THESIS

WHEN IS AGRIVOLTAICS PROFITABLE COMPARED TO AGRICULTURE AND PHOTOVOLTAICS? A JOINT-PRODUCT ECONOMIC FEASIBILITY ANALYSIS

Submitted by

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ABSTRACT

WHEN IS AGRIVOLTAICS PROFITABLE COMPARED TO AGRICULTURE AND PHOTOVOLTAICS? A JOINT-PRODUCT ECONOMIC FEASIBILITY ANALYSIS

Solar is the fastest-growing renewable energy sector in the United States, however, land suitable for solar installations competes with productive agricultural land. Agrivoltaics (AV) offers a potentially promising solution by creating a dual use for land and improving crop yields. This paper examines the trade-offs between agricultural and solar production on a finite amount of land, using tomato cultivation as a case study. The study reveals a significant trade-off between energy production and crop yield. Scenarios maximizing energy production, particularly with bi-facial 5% transparent panels, generate the highest net revenues, highlighting the profitability of energy over agriculture. The rate of product transformation (RPT) indicates an inverse relationship between energy and crop production, averaging a 2% decrease in tons of crops per additional MWh of energy produced. Converting all available land to traditional photovoltaic (PV) solar panels is the most financially viable option for farmers, generating 12.4% more annual revenue as compared to only producing crops. The increase in crop yields from AV does not outweigh the additional costs associated with AV installation and maintenance. This paper identifies the subsidy levels required for AV to break even with crop production and with the traditional PV scenario. The results and discussion contribute to the economic literature on AV by highlighting key aspects of AV field configurations and related policy incentives to keep agricultural land productive while also growing the renewable energy sector.

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1. Introduction

As the urgency to address climate change intensifies, the United States government has set forth ambitious goals to advance renewable energy initiatives. The Biden administration announced that the U.S. has pledged to reduce greenhouse gas emissions by 50-52% by 2030 (The United States Government, 2023). To achieve this goal, the U.S. must transform its energy sector to renewable energy sources. Current U.S. energy generation is comprised of 36% natural gas followed by 31% petroleum, 13% renewable, 12% coal, and 8% nuclear (EIA, 2022). Utility-scale solar development is the country's fastest-growing renewable energy sector and is the most promising path to accomplishing lofty energy goals. It is projected to become the largest portion of renewable energy production in the coming years (Walston et al., 2022).

To meet net zero emissions by 2050, 135 million acres of land must be converted to solar production (Walston et al., 2022). Ideal land for solar is flat, vast, with minimal cloud cover, and close to urban areas. As a result, land suitable for solar development largely overlaps with the land currently in agriculture, presenting a challenge in balancing the competing needs for renewable energy and agricultural productivity. This land-use conflict has created competition between the food and energy sectors, which are both essential for human well-being. The conflict is heightened by an increase in demand for both energy and food in the coming years. The Food and Agriculture Organization (FAO) projects that a 60% increase in food production will be required by 2050 to adequately feed a global population of 9.3 billion (Graziano Da Silva, 2012).

The effects of solar development on farmland have already been felt in many highly productive states, such as California. California’s Central Valley has experienced a loss of 27,000 acres of cropland to solar development (Grout et al., 2018). Many farmers are converting cropland to solar as a financial buffer, to make up for the uncertain profit margins of a typical farm. The conversion of fertile agricultural land into solar sites could pose a threat to the U.S. farming community's ability to meet the increasing demand for food production in the long term. Agrivoltaics, or “AV”, has emerged as a new technology to use the same parcel of land for both agricultural production and solar energy generation (Dupraz et al., 2011).

An AV system is created by installing photovoltaic arrays or “PV’s” directly above crops, thereby utilizing land for a dual purpose. It has been shown that shade-tolerant crops such as squash, cucumbers, lettuce, and tomatoes can thrive under PV (Mamun, 2022). Shade-tolerant crops are crop varieties that can achieve higher yields in low-light conditions (Dupraz et al., 2011). Research shows that a multitude of crops can meet and/or exceed average yields. Not only could AV increase crop yields, but it may also increase soil moisture and lower soil temperatures, creating a microclimate environment. In addition, the efficiency of solar panels in this microclimate increases, and evapotranspiration rates decrease. This evidence from existing research motivates the adoption of AV for agricultural producers. The benefits provided by the PV’s can increase revenue for farmers and act as a revenue diversification strategy as they face weather-related pressures from climate change (Walston et al., 2022). Despite this rapidly expanding body of literature on the technical feasibility of AV, the economic feasibility of AV is relatively less studied.

This paper explores the conditions under which the mutually beneficial relationship between producing crops and PV’s together is sufficient to justify investments in AV compared to pursuing food production and solar energy production as separate and mutually exclusive endeavors. Specifically, we approach this question through the lens of an agricultural producer. The goal is to determine the point at which AV becomes the most profitable development decision for landowners, compared to only producing crops or only producing energy for a fixed resource bundle.

This study uses the production possibilities frontier (PPF) framework to model the production of solar energy (AV) and tomatoes, referred to as the product transformation curve (PTC). The PTC illustrates feasible choices based on fixed input bundles, highlighting output quantities from fixed inputs. The study aims to determine the PTC for AV, rate of product transformation (RPT), and tradeoffs between outputs. By modeling solar and tomato as joint products, the research explores whether integrating both on a parcel of land is more profitable than individual production. We will then simulate three production functions, addressing optimal solar and tomato production. Fixed inputs include land, capital, with sunlight as the sole variable input. We have experimental data from three different solar panels, each with varying levels of transparency, allowing us to manipulate the amount of sunlight that reaches the plants.

We model 15 scenarios that vary the panel transparency and proportion of acreage in AV and crop production on a hypothetical 40-acre parcel of land, where the amount of AV installed varies. The energy in MWh and yield of crops in tons are calculated for each scenario. The energy generation and crop yield are then translated into a Cobb-Douglas production function which is used to simulate a PTC for tomatoes and energy. The shape and slope of the PTC will reveal tradeoffs between AV and crops for a fixed input bundle, leading to a more informed decision-making tool for agricultural producers. Costs associated with each scenario will help determine which scenario is the most economically feasible. The study concludes with sensitivity analyses where we assess the impact of changing key variables and assumptions on the financial outcomes of AV. Policy recommendations to encourage adoption are presented in the conclusion of the paper.

2. Review of Literature

This research will contribute to three areas of literature. First, it will draw from existing studies on AV technology and crop production in shaded environments. Second, it will contribute new insight by framing AV technology in an economic joint-product context. Third, it will consider insights from the technology adoption literature to further consider the potential for widespread diffusion.

2.1 Relevant AV Literature

There is a wealth of literature that supports how AV can increase crop yields and lead to more sustainable farming systems; however, most of these studies do not explore the economic implications of potential tradeoffs or synergies between crop production and electricity generation. Weselek et al. (2021) studied the effect of AV on crop development. They found that in hot and dry weather, shade from PV's lower soil and air temperatures, leads to increased celery yields. Soil temperatures under AV were reduced by 1.3 degrees Celsius in the experiment year of 2018 and the average soil moisture increased by 1.9%. The celery plant grew 30.6% taller under solar panels and its leaf and height area index increased under panels. Dupraz et al. (2011) experimented in Montpelier France and concluded that solar panels create a shaded environment where thermal stress is significantly reduced. They also concluded that AV increases land productivity by 60-70%. Walston et al. (2022) show that the crops planted under PV's can create a cooler environment and increase panel efficiency, generating more energy and translating to increased revenues. Weselek et al. (2021), Dupraz et al. (2011), and Walston et al. (2022) succeed in providing scientific agronomic evidence that solar and crops have a mutually beneficial relationship, which supports the technical modeling approach in this paper.

In addition to the benefit to crop yields, AV can increase land use and water efficiency. Dupraz et al. (2011) expressed the land-use benefits of AV using a Land Equivalent Ratio (LER). They reported an LER of 1.73 for a full-density AV system. An LER of 1.73 implies that the combined production of electricity and crops on a 100-hectare farm using AV methods would equal the output of a 170-hectare farm with separate production systems, not integrating AV. This was the highest recorded LER for any mixed cropping system. Lee et al. (2022) and Weselek et al. (2019) reported that AV can increase land productivity by 60-70%. Using data from Germany's largest AV research facility, Trommsdorff et al. (2021) noted that the LER for AV increased by 56% to 70% in 2017 and nearly 90% during the dry and hot summer of 2018. As for water efficiency, Marrou et al. (2013) reported that the shading from the solar panels led to a decline in the difference between drainage and uptake of water in lettuce and cucumber crops. Elamri et al. (2018) showed that planting lettuce under solar panels leads to 20% less plant water consumption. Though land-use and water-use efficiency improve with AV, it is unclear who is affected by the increased efficiency, other than agricultural producers. This paper aims to quantify the water and land savings in dollars to better understand the benefits.

Exploring the economic implications of the relationship between crops and solar, however, is critical and one of our main contributions. Just because it is technically possible to have a complementary relationship between crops and solar does not mean that it is profitable to do so. The decision to adopt AV systems will depend on the investment cost of the equipment and the relative returns to the crop and electricity generation enterprises. This paper aims to quantify, in dollar values, the increased yields from AV. Our paper will use existing AV literature to motivate the widespread adoption of this new technology.

2.2 Relevant Joint-Product Research

The conceptual framework is based on the microeconomic concept of joint products and builds on the product-product model from the agricultural production economics literature (Debertin, 2017). Previous research has used this model to examine the adoption of new crop technologies, and farmer willingness to enter collaborative water-sharing programs (Kelley and Mooney, 2023). Traxler and Byerlee's (1993) joint analysis of modern cereal varieties (MV's) examines the adoption of crop varieties developed during the Green Revolution in India. They provide a profit-maximizing framework to model a farmer's decision to adopt or not to adopt high-yielding wheat and rice varieties. The authors use a product transformation to express the joint-product relationship between straw and grain. In doing so, they devise a formula for the transformation function that determines the combination of grain and straw attainable given available inputs. Traxler and Byerlee (1993) model the production possibilities curves for modern and traditional grain varieties using experimental data, response function estimation, and hypothesis testing. The authors show the relationship between straw and grain produced at different levels of input X. Instead of straw and grain, we will use production functions for tomatoes and solar, creating the first joint-product analysis of AV.

2.3 Relevant Technological Adoption Literature

The results of this research will have implications for the economics and AV literature that extend beyond the basic comparative profitability results. While most landowners are driven in part by profit objectives, other factors are also important to their decision-making processes. AV is a relatively new technology that is not well understood. It is hard to trial and early adopters likely differ in the sense that they can tolerate some risk of losing money on experimenting with a new technology. A key paper in this field is titled "Uncertainty, learning, and technology adoption in agriculture" written by Chavas et al. (2020). The paper examines farmers' adoption of new technologies amid uncertainty and lack of information. It emphasizes agricultural innovation in meeting global food demand. The paper concludes by highlighting the crucial role of technology in global economic growth and farm productivity (Chavas et al., 2020). As other producers become interested, the type of analysis presented here will become more important. Kuehne et al. (2017) introduce ADOPT (Adoption and Diffusion Outcome Prediction Tool), a predictive model for agricultural practice adoption. ADOPT considers various factors and offers predictions on adoption rates, peak levels, and factors influencing the process. Feuerbacher et. al (2022) analyze the adoption of AV with a comprehensive assessment of the economic viability and adoption potential of AV in Germany. Results highlight the significance of investment costs as primary determinants, with economies-of-scale favoring farms with large arable land areas (Feuerbacher et al., 2022). More research is needed to show the economic drivers that influence AV adoption, extending beyond economies of scale.

Available literature to date has demonstrated the success of AV and its benefits for crops. The research stated above can support why AV should be adopted but does not help to determine exactly how the adoption process will happen, or any costs associated with AV. This research paper will determine how much an AV system will cost a landowner and at which point it will become a profitable decision to implement. Most AV literature comes from a soil science angle, while this paper focuses on agricultural production, maximizing profits, and the tradeoffs associated with an AV system versus a traditional solar array or a traditional farming operation. Since AV is a relatively novel concept, minimal economics literature exists.

3. Conceptual Framework

We consider a farmer with a parcel of land *l* (measured in acres) who must decide whether to adopt AV technology and the quantity of AV they would like to install. The inputs to producing both energy and tomatoes are sunlight, land, capital, and other variable costs such as seed, irrigation, fertilizer, management costs, etc. For this analysis, land and capital are fixed inputs and variable costs will be fixed at optimal levels for peak growing season conditions. This leaves sunlight as the only allocable input to production, which is reflective of our experimental data. By analyzing different types of solar panels, we can evaluate the trade-offs between allocating more or less sunlight to crop production. The solar panels and tomatoes will compete for sunlight. We model the farmer's agrivoltaic decision problem using a product-product conceptual framework (Debertin, 2012; Beattie and Taylor, 1985). The farmer can produce two goods, a marketable crop (C) and electricity (E), using a fixed input bundle that includes land, labor, sunlight, managerial capacity, and capital, as shown by Figure 1. The product transformation curve (PTC) illustrates the array of choices accessible to the farmer based on the resources at their disposal (Figure 1). It visually shows the quantity of each output that can be produced from the fixed inputs and dictates how the farmer allocates those inputs.

Figure 1 illustrates a few potential outcomes of this paper, represented by PTC 1 and PTC 2. PTC 1 shows constant returns to scale, meaning that the farmer would produce all energy or all crops, depending upon which is most profitable, or a combination of the two goods. The linearity of PTC 1 can result in corner solutions, either at point A or B, depending on relative prices. The slope of the PTC is the rate of product transformation (RPT), or the rate at which one output can be substituted for another, as the allocation of inputs changes (Beattie & Taylor, 1985). At Points A and B, the RPT is equal to zero. Now, suppose the inputs to the production of crops increase. The farmer would then move away from a corner solution to Point C, where

q_E is greater than q_C. We anticipate that the PTC for AV and crop yield will resemble PTC 2, where the synergistic relationship between the two goods will cause the PTC to bow outwards, reaching point D. The RPT for PTC 2 is not constant, and each point along PTC 2 represents a unique RPT for the outputs. Points located inside the PTC are inefficient (Point E) and points outside the PTC are unattainable (Point F). This paper will determine the PTC for AV, as well as the RPT, and tradeoffs between the two outputs.

We presume that solar and tomatoes are joint products, meaning that the same finite bundle of resources can be used to produce energy and tomatoes. When employing AV, the farmer will produce at a point on the PTC that is not a corner solution. To simulate the PTC for AV, we will develop 3 production functions for tomatoes grown under solar panels of varying transparencies. Then, we will use the production functions in a profit maximization problem, where we will solve for the optimal amount of solar and tomato production, as shown below.

$$\mathrm{r} = \mathrm{r_s} + \mathrm{r_c}$$

$$where\ R^{\circ} = total\ sunlight$$
$$r_s = portion\ of\ R^{\circ}\ allocated\ to\ solar$$
$$r_c = portion\ of\ R^{\circ}\ allocated\ to\ crops$$

The production function for solar can be written:

$$\mathrm{y_s} = \mathrm{f}\left(\mathrm{r_s}, \mathrm{s_D}, \mathrm{s_y}\!: \mathrm{k}, \mathrm{v_s}\right)$$

$$where$$
$$s_D = solar\ density$$
$$y_s = energy\ production/acre$$
$$s_y = solar\ yield/panel$$
$$k = capital$$
$$v_s = variable\ inputs\ associated\ with\ solar\ (ie.maintenance)$$

Energy production is a function of the amount of sunlight available to convert into electricity (r_s). The density of the solar farm (s_D) is an important element in this study, and it affects the amount of energy produced. Capital (k) and variable costs associated with production

(v_s) are fixed in our analysis and will not vary across our 15 modeled scenarios. For this paper, we will vary the density of AV across 15 different scenarios with varying amounts of AV implemented in a hypothetical 40-acre parcel that maintains a fixed size. However, the proportion allocated to AV can vary. The more acreage of AV installed; the more energy produced.

Solar yield per panel, denoted as s_y in the energy production function, is influenced by the transparency of the panel (T), its orientation (o), and the crops planted beneath the panels (y_c). This variable allows us to model the synergy between the panels and the crops. See below.

$$\mathrm{s_y = g(o, T, y_c)}$$
$$where$$
$$o = panel\ orientation$$
$$T = panel\ transparency$$

The production function for tomatoes varies slightly due to the potential for the tomato yield to experience a penalty. The widespread adoption of AV has been hindered by the additional maintenance costs associated with implementation, such as additional labor or time to navigate between arrays during harvesting. Also, there is a reduction in available land to plant due to the pole mount placement. These additional challenges that farmers may face with AV, will be reflected in the production function for crops below.

$$\mathrm{y_c = h(r_c,\ C_{D,}, C_y, y_s\ :\ k, v_c)}$$
$$where$$
$$C_{D,} = crop\ density$$
$$C_y = crop\ yield$$

Crop density, represented by $C_{D,}$, is like the solar density variable. It is the percentage of the plot that is covered by crops, which ranges from 0% covered to 100% covered. The variable C_y is composed of the base yield as well as the increased yield from the cooling effects of the panels.

The next step is to use the production functions above in a profit maximization problem to determine the optimal combination of AV, solar, and crop production on a given parcel of land with a fixed amount of capital.

$$\mathrm{r_s} = \mathrm{f}'(\mathrm{y_s}, \mathrm{s_d}, \mathrm{s_y}, \mathrm{y_c})$$
$$\mathrm{r_c} = \mathrm{h}'(\mathrm{y_c}, \mathrm{C_d}, \mathrm{C_y}, \mathrm{y_s})$$
$$\mathrm{R}^{\circ} = \mathrm{r_s} + \mathrm{r_c} = \mathrm{k}\,(\mathrm{y_s}, \mathrm{y_c}, \mathrm{s_d}, \mathrm{C_d}, \mathrm{s_y}, \mathrm{C_y})$$
$$\textit{Solve for } y_s$$

4. Methods

4.1 Techno-Economic Analysis

A significant contribution of this paper is a techno-economic analysis where we evaluate the performance of AV technology using various assumptions and parameters from expert opinion and existing literature. Crop yield, energy production, and financial data for each scenario in Figure 2 are calculated in a Microsoft Excel sheet that allows the user to toggle parameters such as panel row spacing, planting distance, or yield per plant. The calculator automatically provides energy production and tomato yield based on design specifications and plant yields for each of the three panels included in this study. The tool also returns revenues and costs associated with each scenario in Figure 2. To derive the production functions, we determine energy output in MWh and crop yield in tons for 15 scenarios. Each scenario represents a 40-acre plot with a different density of AV. We consider low, medium, high, and maximum densities of AV with 10, 20, 30, and 40 acres of AV respectively. We refer to the three solar panels using either first, second, or third generation. The 0% transparent panel is the first-generation panel because it is the most widely available and the least technologically advanced.

Scenario 4 models a 40-acre plot with 10 acres of AV, 40% transparent panels, and 30 acres of traditional tomato crop. Scenarios 1-3 are points of reference where new technology, AV, is not implemented and the farmer adopts traditional PV instead. Scenario 1 models a 40-acre plot with only tomatoes planted, and no AV or PV. Scenario 2 models 20 acres of crops and 20 acres of PV while Scenario 3 is a 40-acre field of all PV. 40 acres is the typical size of a solar installation and equivalent to a quarter-quarter section in the Public Land Survey System of land in Colorado. Figure 2 aids in visualizing all the possible configurations of the 40-acre field. More information about the design of Figure 2 can be found in Table 1.

We scale plant yield data collected from Colorado State University's (CSU) Agricultural Research, Development, and Education Center (ARDEC) to a 40-acre field. The study consisted of yields under three different panel types and full sun control. The first panel is a Cadmium Telluride (Cd-Te), with 40% transparency and a rated output of 57W, or the 3rd generation panel. The 1st generation panel is a 0% transparent Jinko Solar (O-Si) panel with a rated output of 325W. The last panel in the study is a 5% transparent bi-facial monocrystalline (BF-Si), rated at 36W, which we consider the 2nd generation. The arrays are built at an angle the farmer can manually adjust during harvesting procedures. During the growing season, panels were mounted at 35 degrees and were south facing (Uchanski et al., 2023). The goal of this tool is to help farmers decide the amount of AV, if any, that is suitable for them. The customizability of the tool allows farmers to input information about their operations and reduces the need to hire a solar development firm to assess a farmer's operation for AV implementation. We believe that this tool can have real-world implications and can be tailored for any crop or geographical location.

4.2 Empirical PTC and RPT Estimation

The energy production, measured in kilowatt-hours (kWh) and tomato yield in tons is recorded for each scenario and is used to inform production functions. We replicate Debertin's

(2012, pg. 253) general formulation for a multiplicative production function from the same inputs. The following are the general Cobb-Douglas forms for the production functions.

$$1)\ \ y_c = Ar_{y_c}^{a}$$

$$2)\ \ y_s = Br_{y_s}^{b}$$

Equations 1 and 2 include a finite allocatable factor, which is the amount of sunlight allocated to the crop or the solar panels, denoted as *r*. The sunlight is delegated between the solar panels and tomatoes, creating competition between the two. The equation for the allocatable factor is as follows.

$$(3)\ \mathrm{r} = \mathrm{r}_{y_s} + \mathrm{r}_{y_c}$$

Each panel will yield a different value for r_{y_s} and r_{y_c}, based on the panel's transparency. We use values for r from existing AV literature. To find the values of A, B, a, and b, we run two non-linear regressions. A and B are positive constants, while a and b are the elasticities of production, or how much output changes in response to a proportional change in each input. Next, we solve for the inverse production functions, r_{y_s} and r_{y_c}, and plug them into equation 3 to create the PTC equation below.

$$(4)\ r = \left(\frac{y_c}{A}\right)^{1/a} + \left(\frac{y_s}{B}\right)^{1/b}$$

To analyze how changes in outputs y_c and y_s affect the input *x*, we take the total differential of the transformation function (Equation 5) and set it equal to zero. Lastly, we solve for the rate of change of y_s with respect to y_c, which yields the RPT (Equation 6).

$$(5)\ dr = \left(\frac{1}{a}A^{-1/a}{y_c}^{(1-a)/a}\right)dy_c + \left(\frac{1}{b}B^{-1/b}{y_s}^{(1-b)/b}\right)dy_s = 0$$

$$(6)\ \frac{dy_s}{dy_c} = -\left(\frac{\frac{1}{a}A^{-1/a}{y_c}^{(1-a)/a}}{\frac{1}{b}B^{-1/b}{y_s}^{(1-b)/b}}\right)$$

This is the general expression for the rate at which y_s changes with respect to y_c along the isoquant where the total input *r* is held constant. This method involves expressing the inputs in terms of outputs using the production functions, substituting them into the total input equation for *r*, and then differentiating to find the relationship between the changes in the outputs. The result is the RPT between the two outputs.

4.3 Economic Analysis

We will illustrate the joint product comparative profitability framework by evaluating the technical relationship between crop and solar production and the expected profitability of those systems. The data gathered will be used to simulate the PTC and resulting RPT, and will include existing experimental data, values from the AV literature, and expert opinion where needed. We will consider 15 AV array scenarios that differ by PV transparency and PV density. All calculations will be done at the parcel level, assuming a 40-acre parcel (i.e., the size of a quarter-section in the Public Land Survey System). Scenarios 1-3 will serve as the corner solutions of the PTC, which includes a 40-acre plot of traditionally farmed tomatoes, a plot with half traditional farming and half PV installation, and a plot with only PV.

Revenue calculations follow, where crop revenue is derived from the crop yield multiplied by the market price, and solar energy revenue is calculated from the energy produced per acre multiplied by the market price of electricity. Cost calculations involve summing all costs associated with traditional farming and PV panel installation per acre, respectively. The net revenue for crops and solar energy is then determined by subtracting the respective total costs from the revenues. This allows for scenario analysis, where net revenues for each of the 15 AV scenarios are calculated based on different field configurations. The breakeven point is identified by finding the scenario where the net revenue from AV systems equals that of traditional farming or exclusive PV installations. Finally, simulations and sensitivity analyses are conducted to account for variability and uncertainties in key input data, providing insights into how changes in parameters such as market prices and production rates affect the breakeven point. This comprehensive analysis identifies the most economically viable configuration of AV systems, balancing the benefits of crop production and solar energy generation for maximum profitability and environmental sustainability.

5. Data

5.1 Tomato Yield

The tomato production function data is plotted in Figure 3 with data from the techno-economic analysis. We use tomato yield data under various solar panels of differing transparencies collected from CSU ARDEC in Fort Collins, Colorado by Uchanski et al. (2023). The research farm is dedicated to organic vegetable cultivation, coupled with 9 pole-mounted PV arrays installed in a randomized complete block design. Crop yields for bell peppers, jalapenos, summer squash, lettuce, and tomatoes were collected throughout 2020 and 2021. These yields are reported in Table 2. This paper will only include the red racer tomato yield outcomes. The AV technology spanned twelve plots, with three replications. Three plots were designed as control plots in an open field, three tomato plots were situated beneath conventional 0% transparent solar modules (1st generation), another three were under 5% transparent bifacial modules (2nd generation), and the remaining three were positioned beneath 40% transparent thin-film CdTe modules (3rd generation). This amounts to 12 plots in total.

Data collection included multiple parameters, including the total yield per plant, the number of fruits per plant, spectroradiometer readings, air temperature at 30 cm above the soil surface, and soil temperature 2.5 cm beneath the soil surface. Tomato yields were measured every two weeks after the initial harvest until the end of the growing season. The reported tomato yield is in grams per plant, accounting for plant mortality throughout the growing season (Uchanski et al., 2023). Figure 1 shows cumulative results from the 2021 experiment year. We observe that yields are higher under panels with 0% transparency. Tomato yields under 3 panels of different transparencies and controls are reported in Table 2. It is critical to note that the real recorded per-plant yield under the 5% transparent panel was recorded at 1.62 lbs. This value deviates from the understanding that plant yield should increase as transparency increases. For this reason, we assume a per-plant yield of 2.02 lbs. to maintain consistency across the data.

We calculate the number of tomato plants per row and per acre by using the square footage of a tomato plant, and AV planting distance of 4 feet between rows. Based on these design assumptions, the 40% transparent panel fits 306.59 rows per acre, while the 5% and 0% transparent panels fit 252.26 and 253.49 rows per acre. We multiply the number of plants per acre by the reported yield per plant from Uchanski et. al. (2023). For scenarios 1-3, which do not include AV, we use the assumption that in a traditional cropping system, a farmer will plant 4760 plants per acre from Coolong et al. (2015).

5.2 Energy Production

Energy production based on the Excel calculator for each scenario is shown in Figure 4. We determine how many solar panels fit in a 40-acre plot based on panel dimensions and AV design specifications, which can be found in Figure 4 (Sangik et al., 2023) (Lee et al., 2023). Using the values from Figure 4 and the square footage of each panel type, we determine the number of panels that fit in 1 acre of land, or 43,560 square feet. We then scaled our results to match the panel densities for each scenario. Once the number of panels per acre was found, we used the rated output for each panel to calculate the power capacity for each scenario in MW's. The number of panels multiplied by the rated output is considered the total potential power of the system. However, panels do not operate at 100% efficiency, and they may only receive direct sunlight for a large portion of the day. To find the actual energy that is produced from each scenario, we multiplied the potential power by 8760, or the number of hours per year. This calculation returns megawatt hours (MWh) for 1 year if the panels were operating at 100% efficiency. Next, to account for a loss in energy from weather or shading, we multiply the MWh by a solar capacity factor, which is 25% (Freeing Energy, 2020). Based on data from the U.S. Energy Information Administration, solar electricity generation in Colorado has a capacity factor of 25-26 percent. This indicates that, even when installed on schedule, solar power only provides usable electricity to consumers about one-quarter of the time annually (EIA, 2022). This final conversion calculates the total "real" energy from each scenario, in MWh per year.

5.3 Financial Data

AV cost data is a relatively subjective topic, with a wide range of data points available in the current literature. We use the engineering, procurement, and construction (EPC) cost per megawatt (MW) installed by Roy & Ghosh (2017). Their estimate is 1.3×10^6 U.S. dollars per MW of AV. The EPC cost is a one-time investment that covers the expenses involved in project design, equipment procurement, and installation (Berkeley Lab, 2018). Scenarios that have a larger capacity or have more panels will be the most expensive to install. We notice that the 3rd generation panel, with a rated capacity of 0.0000057 MW per panel is the least expensive to install, while the 5% transparent bi-facial panel is the most expensive, with a rated capacity of 0.00036 MW per panel. This is agreeable with current literature on the cost of semi-transparent and non-transparent panels. The more rated capacity that a solar panel has, the more semiconductor material is used. This insight from semi-transparent panel research supports that some semi-transparent panels can be more cost-effective than the 0% transparent counterpart. Also, the surface area of the panel can influence panel cost. When there is more surface area, more materials are used in the manufacturing process, therefore larger panels can be more expensive (Husain, Alaa A.F., et al.). The 5% transparent panel is slightly larger than the 0% transparent panel, which supports why the EPC cost for Scenario 11 (S11) is the highest out of all AV scenarios.

We include an annualized installation cost for each scenario as well as the annual operating costs. According to David (2024) the annual operating cost of a solar farm is 1.4% of the total project cost. We assume that the cost of installing traditional PV is about 33% less than the cost of installing AV (Agostini et al., 2021). The increase in cost for AV installation is due to the additional raw materials needed to elevate panels high enough to accommodate harvesting equipment. The cost of tomato farming varies for AV and traditional farming practices. Based on data from Texas A&M Agrilife Extension (n.d.), the per acre yearly cost of traditionally farming tomatoes is $1,840 which includes seeds, labor, and irrigation expenses. Due to the added nuances of farming under solar panels, we assume an 8% premium when planted in an AV configuration, which amounts to $1,987.2 per acre. We calculate the annual revenue, costs, and net revenue using a 5% discount rate over 30 years. Since AV requires a significant upfront investment, we assume that a farmer would pay off the installation cost over the lifetime of the project. All cost data is translated into present values. According to multiple operating farm budgets for cherry tomatoes, the revenue from 1 ton of tomatoes is $4,400. The revenue from one MWh of energy is $171. We use these values to calculate the annual and net revenue of the system. We report the net revenues in Table 3.

6. Results

6.1 Discrete Analysis

Table 3 shows each scenario and its associated energy and crop yield. Generally, there is an inverse relationship between energy production and crop yield, indicating a trade-off between these two variables. As energy production increases, overall crop yield tends to decrease, despite each plant producing more under all three types of panels compared to the full sun control. This is likely due to the loss of plants caused by the installation of AV in the tomato field. The baseline, Scenario 1 (S1), where all 40 acres are in crop production results in the most crop yield at 181.83 tons per year with an annual net revenue of $726,460. We introduce traditional PV solar in S2 and S3 to serve as additional baselines for S4-S15 where AV is installed. When the 40 acres are split into 20 acres of PV and 20 acres of crops (S2), crop yield is reduced by half, compared to S1, while net revenue increases dramatically to $1,851,163. Additionally, Scenario S3, which maximizes energy production at 19771.79 MWh, results in no crop yield but achieves the highest net revenue of all 15 scenarios at $2,975,866.78, which is about 4 times higher than S1. This scenario emphasizes the financial benefits of solar PV energy production over agriculture.

Intermediate scenarios such as S4 through S7 that model the 40% transparent panel, show minimal energy production (ranging from 86.69 to 346.61 MWh) and relatively high crop yields (142.48 to 153.91 tons), with net revenues between $563,431.60 and $644,108.15, which are atleast $100,000 per year less than S1. These scenarios suggest that low levels of energy production do not sufficiently compensate for the reduction in crop yield due to AV installation. Scenarios S4 through S7 will always return less annual revenue and crop yield than S1, when the farmer has no adopted any solar, suggesting that the farmer would never choose the 40% transparent panel. Scenarios S8 and S9 with the 5% transparent panel with 10 and 20 acres of AV respectively, demonstrate a significant increase in energy production, leading to a substantial rise in net revenue, highlighting the profitability of energy production with the 5% transparent panel. For example, S9, with 7612.65 MWh of energy production, results in a crop yield of 142.66 tons and a net revenue of $1,569,885.34. The annual net revenues as well as the crop production when the 5% transparent panel is used (S8-S11), are always greater than any scenario where the 40% transparent panel is installed (S4-S7).

We notice that the scenarios with the 5% transparent panel and the majority of land occupied by AV result in highest net revenues out of all AV scenarios. S11 has the highest net revenue and energy out of all AV scenarios with $2,603,240 and 15225.31 MWh's, which is over 3 times the annual net revenue of S1. The crop yield for S11 is 146.65 tons, which is above the average AV crop yield of 144.72 tons, indicating an efficient balance of resource allocation. Scenarios S12 through S15 follow similar patterns, with net revenues ranging from $1,005,017.01 to $2,410,476.85, showing that higher energy production correlates with higher profitability, even though overall crop yields decrease when compared to traditional farming methods (S1). Crop yields range from 140.12 to 144.47 tons in S12 through S15, .

Overall, the data illustrates the complex trade-offs between energy production, agricultural output, and financial returns. Higher energy production generally leads to reduced crop yields but significantly increased net revenues, suggesting that energy production may be more lucrative than agriculture alone. Though yield per plant increases when solar panels are introduced, the reduction in planting space leads to AV always decreasing crop yields compared to S1. This suggests that the per plant yield increase is not enough to offset the installation of AV in a field. Identifying the optimal balance between these factors is crucial for sustainable development, ensuring that both energy needs, and agricultural productivity are met effectively. The decision on the optimal scenario should consider the specific priorities and goals, whether maximizing revenue, balancing production types, or maintaining higher crop yields. The full potential of this tool requires careful collaboration with farmers who are interested in adopting AV, and their unique operation and goals.

6.2 Continuous Analysis

The results from the discrete analysis are plotted in Figure 5, with energy production (MWh/Field) on the x-axis and crop production (Tons/Field) on the y-axis. When comparing the conceptual framework to our actual results, we notice that our presumption was correct in that AV allows production to reach a level that is unattainable without AV. Points A, B, and C in Figure 1 are represented by S1, S2, and S3 in Figure 5 and are connected by a yellow linear line, or PTC 1. Points that lie beneath PTC 1 are inefficient, such as S4-S7, like point E in Figure 1. On the other hand, the points that lie to the northeast of PTC 1 are scenarios where you can produce more of one good with the same inputs. Since scenarios 9, 10, 11, 13, 14, and 15 are located outside PTC 1, this would cause PTC 2 to be bowed outwards, as shown in Figure 1. Point D in Figure 1 is shown in our real data as S11 and is the point where the farmer adopts AV and produces more of both outputs, compared to S2. PTC 2 starts are S1 and bows outwards to S11, and links to S3 on the x-axis.

The RPT varies between scenarios and isn’t constant like the RPT for PTC 1. The RPT is shown in Table 4. The RPT between S1 and S3 is -0.0092, indicating that there is an inverse relationship between energy and crop production. For every 1 MWh increase in energy production, there is a corresponding decrease of approximately 0.0092 tons in crop yield. However, the RPT for the first, second, and third generation panels are all positive values, .0462, .0005, and .0004 respectively. As more AV is installed, crop yields increase suggesting that, there might be a complementary relationship between energy production and crop yield, where both can increase together.

6.3 Sensitivity Analysis

Our analysis is based on assumptions that can easily change due to the economy, location, technological advancements, or differences in expert opinion. We change the discount rate, panel row spacing, the tomato price, cost of planting tomatoes under panels, energy prices, and AV installation cost. The effects of these changes on annual net revenue are shown in Table 5. The change that had the largest impact was decreasing the row spacing of panels. When row spacing decreases, the number of panels per field increases, increasing annual net revenues and vice versa. The row spacing of panels is determined by several factors including sun angle, size of harvesting equipment, and topography of the project site. It is possible that when the location for the project is analyzed, more panels can fit in the field. The discount rate can also heavily influence revenues. We notice that increasing and decreasing the discount rate by 2% can increase annual net revenues by $100,481 and decrease them by $103,242. A more favorable discount rate would always return more revenue for the farmer. The tomato-related factors that we manipulated had minimal impact on overall revenues, such as the tomato cost penalty increasing and decreasing by 8%. Energy prices have a large and symmetrical effect on annual net revenue. A $10 change in energy prices, either up or down, results in a $152,253 change in revenue. This demonstrates that energy price volatility is a critical factor in operational costs, affecting revenue by about 5.8% in either direction from the midpoint ($2,603,240). The AV installation cost is a relatively minor factor in the overall sensitivity analysis, with a maximum potential impact of just over $14,000 on either side of the midpoint. The symmetrical nature of the changes suggests that even with slight fluctuations in installation costs, the overall revenue will only be marginally affected. Refer to Figure 6, a tornado-style graph for a visual representation of these changes.

The United States Department of Agriculture (USDA) offers programs to reduce the financial burden on farmers seeking to upgrade or install renewable energy. The Renewable Energy for America Program (REAP) provides loan financing and grants to agricultural producers and rural small businesses for renewable energy systems or energy efficiency improvements (USDA Rural Development, 2024). The REAP loan covers 75% of project costs and the grant covers 50% of the project costs up to one million dollars. The REAP grant and loan would alleviate some of the burden on the agricultural producer, but not enough to justify the most profitable AV scenario over all PV scenario.

7. Discussion

The most profitable scenario is S3, where the farmer converts their 40-acre field to traditional solar and forgoes all agricultural practices. The farmer will make $372,626.50 more revenue yearly compared to the second most profitable scenario, S11. S3 will continue to be more profitable due to the AV installation and maintenance premiums. Our calculations use a few key assumptions and data points that drive these results. One of them is the installation cost of AV versus traditional PV. The installation of AV is around 33% more expensive compared to traditional PV. This is due to the additional raw materials needed to raise the panels to a height that can accommodate harvesting. S3 underscores the superior financial returns prioritizing solar energy production over agriculture.

Interestingly, as more AV is added to the field, crop production increases slightly, though never enough to surpass that of S1. For example, S8-S11 saw an improvement in yields from 140.66 tons to 146.65 tons. In other words, adding 30 acres of AV increases crop yields by about 6 tons, which amounts to $26,353 in extra revenue. This is due to the increased plant yields from the shading effects of the panels, shown in Table 2. This result helps support the ongoing evidence that solar panels benefit plant growth and prosperity. Although crop yields increase, they do not increase enough to offset the substantial cost of installing AV. The profitability of tomatoes is not high enough to make AV worthwhile. For the farmer to earn $26,353 more in crop revenue would cost them $428,967, which is a poor financial decision, especially when a 40-acre field of traditional farming will yield 181 tons of tomatoes (S1). Overall, crop yields will decrease due to AV installation even though plants under panels have a higher yield. This is due to the crowding out of crops from the steel piles being installed.

Intermediate scenarios, specifically S4-S7 which use 40% transparent panels, are a moderate approach that delivers minimal energy production well below the AV average (144.72 MWh) from 86.69 MWh to 346.61 MWh. These scenarios offer relatively high crop yields since the per plant yield under 40% transparent panels is the highest amongst all panels in this study. Specifically, S7 has the highest AV tomato yield at 153.91 tons. Net revenues for these scenarios are low, ranging from 563,431.60 tons to 644,108.15 tons. The tomato yield is significantly lower than S1. A farmer would likely plant all 40 acres of traditional tomato crops before they would invest in S4-S7. It is not until S8 that a farmer would find it more profitable to implement AV compared to traditionally farming 40 acres (S1). Scenarios S8-S15 offer more net revenues than S1 and S2, however they still cannot compete with S3. Scenarios S8 and S9, featuring 5% transparent panels with 10 and 20 acres of AV respectively, show a substantial jump in energy production and a noticeable decrease in crop yield. However, the rise in net revenue is significant, showing the profitability of energy production. For instance, S9, with 7,612.65 MWh of energy production, results in a crop yield of 142.66 tons and a net revenue of $1,569,885.34. This scenario highlights the financial viability of higher energy production despite reduced agricultural output.

Scenarios with the 5% transparent panel and most of the land occupied by AV, such as S11, achieve the highest net revenues among all AV scenarios. Scenario S11, with $2,603,240 in net revenue and 15,225.31 MWh of energy production, also maintains a crop yield of 146.65 tons, above the average AV crop yield of 144.72 tons. This indicates an efficient balance of resource allocation. Scenarios S12 through S15 follow similar patterns, with net revenues ranging from $1,005,017.01 to $2,410,476.85 and crop yields between 140.12 to 144.47 tons. These scenarios affirm that higher energy production correlates with increased profitability, even as crop yields decline in comparison to S1. Higher energy production generally leads to reduced crop yields but significantly increased net revenues, suggesting that energy production may be more lucrative than agriculture alone.

7.1 Policy Recommendations

The main outcome of this research is that when a farmer is presented with a finite amount of land and resources, they will choose to either sell their land to a solar developer or install PV. This assumes that the farmer prioritizes financial returns over biodiversity or food production. To ensure that agricultural land stays in production and deter farmers from installing PV and reducing productive farmland, AV must be subsidized by the local or federal government. The subsidy should be equal to the net revenues of the farmer installing PV less the net revenues of the farmer installing all AV with the most efficient solar panel, the 5% transparent panel. The suggested subsidy, given the outcomes of this paper, would be $372,626.50 per year, amounting to $11,178,795.03 throughout the project life. The subsidy is a little more than half of the annualized installation cost of S11. Subsidies are one of the many tools used to incentivize this new technology.

There are currently policies in place that alleviate some of the burden on agricultural producers interested in renewable energy. The United States Department of Agriculture (USDA) offers programs to reduce the financial burden on farmers seeking to upgrade or install renewable energy. The Renewable Energy for America Program (REAP) provides loan financing and grants to agricultural producers and rural small businesses for renewable energy systems or energy efficiency improvements (USDA Rural Development, 2024). The REAP loan covers 75% of project costs and the grant covers 50% of the project costs up to one million dollars. The federal government Solar Investment Tax Credit (ITC) and the Production Tax Credit (PTC) are also programs aimed at incentivizing renewable energy generation. When enrolled in the ITC program, the solar farm owner pays a reduced federal income tax based on the cost of the solar installation during that tax year. The PTC program is a per kWh tax credit for the first 10 years that the project is producing energy (Office of Energy Efficiency and Renewable Energy, n.d.).

7.2 Limitations

Our analysis does not account for the non-market value of agricultural production and its overall benefit to society. When looking at each scenario's net revenue, the farmer would choose S3 over all other scenarios since it is the most lucrative. This decision results in a loss of 181 tons of tomatoes per year which has a benefit to society by ensuring food security and food supply. The biodiversity of agricultural land and its productivity have value via social and ecosystem services. Farmland can store and filter water as well as provide a home for pollinator plants and other wildlife. To build upon this research, economists can use non-market valuation methods to quantify the value of farmland in Colorado, beyond the net revenues from selling crops. This can be done using a hedonic model, which involves regressing the market process on the non-market attributes of the farmland to determine the real value. Economists can also use revealed preferences, where the willingness to pay for the ecosystem services is determined. Once the external benefits of farmland are realized, it can be added to our model.

Another limitation of this research is our assumption that a landowner makes decisions based solely on financial returns. The landowner will choose the scenario where they make the most net revenue. The landowner's values can differ based on age, socioeconomic status, education, culture, etc. An individual who values ecosystem services and is knowledgeable about the non-market value of farmland might choose an AV scenario over S3. Suppose the landowner has a deep familial tradition of farming and an inherent opposition to solar. In that case, they may continue to farm 40 acres and be unwilling to adopt PV or AV even though their net revenues can increase substantially. An interesting extension of this research is survey data collection. Colorado landowners can reveal certain characteristics and be asked to choose the scenario that would best suit their farm or land. It would be interesting to see how geographic location or political leanings influence an individual’s decision-making when presented with S1-S15.

Other limitations mainly arise from the assumptions used to determine each scenario's energy and crop production. Firstly, we assume about the per-plant yield for the 5% transparent panel to keep our data consistent with expert opinion. It is possible that there was not an error in data collection and the yield was inconsistent with our understanding of panel transparency and plant yield. We also did not use real energy production data from panels, which impacts the validity of the energy output per field. We used the rated output of each panel and the number of panels per field to calculate the energy capacity. Then we considered the solar productivity factor of Colorado and the number of hours in a year to determine the real energy production per year. Ideally, we would have liked to use actual data but due to time and budget constraints, it was not possible. This research would be interesting to replicate with data from already developed solar farms.

8. Conclusion

In this study, we analyzed the potential impact of agrivoltaics (AV) on energy and crop production, considering various scenarios that blend traditional solar and crop production methods. The findings indicate that while AV can boost energy production to unattainable levels by traditional methods, it often reduces overall crop yields. For example, scenarios S8-S15, which incorporate a higher percentage of AV, show increased energy production but a corresponding decrease in crop yield, compared to S1. This demonstrates an overall inverse relationship between energy and crop production.

Our sensitivity analysis indicates that changes in panel row spacing have a significant impact on annual net revenues, with decreased row spacing allowing for more panels per field and thus substantially increasing net revenue. Variations in the discount rate also play a considerable role, with more favorable rates yielding higher revenues, whereas tomato-related factors had minimal impact on overall revenues. This analysis underscores the importance of optimizing panel configuration and economic conditions to maximize profitability. Given the financial advantage of converting farmland entirely to solar (S3) over implementing AV, policy interventions are necessary to maintain agricultural productivity.

Subsidies equivalent to the difference in net revenues between the most profitable AV scenario and traditional PV should be provided to farmers. This would incentivize the adoption of AV while preserving agricultural land. Our research primarily focuses on financial returns, not accounting for the broader societal benefits of agriculture, such as food security and ecosystem services. Future studies should incorporate non-market valuation methods to quantify these benefits. Additionally, our assumptions about panel yield and energy production are based on expert opinion and rated outputs rather than real data, which limits the accuracy of our findings. Further research with actual data from existing solar farms would provide more robust insights. Overall, the study highlights the significant trade-offs between energy and crop production in AV systems. While AV can enhance energy production, it often leads to reduced crop yields, making it less financially attractive compared to traditional solar installations. Policy measures and further research are essential to optimize the balance between these two important outputs and support the sustainable adoption of AV technology.

Table 1. Field Configurations.

				Field Configuration		
		Energy Capacity		**PV**	**Crops**	**AV**
Scenario	**Panel Type**	**(MW/Field)**	**(Plants/Field)**		**(Acres)**	
S1	n/a	0	190400	0	40	0
S2	1st Gen	4.51	95200	20	20	0
S3	1st Gen	9.02	0	40	0	0
S4	3rd Gen	0.04	179100	0	30	10
S5	3rd Gen	0.08	167800	0	20	20
S6	3rd Gen	0.12	156500	0	10	30
S7	3rd Gen	0.16	145200	0	0	40
S8	2nd Gen	1.74	179100	0	30	10
S9	2nd Gen	3.48	167800	0	20	20
S10	2nd Gen	5.21	156500	0	10	30
S11	2nd Gen	6.95	145200	0	0	40
S12	1st Gen	1.58	179100	0	30	10
S13	1st Gen	3.16	167800	0	20	20
S14	1st Gen	4.75	156500	0	10	30
S15	1st Gen	6.33	145200	0	0	40

Note: Scenario numbers refer to those given in Figure 2. PV = Photovoltaics, AV = Agrivoltaics

Table 2. Tomato Yields by Panel Type.

Panel Type	Tomato Yield (lbs./plant)
No Panels (Control)	1.91
0% Transparent	1.99
5% Transparent	2.02
40% Transparent	2.12

Table 3. Energy Production, Crop Yields, and Net Revenues.

Scenario	**Panel Type**	**Energy Production/Field (MWh)**	**Crop Production/Field (Tons)**	**Net Revenue (Dollars/Year)**	**Difference from S1 (Dollars/Year)**
S1	n/a	0	182	$726,461	0
S2	1st Gen	9886	91	$1,851,164	$1,124,703
S3	1st Gen	19772	0	$2,975,867	$2,249,406
S4	3rd Gen	87	142	$563,432	-$163,029
S5	3rd Gen	173	146	$590,333	-$136,128
S6	3rd Gen	260	150	$617,214	-$109,247
S7	3rd Gen	347	154	$644,108	-$82,353
S8	2nd Gen	3806	141	$1,053,208	$326,747
S9	2nd Gen	7613	143	$1,569,885	$843,425
S10	2nd Gen	11419	145	$2,086,563	$1,360,102
S11	2nd Gen	15225	147	$2,603,240	$1,876,779
S12	1st Gen	3464	140	$1,005,017	$278,556
S13	1st Gen	6928	142	$1,473,504	$747,043
S14	1st Gen	10392	143	$1,941,990	$1,215,529
S15	1st Gen	13856	144	$2,410,477	$1,684,016

Table 4. Rate of Product Transformation.

Scenario	Energy Production (MWh)	Crop Yield (Tons)	Rate of Product Transformation (RPT)
Solar no AV			
S1	0	182	---
S3	19772	0	-0.0092
Third Gen			
S4	87	142	---
S7	347	154	0.0462
Second Gen			
S8	3806	141	---
S11	15225	147	0.0005
First Gen			
S12	3464	140	---
S15	13856	144	0.0004

Table 5. Sensitivity Analysis Tornado Graph Values.

	Annual Net Revenue				
Factor	**Low**	**Midpoint**	**High**	**Low Difference**	**High Difference**
Discount Rate (5% ±2%)	$ 2,703,721	$ 2,603,240	$ 2,499,998	$ 100,481	$ (103,242)
Row Spacing (7.90 feet ± 2 feet)	$ 2,932,128	$ 2,603,240	$ 2,354,618	$ 328,888	$ (248,622)
Tomato Price ($4,400/ton ± $300/ton)	$ 2,559,245	$ 2,603,240	$ 2,647,236	$ (43,995)	$ 43,996
Tomato Cost AV Penalty (8% ± 2%)	$ 2,609,128	$ 2,603,240	$ 2,597,352	$ 5,888	$ (5,888)
Energy Price ($171/MWh ± $10/MWh)	$ 2,450,987	$ 2,603,240	$ 2,755,493	$(152,253)	$ 152,253
Annual AV Installation Cost (1.4% Costs ± 2%)	$ 2,617,562	$ 2,603,240	$ 2,588,919	$ 14,322	$ (14,321)

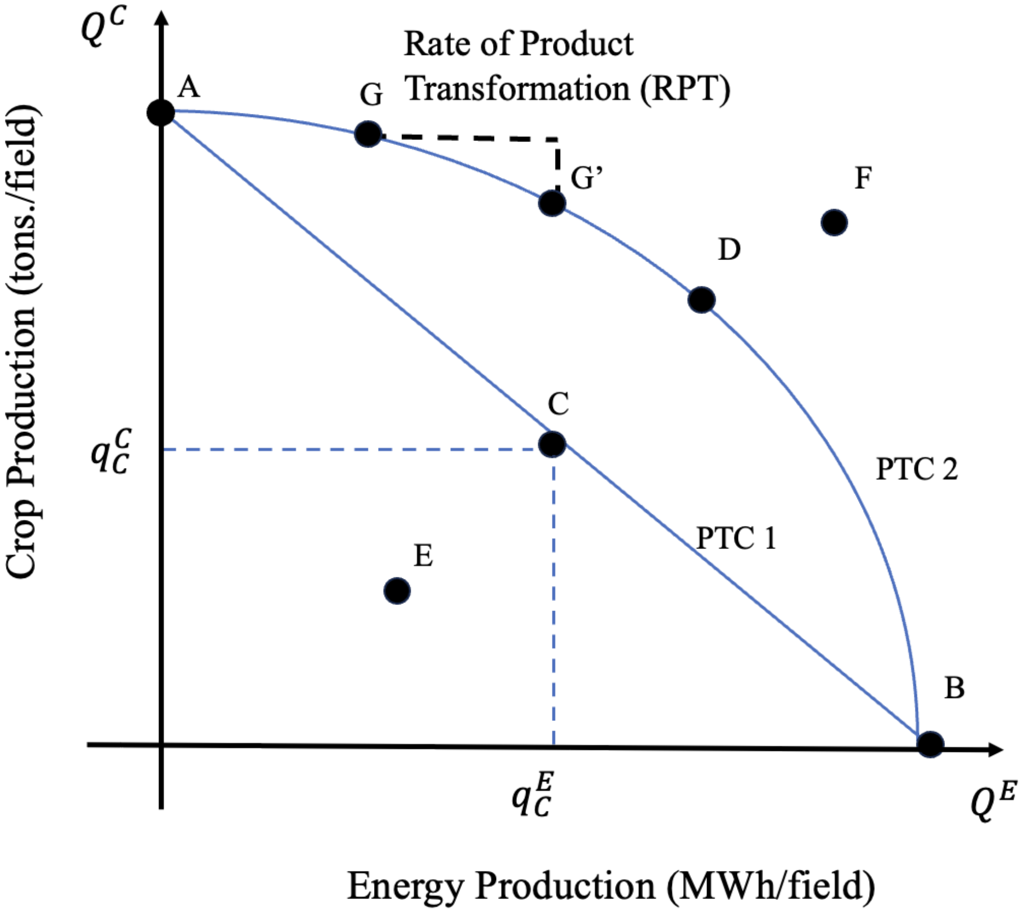

Figure 1. Conceptual Representation of the Product Transformation Curve for Agrivoltaic Technology.

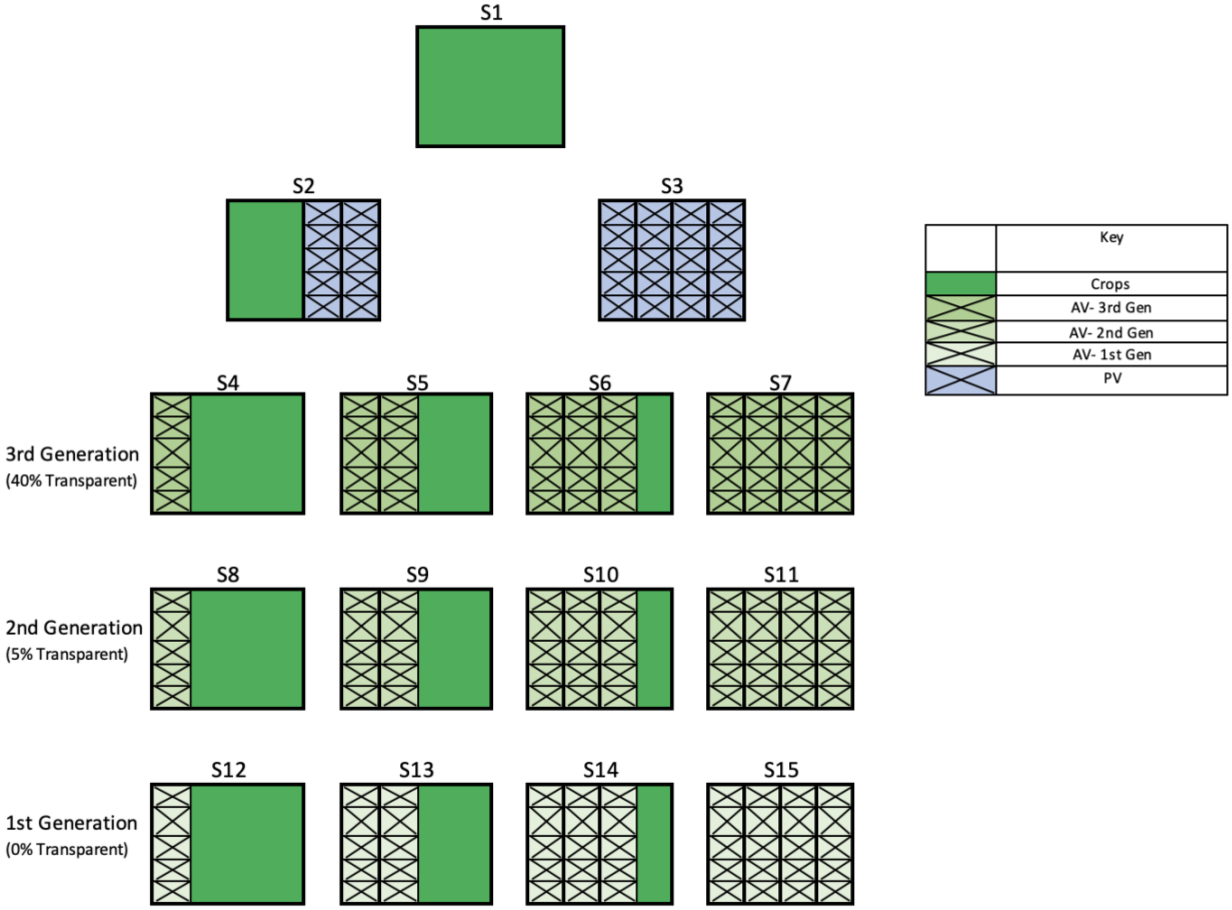

Figure 2. Illustration of Fifteen Agrivoltaic Scenarios Considered in the Empirical Analysis.

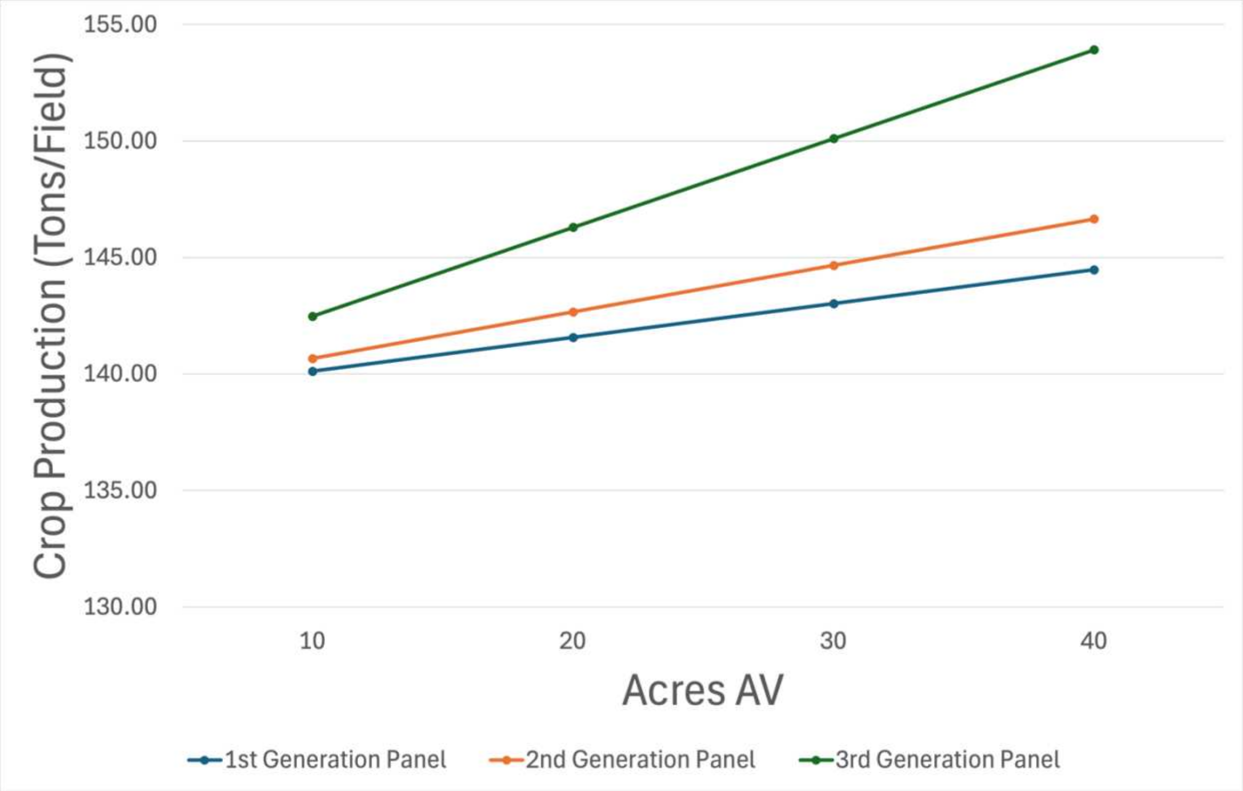

Figure 3. Tomato Production Functions.

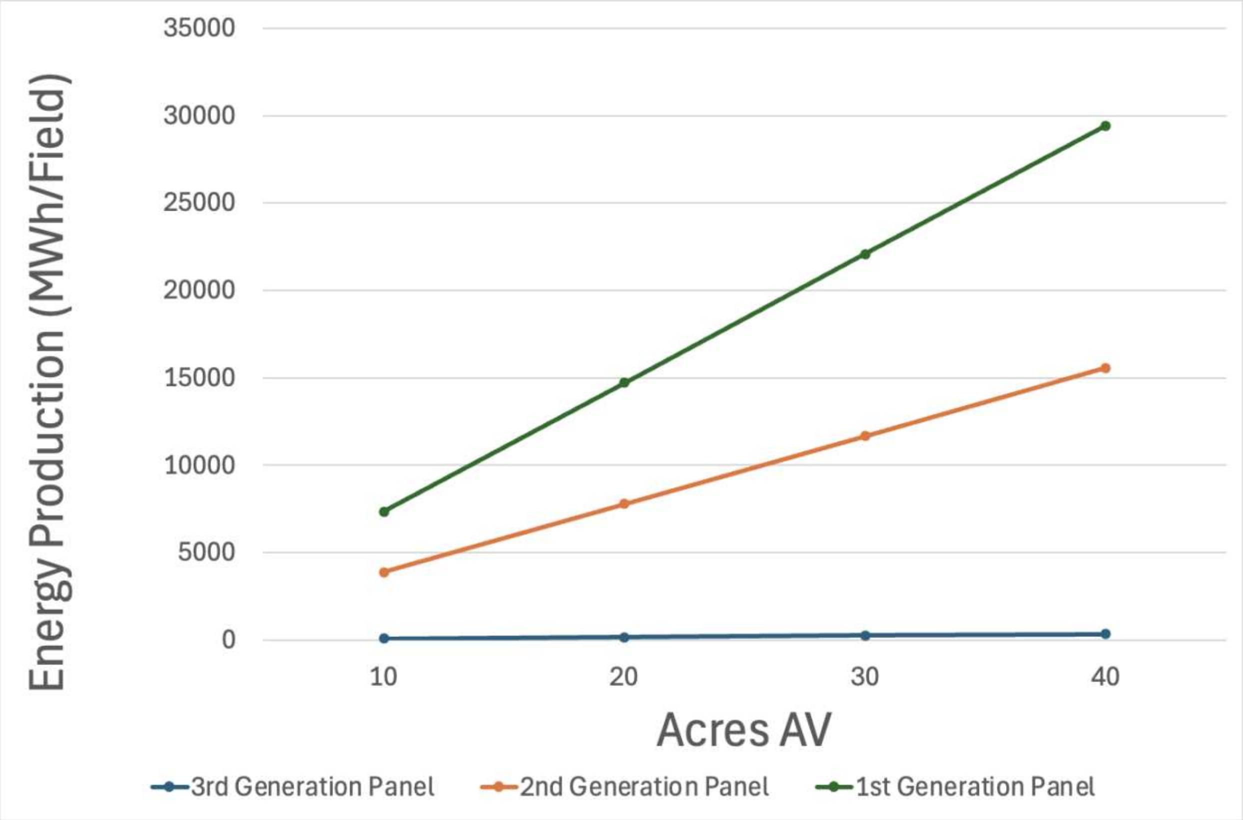

Figure 4. Energy Production Functions.

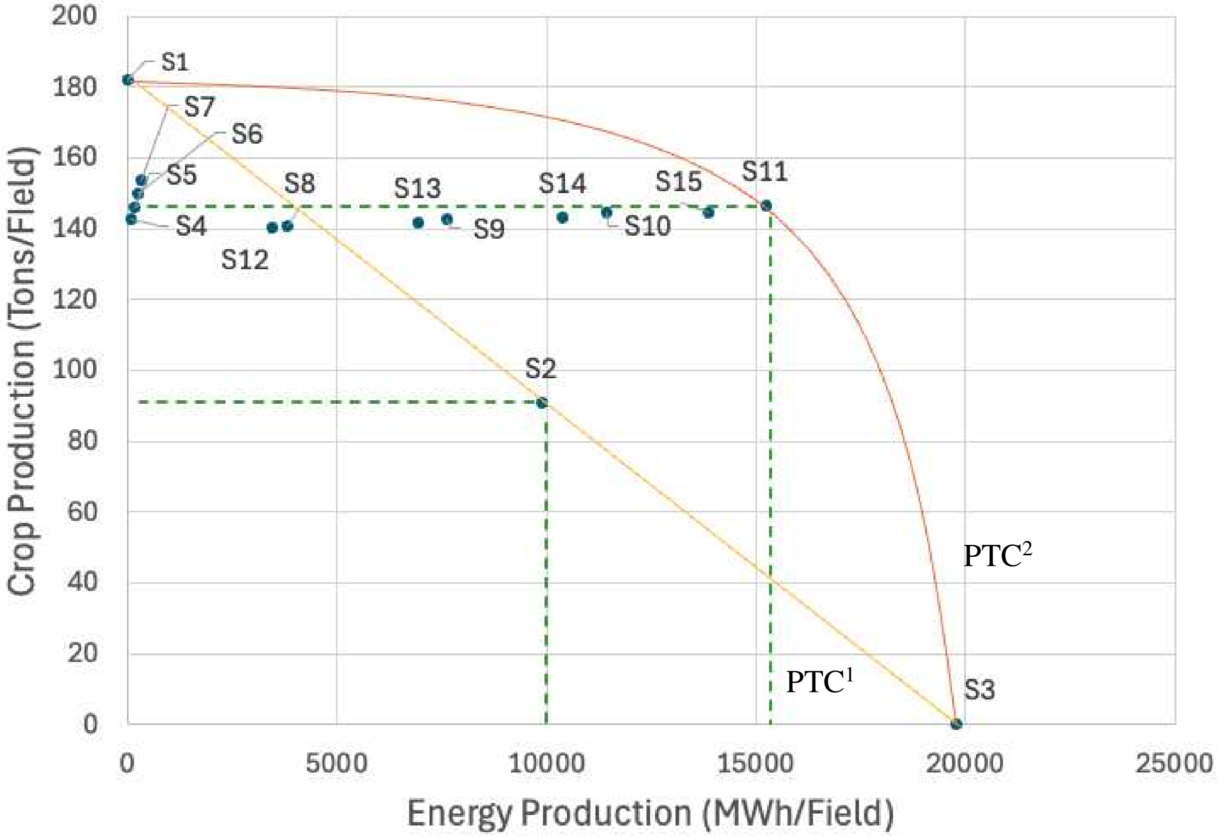

Figure 5. Empirical Product Transformation Curve.

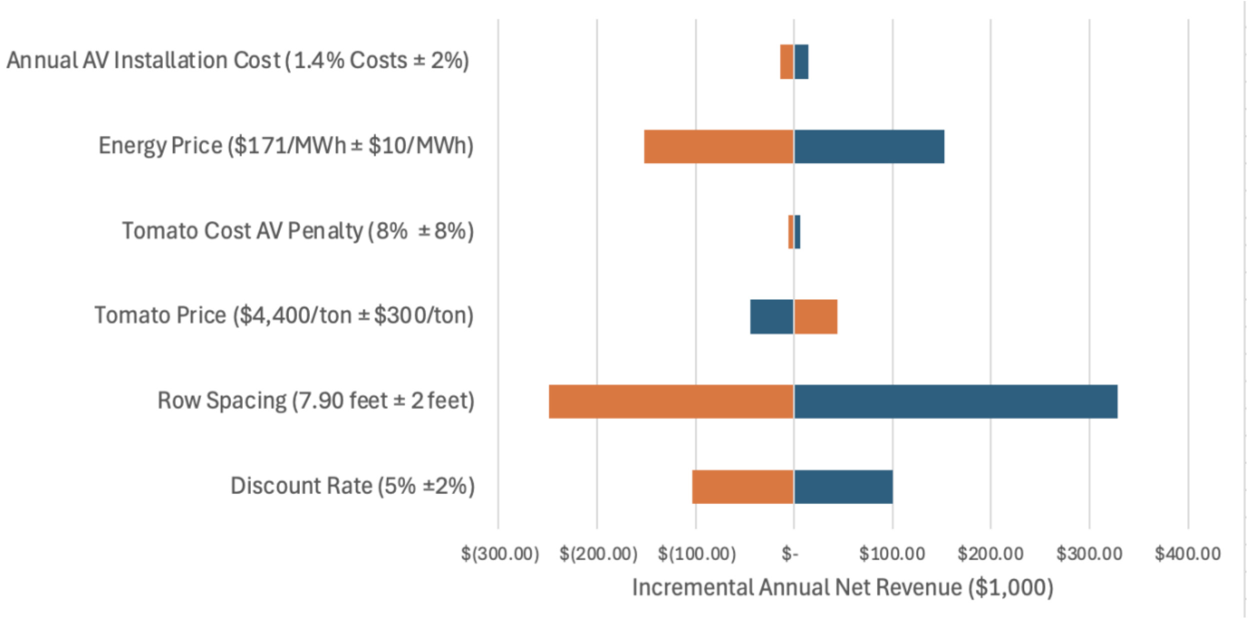

Figure 6. Tornado Diagram of One-Way Sensitivity Analyses.

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Appendix

Table A1. AV Design Specifications

Planting Distance	4 ft.
Panel Distance	7.6 ft.
Column Distance	14.7 ft.

Table A2. Conceptual Framework Symbols, Parameters, and Units

Symbol	**Parameter**	**Unit**
R°	Total Sunlight	W/m^2
r_s	Portion of R° allocated for solar	W/m^2
r_c	Portion of R° allocated for crops	W/m^2
y_s	Energy output	MWh
y_c	Crop yield	tons
s_D	Solar density	Acres
s_y	Solar yield	MWh/panel
k	Capital	$
o	Panel orientation	degrees
T	Panel transparency	%
C_D	Crop density	%
C_y	Crop yield	tons