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A Simulation-Based Energy Assessment of Agrivoltaics on Lettuce Farms in Monterey County, California

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Dr. Tony Kerzmann is an Associate Professor of Mechanical Engineering at the University of Pittsburgh, where he teaches and conducts research in renewable energy systems, sustainability, and engineering education. His work explores solar energy design, agrivoltaics, life cycle assessment, and electric vehicle infrastructure modeling. As a dedicated advisor, Dr. Kerzmann integrates experiential and project-based learning into his courses, guiding students to apply engineering principles to real-world sustainability challenges. He serves The Mechanical Engineering and Materials Science Engineering department as the Associate Director of Undergraduate Academics and contributes to the Mascaro Center for Sustainable Innovation, where he has received multiple Leonard Peters Fellowships for his continued support in teaching and leadership. Dr. Kerzmann's research and service reflect his commitment to advancing clean energy education and empowering the next generation of engineers to build a more sustainable future.

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Abstract

The U.S. agricultural industry faces mounting economic challenges as farm incomes fluctuate with market volatility, weather variability, and generational transition. Agrivoltaics (AgPV), the dual use of land for both solar energy generation and agricultural production, presents a promising strategy to enhance farm sustainability while contributing to clean energy goals. By integrating photovoltaic systems above cropland or grazing areas, AgPV offers farmers an opportunity to diversify revenue streams through consistent energy income while maintaining agricultural productivity. This research investigates the potential scale of AgPV land use required to offset fossil fuel electricity generation of an entire state, using California as a case study.

The study combines literature review with energy production modeling using the National Renewable Energy Laboratory's System Advisor Model (SAM). A standardized per-acre modeling approach is developed to estimate electricity generation from bifacial solar modules mounted on single-axis tracking systems designed for agricultural co-location. Agricultural production data are analyzed alongside solar energy outputs to assess synergies in land use, crop yield, and energy generation.

SAM simulation results indicate that converting just 0.45% of California's agricultural land to dual-use agrivoltaics could offset approximately 64% of the state's 2024 in-state fossil fuel electricity generation. This approach offers a pathway to expand clean energy capacity without displacing food production, while providing farmers with a stable supplemental income stream and supporting rural economic resilience. By quantifying the land and energy potential of these systems, this study positions agrivoltaics as a practical and sustainable strategy for addressing both energy and agricultural demands.

Introduction

As global populations rise and per capita energy demands increase, society has a need to ensure food security while transitioning to clean, renewable electricity. Solar photovoltaics (PV) play a central role in decarbonizing the electricity grid, however, a major challenge in this transition is land use competition. Traditional utility-scale solar installations often occupy vast tracts of potentially arable land, in some cases creating a conflict between energy generation and agricultural production.

At the same time, the U.S. agricultural industry and traditional farming practices face mounting economic challenges. Farmers find themselves navigating volatile commodity markets, fluctuating input costs, and increasingly variable weather patterns. These pressures result in unstable farm incomes and a growing risk of reduced profits and even bankruptcy. Agrivoltaics (AgPV), which is the integration of photovoltaic arrays constructed above cropland and grazing land, presents a promising strategy to address these many converging agricultural challenges.

AgPV systems provide mutually synergistic benefits for both energy and food systems. Figure 1 illustrates the major components of an Agrivoltaic (AgPV) system. As shown, standard photovoltaic arrays are elevated on racking structures high enough to allow farm machinery, livestock, and workers to operate freely underneath. This configuration creates a synergistic dual use of land where solar panels generate clean, renewable electricity while simultaneously modifying the microclimate for the crops or animals. As indicated in the diagram, the partial shading provided by the panels helps protect crops from extreme weather, heat and reduces water evaporation from the soil, allowing agricultural production to thrive alongside renewable energy generation, especially in dryer climates.

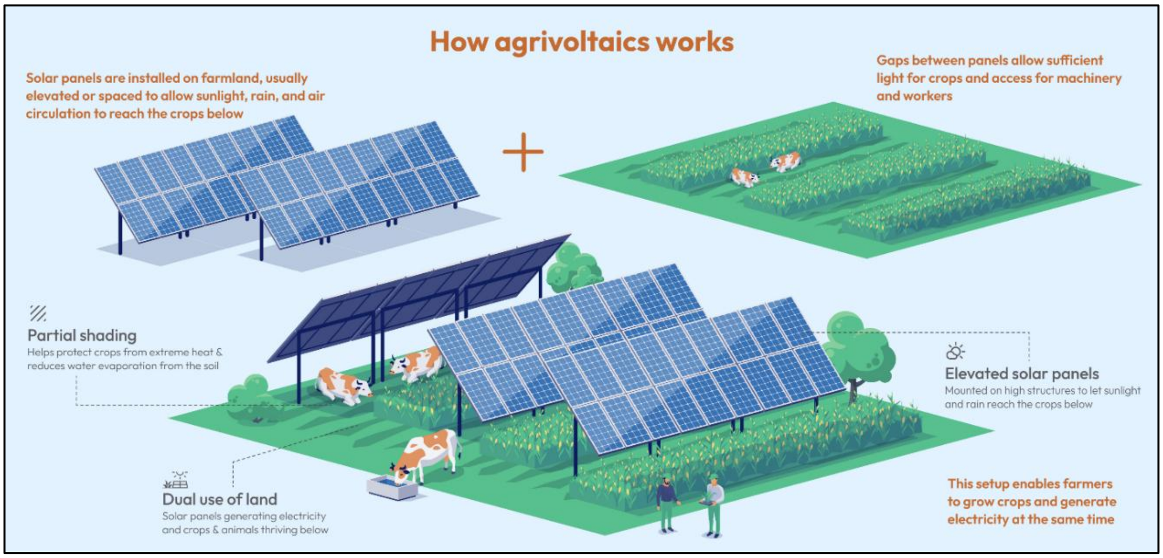

Figure 1: Illustration of an Agrivoltaic Example [1]

Economically, AgPV offers farmers a diversified and consistent revenue stream where farmers receive steady income from leasing land or receive income from the sale of electricity in the case that the farmer owns the solar array. From a biological lens, AgPV systems create a distinct microclimate beneath the panels that can enhance productivity. In arid regions, the partial shade provided by solar panels reduces heat stress and evapotranspiration. Consequently, shade-tolerant crops can thrive in these cooler environments; vegetables such as lettuce, Swiss chard, kale, spinach, parsley, mint, cilantro, chives, carrots, potatoes, onions, radishes, beets, cucumber, and squash to name a few. This demonstrates that improved water use efficiency, especially in arid environments can increase crop yield potential compared to traditional open-field farming.

There is a growing body of evidence supporting the claim that AgPV systems significantly increase crop yields under specific environmental conditions. Barron-Gafford et al. found that AgPV mitigates drought stress and reduces heat exposure, leading to yield improvements in arid-adapted crops. Their study recorded a 33% increase in CO_2 uptake for chiltepin peppers and a 157% increase in water use efficiency for jalapeños compared to control groups. [2] Similarly, during the extreme heat of the 2018 growing season near Lake Constance, Germany, Trommsdorff et al. observed that shading from AgPV systems improved yields for winter wheat, potato, and celeriac by 3%, 11%, and 12%, respectively, relative to unshaded reference areas [3]. In the case of leafy greens, research by Jamil et al. demonstrated that using PV modules tuned for improved crop growth, agrivoltaic environments could boost romaine lettuce fresh weight by as much as 483% compared to unshaded control environments, and by over 243% relative to the national average yield [4]. Collectively, these findings validate the potential for AgPV to enhance agricultural productivity in tandem with energy generation.

Economic considerations are important in assessing the broader viability of AgPV at scale. The existing literature provides consistent evidence of favorable economic outcomes. Schindele et al. found that the dual-use nature of AgPV increases economic output per unit area while diversifying farm income and enhancing growers' resilience to climate-related risks [5]. Barron-Gafford et al. further demonstrated that the under-panel microclimate can extend growing seasons and generate supplemental revenue through land-lease arrangements [6]. In addition, Dinesh and Pearce reported that pairing solar electricity generation with shade-tolerant crops such as lettuce yields more than a 30% increase in farm economic value while minimizing yield losses, thereby supporting crop price stability [7].

Despite the growing body of research demonstrating the agricultural advantages of Agrivoltaics (AgPV), there is still a limited amount of literature quantifying the macro-scale land use and energy implications of its widespread adoption. This study adds to the literature by investigating the technical feasibility of offsetting a portion of a state's fossil-fuel electricity generation exclusively through dual-use farming operations.

Figure 2 presents a Pareto chart of California's electricity consumption for 2024. Total electricity consumption reached 278,338 GWh, of which 78% (216,181 GWh) was generated in-state and the remaining 22% was imported from neighboring states. Although renewable sources such as solar, hydropower, biomass, and wind collectively accounted for approximately 51% of in-state generation, natural gas remained the single largest contributor. Together with smaller contributions from coal and oil, fossil fuels supplied 40% of the state's total electricity generation, or 86,976 GWh. This study compares the electricity generated by AgPV systems on lettuce farmland in Monterey County against in-state generation only; out-of-state imports are excluded from the analysis.

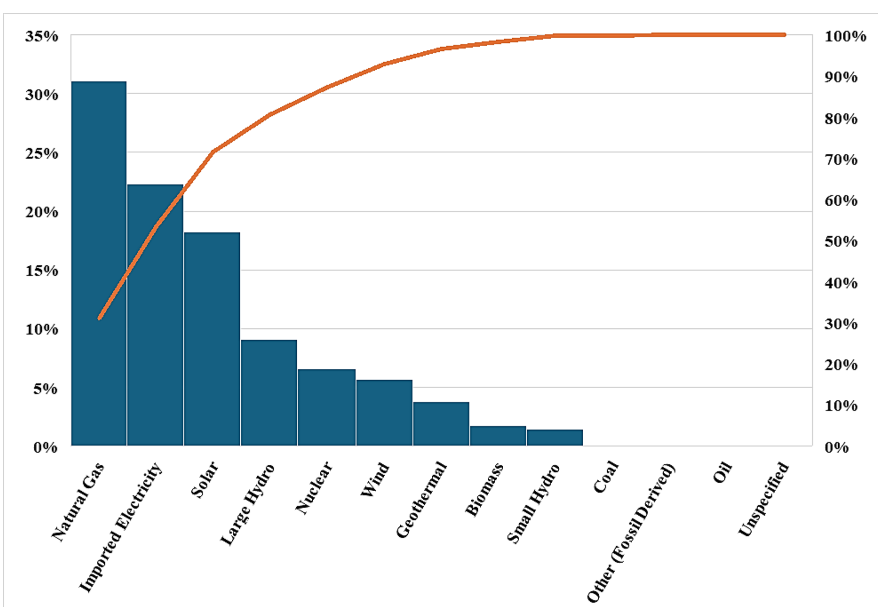

Figure 2: Pareto Chart for California's Electricity Consumption [8]

This paper presents a simulation-based methodology, using California as a case study due to its high solar insolation and extensive agricultural output. This study models the land area required to offset the state's electricity generation via AgPV, utilizing government-published data to establish system parameters. Lettuce was selected as the focal crop for this model because it benefits significantly from the cooler microclimates and reduced heat stress created by the shade from the solar array. The lettuce benefits from the partial shading of the solar panels in the hot California sun. The panels act as a buffer from extreme heat and the lower shaded temperatures under the panels decrease evapotranspiration, leading to lower water demand. Monterey county is the leading California county in lettuce production and was therefore chosen for our case study. Finally, this paper reflects on the undergraduate research experience, utilizing learning frameworks to demonstrate the educational value of simulation-based engineering projects.

Methodology

The first step in conducting this research was to select the case study location and to determine suitable land availability. To evaluate the technical potential of widescale AgPV deployment, this study selected Monterey County as the primary case study due to its status as California's leading producer of lettuce. According to the 2024 County of Monterey Crop & Livestock Report, Monterey county harvested 107,200 acres of lettuce in 2024 [9]. In this study, we use this land area along with our electricity simulation results to estimate the total electricity generation if this land area were converted to dual-use AgPV farmland.

The electricity generation was modeled using the System Advisor Model (SAM), a performance prediction software developed by the National Renewable Energy Laboratory (NREL). SAM is designed to calculate the hourly and annual energy output of renewable energy systems based on detailed geographic information, weather data and electrical specifications.

To accurately simulate the performance of a solar array in Monterey County, location-specific meteorological data was acquired from the National Solar Radiation Database (NSRDB). This database provides high-resolution weather files which contain hourly data for parameters such as global horizontal irradiance (GHI), direct normal irradiance (DNI), ambient temperature, pressure, humidity, rainfall, and wind speed [10]. When imported into SAM, these files enable the model to account for local climatic variations [11]. SAM was used to simulate the annual electricity production of a standardized photovoltaic array under the specific solar irradiance and meteorological conditions of Monterey County. An image of California counties is shown in Figure 3 with Monterey county highlighted.

Figure 3: Map of California with Monterey County Highlighted [12]

A standardized system capacity of 1.00 MWdc was established as the baseline for all simulations. This normalization enables the determination of Annual Energy Production in megawatt-hours per megawatt (MWh/MW), facilitating linear extrapolation of energy potential across the total identified agricultural acreage.

The photovoltaic array was modeled with single-axis horizontal tracking to optimize diurnal solar capture by following the solar azimuth from east to west. The mechanical configuration utilizes a 1-in-portrait (1P) layout, where a single module is mounted vertically along the torque tube, as shown in Figure 4.

Figure 4: 1p Module Array with Single-Axis Tracking [13]

The specific 1 MWdc array modeled in this study is comprised of 1,650 bifacial modules, each rated at 610W. Bifacial technology was selected to account for albedo reflection from the ground, a relevant factor in AgPV applications. The array layout consists of 33 tracking rows, with each row containing 50 modules. Power conversion is managed by Yaskawa Solectria 250kW DC-to-AC inverters. The PV array was modeled with single-axis horizontal tracking to optimize daily solar capture by following the solar azimuth from east to west. To further optimize performance, the tracking algorithm incorporates industry-standard backtracking modeling, which adjusts the panel angle during periods of low solar elevation to minimize inter-row shading losses. Table 1 summarizes the specific technical parameters input into the SAM simulation.

SAM System Parameters for 1.00 MW Solar Array Simulation	
Location	Monterey County, CA (Long: -121.66, Lat: 36.69)
Module Manufacturer	Heliene 156HC-610W M10 Bifacial
Module Efficiency	21.97%
Module Width	1.174 m
Module Length	2.360 m
Inverter	Yaskawa Solectria Solar XGI 1500V 250kW
Tracking	Single-Axis with Backtracking
Tracker Rotation Limit	± 45°

Table 1: SAM PV Simulation Parameters [14],[15]

Results

A critical design parameter for AgPV systems is the Ground Coverage Ratio (GCR), defined as the ratio of the PV module area to the total land area, as shown in Figure 5. GCR determines the inter-row spacing; a lower GCR increases the distance between rows, which is essential for maintaining solar access for crops and accommodating farm machinery. However, this increased spacing inherently expands the total land area required per megawatt of installed capacity.

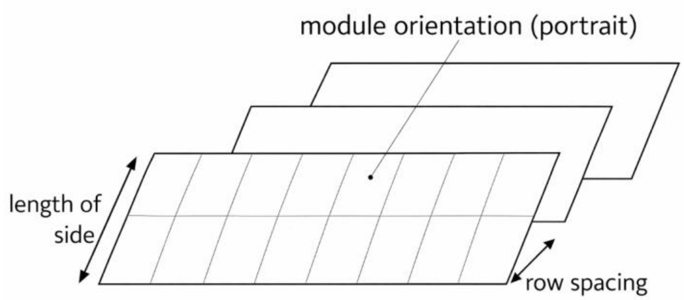

Figure 5: Image of 2p Solar Array Configuration Showing Parameters for GCR Calculation [11]

$$GCR = \frac{Length\ of\ Collector}{Row\ Spacing}$$

To determine the solar land density in Acres/MWdc for this model, iterative simulations were conducted in SAM using varying GCR values from 0.15 to 0.45. This analysis quantified the trade-offs between GCR, total system footprint, and annual energy yield. The results were applied to the 107,200 acres of identified lettuce farmland in Monterey County to estimate AgPV electricity production.

Ground Coverage Ratio (GCR)	Annual Electricity Generation (MWh/MWdc)	Row Spacing (m)	Land Area for 1 MWdc (Acres)
0.15	2,142	15.7	7.53
0.20	2,124	11.8	5.65
0.25	2,101	9.4	4.52
0.30	2,078	7.9	3.77
0.35	2,052	6.7	3.23
0.40	2,021	5.9	2.82
0.45	1,988	5.2	2.51

Table 2: Ground Coverage Ratio Effect on System Dimensions & Electricity Output

Table 2 presents the simulation results. The data reveals an inverse relationship between GCR and both system performance and land efficiency. As GCR increases (densifying the array), the Annual Electricity Generation for a 1 MW array decreases due to increased row-to-row shading losses. Conversely, the land requirement decreases significantly as the system becomes more compact. These relationships are visually represented in Figure 6, which illustrates the impact of GCR on energy yield, and Figure 7, which correlates GCR with total land area requirements

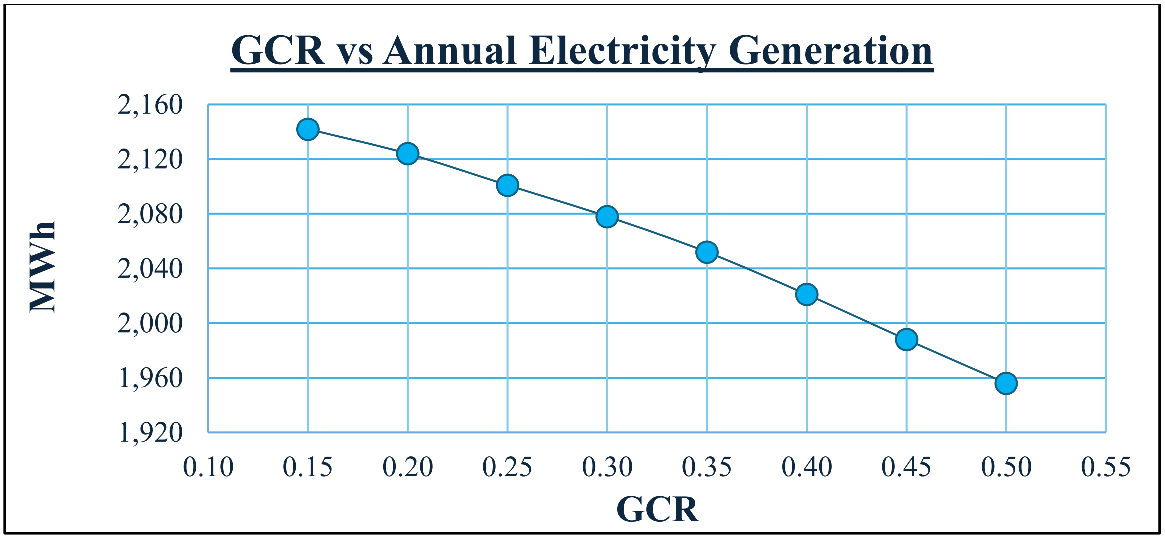

Figure 6: Effect of GCR on Annual Electricity Output in Monterey County, CA

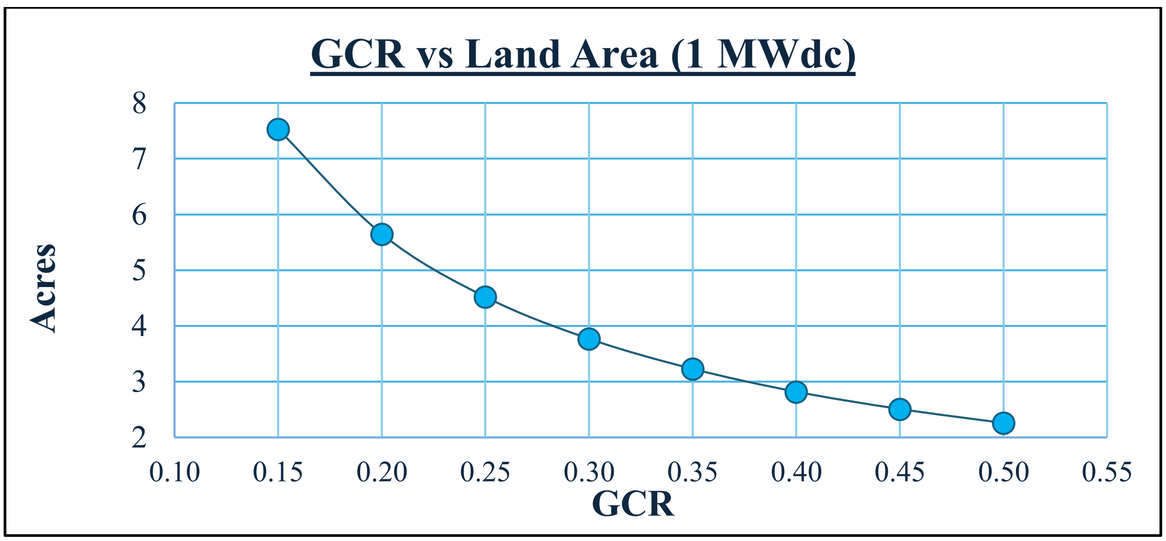

Figure 7: Effect of GCR on Land Area: Acres per 1 MW of Solar Array

To select a Ground Coverage Ratio (GCR) and power density that reflects current utility-scale standards, this study references empirical data from the Lawrence Berkeley National Laboratory (LBNL). LBNL evaluated 723 utility-scale solar installations commissioned between 2011 and 2019 to determine median power density trends. As illustrated in Figure 8, the power density for single-axis tracking systems has increased linearly over this period, rising from approximately 0.17 MWdc/acre in 2011 to 0.24 MWdc/acre in 2019 [16].

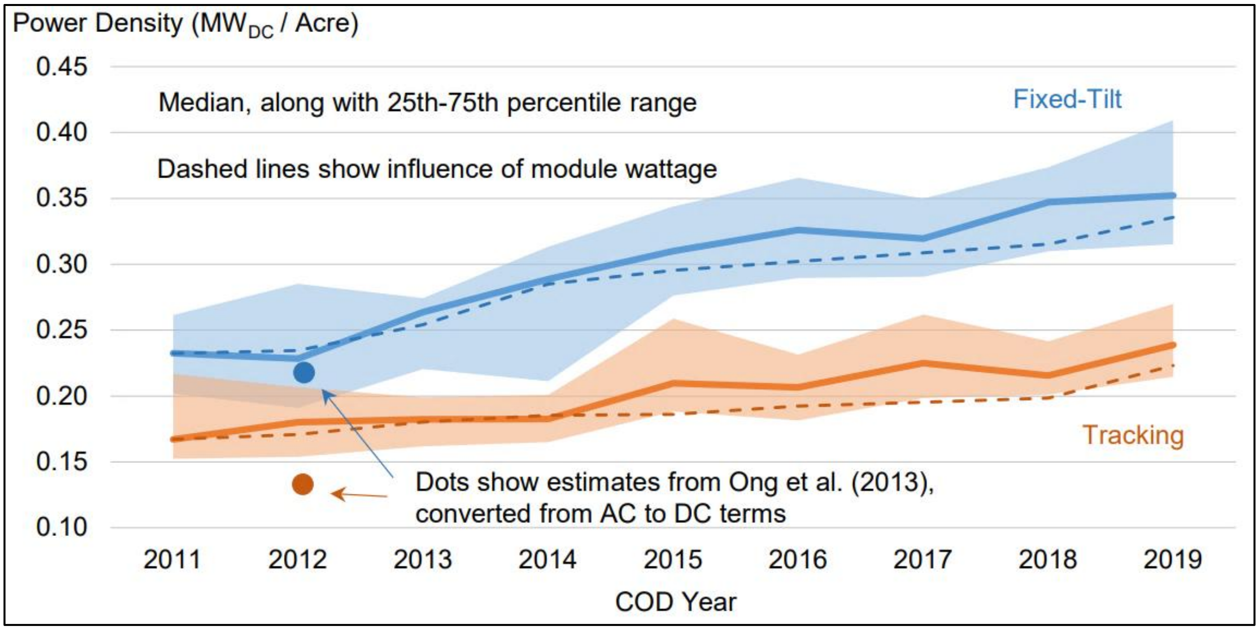

Figure 8: Lawrence Berkeley National Laboratory Utility Scale Solar Power Density Empirical Data from 2011 to 2019 [16]

This upward trend shows the effects of the consistent improvements in photovoltaic module efficiency and array design optimization within the solar industry. By extrapolating this historical trend to the present day, we projected a median power density of approximately 0.293 MWdc/acre for 2025. A power density of 0.293 equates to 3.41 acres per 1 MWdc installed solar, which aligns well with modern industry standards for single tracking systems.

$$\frac{0.24 - 0.17}{2019 - 2011} = 0.0088\ (\mathrm{MW/Acre \cdot Year})$$

$$0.0088 * (2025 - 2019) = 0.0525\ (\mathrm{MW/Acre})$$

$$0.24 + 0.0525 = 0.293\ (\mathrm{MW/Acre})$$

To determine the realizable energy yield per acre, the extrapolated power density was adjusted to account for civil infrastructure. In a standard solar farm, land is required not only for the panels but also for access roads, setbacks, inverter pads, and interconnection equipment. While agricultural land is typically flat and cleared (ideal for solar deployment), we conservatively assume that 85% of the total farmland area is available for module placement and the remaining 15% is allocated to supporting infrastructure, including setbacks, interconnection areas, and access roads. This results in a land-use requirement of 4.01 acres per MWdc. Combining this with the annual generation rate of 2,081 MWh/MWdc, linearly interpolated from Table 2, equates to a specific yield of 519 MWh per acre.

If Monterey County's 107,200 acres of farmland were converted to AgPV, this would generate approximately 55,637 GWh annually. Comparing this AgPV generation to the 86,976 GWh produced by fossil fuels in California in 2024, the AgPV implementation on lettuce farms in

Monterey county has the potential to replace 64.0% of California's in-state fossil fuel electricity generation.

These results provide insightful implications for energy policy and land use planning. The 107,200 acres of lettuce farmland utilized in this model represents 0.45% of California's 23.8 million acres of farm and ranch land. [9] This indicates that grid-scale decarbonization can be achieved with a minimal land footprint relative to the state's total agricultural land use. Additionally, beyond the reduction in polluting emissions, this type of clean energy transition would provide farmers with a diversified, steady income stream, while likely improving crop yield and resilience in farming regions that are affected by heat stress.

Undergraduate Research Experiential Learning

This AgPV research project provided a robust platform for undergraduate education through experiential learning. The student researcher's role was multifaceted, encompassing a comprehensive literature review, the selection of optimal vegetable groups for use with the partial shade of the PV panels, energy simulations, and the quantification of land use within California's farming industry. A core component of this work involved learning the System Advisor Model (SAM) software and performing iterative simulations to explore the effects of varying parameters such as Ground Coverage Ratio (GCR), geographic location, and sun tracking variables on the electrical output of the solar arrays.

The research experience provided experiential educational benefits that engaged the student in the highest levels of cognition. Bloom's taxonomy classifies cognitive learning processes into a hierarchy from basic recall to the creation of original work [17]. This framework, shown in Figure 9, provides a pyramid view of Bloom's Taxonomy where the highest levels of cognitive development are engaged in the top three levels.

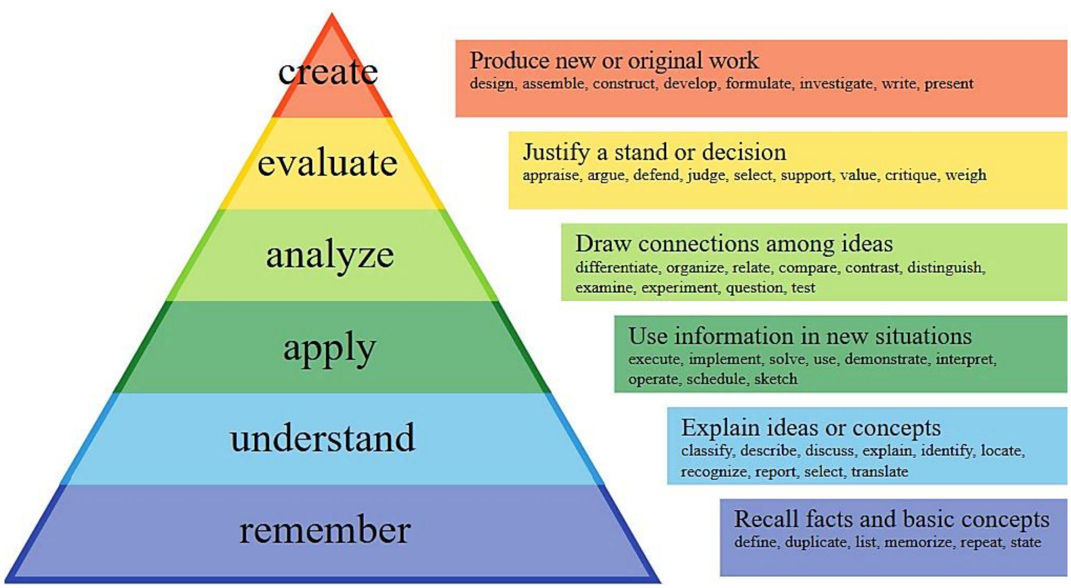

Figure 9: Visualization of Bloom's Revised Taxonomy [17]

The majority of the research tasks associated with this research most certainly included drawing connections between multiple interconnected domains, evaluating energy and agricultural systems, and creating a methodological framework for modeling AgPV energy generation. Below is a detailed description of how this research experience engaged every level of Bloom's Taxonomy:

- **Remember & Understand:** The undergraduate student began by performing a literature review facilitated by the faculty mentor. This phase required recalling fundamental engineering concepts and developing an understanding of the current landscape of AgPV practices.
- **Apply:** The student applied theoretical knowledge by constructing models in SAM. This involved downloading annual NSRDB weather data files and importing them into SAM, as well as understanding the interconnection between the literature and the model.
- **Analyze:** The research required in-depth analysis of energy and agricultural system variables. The student iterated through simulations to create important correlations, such as how changing the GCR influences land-use efficiency and specific energy yield.
- **Evaluate:** The student moved to the evaluation phase by finalizing system parameters and verifying them against empirical data, literature and industry standards. Decisions regarding module orientation, GCR, and DC/AC ratio were evaluated to ensure compliance with standard commercial practices.
- **Create:** Finally, the student created a novel methodology for calculating the total annual electrical energy output for specific crop categories producing an original contribution that quantifies the substantial potential of AgPV in California.

This research project significantly developed the student's ability to conduct research, confidence in developing research methodology, and technical communication skills. The process of digesting complex literature and explaining original results required a disciplined approach to technical writing. As an engineering student with a focus on renewable energy, this experience provided a strong foundation for future research. It not only deepened the student's technical grasp of photovoltaics but also brought to light some of the many advantages to dual use agrivoltaic applications in solving growing energy demands and reducing energy emissions. By transitioning from theoretical coursework to applied research, the student gained an understanding of the transformative role AgPV can play in a sustainable future.

To support continued research and broader educational use, instructional materials were developed to introduce new researchers to the methodology and to the use of the System Advisor Model (SAM) for simulating AgPV systems across a range of scales and geographic locations. The methodology presented in this paper lends itself well to a structured, step-by-step format that highlights the important aspects of the SAM software and includes several key system parameters. A SAM onboarding slide deck was produced by the student and has since been used to familiarize undergraduate researchers with the software, enabling future research groups to expand the scope of the research presented here.

Conclusion

This research demonstrates that Agrivoltaics (AgPV) represents a potentially transformational solution for the clean energy transition and for stabilizing the economics in agricultural sectors. The major finding of this study has significant implications for AgPV in California and countries around the world that have significant shade-tolerant farming. The researchers found that by converting 107,200 acres of lettuce farmland in Monterey County to dual-use AgPV systems, the region could generate approximately 55,637 GWh of clean electricity annually. This capacity is theoretically sufficient to displace 64.0% of California's in-state fossil fuel electricity generation (86,976 GWh) in 2024, utilizing 0.45% of the state's total agricultural land area.

Beyond the potential for decarbonization, AgPV presents a symbiotic advantage over conventional solar arrays by co-locating energy generation with agriculture, thereby avoiding land displacement and potentially optimizing crop growth. The methodology developed in this study is replicable for any location with accessible meteorological data, demonstrating that clean, renewable energy targets do not need to conflict with food production, but rather that the two can be mutually beneficial. By maintaining the same crop acreage, AgPV provides an additional revenue stream that can provide farmers with economic stability in volatile agricultural and supply markets. Additionally, while this study focused on quantifying electricity generation, the literature suggests that the microclimate created by the solar array offers mutual benefits for plant and modules alike. The shade provided by panels can reduce heat stress seen by crops, potentially increasing crop yields and reducing irrigation demands. Conversely, the evapotranspiration from the crops cools the photovoltaic modules which can improve electrical conversion efficiency.

The research study provided a beneficial platform for experiential STEM education. As the student progressed through the stages of research, they experienced all levels of Bloom's Taxonomy. The student researcher transitioned from passive background research to active, high-level cognitive development. The iterative process, moving from preliminary literature reviews to complex SAM simulations, engaged the student in the highest levels of the taxonomy: Analyze, Evaluate, and Create. This required the student to analyze relationships between variables such as GCR, energy yield and land area. The student also had to compare the simulation inputs and results against industry standards while creating a methodological framework for regional AgPV energy assessment. This research process developed a deep understanding of photovoltaic energy systems modeling that classroom instruction alone could not achieve.

While the clean, renewable energy potential of AgPV is clear, this study identifies several potential directions for future research to move AgPV toward broader implementation. Although outside the scope of this study, economic considerations and return on investment would be important areas to investigate. Future studies could analyze installation costs, operation and maintenance expenses, and the return on investment for farmers as compared to traditional farming. Solar generation is consistent year after year, but it is intermittent. Future research could include the modeling of energy storage capacity and grid integration. This might include the energy capacity and power capacity needed to replace the baseload electricity provided by fossil fuel electricity generation. Although there are many studies that have evaluated the effects of AgPV on agricultural production, more research is needed to fully understand the many variables that affect plant growth, crop yield, maturation times, heat and water stress, susceptibility to pests, and a whole host of other biological considerations.

In summary, Agrivoltaics presents a "win-win-win" scenario. It offers a sustainable pathway to generate clean, renewable, and resilient electricity, it promotes efficient land-use practices that preserve agricultural land and farm ownership, and it provides farmers with a stable, diversified income. By leveraging the synergy between clean electricity, agriculture, and the grid, AgPV can be a foundational technology for a sustainable future.

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