and in compliance with property-specific requirements and applicable local and federal laws and regulations.

Figure 24 - Hyperion Systems LLC. (2025). UMass Amherst – Broccoli, bell peppers, kale, and Swiss chard growing under the dual-use solar array [Photograph]. Hyperion Systems LLC. https://hyperionsystemsllc.com/projects/umass-amherst/

Agrivoltaics has largely been developed in a site-specific manner thus far. Farmers have often been forced to create their own unique APV setups (Figure 24) in order to test them, creating a more diverse research environment. In a case study of 15 built Agrivoltaics systems in

the Netherlands, no two were identical in orientation or size, and several different configurations were all present and established for at least 5 years (Sirnick et al., 2024). The same study recommends to policymakers, based on the study of such varied design and site choices, to establish site-selection and design criteria which respond to the specific characteristics of a potential site or system. While some research methods show some applicability in many different cases, the wide variety of APV setups that have been researched in *other* ways makes finding applicable research possible for many different situations. Ultimately, the responsibility rests on the individual to use the methods that others have developed for their own land.

The Electrical Grid

As with all the technical discussion in this report, it is a good idea to always consult with licensed electricians and local/code officials to ensure any system built is compliant with local

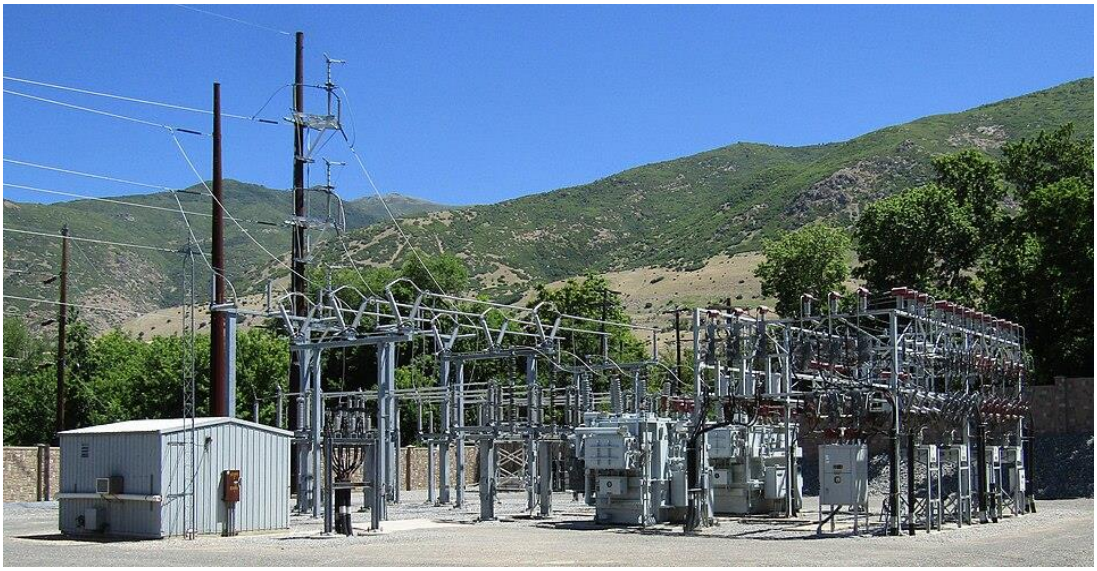

Figure 25 - Ben P L. (2018, July 1). Farmington Substation (43837950172).jpg [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Farmington_Substation_(43837950172).jpg

laws and regulations. When tying into an existing grid, this is also essential to the safety of both farm operators and utility workers. Briefly, we'll discuss the electrical infrastructure which exists

in the United States (especially the Central U.S.) and what it can mean for a grower interested in agrivoltaics.

Electricity is moved from large power plants along the electrical grid (Figure 25), which consists of ‘transmission’ and ‘distribution’ systems (nrel.gov/research/power-grid). Transmission lines move large amounts of electricity across vast distances, typically via high voltage power lines. Distribution systems’ prepare the electricity and deliver it to homes, businesses, and more, in a way that can be utilized by modern appliances. Solar power-generation systems usually fit somewhere between ‘transmission systems’ and ‘distribution systems’ since they produce power at a lower voltage/amperage than large-scale power plants (Figure 26). For growers planning solar applications with less than one megawatt, the distribution system will suffice when considering the grid.

When a solar power generation system is added to the grid, the addition is usually called an interconnection, which comes with rules, regulations, and required permits. Interconnection permits will often have requirements regarding net metering (NREL, 2025a). Calculating net metering economics can be difficult and should be done in consultation with a licensed engineer/electrician. Essentially, net metering is how one gets paid for selling electricity. Permitters are generally interested in determining the reliability of the grid, and how the system will need to be responsive to grid failures and changes.

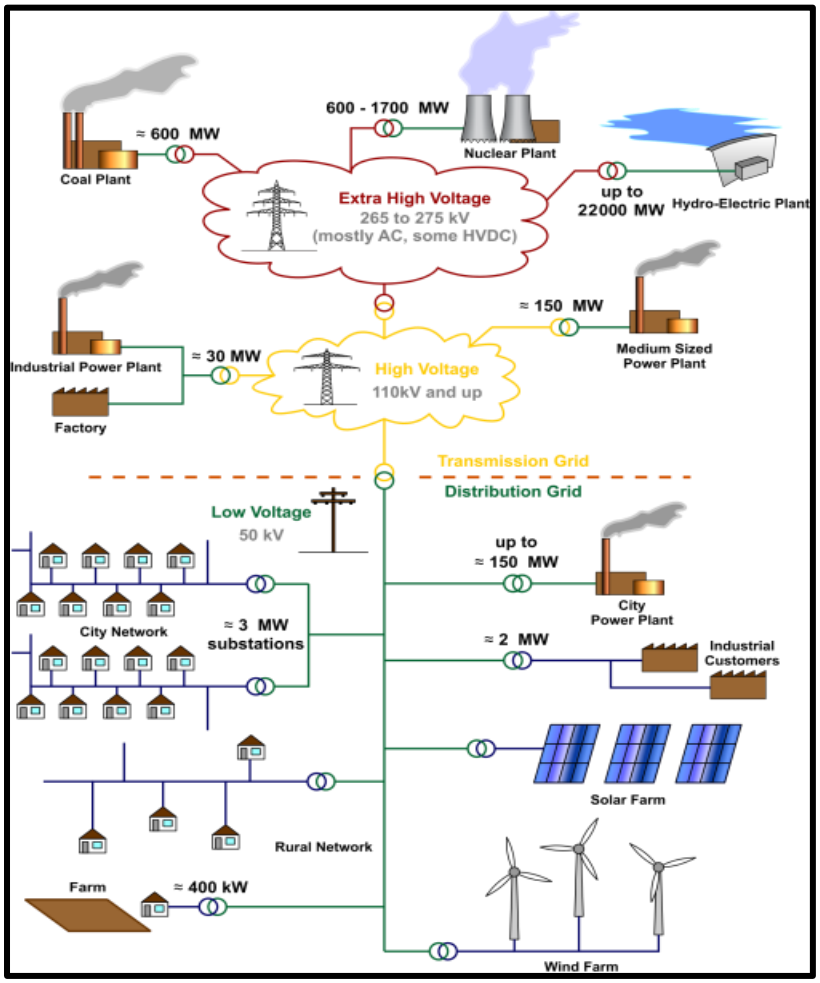

Figure 26 - MBizon. (2010, March 7). Electricity grid schematic, English [Diagram]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Electricity_Grid_Schematic_English.svg

Power supply companies may also provide resources related to connecting to the electrical grid. In fact, there are usually readily-available resources for anyone looking to generate power. For example, in Eastern Kansas, Evergy customers can find most of the information they need to get an interconnection permit at the following website (as of October 2025): https://www.evergy.com/smart-energy/renewable-resources-link/private-solar-and-net-metering.

Measuring the Potential of Solar Power

Solar power generation works more effectively in places that receive more sun than others. In order to predict the production of any given new system, it is vital to first understand the solar resource present at the property.

There are three major concerns when trying to determine the solar resource of a site:

1) **Latitude** –this is how far north/south a plot is, in degrees, of the equator.
    a) Locations further north or south get less sunlight compared to tropical regions in alternating seasons due to the shape of the Earth as well as its axial tilt. Kansas City, KS has a latitude of about **39ºN**.
2) **Geography** – refers to the actual, physical surroundings, including topography and other landscape elements.
    a) The surroundings of a site, especially if those surroundings are large and located at higher altitude (e.g., a mountain range to the east, limiting sunlight in the morning) can have drastic effects on the solar resource of a site. Site characteristics like slope and smoothness can affect the uniformity of light present at the site, further complicating and reducing potential solar resource.
3) **Weather** – is dependent on the season, surroundings, and typical climate patterns at the site.
    a) Clouds and precipitation are immediately important in blocking the sun in even mild conditions. Temperature also affects panel performance, with hotter temperatures generally reducing their efficiency. Intense weather also has the potential to damage solar power systems with electrical parts exposed, making the potential for disasters worth consideration as well.

There are many online tools to determine the solar resource readable on an interactive map, or by inputting the site address. Two such resources are located here:

https://dqydj.com/solar-irradiance-calculator/ ;

https://www.arcgis.com/apps/OnePane/basicviewer/index.html?appid=680360a7807a40e692ae36b925472fda

System Design Considerations

This section of the report aims to provide sufficient background information to ensure familiarity with some key concepts that may arise when planning APV installations with a licensed engineer or electrician.

Array Geometry

- Array geometry refers to the **spatial design** of panels: distances to the ground, to property boundaries, to each other, etc. Array geometry is determined by the system needs: property/setback constraints, where power must be delivered once it is generated, where physical or equipment access is needed, etc. This is an expansive term – and often the very first thing that should be determined.
- Example: Some counties require a minimum 'setback' for development; this means that solar panels and other structures cannot be built within a certain distance from the property line.

Array Number / Row Spacing

- Within array geometry, more specific terms like "array number" (**how many** arrays of panels will be built) and "row spacing" (linear measurement between the panels, i.e. **how wide** crop/equipment paths are) define the position of arrays on the property. In agrivoltaic systems, row spacing can be crucial. Depending on the array design, row

spacing can determine equipment access, how intense shading of crop rows by PV rows is, and a multitude of other factors like irrigation, labor/equipment use, etc.

- Example: When designing an Agrivoltaics array, the row spacing must be wide enough to let through the largest piece of equipment which needs to traverse it, which then limits the array number.

Ground Cover Ratio

- The ground cover ratio, expressed usually as a decimal value between zero and 1.0, describes, on average, how much light the panels intercept (PVsyst SA, 2025). This ratio can be crucial in determining array number/spacing. Plants and especially fruiting crops require an adequate amount of sunlight to pass the panels unaffected in order to be productive. Conversely, in livestock APV systems, shading may be preferred, and thus a higher ground cover ratio may be ideal. It is critical to have an understanding of what type of agricultural enterprise will be utilized when determining the proper ground cover ratio.
- Example: A field covered entirely by solar panels, with no sunlight reaching the soil, would have a ground cover ratio of 1.0; a field with half as much ground covered would have a ground cover ratio of 0.5 (50% of light reaching the soil).

Module Size

- The size of panels/modules, measured on the sun-facing side, is an important consideration when designing the array geometry and is likely specific to the racking system being used. Planning for a single module size will greatly simplify the array geometry and planning process. A licensed professional will likely suggest purchasing all

modules from the same provider, with the same model and size, for this reason and for other maintenance concerns.

- Example: Building an array with multiple array sizes might require additional steel racking structures to ensure that each panel is well-supported.

Some very good info (and further reading links) on array configuration choices can be found here: https://docs.nrel.gov/docs/fy25osti/91672.pdf

System Operation & Maintenance (O&M)

Once an APV system is built, it will need to be operated and maintained for optimum performance. It is important to note that in some financing situations, the landowner may be expected to keep the solar array clean, safe, and operational. This can include regular cleanings with water, addressing panel damage or repairing wiring, and vegetation management, among others.

An **O&M Guidesheet** is included at the end of this report. The purpose of the worksheet is to help streamline some of the more complicated aspects of maintaining a photovoltaics system.

Three Rs of Power System Reliability

NREL describes energy production within a framework called the Three Rs of Power System Reliability, or, more succinctly, the "Three Rs of Power" (Geocaris, 2022). In this section, we will describe how these characteristics can be applied to agrivoltaics. This approach can be useful for planning all types of agrivoltaics systems, and particularly helpful when considering off-grid applications that are not able to be supported by utility power service.

[R]esource adequacy

⇒ *This term describes how 'available' the energy is in the form in which it is being generated. For photovoltaics, this is best-understood as the **Solar Resource**, which was described previously in the section on Solar Power Fundamentals.*

- How much power is produced, on average, compared to how much is needed?
- In an agrivoltaics system, the power required can be farm equipment requiring a charge, an irrigation system powered by electric pumps, regular electric load of a farm, like lights, refrigeration, and more. The resource of a power system, APV or not, must be designed to be adequate in powering the operations it is intended to support.

[R]eliability

⇒ *This term describes how consistent the power system is in terms of time and amount of productivity.*

- Is power produced on time and/or when it is needed? How predictable is the amount or rate of energy produced by this system? Is adequate power provided during the winter or other times when conditions are less conducive to power generation?

- Depending on how a solar installation is designed and implemented, reliability can be affected by the use of agrivoltaics. Solar panels are most productive at certain times of day, and agricultural activities are similarly constrained. Regular farming practices can thus interrupt power generation if panels are moved or disconnected during their productive periods. Power generation can similarly be reduced by shading from crops, tilt adjustments during working periods, and cloudy weather. Panels may also require more regular cleaning to ensure reliability as the result of increased dust from tillage, spraying, irrigation, etc. To determine if an APV system would be reliable, all types of generation have to be considered at once.

[R]esilience

⇒ *Resilience can be understood as ability to withstand major changes, strength in 'adverse conditions' like storms, or other unexpected events.*

- Can the power system survive the weather? For how many years? What is the lifespan of the materials utilized? Is there a contingency plan in place in case of a catastrophic event?
- The integration of agrivoltaics may not affect resilience as much except for unusual circumstances such as damage to the system due to an agricultural operation. However, agrivoltaics may rely heavily on power systems to have high resilience. The unexpected loss of critical appliances on the farm such as irrigation pumps, refrigerators or greenhouse fans can lead to serious challenges to an agricultural operation.

Battery Storage

A common question is whether solar power generation systems should include battery storage. Depending on the goal, battery storage may not be required, even for off-grid applications. For systems that have an interconnection with the power grid, they can also be useful during outages. When a battery storage system is installed along with solar panels, this is less of a "power outage" and more a "power event" (NREL, 2025b). Grid-isolated battery systems can be enabled to continue powering homes and business. Conversely, in an off-grid system, batteries are likely critical to achieve full functionality for appliances that need to have power access more than 12-16 hours per day (e.g., refrigeration, heating, etc.). Batteries, whether in a grid-tied or off-grid installation, allow for power production to dip below the expected level without system failure, as stored energy makes up for the lost production for a time. In designing an effective battery storage system, the **Three Rs** framework mentioned above is highly applicable:

CAUTION:
Lithium-ion batteries can release noxious gases when damaged, overcharged, or exposed to high temperatures. These off-gasses, which may include hydrogen fluoride, carbon monoxide, and various hydrocarbons, pose serious health and safety risks due to their toxicity and flammability. In enclosed or poorly ventilated spaces, gas accumulation can lead to respiratory irritation, chemical burns, or even explosion hazards. Proper battery handling, thermal management, and adherence to manufacturer safety guidelines are essential to prevent off-gassing incidents and ensure safe operation.

1. Battery **Resource**: It is important to determine how much energy a farm/business currently requires for essential operations, opting for the largest value to be conservative. The cost of energy from the grid, compared with the Levelized Cost of Energy (LCOE) from the hypothetical APV system, should be considered here as well.

2. Battery **Reliability**: When installing a battery system, one can design for certain appliances to be powered first, so energy isn't wasted during an outage on non-essential devices. This ensures the battery system isn't drained by non-essential power use.
3. Battery system **Resilience**: This refers to the longevity of a system. Choosing batteries which are constructed to last longer, such as lithium-ion cells, can increase system resilience to changes and stresses (like charge cycles, weather, or natural disasters) over the life cycle of the system (Krieger et al., 2013).

There is a **Battery Bank Worksheet** at the end of this report which can be filled out prior to conversations with a licensed engineer/electrician. It was written in collaboration with engineers who frequently work with agrivoltaics-interested growers and landholders to help guide APV design considerations.

Designing a system that will work well every time it is stressed will better justify the cost of installing it. Having alternative power supply available can pay for itself in a single power event, if it is capable of offsetting the major economic consequences that a poorly-timed power outage can have for farms (Clack, 2022). Careful consideration of battery and power systems can allow for an agrivoltaics system to provide substantially improved power Resource, Reliability, and Resilience to a business.

Battery Storage Temperatures

Lithium-ion batteries should be stored in a cool, dry, and well-ventilated environment, ideally around 15 °C (59 °F). Batteries should be maintained at approximately 40–60% of full charge before long-term storage to reduce aging and self-discharge effects. Avoid exposing

batteries to high temperatures (> 30°C or 86°F) or extreme cold (< 0°C or 32°F), and ensure they are kept away from direct sunlight and heat sources (Creating Technology Solutions LLC, 2014).

Photovoltaic System Design Software

There are numerous resources and software tools available to understand the potential solar power resource of a system at a given site (AgriSolar Clearinghouse, 2025b). However, none are quite as robust and far-reaching as the System Advisor Model ('SAM') from the National Renewable Energy Laboratory (https://sam.nrel.gov/). Using this software and other online resources available through NREL, one can model an entire hypothetical solar power system (Figure 27) – from the individual modules to specific electrical equipment & batteries. Modeling can even account for expected lifecycle(s), depreciation of value, and function. SAM is used by industry players and regulators across the United States when considering potential solar power developments (Locus Energy & National Renewable Energy Laboratory, 2014). Growers interested in developing solar can develop case studies with theoretical geometries and layouts, compare the simulated performance of different modules or other system equipment, or manipulate other system design parameters to compare simulated outputs generally. While SAM is a helpful tool, it is only an estimate in predicting the power and financial outcomes of a given, hypothetical model. In the case studies presented

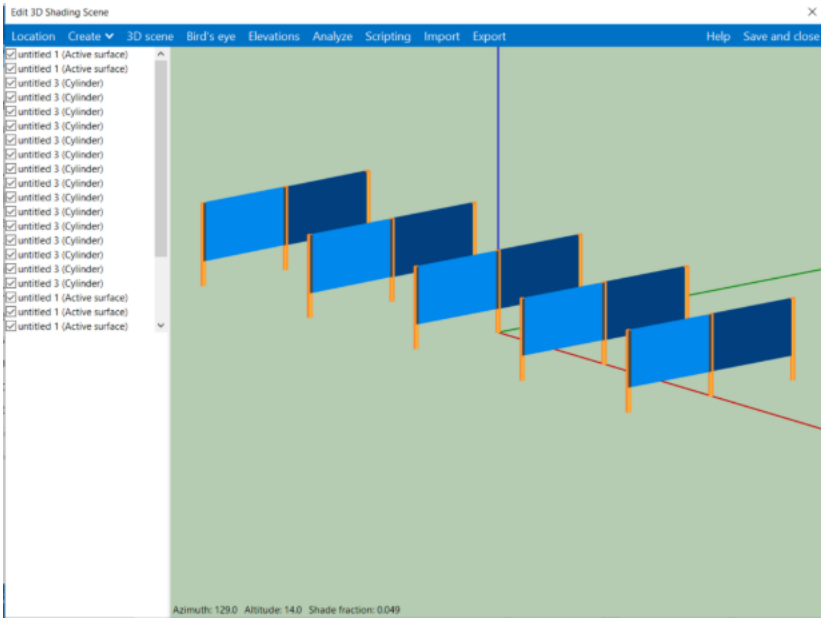

Figure 27 - Screenshot from '3d Shading Scene' Editor in System Advisor Model; vertical-bifacial arrays shown in figure.

below, further details about how the SAM system can be utilized are provided to understand the value of this tool.

To predict the relative outputs for the three case studies, three scenarios were created within SAM which reflect the three different case study configurations at the scale and location of the VB site (Figure 28). Then, keeping row spacing and array height the same, the model was duplicated and edited twice. In the first duplication, panels were set to be at latitude-tilt, facing directly south. With all else held constant, SAM estimated the LT configuration would generate approximately 9,468 kWh annually. In a similar fashion, system parameters were held as constant as possible for the third case, wherein panels were programmed to have uniaxial-tracking of the sun, as in the UT case study. This case (UT) simulated in SAM predicted approximately 13,736 kWh of annual power production. Finally, when the VB system was simulated by the model, the first year of potential AC energy produced was determined to be approximately 18,233 kWh. These three hypothetical systems would likely be built and perform in ways that SAM cannot predict. While SAM is useful for understanding how to design and improve a solar power system, it is not a perfect predictor of how built environments will perform in reality, and these simulation results only serve to show how comparable the systems could be, in terms of power generation.

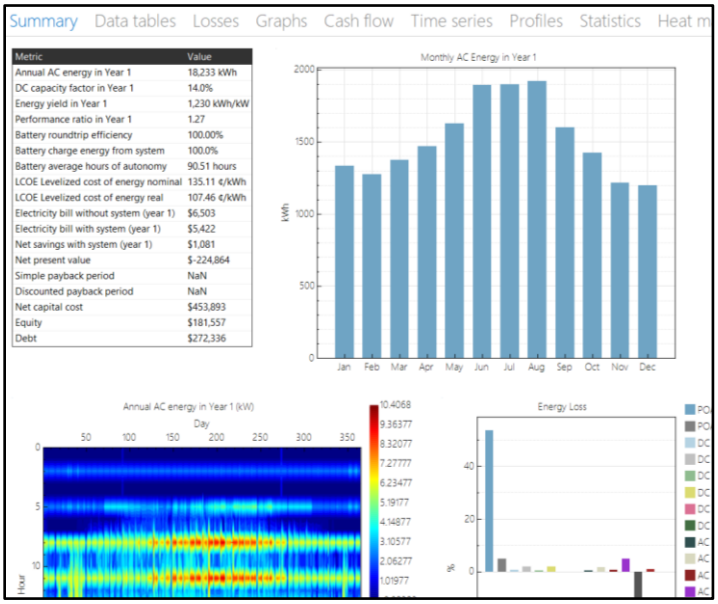

Figure 28 - Part of VB simulation output in SAM. Shows summary power and financial model outputs as well as multiple graphical representation of system simulation results.

Additionally, SAM cannot account for any indirect, interactive, or other effects on which agrivoltaics systems can be highly dependent; using the simulation reports to test individual system parameters of the simulation can still be useful. These simulations allow for an initial comparison, and to understand how different design aspects like inverters, number of modules per array, etc. can alter how a solar production system might be modified to function better, or worse. For the purposes of this report, SAM was helpful to gain a general understanding of how these three different racking systems compare given similar parameters, like location, panels, and inverters.

Ownership and Financial Considerations

Ownership and leasing in agrivoltaic systems introduce challenges that are uncommon in standard solar or agricultural operations. Because the same land supports both energy generation and farming, contracts must clearly define responsibilities for installation, maintenance, and daily agricultural work. Elevated solar structures and shared infrastructure may require detailed agreements regarding site access, equipment safety, and potential disruptions to crop or livestock productivity (Colorado Agrivoltaic Learning Center, 2024).

Financial arrangements also become more complex. Landowners may receive lease payments, share in energy revenue, or take on partial ownership of the solar array (AgriSolar Clearinghouse, 2025a). These decisions affect insurance, tax incentives, and long-term cash flows, particularly when capital expenditures are higher than for traditional solar installations. As a result, agrivoltaic leasing agreements require careful consideration of both technical and financial factors to balance agricultural productivity with solar revenue generation (Vezzoni, 2025).

County and other governments also regulate solar and agrivoltaic developments, which can further complicate the design and startup process. Some counties in Kansas have even flatly prohibited new solar in their zoning ordinances (Osage County Board of Commissioners, 2023). It is vital to understand the legal, governmental background of a site before development on that site can go forward, otherwise the risks presented in this section can threaten the entire project's viability.

Three Case Studies for Racking/Array Systems

This section of the report includes three case studies of light measurements taken under different array geometries in Kansas, representing three ways that growers could incorporate energy production among and/or near their crops. Furthermore, we will provide considerations for urban agriculture applications of these different arrays for agrivoltaics applications.

The three case studies in this report evaluate light conditions across three photovoltaic configurations in eastern Kansas, focusing on how structural design influences the quantity and quality of light available for crop production. Central to this work were measurements of Photosynthetically-Active Radiation (PAR) and Daily Light Integral (DLI), which serve as key

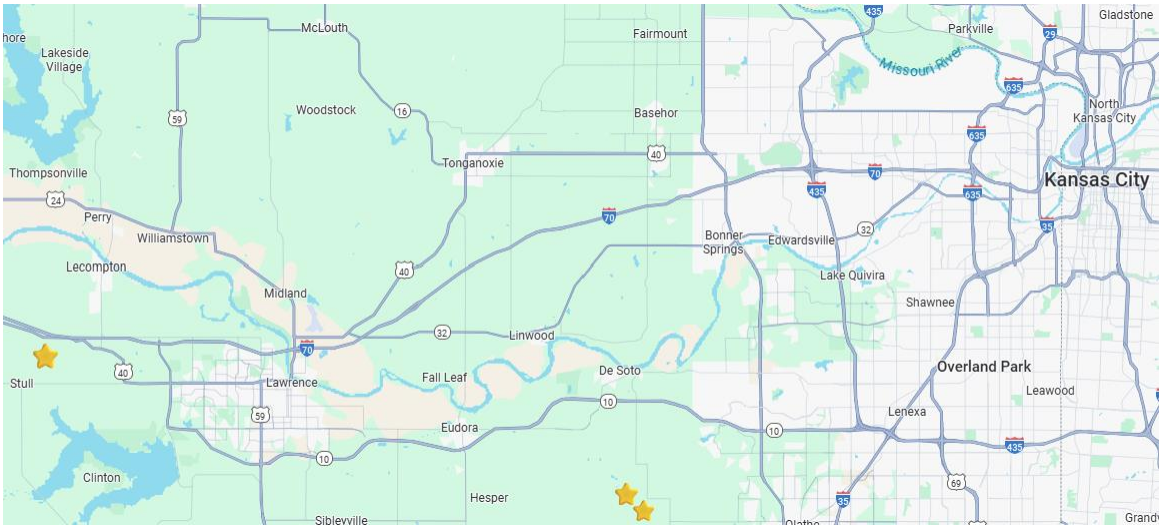

Figure 29 - Screenshot from Google Maps with markup (gold stars) over approximate location of three case studies. Kansas City located in top-right (NE) corner.

indicators of plant-available light. PAR quantifies the range of wavelengths used in photosynthesis, and DLI is known to characterize the baseline availability of productive light that plants can use in a given environment (Faust & Logan, 2018). Light data were collected using HOBO Photosynthetic Light (PAR) Smart Sensors (Part #: S-LIA-M003), USB Micro Station Data Loggers (H21-USB), and Smart Sensor 25m Extension Cables (S-EXT-M025) from Onset Computer Corporation. PAR data from these sensors were used to calculate DLI in Microsoft Excel via Riemann summation, and statistics (One-Way ANOVA, Descriptive Statistics, and Tukey's HSD tests) were conducted in Excel as well, utilizing the XRealStats macro from real-statistics.com. The locations of the three case studies are shown in (Figure 29).

Fixed Latitude-Tilt Array (LT) Case Study

Figure 30 - Sensors (circled in red markup) placed behind panel array at LT site.

Methods and Measurements

The Latitude-Tilt (LT) case study was developed around existing photovoltaic operations in eastern Kansas. The system was located at the Kansas State University Olathe Horticulture Research and Extension Center (OHREC) in Olathe, KS, and utilized modules sized 1m by 2m, similar in size to those in the other array configurations. This fixed, latitude-tilt array was used for agrivoltaic crop production, with species including spinach, sweet potato, and pumpkin. Yield data was collected for some of these crops but is not provided in this report.

Four sensors were installed at the LT site, distributed at even intervals across the alleyway, spaced 4’ apart. Each sensor was positioned at approximately 2’ above the ground surface to simulate the available light for a typical, mature vegetable crop. Sensors recorded PAR at 10-minute intervals, which were then recorded, integrated using the 10-minute interval, and normalized for the number of days within each month to calculate the monthly average DLI for

each sensor. At the LT site, four sensors were placed in a northerly line leading from the center of the array backside and are labelled ‘South’, ‘Mid-South’, ‘Mid-North’, and ‘North’. A fifth, ‘Control’ sensor located in a nearby open field was utilized to determine the monthly control average DLI.

Results

To illustrate the continuous nature of the PAR data collected, and to give an example of how shade-patterning at the site influenced PAR values sensed throughout the season/day, a graph is presented below which demonstrates how different sensors detected varying levels of light throughout the day. Apparent shadows and full-sun exposure can be inferred from PAR rising from or falling to ‘zero’ or very low values of PAR. Graphs were generated using Google Colab and the Python software language.

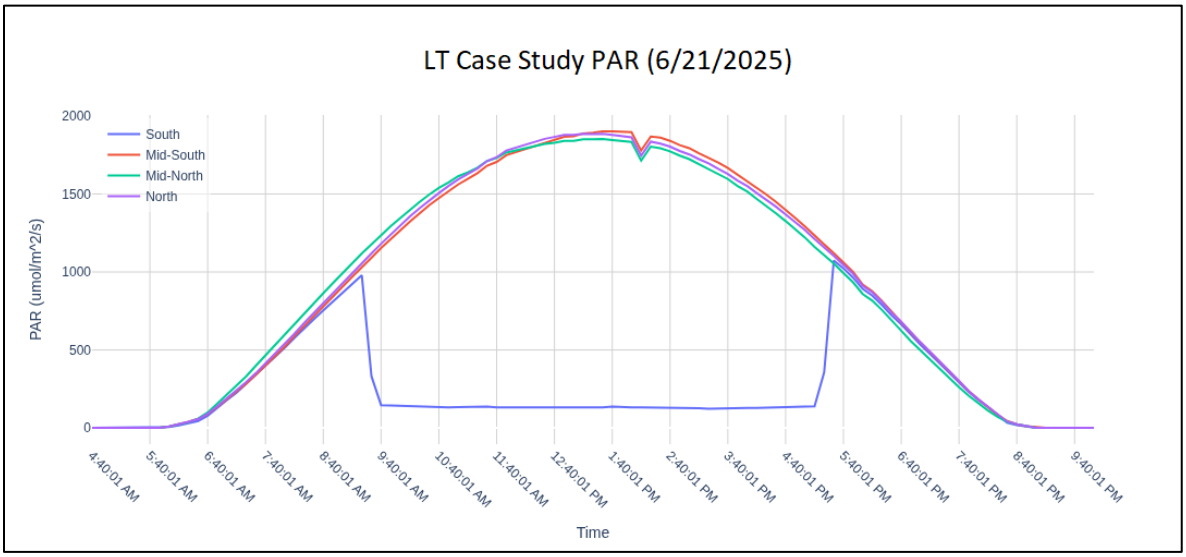

Figure 31 - Line graph showing Photosynthetically Active Radiation (PAR) sensed across the row at the LT site on June 21st, 2025. Sensors are indicated by the legend on the left, and distinct in color. 'Control' sensor is not included in this figure, as data from it was collected as part of the VB case.

The monthly DLI values from the LT case are presented below, along with the monthly Control DLI values from the Control sensor at the OHREC. For the month of August, only the first 5 days of the month were included in the Control DLI value, due to equipment failures. For

the month of September, DLI for Control is from sensor at UT case, which was functional during September and at comparable latitude to the LT case.

Table 1 - Monthly DLI values for each sensor at the LT site are presented April-September. DLI was calculated from PAR measurements, integrated over each month, and normalized.

Latitude-Tilt Case	**Average DLI (mol/m^2/d)**				
Sensing Interval	**South**	**Mid-South**	**Mid-North**	**North**	**Control**
April	3.22	8.79	7.25	8.25	28.45
May	12.04	40.3	40.07	42.85	40.46
June	14.65	44.84	41.88	44.16	43.22
July	14.31	47.31	44.1	45.58	43.82
August	11.62	42.75	37.96	41.61	42.67
September	7.53	30.18	12.29	29.05	26.71

These values are shown in the summary bar graph below.

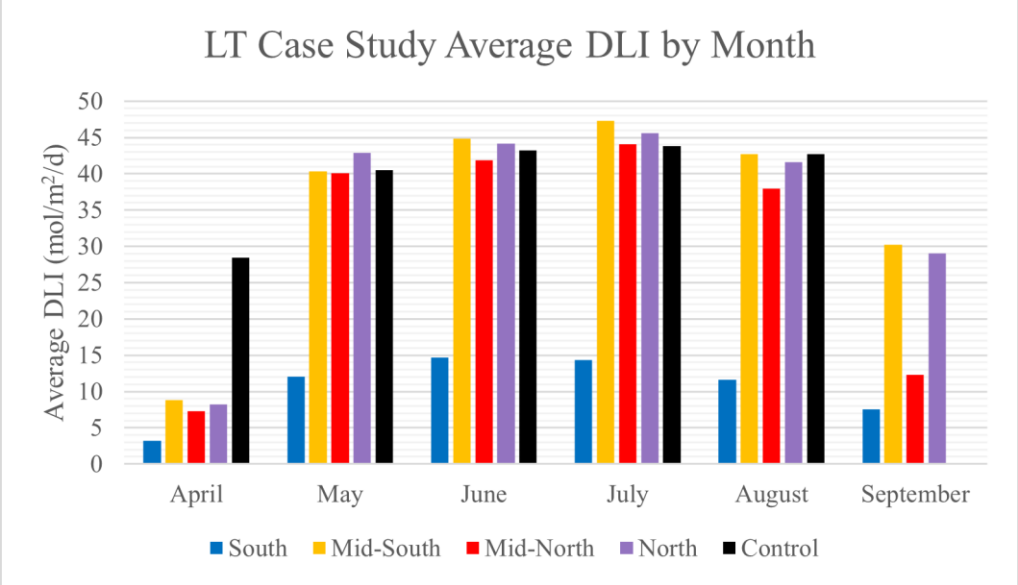

Figure 32 – Bar graph showing monthly calculated DLI values from LT site April-September. Since 'Control' sensor was non-functional for September, its value is excluded for that month. Sensors are denoted by color in legend at the bottom of the graph.

To compare the DLI values more directly, the percent reduction in PAR from the control value for each month, and averaged over the entire six months studied, are presented below.

Table 2 - Shows the percent deviation by month of each sensor's associated DLI value from the calculated control DLI. Average DLI over the entire growing season are presented for each sensor in the bottom row.

Latitude-Tilt Case	**Deviation from OHREC Control Value (%)**			
Sensing Interval	**South**	**Mid-South**	**Mid-North**	**North**
April	-89%	-69%	-75%	-71%
May	-70%	0%	-1%	6%
June	-66%	4%	-3%	2%
July	-67%	8%	1%	4%
August	-73%	0%	-11%	-2%
September	-72%	13%	-54%	9%
AVERAGE:	-73%	-7%	-24%	-9%

Discussion

In the LT array, treatment sensors saw an average of 11-73% less sun than the open field over the course of a growing season. The strongest treatment effect was observed on the southernmost sensor and an average of 73% less DLI than the control was observed. It is important to note that this sensor was placed directly beneath the panel and this sensor was completely shaded by the panels for the entire growing season. However, the sensors located further north did not see a gradient increase in DLI, as one might expect. This may be due to the sun being directly overhead (no shading from the array) during the summer months. All of these sensors remained within 11% of the control DLI values for the months of May-August, which supports this theory.

Without complicated controls, latitude-tilt arrays are simply installed and kept clean and functional. Fixed arrays are also adaptable for a wider range of topography, as the angle of the tilt can be adjusted accordingly to compensate for uneven ground (Soeasy Robot, 2024).

Since latitude-tilt arrays are lower-cost options than several others, and since they are so uncomplicated to install and keep in operation, their applicability to small-scale agrivoltaics is

apparent at least in an economic sense. The presence of apparent dead zones (Wang et al., 2017), areas between panels where insufficient light for crop productivity exists, complicates the picture, however. Since the sensor closest to the panel array 'South' was the only one which showed a sizable, significant difference from the control value when analyzed with Tukey's HSD (Mean DLI = 10.56, p-value when compared to Control = 0.007) it can be inferred both that the South sensor is within a dead zone and that the said dead zone likely exists to a point beyond the South sensor, but excluding the Mid-South sensor. The other three sensors were not statistically significantly different from the Control DLI values (.86, .99, and .99 respectively) and so may have received a comparable amount of plant-available light to open field conditions. Thus, in looking at latitude-tilt systems' applicability to agrivoltaics, it is important to note that dead zones may exist, and that their size and location may not be explicitly known without testing.

Uniaxial-tilt Tracking Array (UT) Case Study

Figure 33 - PAR sensors (circled in red markup) between uniaxial-tracking arrays at UT site in Douglas County, KS

Methods and Measurements

The Uniaxial-Tilt (UT) case study was conducted at a local utility-scale photovoltaic production facility in Douglas County, KS. Unlike the agrivoltaic OHREC sites, no crops were grown at this location; vegetation consisted of a native, perennial grass and forb mix that was planted in December 2024. The array utilized modules of similar size to those in the other configurations studied and employed a single-axis tracking system to optimize solar exposure throughout the day.

Five sensors were installed along the row width beneath the panels, spaced 4.5’ apart on center, with each positioned about 2’ above the ground surface to simulate the light available to typical, mature vegetable crops.

Sensors recorded Photosynthetically-Available Radiation (PAR) at 10-minute intervals, which were then recorded, integrated, and normalized for the number of days within each month to calculate the monthly average DLI. Sensors at the UT site were labeled ‘East’, ‘Mid-East’, ‘Middle’, ‘Mid-West’, and ‘West’, corresponding to their relative position within the row. A sixth, ‘Control’ sensor was placed away from the panels to the north within the same property to determine the monthly average DLI in open-field conditions for the site.

Results

To illustrate the continuous nature of the PAR data collected, and to give an example of how shade-patterning at the site influenced PAR values sensed throughout the season/day, a graph is presented below which demonstrates how different sensors detected varying levels of light throughout the day. Apparent shadows and full-sun exposure can be inferred from PAR rising from or falling to ‘zero’ or very low values of PAR. Graphs were generated using Google Colab and the Python software language.

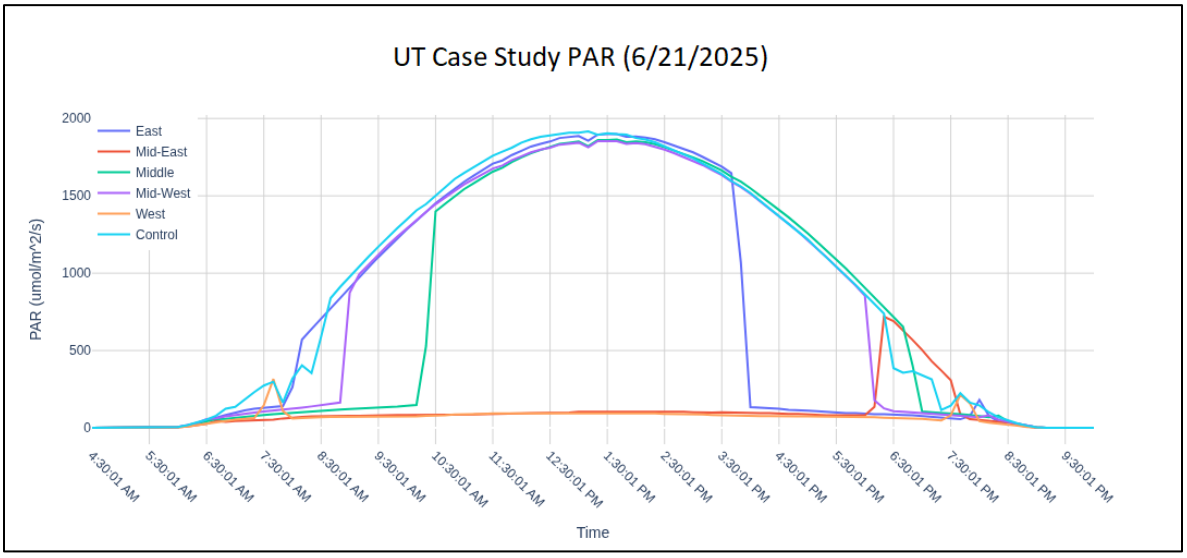

Figure 34 - Line graph showing Photosynthetically Active Radiation (PAR) sensed across the row at the UT site on June 21st, 2025. Sensors are indicated by the legend on the left, and distinct in color.

The monthly DLI values from the UT case are presented below, along with the monthly Control DLI values from the Control sensor at the UT site. For the month of August, DLI for Control is from sensor at VB case, as the UT Control sensor was not properly functional.

Table 3 - Monthly DLI values for each sensor at the UT site are presented April-September. DLI was calculated from PAR measurements, integrated over each month, and normalized.

Uniaxial-Tilt Case	**Average DLI (mol/m^2/d)**					
Sensing Interval	**East**	**Mid-East**	**Middle**	**Mid-West**	**West**	**Control**
April	25.13	6.08	27.36	28.2	4.85	31.22
May	33.43	6.62	35.3	37.02	5.00	40.77
June	36.56	7.58	38.32	40.91	5.71	43.84
July	35.68	7.27	38.43	40.66	5.23	43.23
August	30.79	6.6	32.16	34.57	4.03	20.61
September	22.92	4.91	22.28	25.45	3.48	26.71

These values are shown in the summary bar graph below.

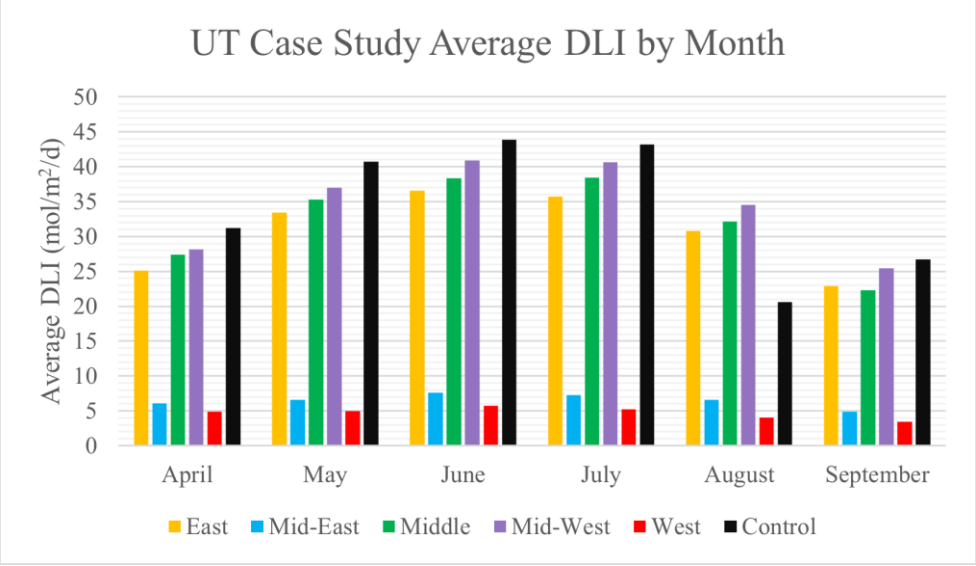

Figure 35 – Bar graph showing monthly calculated DLI values from UT site April-September. Sensors are denoted by color in legend at the bottom of the graph.

To compare the DLI values more directly, the percent reduction in PAR from the control value for each month, and averaged over the entire six months studied, are presented below.

Table 4 - Shows the percent deviation by month of each sensor's associated DLI value from the calculated control DLI. Average DLI over the entire growing season are presented for each sensor in the bottom row.

Uniaxial-Tilt Case	**Deviation from Stull Control Value (%)**				
Sensing Interval	**East**	**Mid-East**	**Middle**	**Mid-West**	**West**
April	-20%	-81%	-12%	-10%	-84%
May	-18%	-84%	-13%	-9%	-88%
June	-17%	-83%	-13%	-7%	-87%
July	-17%	-83%	-11%	-6%	-88%
August	-28%	-85%	-25%	-19%	-91%
September	-14%	-82%	-17%	-5%	-87%
AVERAGE:	-19%	-83%	-15%	-9%	-87%

Discussion

At the UT site, average deviations from the control DLI value ranged from 7-86% for the five treatment sensors. Assuming that the shadows cast by the linear arrays of panels are linear, it can be inferred that the two most-shaded sensors are located in dead zones ('West' Mean DLI = 4.72, p-value compared to control < 0.001; 'Mid-East' Mean DLI = 6.51, p-value compared to control < 0.001). These two were the only sensors which showed statistically-significant decreases from the Control DLI values. It could be inferred as well that the linear areas corresponding to the locations of the 'East,' 'Middle,' and 'Mid-West,' (p-values 0.89, 0.99, and 0.999 respectively when compared with control). with DLI deviations from control all below 20% on average, are areas wherein crops could potentially still grow and remain comparably healthy to the same crops grown in full sun. However, in order to confirm this, more studies should be conducted, with a higher sensor frequency in order to provide better resolution. Furthermore, multiple repetitions within the same interrow region would confirm specific width of the dead zone(s) and whether or not they extend linearly along the array length.

As with other installations, the goal of this study was to characterize light availability between panel rows. These panels rotate throughout the day to follow the sun, causing their

shadows, and the light environment in total, to shift continuously at ground level—an important factor when considering potential crop placements beneath or between them. Tracking arrays are more complex than latitude-tilt systems in both construction and operations & maintenance (Di Lorenzo, 2020). They require more expensive steel infrastructure, skilled contractors and operators capable of managing the tracking system effectively, and more involved upkeep, since both the energy production and tracking mechanisms must remain in working order. However, the ability to rotate the panel during equipment operations or harvesting is a real logistical advantage for agrivoltaics applications. Angle adjustments can also be made in response to wind or hailstorms, increasing the resilience of the system. Tracking the movement of the sun throughout the day—even without latitude-angle adjustment—is generally accepted as a more efficient method of capturing sunlight. Tracker systems consistently outperform similarly sized latitude-tilt or vertical bifacial arrays using the same panels and inverters (Sawicka-Chudy, 2018).

Vertical-Bifacial Array (VB) Case Study

Figure 36 - Sensors (circled in red markup) placed between panel arrays at VB site.

Methods and Measurements

The Vertical-Bifacial (VB) case study was conducted at the OHREC in Olathe, KS. This system employed vertically oriented bifacial modules of similar size to the other arrays studied and was used for agrivoltaic crop production. Crops grown under this configuration included spinach, beets, lettuce, tomato, green (snap) beans, watermelon, and zucchini. Yield data were collected for many of these crops but are not provided in this report. Nonetheless, maintaining the research plots provided critical insights into how day-to-day crop management can be affected and is reported here.

In the VB case, four sensors were installed along an east-west line, spanning the row width and perpendicular to the panels, spaced 55” apart. Each sensor was positioned roughly 2’ above the ground surface to approximate the light available to a typical, mature vegetable crop.

Sensors recorded PAR at 15-minute intervals, which were recorded, integrated over 15-minute intervals, and normalized for the number of days within each month to calculate the monthly average DLI. Sensors were labelled ‘West’, ‘Mid-West’, ‘Mid-East’, and ‘East’ according to the sensor’s location in the row. A fifth, ‘Control’ sensor was used to determine the monthly average DLI in open-field conditions, positioned south of the VB sensors in full sunlight.

Results

To illustrate the continuous nature of the PAR data collected, and to give an example of how shade-patterning at the site influenced PAR values sensed throughout the season/day, a graph is presented below which demonstrates how different sensors detected varying levels of light throughout the day. Apparent shadows and full-sun exposure can be inferred from PAR rising from or falling to ‘zero’ or very low values of PAR. Graphs were generated using Google Colab and the Python software language.

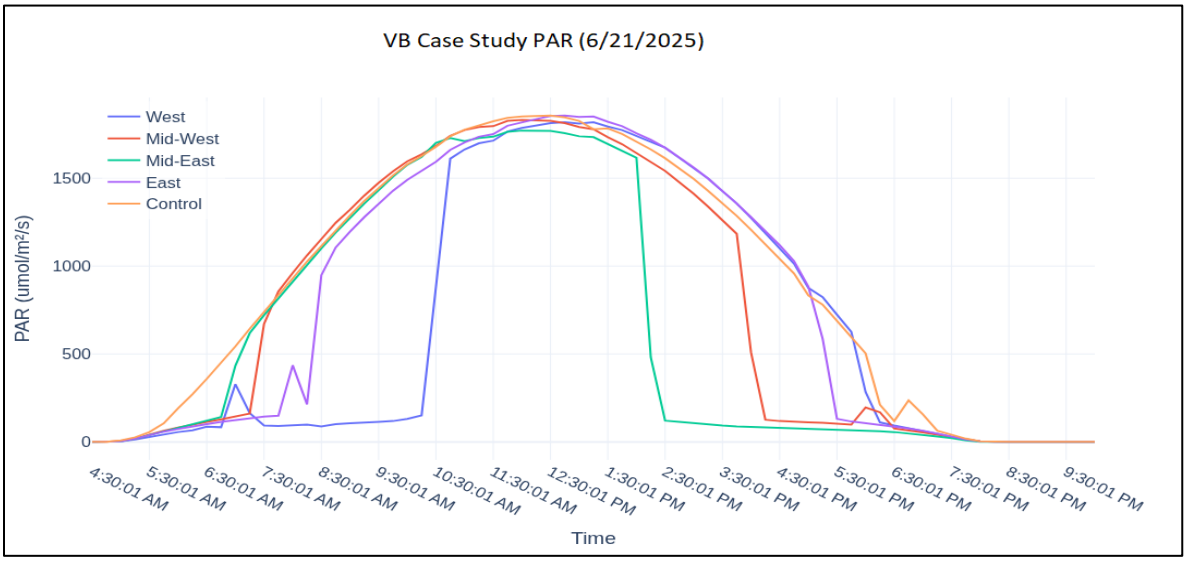

Figure 37 - Line graph showing Photosynthetically Active Radiation (PAR) sensed across the row at the VB site on June 21st, 2025. Sensors are indicated by the legend on the left, and distinct in color.

The monthly DLI values from the VB case are presented below, along with the monthly Control DLI values from the Control sensor at the OHREC. For the month of August, only the

first 5 days of the month were included in the Control DLI value, due to equipment failures. For the month of September, DLI for Control is from sensor at UT case, which was functional during September and at comparable latitude to the VB case.

Table 5 - Monthly DLI values for each sensor at the VB site are presented April-September. DLI was calculated from PAR measurements, integrated over each month, and normalized.

Vertical-Bifacial Case	**Average DLI (mol/m^2/d)**				
Sensing Interval	**West**	**Mid-West**	**Mid-East**	**East**	**Control**
April	22.44	26.19	21.28	27.37	28.45
May	29.88	30.75	24.60	34.80	40.46
June	32.14	36.71	30.28	38.59	43.22
July	33.39	38.15	31.01	39.98	43.82
August	29.67	34.44	29.43	35.74	42.67
September	21.26	23.78	20.44	25.16	26.71

These values are shown in the summary bar graph below.

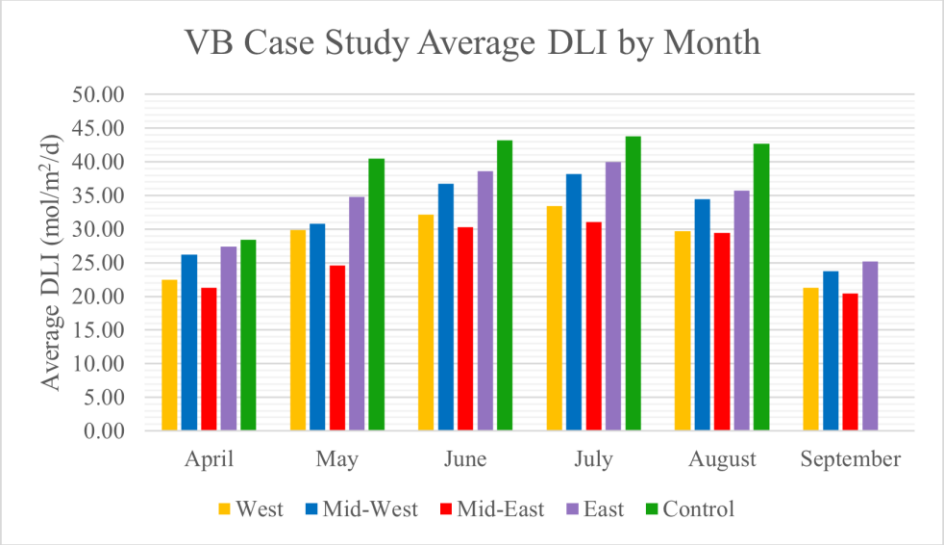

Figure 38 – Bar graph showing monthly calculated DLI values from VB site April-September. Since 'Control' sensor was non-functional for September, its value is excluded for that month. Sensors are denoted by color in legend at the bottom of the graph.

To compare the DLI values more directly, the percent reduction in PAR from the control value for each month, and averaged over the entire six months studied, are presented below.

Table 6 - Shows the percent deviation by month of each sensor's associated DLI value from the calculated control DLI. Average DLI over the entire growing season are presented for each sensor in the bottom row.

Vertical-Bifacial Case	**Deviation from OHREC Control Value (%)**			
Sensing Interval	**West**	**Mid-West**	**Mid-East**	**East**
April	-21%	-8%	-25%	-4%
May	-26%	-24%	-39%	-14%
June	-26%	-15%	-30%	-11%
July	-24%	-13%	-29%	-9%
August	-30%	-19%	-31%	-16%
September	-20%	-11%	-23%	-6%
AVERAGE:	-25%	-16%	-31%	-11%

Discussion

In the case of the vertical-bifacial array, the resulting light environment was very different than the other two. All four sensors were within 21% of each other when averaged over the growing season, a much narrower range than seen in the data from the other two arrays. All four sensors ranged from 10-25% less than the control value. This indicates that sunlight reaches all areas between the panels to at least 75% of its full potential. Only one sensor sensed PAR values significantly different from the Control sensor (p=0.02), while the other three sensors were all statistically similar (p-values: 'West'=0.08, 'Mid-West'=0.45, and 'East'=0.78) indicating that these sensors saw light amounts comparable to open field conditions. This finding would have to be confirmed with further studies and greater sensor resolution as there could still be dead zones that were not detected. With the current study

Figure 39 - Bee pollinating a flower at a solar farm in KS.

results, however, it appears that vertical-bifacial arrays have the most consistent sunlight available to plants across the width of the interrow region between arrays.

Vertical-bifacial (Figure 36) arrays can be understood much like a fixed-tilt array, but with some major differences. Similar to latitude-tilt arrays, modules in vertical-bifacial arrays remain stationary. Unlike other common solar power systems, panels in this array are oriented vertically with modules facing east (for sunrise) and west (for sunset), usually in a 50/50 split so panels see both directions evenly, when averaged over a whole day. This construction offers several advantages for agrivoltaics systems and particularly horticultural crop production. When built with sufficient row spacing to allow for the largest equipment being used in an agrivoltaics system, these arrays allow for easier regular equipment access. They also generate electricity during peak demand periods—mornings and evenings—when electricity is more valuable, potentially improving net metering rates in the favor of the operator. Using bifacial panels split evenly between east- and west-facing orientations further enhances this benefit, optimizing the cost-effectiveness of the electricity produced. Construction and maintenance of vertical-bifacial arrays are comparable or lower in cost and complexity to latitude-tilt arrays, with both types avoiding the need for moving components. Vertical arrays may require less frequent cleaning, but their orientation exposes both sides of the modules to equal amounts of sun, wind, and precipitation. In Kansas, a significant benefit to this array type is reduced risk of hail damage. A professional engineer familiar with local solar conditions can help determine whether a vertical array is economically viable for a given property.

Conclusions from the Light Studies – Dead Zones

Dead zones are important to discuss because they pose a potentially compromising aspect to planting crops between solar panels. Growers utilizing agrivoltaics systems need to know if a

certain area of the field is not viable for crop growth, or if certain areas are better than others. Studying where these dead zones might exist could prove instrumental in APV system design including their location, size, and ground surface ratio. Finally, knowing where dead zones are plays a large role in determining equipment access needs in a given array or configuration. Tractors must not only be narrow enough to fit between arrays safely, but their attachments (including tillers, discs, seeders, etc.) have to be able to reach the areas of the field which are intended to be cultivated. By identifying unusable growing space within rows prior to planting, growers can strategically approach production under solar panels and avoid potential dead zones.

It is imperative that further studies be done with a higher sensor resolution and repetition to determine the size, location, and nature of dead zones more precisely in various solar array configurations. This knowledge would drive design decisions like configuration choice, row spacing, and even crop selection, as dead zones could be avoided or planted with crops that have lower light requirements. Further research at these same sites, again with higher sensor resolution, would also provide insight into any dead zones which were not detected from the data presented above, or even find areas which are typically unshaded. In any future case, the sensor placement and data analysis could be repeated as above to produce comparable tables and figures, and to better understand the presence and nature of dead zones in these configurations.

Recommendations for Agrivoltaics in Urban Agriculture

Latitude-tilt arrays (Figure 40) are often considered for applications within urban agriculture. The relatively simple design, lower cost, and compatibility with uneven terrain of this configuration make it a strong candidate for integration into community gardens, rooftop farms, or compact plots where space and budget are limited. The predictable shadow patterns and

fixed orientation can help growers plan crop placement more effectively, and the reduced maintenance demands make it more accessible for operators without specialized solar expertise. However, since it does not feature a tracking mechanism, it will not provide as much energy per panel as a tracking system could. Panels installed at an angle take up more projected ground space and may restrict what equipment can be used in certain areas. Often, fixed arrays are integrated into existing structures, reducing their footprint on ground area, and sometimes reducing installation costs. Since many rooftops in urban and suburban areas are tilted, these surfaces could be re-purposed to support solar panel racking without taking up any production space at all. Although this may not be considered co-location, it is a common strategy for people installing solar in the United States already, and small- and mid-scale urban farmers are likely familiar with it (Neumann & Dutzik, 2024).

Figure 40 - Solar panels over crops with high-tunnels and greenhouses in the background at OHREC.

Tracking arrays offer a unique dual benefit: optimized solar capture and improved equipment access. When positioned vertically (at sunrise or sunset), tracker arrays open wide lanes between rows, allowing farm machinery—such as combines, sprayers, and tractors—to move freely through the site. A trained operator can adjust the panels' angle at will, coordinating solar tracking schedules with planting, cultivation, or harvest cycles. This flexibility enables a seamless balance between energy generation and field productivity, ensuring that neither operation limits the other. For example, a soybean producer can tilt panels upright during harvest

to allow for combine passage, a vegetable grower might adjust orientation during cultivation to reduce shade stress on crops. Similarly, a grower could raise panels to permit equipment access before returning to solar-optimized angles. Though tracking systems may not fit dense urban cores, sub-urban and peri-urban farms across the Midwest are already demonstrating success by leasing smaller land parcels for solar generation (Milhollin & Tsay, 2024). Agrivoltaics can naturally extend these arrangements, strengthening local energy partnerships and providing farmers with stable, diversified income.

In urban agriculture, vertical-bifacial arrays (Figure 41) could potentially be extremely versatile. Their applicability in very small areas, including as fences or walls, makes these arrays extremely space-efficient, a central aspect of urban agriculture. Vertical arrays can be installed on pedestrian-accessible rooftops to existing structures, without having to determine the correct angle, or install a complicated tracking system. Urban farmers can utilize exterior walls and structures which already receive large amounts of daily sunlight to install vertical panels, and not shade out any crops in the process. As equipment access is already difficult and constrained in dense, urban areas, vertical arrays are well-suited, producing a comparable amount of electricity at an improved price while sacrificing the least ground area per panel. More research needs to be done to understand shading effects from vertical panels. Urban growers may want to

Figure 41 - Tomatoes ripening between solar panels at the VB site.

consider how shading in the morning/evening may affect their crops before installing vertical arrays among them.

Conclusion

There are many different ways to implement agrivoltaic production systems. One of the goals of agricultural research and extension is to provide individuals with the capability and resources they need to make informed decisions. In the context of agrivoltaics, it is difficult to know what the best practices are, given the recent development and wide array of options for agrivoltaics. The site-specific nature of agrivoltaics development has only become more established as additional approaches are developed worldwide (Lepley et al., 2025). Thus, in order to get started in agrivoltaics, farmers need: some fundamental solar energy concepts to understand the technology; a solid concept of co-location and some of the effects it can include; and what other people have been trying on their own farms. Each farm can have a unique topography, solar resource, climate, location, and goal for integrating photovoltaic power generation into their operation. This uniqueness requires a system specific to the plot of land, so it is likely that no two agrivoltaics systems will be identical.

This report aims to cultivate confidence and curiosity about pursuing agrivoltaics. The technology seems complex, but there are numerous resources available and different ways that agrivoltaics can be successfully implemented. Agrivoltaics is a new term, but the concept of improving land-use efficiency and diversifying enterprises on the farm has been a goal for farmers throughout history. Efficiency and responsibility, form the ethic by which land-use improves. Turning our energy demands to renewables like solar, while still prioritizing the production of food may be the next big challenge in agriculture: “to live on a piece of land without spoiling it.” – *Aldo Leopold, A Sand County Almanac*

Key Terms

Agrivoltaics – The practice of growing/producing agricultural products (crops, livestock, apiary, etc.) either underneath or between/within solar panel arrays.

Array – This refers to any set of multiple solar modules which have been arranged in such a way as to deliver the electricity they generate as one; arrays are often repeated multiple times to make a full-size solar installation.

Battery storage – This term refers to the amount and availability of stored, unused electricity from a given system; battery storage is often calculated as the amount required to 'survive' a typical/expected grid failure in the future.

Bi-facial – This refers to modules which have been designed to either 1) have solar cells facing both the 'front' and 'back' of the module, or 2) have cells designed such that light can enter from either side; bi-facial modules will *always* have visible cells on both sides.

Cell – The smallest iteration of photovoltaic power; a manufactured, double-layer piece of silicon capable of producing electric current.

Co-location – Producing two different outputs of whatever kind (crop/energy/commodity) on one piece of land, in a repeating pattern, either vertically or horizontally interspaced.

Configuration – The organization, in 3D space, of panels in an array; this refers to their number, angle, spacing, etc.

Daily Light Integral (DLI) – Daily/interval measurement of PAR. This value is calculated from the cumulative PAR measurements taken over a given day, aggregating them over known time periods (in this case, sensors took PAR measurements every 10 or 15 minutes) to give the "total" daily light sensed at that location. In this report, DLI is presented as an average over a monthly period, to account for weather conditions and other daily variations in sunlight. Unit: moles per meter-squared per day [$mol/m^2/d$]

Dead zones – In the field of agrivoltaics, dead zones are the places under/near panels where shading is too intense for crops to effectively gather sunlight and grow.

Direct Effects – This term refers to the known and unknown effect that APV-style production can have on crop yield and quality, especially when considering per-area production terms (lb/acre) or crop nutrition.

Electrical Grid – The interconnected system of power generators and transmission/distribution lines which covers almost the entire continental USA; electricity flows from centralized sources to neighborhoods and businesses, and solar systems often supply power directly into the local part of that network.

Equipment access – This refers to how easily machinery like tractors, combines, or mowers can enter, move through, and operate on a site; **access** ought to be defined for *all* the machinery that passes through, taking into account frequency and duration.

Grid failure – When the electrical grid connected to a home/business/town stops working correctly, and electricity stops flowing; outages can have different durations, and some (usually the result of natural/manmade disasters) are indefinite in length.

Grid-isolated – When a solar power system is built to be grid-isolated, it can safely disconnect from the grid and continue supplying electricity to a home or business without risking harm to the local grid or utility workers/equipment; usually, this involves specific electrical equipment be installed to enable grid-isolation.

Indirect Effects – This term refers to known and unknown effects that arise between the two production systems, and can involve anything from reduced need for irrigation (from shading) to increased need for worker training (for equipment access issues) to anything else that arises as a result of the interaction of the power and agricultural production systems.

Interconnection – This term, in a solar power context, refers to the technical and legal requirements for connecting a project to the grid and sharing electricity.

Interrow – This refers to the regularly spaced gaps between parallel rows in a solar array or agricultural field, often used for access, vegetation, or drainage.

Inverter – Usually installed per array (or per system for smaller systems) this refers to an electrical device in a solar system that converts electricity from DC to AC: the form homes and businesses readily use; some newer systems use microinverters, which are simply small inverters placed the back of each module.

Land-cover/land-use – "Land-cover" refers to what physically exists on the land (like grass, crops, pavement, or trees) while "land-use" describes how people use that land, such as farming, grazing, or energy production; *as land-use changes, so will land-cover*.

Levelized Cost of Energy (LCOE) – LCOE is the average cost to produce one unit of electricity over the lifetime of a power system, including all expenses; calculating a potential LCOE will involve accounting for capital costs from construction, depreciation, loans, and any other financial aspect of the system, positive or negative. LCOE = (total lifetime energy generation) / (total lifetime cost)

Modules – A solar panel which has been wrapped in metal for structural support and has had electronic equipment installed so that it can easily be installed with other modules or into an existing electric system; often, when people "see solar panels," what they <u>see</u> are actually *modules* which *contain* panels.

Mono-facial – This refers to modules with photovoltaic cells on *only one side*; often these modules have solid, opaque layers on the back so no cells are visible except on the front side.

Net Metering – Typically, this is a billing system that tracks how much solar energy is shared with the grid and gives credit in return; each energy utility will have a different net metering structure, and some may not have one at all.

Operation & Maintenance (O&M) – O&M refers to the ongoing work, after construction, needed to keep a solar power system running safely, efficiently, and reliably – this includes monitoring performance, cleaning panels, checking electrical components, and fixing any issues that come up.

Peak Power Production – The highest amount (in kW) of electricity a solar power system can generate under *ideal* sunlight and operating conditions.

Photosynthetically-Available Radiation (PAR) – Rate/instantaneous measurement of light, when considering only wavelengths from 400-700nm. These are the spectra of light which plants regularly use for photosynthesis. This term thus describes how much light a plant is getting at a given moment, i.e. how much 'usable' sunlight. Unit: micro-mole per meter-squared per second [umol/m^2/s]

Photovoltaic – A kind of solar power which uses n- and p-type silicon layers to harness energy from the sun; light from the sun 'knocks electrons loose' between the two layers, causing a voltage drop and subsequent current flow.

Row spacing – In solar design, row spacing determines how close or far apart panel rows are placed; it influences energy production, equipment access, and vegetation growth.

Semi-Transparent – A trait of some panels, this term refers to those which allow some sunlight to pass through unmodified and untapped, so that plants or soil below are not fully shaded, even when fully under a shadow.

Sensor resolution – This term refers to the number of sensors used per sampling boundary; for instance, having 20 sensors in a 20 square foot area would provide double the sensor resolution that the same study with only 10 sensors would provide.

Shade-patterned – Systems which utilize a sort of 'checkerboard' of sunlight, wherein areas are alternately shaded and sunned throughout the day, as a consequence of the system geometry.

Silicon – A mineral that is known to be a semiconductor; doping it with different elements creates the two layers (n- and p-type) of silicon in a panel which allow for sunlight to excite electrons and generate electricity.

Solar noon – This refers to the time of day when the sun is highest in the sky; it is important to know that this time is very rarely the same time as local noon or 12:00pm; this is determined with astronomical records and projections, and can be determined for basically any date in the past or future using online calculators.

Solar panels – A specific application of photovoltaic technology; comprised of many solar cells encased in transparent materials, a panel outputs a standard amount of electricity.

Solar power – Electricity that is generated from: certain silicon-based chemical reactions; from concentrating/redirecting heat from the sun; or from other, more-selective technologies which utilize specific portions of sunlight.

Solar Resource – This describes the intensity and duration of sunlight at a specific place, which is used to estimate solar power potential; usually expressed in units of $kWh/m^2/d$.

Three Rs of Power System Reliability – These are key principles used to evaluate how well an energy system can deliver consistent and dependable electricity.

1. **Resource Adequacy** – In planning for solar power generation, Resource Adequacy refers to whether a location receives enough consistent and sufficient energy from the sun to justify installation.

2. **Reliability** – This refers to how 'smoothly' the system operates, or how predictably; within this term is included the understanding of how effectively the system can meet surges in demand.

3. **Resilience** – Resilience is the ability of a power system to prepare for, withstand, and quickly recover from disruptions like extreme weather, cyberattacks, or wildlife damage.

Tracker – This refers to systems or system *controls* which rotate solar panels to stay aligned with the path the sun takes throughout the day, helping capture more sunlight and boost efficiency.

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Appendix A

Battery Bank Worksheet

For this, you'll need an electricity bill from last July/August, or whichever month is heaviest in power consumption. If you aren't sure, summer months are usually a good bet. This is meant as a **guide** to understand your farm's basic solar-battery needs. Consult with a licensed Engineer/Electrician before installing solar equipment! And bring your answers to these questions when you do!

1: How much energy did you use during the **entire** billing period? (Find the "Energy Use" number for that month, & make sure it's in kWh)

_____

2: When, during an average day in this period, were you using the most energy?
(Morning/Noon/Evening – some Evergy bills show a "daily use" graph which shows this)

_____

3: How 'certain' do you need your energy to be? (in other words: How easily can you currently 'survive' a grid power-outage?) Provide a percentage rating 1-100%:

_____

4: List your most crucial appliances & their energy need: *(list everything that, if it lost power for more than a few minutes, would cause you major financial / operational headaches)*

Appliance	#/ct.	Amperage
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____

Appendix B

O&M Guidesheet

Before you move on from this guide sheet: Always consult with a licensed Engineer/Electrician before you build any solar equipment! And bring your answers to these questions when you do!

1. What is the primary purpose of the system? (Offset your bills, power irrigation, etc.)

   _____

2. What would be the process, as far as you're aware, to begin permitting construction on your land? (*e.g., city/county permits, existing easements, HOAs, etc.*)

   _____

   _____

3. Who is your current electricity provider?

   _____

4. Do you think you'll want to "tie" your system into the electrical grid?

   (Y/N)_____

   →**Evergy customers can look here for info on interconnection:** https://www.evergy.com/smart-energy/renewable-resources-link/private-solar-and-net-metering

5. Do you want to include batteries for energy storage?

   (Y/N)_____

   →If yes, **please see the Battery Bank Sizing Worksheet** also found in this report!

6. How often are you *now* getting into the field where the panels *would* go, for plantings, maintenance, harvest, etc.?

   _____

7. Would you be able to keep up with (approximately-) monthly cleanings of your panels? (*"monthly cleanings" usually consists of simply hosing new dirt off*)

   (Y/N)_____

8. Do you want to be able to monitor the panels' performance in real time, via Internet?

(Y/N)_____

→If **Yes**, is there Internet available <u>now</u> where the panels will be?

(Y/N)_____

(*If there isn't, you may have to get a Wi-Fi extension or cellular data*)

9. Are you interested in Federal, State, or other grant programs to assist you in affording the system?

(Y/N)_____

(Keep in mind: this might entail some extra work on your end to submit documentation / applications!)

10. How long do you expect/want your system to last?

_____

(*Quick note: most panels are guaranteed for ~25y from the manufacturer*)

11. Do you expect to <u>scale the system up</u> at any point in its lifetime?

(Y/N)_____

12. Where will the system be located?

*(Include some details: anything you know about what happens there (birds, pests, crops, etc.) and what kind of weather commonly occurs on the plot, <u>especially how much dust</u> you see at the site on a regular basis. It's a good idea to bring **<u>pictures of the plot</u>** you're planning to develop along with this questionnaire to a Licensed Engineer.)*

_____

_____

_____

13. What's your budget? (*Or, if you're unsure: How much MORE or LESS than your current electric bill do you want to spend/month on the system and the electricity it provides?*)

_____