THE ECONOMIC ANALYSIS OF AGRIVOLTAICS IN THE US

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Master of Science

by
Zihan Zhang
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ABSTRACT

This paper presents an economic analysis of agrivoltaics in the United States, focusing on their impacts on energy capacity factor, electricity generation efficiency, and land use efficiency in terms of both revenue and profit. The analysis uses data from 4,160 photovoltaic projects, including 599 AV farms. Two-way fixed effects models with interaction terms are employed to assess the effects of AV status, sheep density, and PV panel density across farms of varying sizes. The results show that AV increases the capacity factor of PV panels by .98%, regardless of farm size. Although electricity revenue per acre tends to decrease under AV systems due to lower PV density, the overall revenue performs differently. Small farms experience a 34.5% increase in the overall revenue per acre, but revenue per unit area declines with the increase in farm size: for farms larger than 100 acres, AV reduces the overall revenue per acre by 28.5%. Most profits from dual-land use come from sheep grazing, and the effect is strongest when the sheep sources are through breeding rather than auction. In such scenarios, the impact of sheep density on profitability is particularly significant.

Keywords: agrivoltaics, solar grazing, dual-use land, capacity factor, renewable energy.

BIOGRAPHICAL SKETCH

I completed my K-12 education in the People's Republic of China, cultivating a broad range of interests and training in the arts and sciences. During my undergraduate studies, I explored diverse research fields, including European philosophy and languages, modern history and politics, music, biology, physics, et cetera. I majored in economics because of my interests in social science and mathematics. I was concerned about the impact of political and economic reforms in developing countries, so I conducted research on the effect of China's household registration integration reform on the urban-rural income gap for my thesis and graduated cum laude from the University of Colorado Boulder.

I continued my study at Cornell, focusing on economics in agriculture and energy. Combining my internship experience in industrial research on energy, I analysed the economic impact of agrivoltaics as my master's graduation topic. I will always feel gratitude for the experience I had and the values I learned in the United States.

ACKNOWLEDGMENTS

I appreciate the academic support from Professor Calum G. Turvey and Professor Christopher Allen Wolf. Their professional suggestions on methodology and revisions were greatly helpful in improving the thesis. I also appreciate all the professors who gave me help and ideas. The thesis cannot be completed without their help. I am also thankful for the love and encouragement from all my family members and friends.

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LIST OF ABBREVIATIONS

Abbreviations	Definition
AV	Agrivoltaics
LCOE	Levelized Cost of Energy
LER	Land Equivalent Ratio
LUE	Land Use Efficiency
NPV	Net Present Value
PV	Photovoltaics

LIST OF SYMBOLS

Symbols	Definition
y_{it}	Dependent variable
α_i	County fixed effects
δ_t	Year fixed effects
$\boldsymbol{x}'_{\boldsymbol{it}}$	Vector of explanatory variables
$\boldsymbol{\beta}$	Vector of coefficients
ε_{it}	Error term

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1 Introduction

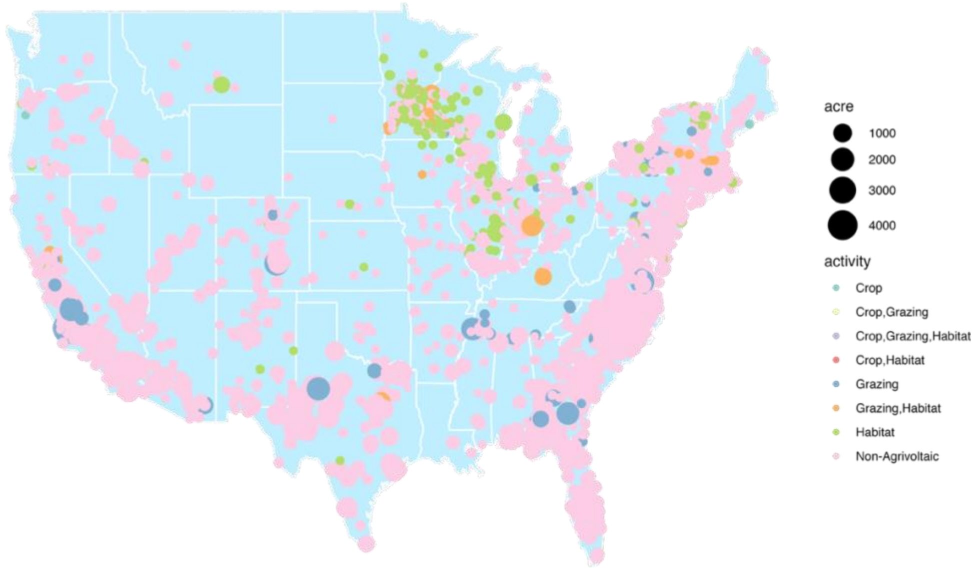
The AV (agrivoltaics) system combines land uses for agriculture and solar energy production, addressing the conflicts between increasing energy and food demands and the shrinking available land for both solar energy and food (Wagner et al., 2023). This essay focuses on the economic impacts of AV in the US.

Solar PV (Photovoltaics) has expanded rapidly. A report by the International Renewable Energy Agency (IRENA) shows that the cost of utility-scale solar PV has decreased by 82% between 2010 and 2020, making it one of the most competitive sources of electricity generation worldwide (Lempriere, 2020). The growing solar PV industry provides low-carbon, clean electricity, but its expansion has increased conflicts with other land uses, such as agricultural lands. Agrivoltaics combines the land uses of PV panels and agricultural production, and it has been an economically feasible way to address the conflict (Neesham-McTiernan et al., 2025). The US has implemented several policies that support the development of AV, including allowing AV lands to retain favourable tax assessments and signing long-term contracts with solar programs, which include bonuses for AV features (Macy et al., 2025).

Figure 1 presents the geographic distribution of solar projects by agricultural activity type. It shows that most projects are conventional solar farms, which are densely clustered on the coasts, while AV projects, which often involve grazing and habitat, are less prevalent. Figure 2 shows the annual installation additions of AV, which indicate that most AV projects have capacities of around 5 MW. Figure 3 illustrates cumulative capacity density by agricultural type. Conventional PV maintains a relatively constant density over time, while most AV systems have lower capacity density, especially for grazing AV farms.

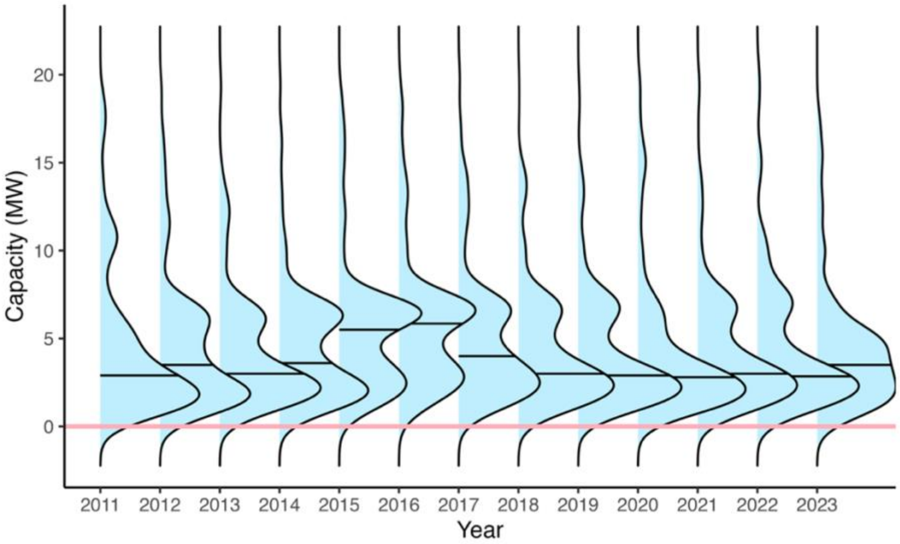
This paper investigates the economic potential of AV systems in the United States, focusing on land use efficiency, capacity factor, revenue and profitability. It assesses how AV influence those key variables, and it explores the heterogeneous effects of AV across different farm sizes and sheep sourcing scenarios. A project-level dataset examines the impact of dual-use land on energy generation and economic returns, identifying optimal combinations of sheep and PV density to enhance revenue or profit across farms of varying sizes. Section 2 concludes with the benefits of AV. Section 3 describes the database and the definitions of variables. Section 4 details the empirical strategy, and Section 5 reports the main results. Section 6 concludes the main findings and discussion.

Figure 1: Installation Density by Agriculture Activity



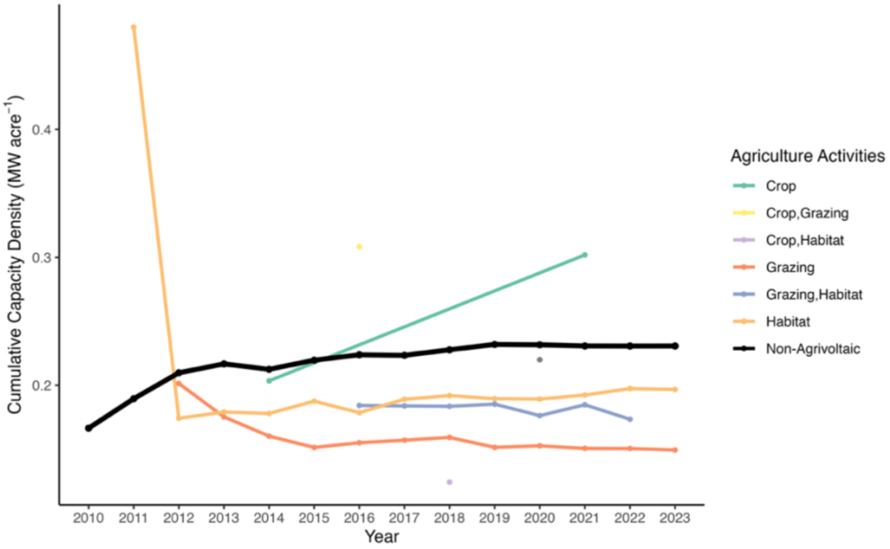
Note. The data visualisation is created by the author using data from InSPIRE (2025). Retrieved from https://openei.org/wiki/InSPIRE/Agrivoltaics_Map.

Figure 2: Installation Capacity



Note. The data visualisation is created by the author using data from USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25

Figure 3: Installation Density by Agriculture Activity



Note. The data visualisation is created by the author using data from InSPIRE (2025). Retrieved from https://openei.org/wiki/InSPIRE/Agrivoltaics_Map. The line of habitat sharply declined in 2011 because there was only one AV farm used for habitat, and the density of PV panels on this farm was much higher than that of subsequent ones. The PV density is influenced by numerous factors such as the AV activities and subjective intentions.

2 Literature Review

2.1 Resource Utilisation

AV provides a microclimate that benefits crop production and grazing, particularly for shade-tolerant crops and sheep. The AV system provides shade for animals and plants, reducing their exposure to extreme heat and increasing grazing time, as well as lowering water consumption since they have lower water intake under shade (Andrew et al., 2021). Table 1 illustrates the reduction in water consumption caused by AV worldwide. AV generally improves water-use efficiency, and the reduction in amount varies by region, crop or animal type, and method of installation (vertical or horizontal). The decreased soil and air temperatures also benefit crop production for some plants, as they reduce evaporation from the soil and transpiration from plant canopies. Additionally, the reduced surrounding temperature alleviates the PV panel heat stress issue, improving PV panel performance in scorching areas. A study in Arizona shows a 3% increase in energy generation due to the cooled temperature provided by AV compared to ground-mounted arrays from May to July (Barron-Gafford et al., 2019). In Germany, research shows a 2.7% and 11% increase in winter wheat and potato crop yields in 2018 summer, although the overall photosynthetic radiation was reduced by 30% under AV from 2017 to 2018 (Weselek, Bauerle, Hartung, et al., 2021).

2.2 Environmental Impact

AV reduces the demand for fossil fuels in agricultural activities (La Notte et al., 2020), such as replacing the water-pumping system driven by diesel, which emits 4,005 kg CO2 for a 0.15 ha farmland, with solar energy (Campana et al., 2016; Neupane Bhandari et al., 2021). Numerous studies demonstrate a substantial reduction in CO2 emissions resulting from the adoption of AV. The collocation of energy and agricultural activities enhances energy efficiency, which in turn reduces CO2 emissions. The widescale installation of AVs is equivalent to removing 71,000 cars from the road annually in the US (Proctor et al., 2021). A pasture-based AV system yields a 69.3% reduction in emissions and an 82.9% decrease in fossil fuel demand (Pascaris et al., 2021). In rural India, a plant-level study indicates that a 1,000-kW AV project reduced 57,834 tons of CO2 emissions in its 30-year lifespan (John & Mahto, 2021). A life-cycle carbon emission estimation for a tomato AV field is approximately 12% lower than that of a conventional tomato field in Japan (Leon & Ishihara, 2018). Those findings suggest that AV contributes to reducing emissions from agricultural activities by improving energy efficiency through collocation and the adoption of clean energy sources.

2.3 Previous Methods

The LER (land equivalent ratio) is a standard method for measuring land efficiency, as detailed in the methodology section (Riley, 1984). When LER is greater than 1, it indicates that dual-land use is overall efficient for co-located solar and agricultural land uses, and the optimal situation occurs when LER equals 2. Some studies suggest LER is always greater than 1 for AV and ranges from 1.20 to 1.73 (Zheng et al., 2021; Trommsdorff et al., 2021; Campana et al., 2021; Dupraz et al., 2011; Amaducci et al., 2018). This paper uses LUE (land use efficiency) to replace the role of LER.

2.4 Economic Benefits

The economic feasibility is one of the most vital incentives for AV installation. A study about AV across the US shows a 2.5% to 24.0% increase in overall revenue (Lytle et al., 2021). Previous studies in Europe have widely discovered an overall increase in economic performance, land-use efficiency, and a reduction in total capital expenditure due to the synergistic effects (Garrod et al., 2024; Dupraz et al., 2011; Trommsdorff et al., 2023). The profit and revenue generated by AV are many from solar energy generation. A 32-year study in Germany shows 311 euros ha^{-1} net present value of the AV system in total, and only 62 euros ha^{-1} net present value is from agriculture generation, accounts for only 19.94% of the total NPV (Net Present Value), and the revenue from agriculture is 407 euros ha^{-1}, accounts for 24.04% of total AV revenue (Trommsdorff et al., 2023), the overall economic performance is relatively insensitive to agriculture activities due to its weaker economic impact (Agostini et al., 2021).

Compared to conventional farmland, AV lands generally exhibit reduced crop yields due to a lower level of photosynthesis. The inhibiting effect is weaker for shade-tolerant plants (Potenza et al., 2022; Weselek, Bauerle, Hartung, et al., 2021; Gonocruz et al., 2021; Weselek, Bauerle, Hartung, et al., 2021). The appropriate shade AV provides increases crop yield for shade-tolerant plants, such as berries, forages, and fruiting vegetables. However, for maise, grain legumes and other non-shade-tolerant plants, the reduction in solar radiation caused by AV usually reduces crop yield (Laub et al., 2022). For grazing, the lamb yield almost stays the same compared to open pasture. A study shows a 38% reduction in herbage, but the forage quality has improved. As a result, there is no significant difference between grazing sheep on AV and open pastures as an aspect of lamb yield, but the wool quality increases due to the shade provided by AV (Andrew et al., 2021; Handler & Pearce, 2022). The electricity generation may increase slightly due to the cooler surrounding environment of AV compared to that of conventional PV. However, the revenue from electricity generation generally decreases due to the reduced intensity of PV panels, and the LCOE (Levelized Cost of Energy) is often higher than that of conventional solar farms (Thomas et al., 2023; Mamun et al., 2022).

The findings above may vary depending on the type of agricultural activities, installation methods, level of irradiance, AV farm size, temperature, and other factors. Furthermore, the findings above are mostly discovered at the firm level in European countries, whereas researchers rarely conduct economic and environmental analyses on AV across projects in the US.

Table 1: Water Consumption Decline Due to AV

Region	Crops/Animals	Water Consumption Changes	Source
Chanco, Chile	Cereal	$-1{,}410\text{m}^3/\text{ha}$	(Bruhwyler et al., 2023)
Heihe River, China	Wheat/Oilseed Rape/other Crops	$-15.45\%/-10.32\%/-4.61\%$	(Liu & Song, 2020)
Lavalette, France	Lettuce	-20%	(Elamri et al., 2018)
Oregon, USA	Sheep	$-0.72\text{L head}^{-1}\text{d}^{-1}$	(Andrew et al., 2021)
Pakistan	General Crops	-41%	(Raza et al., 2022)
Southwestern USA	General Crops	$-30{\sim}40\%$	(Warmann et al., 2024)
Southern Italy	Tomato	$-15{\sim}20\%$	(Mohammedi et al., 2023)

3 Data

3.1 Data Sources

The database contains 4,160 solar projects, 599 of which are AV projects installed from 1985 to 2024. The revenue and profit of those AV projects are divided into electricity generation and grazing. Basic information about the solar and AV projects is from the US Large-Scale Solar Photovoltaic Database (USPVDB) and Innovative Solar Practices Integrated with Rural Economics and Ecosystems Database (InSPIRE). The U.S. Large-Scale Solar Photovoltaic Database (2025) provides information about PV projects with a capacity of over 1 megawatt, including the type of panel and the initial year of installation. Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE, 2025) summarises the type of agriculture for each AV project. United States Department of Agriculture (USDA) provides the sold prices of sheep by state and year.

Regarding the electricity aspect, the energy, capacity, and total market value for solar projects per MWh are sourced from Berkeley Lab (2025). The US Energy Information Administration (EIA, 2025) provides data on each plant's gross and net generation. National Renewable Energy Laboratory has the Levelized Cost of Energy for each energy source, including Utility PV (NREL, 2025). The National Solar Radiation Database measures the average horizontal solar irradiance (NSRDB, 2025), which can impact the capacity factor of PV panels. The time ranges from 2012 to 2023, and the database includes all 48 US states, excluding Hawaii and Alaska. Most projects are distributed on the East Coast and the West Coast.

3.2 Variable Definition

$\text{AV Status} = 1 \text{ means AV farms}, \text{AV Status} = 0 \text{ means PV farms}$

$\text{Capacity} = \text{Total Installed Capacity of Solar Panels}, \text{Unit: MW}$

$$\text{Capacity Factor} = \frac{\text{Actutal Output of Electricity}}{\text{Maximum Possible Output of Electricity}}$$

$$= \frac{\text{Actutal Output in a year}}{\text{Capacity} \times 24 \times 365}, \text{Unit: } \%$$

$$\text{Gross Efficiency} = \frac{\text{Gross Output of Electricity}}{\text{AV farm acres}}, \text{Unit: } \frac{\text{MWh}}{\text{acre}}$$

$$\text{Net Efficiency} = \frac{\text{Net Output of Electricity}}{\text{AV farm acres}}, \text{Unit: } \frac{\text{MWh}}{\text{acre}}$$

$$\text{Total Value} = \text{Capacity Value} + \text{Energy Value}, \text{Unit: } \frac{\$}{\text{MWh}}$$

$$\text{Radiation} = \text{Average Daily Solar Irradiance}, \text{Unit: } \frac{\text{kWh}}{\text{Day} \times \text{m}^2}$$

$$\text{Sheep Density} = \frac{\text{\# of sheep}}{\text{AV farm acres}}, \text{Unit: } \frac{1}{\text{acre}}$$

$$\text{PV Density} = \frac{\text{Total Direct Current of PV}}{\text{AV farm acres}}, \text{Unit: } \frac{\text{MW}}{\text{acre}}$$

$$\text{LUE for Elec} = \frac{\text{Revenue or Profit from Electricity Generation}}{\text{AV farm acres}}, \text{Unit: } \frac{\$}{\text{acre}}$$

$$\text{LUE for Sheep} = \frac{\text{Revenue or Profit from Sheep Grazing}}{\text{AV farm acres}}, \text{Unit: } \frac{\$}{\text{acre}}$$

$$\text{LUE} = \text{LUE for Elec} + \text{LUE for Sheep}, \text{Unit: } \frac{\$}{\text{acre}}$$

$$\text{LUE for Revenue}$$

$$= \frac{\text{Gross Generation} \times \text{Total Value}}{\text{AV farm acres}}$$

$$+ \frac{\text{the Selling Price of Sheep} \times \text{\# of Sheep Sold}}{\text{AV farm acres}}, \text{Unit: } \frac{\$}{\text{acre}}$$

$$\text{LUE for Profit} = \frac{\text{Net Generation} \times (\text{Total Value} - \text{LCOE})}{\text{AV farm acres}}$$

$$+ \frac{\text{the Selling Price of Sheep} \times \text{\# of Sheep Sold} \times \text{Profit Margin}}{\text{AV farm acres}}, \text{Unit: } \frac{\$}{\text{acre}}$$

3.3 Data Processing

The data from Inspire and EIA is scraped from their official websites. Using R Studio for all plotting and regression processes. Database integration is according to the same plant codes or state and county names. Some illogical data are removed, such as when the capacity factor exceeds 100%. The paper constructs a dummy variable to indicate the AV status of each farm. When AV equals one, the farm is AV. Otherwise, the farm is a conventional PV farm. The paper performs logarithmic processing on some dependent variables, such as revenue and profit, to enhance the understanding of the relationships between different variables. The log-linear model is commonly used in later works. The profit margin is estimated by Gasch et al. (2025). There are six scenarios, categorised by two lamb sources: breeding or auction, and three degrees of optimism: high-profit, base-profit, and low-profit margins. The data source and processing are on https://github.com/zizh4693/Agrivoltaics.

3.4 Descriptive Statistics

Table 2 and Table 3 summarise the descriptive statistics for key variables across conventional utility-scale PV and AV projects.

In Table 2, the database has 34,442 observations. The average installed capacity is 16.99 MW, and the average capacity factor is 20.80 %. Solar radiation ranges from 4.28 to 6.68 kWh/m²/day. The density of PV panels averages .28 MW per acre. As for value and cost, the total value of solar electricity averages \$53.65/MWh, while the average LCOE is \$45.73 per acre. In some projects, the LCOE exceeds the total value of solar energy. The land use efficiency for total revenue is approximately \$20,584 per acre, which is higher than that for electricity revenue, at $20,098 per acre. Some projects have negative LUE for revenue, which the high LCOE can explain.

Table 3 shows 364 AV observations. The density of sheep averages 2.42 head per acre. The average installed capacity is 57.57 MW. The capacity factor of AV is 19.13%, which is lower than that of PV. Solar radiation for AV projects is slightly lower (4.79 kWh/m²/day). Most large-scale projects are located in California, while the majority of small-scale projects are found on the East Coast. For AV projects, the LUE for revenue is $13,745.36 per acre, which is lower than the LUE for electricity revenue of $18,324.36 per acre. This is caused by large-scale AV projects, which are usually not economically beneficial.

Table 2: Descriptive Statistics for PV

Variable	Mean	SD	Min	Max
Capacity (MW)	16.99	44.56	0.53	752.10
Capacity Factor (%)	20.80	5.44	0.00	77.79
Radiation (kWh/m²/day)	5.09	0.55	4.28	6.68
PV Density (MW/acre)	0.28	0.20	0.01	5.10
LCOE ($/MWh)	45.73	6.08	34.21	54.95
Total Value ($/acre)	53.65	20.08	-47.53	165.35
LUE for Electricity ($/acre)	20097.52	17805.23	-18943.45	710434.87
LUE for Revenue ($/acre)	20583.97	18141.97	-18943.45	710434.87

Note. N=34442 observations, data source:
USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25
Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
NREL (2025). Retrieved from https://maps.nrel.gov/slope
EIA (2025). Retrieved from https://www.eia.gov/opendata/

Table 3: Descriptive Statistics for AV

Variable	Mean	SD	Min	Max
Capacity (MW)	57.57	158.20	0.53	752.10
Capacity Factor (%)	19.13	4.53	6.89	31.02
Radiation (kWh/m²/day)	4.79	0.35	4.57	5.85
Sheep Density (acre^{-1})	2.42	1.13	0.17	3.33
PV Density (MW/acre)	0.29	0.13	0.11	0.89
LCOE ($/MWh)	50.52	5.58	38.28	54.95
Total Value ($/acre)	52.55	20.77	24.33	165.35
LUE for Electricity ($/acre)	18324.85	14273.82	2142.98	118435.27
LUE for Revenue ($/acre)	13745.36	7465.83	2188.30	36940.99

Note. N=364 observations, data source:
InSPIRE (2025). Retrieved from https://openei.org/wiki/InSPIRE/Agrivoltaics_Map.
USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25
Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
NREL (2025). Retrieved from https://maps.nrel.gov/slope
USDA (2025). Retrieved from https://quickstats.nass.usda.gov/
EIA (2025). Retrieved from https://www.eia.gov/opendata/

4 Methodology

4.1 Model Specification

This model estimates the average difference in outcomes between AV and non-AV farms by regressing variables on AV indicators such as LUE and capacity factor. This model examines the mechanisms underlying AV performance by incorporating PV density, sheep density, and their interaction, which tests whether synergies or trade-offs between agricultural production and energy generation activities drive AV performance. The primary dependent variables in the model are LUE for electricity, revenue and profit. Those variables indicate the overall performance difference of electricity generation and economic outcomes between AV and non-AV farms.

The paper employs the log-linear model to examine the elasticity relationships between regressors and regressed variables, except when the dependent variables are capacity factors, as they are already expressed as percentages. A linear-linear model is also added when the dependent variable is LUE for revenue and profit to study the magnitude of the effect of AV on LUE. To determine whether a fixed or random effects model is more suitable, the paper conducts a Hausman test. The null hypothesis is that the random effects model is consistent and efficient. The p-value of the Hausman model is much less than .01, which suggests that the random effects model is inconsistent. Therefore, the county-fixed and year-fixed effects are included in this paper. Radiation is also a vital control variable in the paper, which directly influences the electricity generation of PV panels.

$$log(y_{it}) = \alpha_i + \delta_t + \boldsymbol{x}'_{\boldsymbol{it}}\boldsymbol{\beta} + \varepsilon_{it}$$

There are six regressed variables: capacity factor, gross efficiency, net efficiency, LUE for revenue, LUE for Profit, and LUE for Electricity. The capacity factor and efficiency indicate how AV activities and PV panels impact energy generation, and LUEs study the economic effects of AV activities and PV panels.

There are two combinations of regressors: the AV status, which captures the difference between utility AV and conventional PV. The second is the densities of sheep and PV panels. There is a strong relationship between the two variables, so the model includes an interaction term. The interactive term has a complementary or substitute relationship. In this paper, a substitute relation exists in AV farms due to the competitive nature of dual-land use, which aims to achieve better economic performance. All models are using Ordinary Least Squares.

Specification 1: AV status model

$$log(y_{it}) = \alpha_i + \delta_t + AV_i + \boldsymbol{x}'_{it}\boldsymbol{\beta} + \varepsilon_{it}$$

Specification 2: Interaction model with densities

$$\begin{aligned}\log(\mathrm{y_{it}}) = \alpha_\mathrm{i} + \delta_\mathrm{t} + \beta_1 \cdot \text{sheep density}_{it} + \beta_2 \cdot \text{PV density}_{it} + \beta_3 \cdot \text{sheep density}_{it} \\ \cdot \text{PV density}_{it} + \mathbf{x}'_{\mathbf{it}}\boldsymbol{\beta} + \varepsilon_{\mathrm{it}}\end{aligned}$$

4.2 Heterogeneity by Land Area & Optimal Density Ratio

To test the impact of land scale on AV performance, the model used three levels of land area: small (<10 acres), medium (10–100 acres), and large (≥100 acres), as well as a continuous area. The heterogeneity by farm size is a consistent theme throughout the paper. The farm-size strategy also tests the robustness of the relationship between the ratio of sheep and PV densities. To determine the optimal densities of sheep and PV panels for achieving maximum revenue, the paper employs the method of partial differentiation.

$$\frac{\partial \log\,(y)}{\partial \text{Sheep density}} = \beta_1 + \beta_3 \cdot \text{PV density} = 0 \Longrightarrow \text{PV density} = -\frac{\beta_1}{\beta_3}$$

$$\frac{\partial \log\,(y)}{\partial \text{PV density}} = \beta_2 + \beta_3 \cdot \text{Sheep density} = 0 \Longrightarrow \text{Sheep density} = -\frac{\beta_2}{\beta_3}$$

5 Results

5.1 Capacity Factor

AV projects are associated with higher capacity factors, while the impact of PV density on capacity factors is insignificant. The total value of electricity decreases the capacity factor in small and medium farms, and the effect is more potent in small farms. Radiation always increases the capacity factor, but the effect is more potent in small farms. Radiation is the strongest predictor of capacity factor across all groups, with a coefficient ranging from 1.83 to 4.87. The increase in sheep density is associated with a higher capacity factor in small farms. AV land has a .98% higher capacity factor than conventional PV farms, and this effect is more pronounced in medium-sized farms. Grazing can effectively control vegetation over PV panels and reduce shadows on them. The role of sheep in vegetation management indirectly increases the capacity factor of PV panels (Stewart et al., 2025). Sheep activities make the land surface more compact, resulting in decreased dust, and the reduction in shading increases the capacity factor (Asa'a et al., 2024). Figure 4 shows monthly capacity factors for AV and non-AV projects. AV projects exhibit higher median capacity factors throughout the year, particularly during peak solar months, from May to August, indicating improved generation efficiency for PV panels.

Table 4: The Impact of AV Status on Capacity Factor Linear Model

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
Agrivoltaics Status	0.982**	0.881	1.146***	-0.974
	(0.317)	(0.599)	(0.308)	(1.484)

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
PV Density	-0.415	0.771	-0.681	1.540
	(0.513)	(0.598)	(1.117)	(2.204)
Total Value	-0.026***	-0.049***	-0.019*	0.002
	(0.008)	(0.014)	(0.007)	(0.013)
Radiation	4.866***	6.665***	4.822***	1.831**
	(0.752)	(1.210)	(0.821)	(0.625)
Num.Obs.	34432	9967	19570	4895
R2	0.459	0.417	0.444	0.575
R2 Adj.	0.448	0.397	0.430	0.553

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

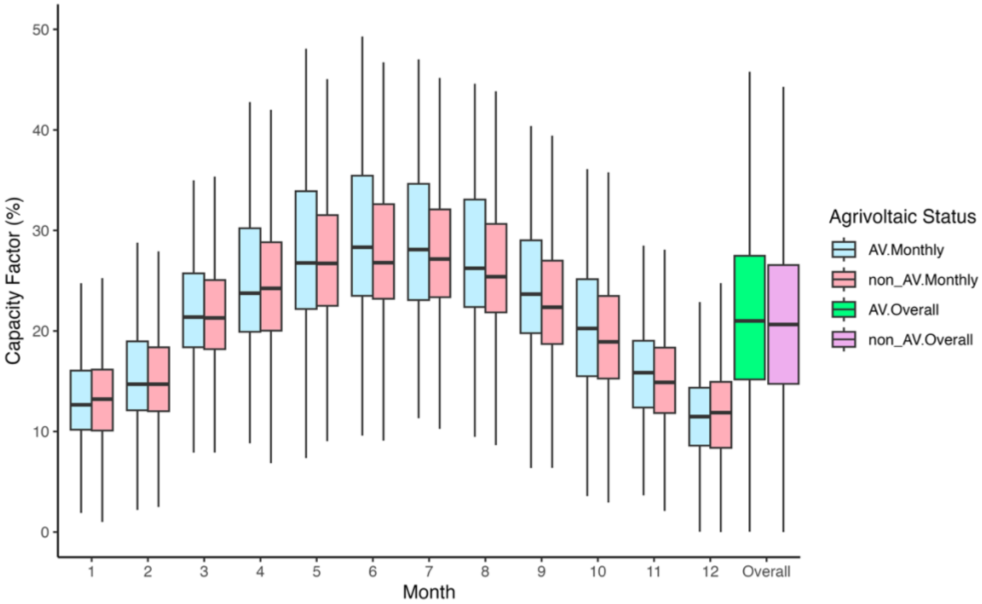
Table 5: The Impact of Densities on Capacity Factor Linear Model

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
PV Density	-0.312	0.895	-0.328	1.870
	(0.536)	(0.613)	(1.065)	(2.224)
Sheep Density	1.575***	2.425**	0.484	1.678
	(0.445)	(0.737)	(0.302)	(4.888)
PV × Sheep Interaction	-4.299***	-5.811***	-1.482	-15.096
	(1.096)	(1.359)	(1.173)	(28.308)

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
Total Value	-0.028***	-0.049***	-0.019**	-0.003
	(0.007)	(0.015)	(0.007)	(0.012)
Radiation	5.541***	6.576***	5.330***	2.197**
	(0.710)	(1.485)	(0.810)	(0.693)
Num.Obs.	32280	9271	18364	4645
R2	0.469	0.422	0.461	0.580
R2 Adj.	0.459	0.402	0.447	0.558

- p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Figure 4: Capacity Factor by Month



Note. The data visualisation is created by the author using data from:
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Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
EIA (2025). Retrieved from https://www.eia.gov/opendata/

5.2 Gross/Net Efficiency

AV appears to reduce energy efficiency compared to conventional PV. The reduction of PV panels is the leading cause of this. The gross efficiency of AV is 16.9% higher than that of conventional PV farms, while the decline in net efficiency is 15.6%, which is less than the decline in gross efficiency. This can be explained by the findings in Section 5.1, which state that sheep help maintain the microenvironment around PV panels, thereby improving power generation efficiency. The electricity generated by PV panels must be utilised in the cooling system to maintain operation. The reduced weeds lower heat storage and help reduce power loss in PV panels. As a result, the amount of electricity delivered to the power grid increases, leading to improved economic benefits (Gill et al., 2024).

Figure 5 shows the impact of AV status on net efficiency. The reduction of capacity-value net efficiency caused by AV is much greater than that of energy-value net efficiency. “The capacity value can be defined as the expected possible amount of the energy output of a technology during the peak residual load” (Schram et al., 2021), while energy value is the electricity value sold to customers (Voices, n.d.).

Table 6: The Impact of AV Status on Gross/Net Efficiency Log Model

	Gross Efficiency	Net Efficiency
Agrivoltaics Status	-0.169***	-0.156***
	(0.040)	(0.040)
PV Density	1.217***	1.215***
	(0.151)	(0.148)
Total Value	-0.001+	-0.001+

	Gross Efficiency	Net Efficiency
	(0.000)	(0.000)
Radiation	0.360***	0.367***
	(0.066)	(0.068)
Num.Obs.	34430	34432
R2	0.442	0.435
R2 Adj.	0.431	0.424

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

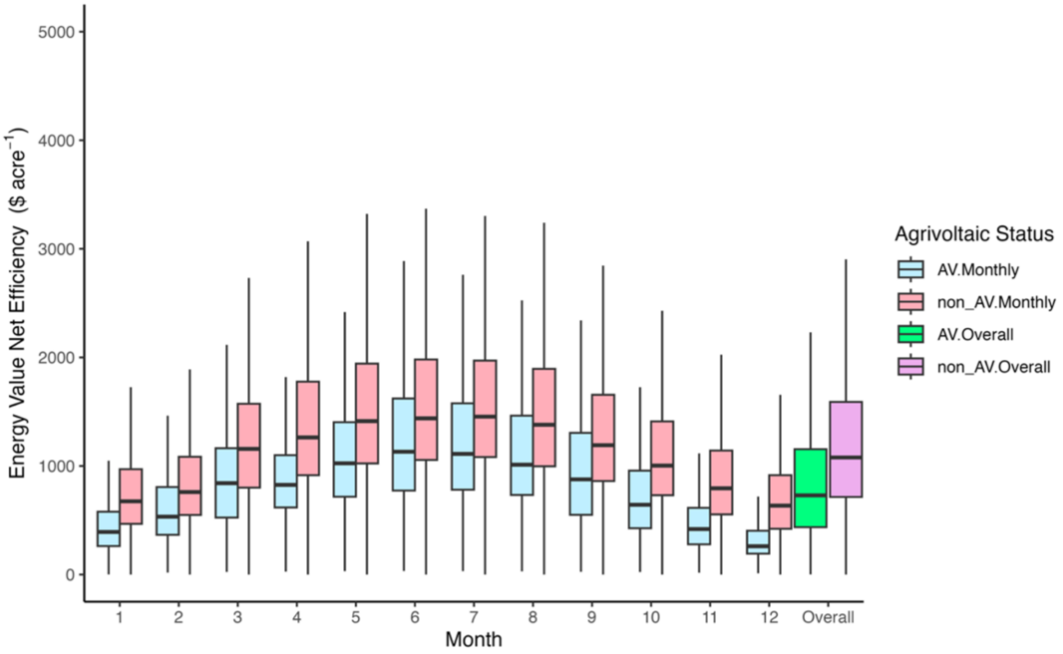
Table 7: The Impact of Densities on Gross/Net Efficiency Log Model

	Gross Efficiency	Net Efficiency
PV Density	1.241***	1.238***
	(0.155)	(0.153)
Sheep Density	0.090	0.092
	(0.070)	(0.070)
PV × Sheep Interaction	-0.233	-0.235
	(0.160)	(0.161)
Capacity Factor	0.049***	0.048***
	(0.005)	(0.005)
Total Value	0.000	0.000

	Gross Efficiency	Net Efficiency
	(0.000)	(0.000)
Radiation	0.082	0.096
	(0.057)	(0.060)
Num.Obs.	32278	32280
R2	0.602	0.583
R2 Adj.	0.594	0.575

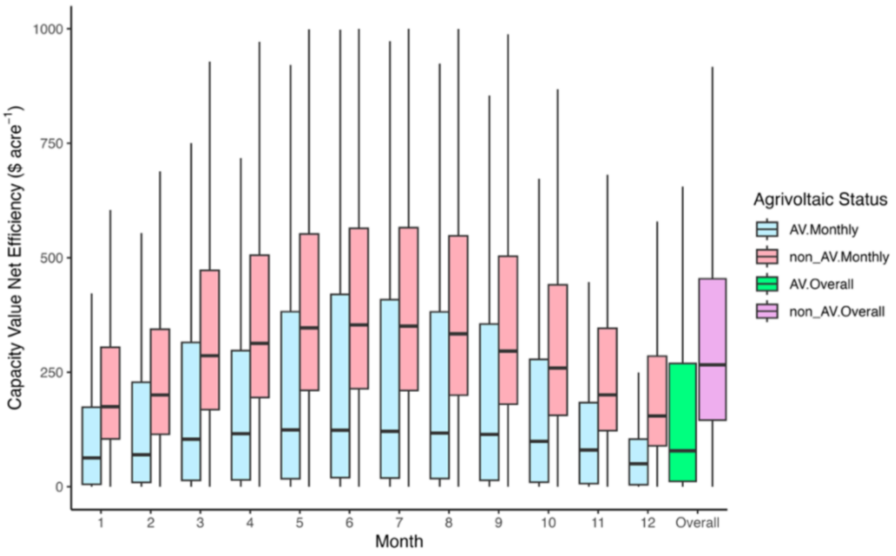
- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 5: The Impact of AV Status on Net Efficiency (Energy Value)



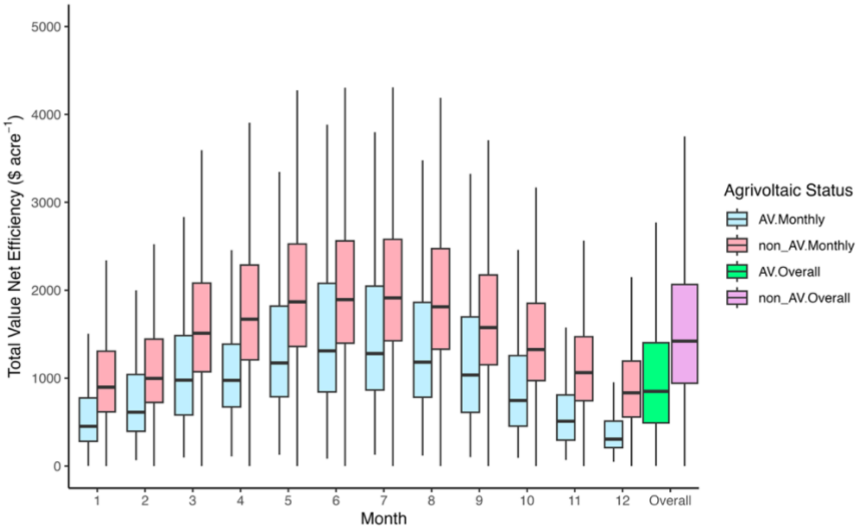
Note. The data visualisation is created by the author using data from:
USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25
Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
EIA (2025). Retrieved from https://www.eia.gov/opendata/

Figure 6: The Impact of AV Status on Net Efficiency (Capacity Value)



Note. The data visualisation is created by the author using data from:
USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25
Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
EIA (2025). Retrieved from https://www.eia.gov/opendata/

Figure 7: The Impact of AV Status on Net Efficiency (Total Value)



Note. The data visualisation is created by the author using data from:
USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25
Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
EIA (2025). Retrieved from https://www.eia.gov/opendata/

5.3 LUE for Electricity

Although AV projects slightly improve the performance of individual PV panels, as sections 5.1 and 5.2 demonstrate, the increases in capacity factor and saved energy do not lead to higher electricity revenue per acre. Figure 8 illustrates the reduction in electricity generation caused by AV, and as shown in Table 8, the LUE for electricity decreases in AV systems, particularly in medium- and large-scale farms. The main reason is the reduction in PV density. Fewer PV panels are installed per acre to accommodate grazing, resulting in a decline in revenue. PV density consistently increases the electricity value per acre, and this effect is amplified as PV farm size increases. In large farms, a 1 kW increase in PV capacity per acre is predicted to increase the electricity revenue by .36%. These findings suggest a trade-off between sheep grazing and PV panels.

Table 8: The Impact of AV Status on LUE for Electricity Log Model

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
Agrivoltaics Status	-0.211***	-0.064	-0.261***	-0.228***
	(0.042)	(0.082)	(0.040)	(0.038)
PV Density	1.236***	0.927***	2.242***	3.620***
	(0.149)	(0.109)	(0.521)	(0.276)
Capacity Factor	0.046***	0.059***	0.045***	0.044***
	(0.004)	(0.010)	(0.003)	(0.005)
Total Value	0.017***	0.017***	0.017***	0.018***

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
	(0.001)	(0.001)	(0.001)	(0.001)
Radiation	0.158**	0.301	0.100*	0.235***
	(0.053)	(0.227)	(0.048)	(0.054)
Num.Obs.	34394	9967	19556	4871
R2	0.721	0.703	0.848	0.893
R2 Adj.	0.716	0.693	0.844	0.887

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

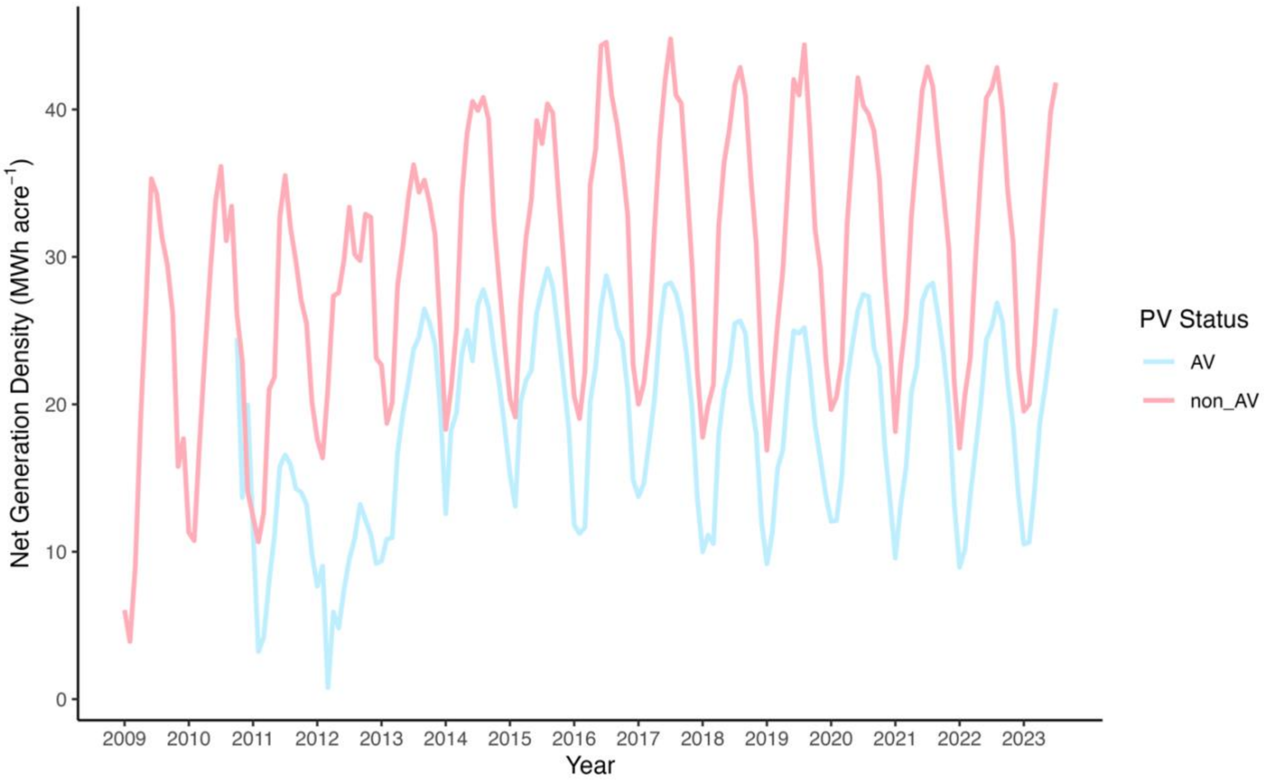
Table 9: The Impact of Densities on LUE for Electricity Log Model

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
PV Density	1.240***	0.928***	2.270***	3.638***
	(0.154)	(0.110)	(0.555)	(0.266)
Sheep Density	0.094	0.270***	-0.026	-0.249
	(0.070)	(0.072)	(0.089)	(0.428)
PV × Sheep Interaction	-0.238	-0.366***	0.053	-0.211
	(0.160)	(0.091)	(0.287)	(2.547)
Capacity Factor	0.047***	0.059***	0.046***	0.044***
	(0.005)	(0.011)	(0.003)	(0.005)
Total Value	0.017***	0.016***	0.017***	0.018***

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
	(0.001)	(0.001)	(0.001)	(0.001)
Radiation	0.109+	0.363	0.087+	0.211***
	(0.058)	(0.291)	(0.051)	(0.059)
Num.Obs.	32244	9271	18352	4621
R2	0.707	0.697	0.843	0.901
R2 Adj.	0.702	0.686	0.839	0.896

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 8: Net Generation Density



Note. The data visualisation is created by the author using data from:

USPVDB (2025). Retrieved from https://eerscmap.usgs.gov/uspvdb/viewer/#3/37.25/-96.25
Berkeley Lab (2025). Retrieved from https://emp.lbl.gov/utility-scale-solar-value
EIA (2025). Retrieved from https://www.eia.gov/opendata/

5.4 LUE for Revenue

In all area scales, PV density, capacity factor, and total electricity value are strongly associated with higher LUE for revenue. However, the impact of AV on LUE for revenue shows apparent variation by farm size. For the all-areas scale, AV reduces LUE for revenue. However, AV significantly increases revenue per acre when focusing on small farms. AV land has a 34.5% higher revenue LUE than conventional PV farms. This benefit disappears on medium-sized farms and becomes increasingly negative in large farms. The results reflect shifts in the composition of revenue. On small farms, grazing contributes significantly to total revenue, resulting in dual-land use that generates additional income. However, as farm size increases, electricity becomes the primary source of revenue. As Section 5.3 has shown, PV density increases electricity revenue, and the effect becomes stronger with the increase in farm scale. This explains why AV benefits diminish in larger farms: electricity generates the majority of revenue.

To achieve the optimal LUE for revenue, the optimal sheep density should be .40 head per acre and a PV density of .27 MW per acre. The best density of PV should be .32 MW per acre. Those findings are statistically significant.

Table 10: The Impact of AV Status on LUE for Revenue Log Model

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
Agrivoltaics Status	-0.236*	0.345***	-0.048	-0.285***

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
	(0.101)	(0.014)	(0.095)	(0.085)
PV Density	1.241***	0.928***	2.271***	3.636***
	(0.154)	(0.110)	(0.555)	(0.266)
Capacity Factor	0.047***	0.059***	0.046***	0.044***
	(0.005)	(0.011)	(0.003)	(0.005)
Total Value	0.017***	0.016***	0.017***	0.018***
	(0.001)	(0.001)	(0.001)	(0.001)
Radiation	0.117*	0.359	0.086+	0.207***
	(0.058)	(0.290)	(0.051)	(0.061)
Num.Obs.	32110	9205	18294	4611
R2	0.710	0.697	0.843	0.902
R2 Adj.	0.704	0.686	0.839	0.897

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 11: The Impact of Densities on LUE for Revenue Log Model

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
PV Density	1.242***	0.929***	2.270***	3.638***
	(0.154)	(0.110)	(0.555)	(0.266)
Sheep Density	0.081	0.630***	-0.302*	-0.248

	All Areas	Area < 10	10 ≤ Area < 100	Area ≥ 100
	(0.339)	(0.025)	(0.131)	(0.429)
PV × Sheep Interaction	-0.436	-2.309***	0.938*	-0.188
	(1.098)	(0.127)	(0.391)	(2.554)
Capacity Factor	0.047***	0.059***	0.046***	0.044***
	(0.005)	(0.011)	(0.003)	(0.005)
Total Value	0.017***	0.016***	0.017***	0.018***
	(0.001)	(0.001)	(0.001)	(0.001)
Radiation	0.115*	0.359	0.087+	0.211***
	(0.059)	(0.290)	(0.051)	(0.059)
Num.Obs.	32110	9205	18294	4611
R2	0.709	0.698	0.843	0.901
R2 Adj.	0.704	0.687	0.839	0.896

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 12: Optimal Densities for Sheep and PV Panels

	All Areas	Area<10	10 ≤ Area < 100	Area ≥ 100
Best Sheep Density	2.85	0.40***	-2.42***	19.35
Best PV Density	0.19	0.27***	0.32*	-1.32

*: According to the p-value displayed in Table

5.5 LUE for Profit

Although AV decreases the LUE for revenue with an increase in farm scale, AV projects consistently improve LUE for profit; however, the effect varies by farm size and sheep source. As shown in Table 13, when sheep are from breeding, AV increases profit by 246%, compared to 175% from auction. Breeding saves more costs, making it profitable. The benefit of AV is maximised on small farms, where grazing is more concentrated and cost-saving effects are more pronounced. However, the profit diminishes with an increase in farm size. Table 14 illustrates the impact of AV on LUE for profit across 6 scenarios, where AV increases it by 136% to 252%. Table 15 also shows this estimation across scenarios. AV increases the profit from $31 to $112 per acre. With an increase of one head of sheep per acre in an AV farm, the profit is estimated to increase by 14 to 49 dollars per acre. While electricity generation drives revenue, sheep contribute more consistently to profit. The primary reason is that the LCOE for solar energy is high, and some PV projects are losing money.

Tables 16 to 18 show the impact of densities on LUE for profit. In Table 16, the increase in sheep density always increases LUE for profit in small and medium farms by 92% to 174% but decreases LUE for profit in large farms, while the increase in PV density continuously decreases LUE for profit. Table 17 also shows sheep density increases LUE for profit by 71% to 154%, PV density decreases LUE for profit and has a competitive relationship with sheep. Table 18 indicates that for every one sheep per acre increase in farms, the LUE for profit is predicted to increase by $17 to $49 in six different scenarios.

Tables 14, 17, and 18 show a fixed impact of PV-related variables on profit, as the sources of profit are from electricity generation and sheep sales. Different columns have different sheep sources, but they all share the same electricity generation data. Therefore, the impact of sheep-related variables on total profit differs by column, but the impact of PV-related variables on total profit remains the same, as the following formula shows.

$$\text{LUE for Profit} = \frac{\text{Net Generation} \times (\text{Total Value} - \text{LCOE})}{\text{acres of a AV farm}}$$

$$+ \frac{\text{the Selling Price of Sheep} \times \#\text{ of Sheep Sold} \times \text{Profit Margin}}{\text{acres of a AV farm}} = \# \frac{\$}{\text{acre}}$$

Table 19 presents six profit-margin scenarios based on revenue and costs estimated by Gasch et al. (2025). When sheep are bred on farms, the cost of purchasing sheep is reduced, resulting in higher profits compared to those from auctions. High means the highest possible revenue and the lowest possible cost; low means the lowest possible revenue and the highest possible cost; base means the most common revenue and the most common cost.

Table 13: The Impact of AV Status on LUE for Profit by Area Log Model

	Breeding (All Areas)	Breeding <10	Breeding 10–100	Breeding ≥100	Auction (All Areas)	Auction <10	Auction 10–100	Auction ≥100
Agrivoltaics Status	2.461***	4.037***	3.208***	1.161+	1.746***	3.054***	2.354***	0.461
	(0.294)	(0.076)	(0.206)	(0.596)	(0.234)	(0.076)	(0.173)	(0.378)
PV Density	-0.033	-0.026	-0.093	-0.047	-0.033	-0.026	-0.093	-0.061
	(0.052)	(0.057)	(0.059)	(0.323)	(0.052)	(0.057)	(0.059)	(0.321)
Capacity Factor	-0.001	-0.009	0.001	0.001	-0.001	-0.009	0.001	0.001
	(0.002)	(0.006)	(0.003)	(0.007)	(0.002)	(0.006)	(0.003)	(0.006)
Total Value	0.051***	0.057***	0.052***	0.040***	0.051***	0.057***	0.052***	0.040***
	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.002)

	Breeding (All Areas)	Breeding <10	Breeding 10–100	Breeding ≥100	Auction (All Areas)	Auction <10	Auction 10–100	Auction ≥100
Radiation	0.637***	0.606**	0.742***	-0.074	0.641***	0.607**	0.745***	-0.062
	(0.138)	(0.215)	(0.179)	(0.136)	(0.138)	(0.215)	(0.179)	(0.125)
Num.Obs.	19693	5060	11809	2824	19683	5060	11809	2814
R2	0.743	0.735	0.776	0.756	0.742	0.732	0.773	0.759
R2 Adj.	0.735	0.718	0.767	0.734	0.734	0.715	0.763	0.737

- p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Table 14: The Impact of AV Status on LUE for Profit by Profit-Margin Scenario Log Model

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
Agrivoltaics Status	2.517***	2.461***	2.423***	1.885***	1.746***	1.356***
	(0.289)	(0.294)	(0.284)	(0.268)	(0.234)	(0.238)
PV Density	-0.033	-0.033	-0.033	-0.033	-0.033	-0.033
	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)
Capacity Factor	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Total Value	0.051***	0.051***	0.051***	0.051***	0.051***	0.051***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
Radiation	0.637***	0.637***	0.637***	0.638***	0.641***	0.647***
	(0.138)	(0.138)	(0.138)	(0.137)	(0.138)	(0.138)
Num.Obs.	19693	19693	19691	19687	19683	19681
R2	0.744	0.743	0.743	0.741	0.742	0.741
R2 Adj.	0.735	0.735	0.735	0.733	0.734	0.733

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 15: The Impact of AV Status on LUE for Profit by Profit-Margin Scenario Linear Model

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
Agrivoltaics Status	112.295***	107.240***	100.920***	56.684***	45.309***	31.406***
	(16.124)	(15.396)	(14.487)	(8.119)	(6.482)	(4.482)
PV Density	-0.023	-0.024	-0.025	-0.031	-0.032	-0.034
	(0.105)	(0.104)	(0.101)	(0.088)	(0.086)	(0.084)
Capacity Factor	0.019	0.019	0.019	0.019+	0.019*	0.019*
	(0.016)	(0.016)	(0.015)	(0.011)	(0.010)	(0.009)

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
Total Value	1.006***	1.006***	1.006***	1.007***	1.007***	1.008***
	(0.007)	(0.007)	(0.007)	(0.005)	(0.005)	(0.004)
Radiation	12.588***	12.575***	12.558***	12.444***	12.415***	12.379***
	(1.715)	(1.701)	(1.685)	(1.597)	(1.583)	(1.570)
Num.Obs.	32146	32146	32146	32146	32146	32146
R2	0.954	0.957	0.961	0.984	0.989	0.993
R2 Adj.	0.953	0.956	0.960	0.984	0.989	0.993

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 16: The Impact of Densities on LUE for Profit by Area Log Model

	Breeding (All Areas)	Breeding <10	Breeding 10–100	Breeding ≥100	Auction (All Areas)	Auction <10	Auction 10–100	Auction ≥100
PV Density	-0.033	-0.026	-0.091	-0.096	-0.033	-0.026	-0.091	-0.099
	(0.052)	(0.057)	(0.059)	(0.319)	(0.052)	(0.057)	(0.059)	(0.320)
Sheep Density	1.516***	1.204***	1.737***	-2.187+	1.008***	0.923***	1.350***	-1.852*
	(0.348)	(0.033)	(0.273)	(1.117)	(0.245)	(0.032)	(0.237)	(0.738)
PV × Sheep Interaction	-1.419	0.116	-2.448**	20.203**	-0.707	0.037	-2.038*	13.241**
	(1.141)	(0.127)	(0.927)	(6.530)	(0.826)	(0.127)	(0.806)	(4.378)

	Breeding (All Areas)	Breeding <10	Breeding 10–100	Breeding ≥100	Auction (All Areas)	Auction <10	Auction 10–100	Auction ≥100
Capacity Factor	-0.001	-0.009	0.002	0.001	-0.001	-0.009	0.001	0.001
	(0.002)	(0.006)	(0.003)	(0.006)	(0.002)	(0.006)	(0.003)	(0.006)
Total Value	0.051***	0.057***	0.052***	0.041***	0.051***	0.057***	0.052***	0.041***
	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Radiation	0.628***	0.607**	0.739***	0.053	0.632***	0.607**	0.743***	0.033
	(0.137)	(0.215)	(0.179)	(0.172)	(0.136)	(0.215)	(0.179)	(0.156)
Num.Obs.	19693	5060	11809	2824	19683	5060	11809	2814
R2	0.747	0.735	0.777	0.760	0.745	0.732	0.774	0.760
R2 Adj.	0.739	0.718	0.768	0.738	0.737	0.715	0.764	0.739

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 17: The Impact of Densities on LUE for Profit by Profit-Margin Scenario Log Model

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
Sheep Density	1.544***	1.516***	1.486***	1.154***	1.008***	0.709**
	(0.354)	(0.348)	(0.342)	(0.273)	(0.245)	(0.217)
PV Density	-0.033	-0.033	-0.033	-0.033	-0.033	-0.033
	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)
PV × Sheep Interaction	-1.457	-1.419	-1.384	-0.939	-0.707	-0.160

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
	(1.159)	(1.141)	(1.121)	(0.910)	(0.826)	(0.733)
Capacity Factor	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Total Value	0.051***	0.051***	0.051***	0.051***	0.051***	0.051***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Radiation	0.628***	0.628***	0.628***	0.629***	0.632***	0.639***
	(0.137)	(0.137)	(0.137)	(0.136)	(0.136)	(0.137)
Num.Obs.	19693	19693	19691	19687	19683	19681
R2	0.748	0.747	0.747	0.746	0.745	0.745
R2 Adj.	0.739	0.739	0.739	0.737	0.737	0.736

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 18: The Impact of Densities on LUE for Profit by Profit-Margin Scenario Linear Model

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
Sheep Density	49.129***	46.944***	44.213***	25.095***	20.179***	14.171***
	(1.449)	(1.377)	(1.288)	(0.693)	(0.559)	(0.428)

	Breeding High-Profit %	Breeding Base-Profit %	Breeding Low-Profit %	Auction High-Profit %	Auction Base-Profit %	Auction Low-Profit %
PV Density	-0.040	-0.040	-0.040	-0.039	-0.038	-0.038
	(0.083)	(0.083)	(0.083)	(0.083)	(0.083)	(0.083)
PV × Sheep Interaction	8.716+	8.222+	7.605+	3.286	2.176	0.819
	(4.564)	(4.332)	(4.045)	(2.163)	(1.773)	(1.444)
Capacity Factor	0.018*	0.018*	0.018*	0.019*	0.019*	0.019*
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Total Value	1.007***	1.007***	1.008***	1.008***	1.008***	1.008***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Radiation	12.179***	12.185***	12.192***	12.240***	12.253***	12.268***
	(1.564)	(1.564)	(1.564)	(1.562)	(1.562)	(1.561)
Num.Obs.	32146	32146	32146	32146	32146	32146
R2	0.998	0.998	0.998	0.997	0.997	0.997
R2 Adj.	0.998	0.997	0.997	0.997	0.997	0.997

- $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 19: Profit-Margin Scenarios

	High-Profit Margin	Base-Profit Margin	Low-Profit Margin
Breeding	89%	85%	80%
Auction	45%	36%	25%

Note: estimated by Gasch et al. (2025).

$$\text{Gross Profit Margin} = \frac{\text{Sales} - \text{Cost of Sales}}{\text{Sales}}$$

6 Conclusion

6.1 Findings

After the OLS regression on conventional PV and AV farms, the results show that AV projects slightly increase the capacity factor of individual PV panels, especially in medium farms, with a 1.15% increase in capacity factor. The reduction in net efficiency is less than that in gross efficiency, indicating better performance of PV panels.

An apparent heterogeneity by farm size is observed. The analysis reveals that AV significantly improves LUE for revenue on small farms. However, AV decreases LUE for revenue in medium- and large-scale farms, while the increase in PV density always increases LUE for revenue across all area scales. Regarding LUE for profit, the increase in sheep density always increases profit, but the increase in PV density decreases it. When the sheep source is from breeding, the increased profit from sheep density will be higher than that of auction.

6.2 Contributions & Limitations

The paper is grounded in the growing literature on AV and offers a project-level analysis of its economic performance. It introduces an empirical framework that utilises fixed effects, interaction terms, and farm-size heterogeneity to capture the trade-offs in the dual land uses and also incorporates sheep source scenario assumptions. The paper presents a method for computing optimal combinations of sheep and PV densities, providing practical guidance for AV system design.

Most AV papers are farm-level case studies, and the project-level data for AV studies is limited. For instance, grass quality in pastures, methods of sheep management, and other factors significantly impact LUE; however, such data are limited to a small number of farms, and the measurement method also varies.

This paper does not address the problem of endogeneity despite the inclusion of an interactive term in the model. The farmers determine the PV and sheep densities. A farmer may determine the distribution density of PV and sheep based on factors such as soil quality, irradiance conditions, or the property of the land, including whether it was previously used for farming or PV, or whether a dual-land-use strategy was already implemented from the beginning. A causal relationship may not exist for the reasons above. Despite those limitations, an economic analysis of AV in the US is also very vital. Most previous studies were case studies, and subsequent research can build upon this paper as the database is further developed.

This study does not evaluate crop-based AV systems due to the limited availability of data. As a result, the analysis focuses only on grazing projects. As more detailed data become available, future research could apply the same framework to crop-AV farms.

6.3 Discussions

The paper focuses on both AV's revenue and profit. Although profit is often used as a key indicator of economic performance, it is insufficient to capture the full value of an AV system due to the high LCOE for most clean energy projects; many of these generate low or even negative profits. However, these projects can still yield significant economic and environmental benefits through clean energy generation, carbon emission reduction, and support for rural development.

Despite the economic benefits of AV, grid access may remain limited for small-scale operators, particularly in rural areas. The cost of installing PV per MW for small farms is higher than that for large-scale photovoltaic projects, negatively impacting their profits. The government can make this dual-land use more common by subsidising small-scale farmers more, thereby improving land use efficiency.

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