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Divergent Dynamics of Farmland Rents and Local Employment under Utility-Scale Solar Expansion: Evidence from U.S. Counties

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Article

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Posted Date: November 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11610379/v1

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Additional Declarations: No competing interests reported.

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*The main text contains **7,259 words**, excluding the abstract, references, tables, figures, and figure legends.*

Abstract

Utility-scale solar expansion creates competing demands for land while generating local investment and employment opportunities. Land rental costs and employment gains may, however, follow different time paths. This study links georeferenced solar projects with agricultural cash rents and employment in 1,403 U.S. counties (12,627 county-year observations) during 2016–2024. Using doubly robust staggered difference-in-differences, dynamic event studies, and spatial exposure comparisons, we examine responses to the first entry of a qualifying ground-mounted solar project. During the commissioning year and the following two years, real nonirrigated cropland cash rents rise by an estimated 7.12%, while private-sector employment increases by 1.26%. Rent effects strengthen over time, whereas employment gains diminish after commissioning; construction employment exhibits a pronounced initial response. Rent effects are larger where reliance on rented land or the cropland share is higher, while employment gains are stronger in counties with larger manufacturing sectors. Neighboring-county solar exposure is associated with smaller positive responses in rents and employment. These findings highlight divergent timing and spatial patterns of agricultural land costs and local employment returns, informing solar siting and sustainable land-use planning.

Keywords: Utility-scale solar; Farmland cash rents; Land-use competition; Local employment; Spatial spillovers; Sustainable land management

1. Introduction

In August 2022, the United States enacted the Inflation Reduction Act, further advancing the energy transition through incentives for clean energy investment. As renewable generating capacity continues to expand, utility-scale ground-mounted solar has become an important component of U.S. electricity infrastructure development. In 2024, the United States added approximately 30 GW of utility-scale solar capacity, accounting for 61% of all utility-scale generating capacity added that year. Solar development changes the energy mix while increasing demand for land. In agricultural regions, its long-term land requirements create new competition with agricultural production, drawing attention to land allocation and local economic outcomes during the energy transition.

Utility-scale ground-mounted solar development involves adjustments in both land and labor markets. Solar projects provide an alternative to agricultural land use, potentially increasing the opportunity value of land and affecting farmers' rental costs through changes in the supply of cropland available for lease. Project investment can also stimulate construction and local employment, although construction labor demand may not persist during operation.

Changes in land costs and employment returns may therefore follow different time paths. This difference affects the distribution of benefits among landowners, agricultural operators, and workers, as well as the long-term local economic value of renewable energy investment.

Existing research examines the land footprint, land-use changes, asset prices, and local employment effects of solar facilities, while the relationship between agricultural cash rents and employment dynamics warrants further investigation. Compared with land prices, which reflect long-term asset values, agricultural cash rents more directly capture recurring land operating costs. The persistence of employment effects, in turn, reflects the connection between renewable energy investment and local economic activity. Land leasing, construction, and labor mobility can also cross county boundaries, allowing economic effects to spread spatially. Evaluating the local effects of solar expansion therefore requires joint consideration of land markets, employment dynamics, and spatial distribution.

Against this background, this study addresses three questions. How does utility-scale solar entry affect agricultural cash rents and private employment? Do these effects differ in persistence? How do land-use structure, the industrial base, and neighboring-county exposure shape economic responses? The analysis combines U.S. solar project, agricultural rent, and county economic data into a county panel covering 2016–2024. Group–time doubly robust difference-in-differences identifies average treatment effects, while dynamic event studies, robustness checks, heterogeneity analysis, and spatial exposure comparisons examine different adjustment paths. Fixed-effects restricted cubic splines further characterize nonlinear associations between capacity intensity and economic outcomes.

The results show that agricultural cash rents and private employment both increase following utility-scale solar entry, but their time paths differ markedly: rent increases are relatively persistent, whereas employment gains are concentrated in the initial period after commissioning. Further analysis indicates that agricultural land structure and the local industrial base shape economic responses, construction activity follows a stage-specific pattern, and neighboring-county exposure is associated with positive economic responses. These findings indicate that the local consequences of energy investment extend beyond employment levels to recurring land-use costs and their spatial distribution.

This study makes three contributions. First, it examines land-market adjustment to solar expansion through agricultural cash rents, extending understanding of competition between energy development and agricultural land use. Second, it jointly analyzes the dynamic effects on rents and employment, revealing differences in the persistence of land costs and local economic returns. Third, it combines land-use characteristics, industrial structure, and spatial

exposure to characterize heterogeneous local effects and transmission across counties, informing renewable energy development and sustainable agricultural land management.

2. Literature Review and Hypotheses

2.1. Solar Development and Land Markets

Utility-scale ground-mounted solar expansion creates new choices in allocating land between energy production and traditional uses. Advances in the spatial identification of solar facilities have enabled increasingly systematic measurement of the geography and land requirements of energy development (Kruitwagen et al., 2021). Renewable energy land requirements vary with generating technology, facility configuration, and land cover, while improvements in solar technology and installed capacity per unit of land continue to change the land-use efficiency of energy production (Bolinger & Bolinger, 2022; Lovering et al., 2022; van de Ven et al., 2021). The effects of solar expansion on land markets therefore depend on project location, land supply conditions, and facility design, as well as the amount of new capacity.

Land constraints further shape the spatial allocation of energy investment. Renewable deployment requires trade-offs among generation costs, land suitability, and existing land uses, potentially altering project siting and regional energy mixes (Patankar et al., 2023). As solar capacity expands, potential conversion pressures on agricultural and natural land exhibit substantial spatial variation (Diffendorfer et al., 2024). Competition between energy development and food production is particularly salient in agricultural regions. Land-use adjustment concerns both energy production efficiency and the continuity of farming and distribution of local benefits (Goldberg, 2023; Moore et al., 2022). The long-term leasing opportunities provided by solar projects may increase the value of alternative uses for some parcels, encouraging landowners to reallocate land between farming and energy development and creating new patterns of benefit distribution (Spangler et al., 2024).

Land prices can reflect these changes in resource allocation. Solar development opportunities and grid access may jointly affect the expected returns and market value of agricultural land, while zoning and development eligibility also influence price formation (Abashidze & Taylor, 2023; Chang & Lin, 2023). Different land assets exhibit distinct price responses to solar facilities, reflecting the combined effects of energy development returns, land-use conversion, and proximity externalities (Hu et al., 2025). Residential price responses also vary with project scale, prior land use, and local conditions, indicating substantial spatial

heterogeneity in the land-market effects of energy facilities (Dröes & Koster, 2021; Elmallah et al., 2023; Gaur & Lang, 2023).

This literature provides a foundation for understanding solar land requirements and changes in asset values, while highlighting the importance of extending land competition analysis to agricultural rental markets. Land asset prices primarily capitalize expected returns and development opportunities, whereas agricultural cash rents more directly measure the recurring land-use costs paid by agricultural operators. When land acquires a new energy development use, landowners' leasing choices and the supply of land available for agriculture may adjust, affecting surrounding agricultural operating costs through rental markets. Examining cash rents following solar entry thus helps explain land-market adjustment and its persistence from the perspective of land users during the energy transition.

2.2. Energy Investment and Local Employment

Renewable energy investment affects regional economies through facility construction, industrial linkages, and local public finance. Project construction and operation can generate changes in employment and income, with local returns also depending on project scale, regional economic conditions, and industrial structure (Brown et al., 2012; Brunner & Schwegman, 2022). Changes in the tax base and fiscal revenue associated with energy facilities may further influence the allocation of local public resources, extending economic benefits beyond direct labor demand (Brunner et al., 2022). Evaluating local energy investment effects therefore requires consideration of employment, income, and their links to local economic activity.

Labor demand differs across energy technologies and project stages. Solar projects typically create concentrated employment demand during construction, equipment installation, and supporting electricity infrastructure development. Employment composition and labor demand then adjust as projects enter operation. Existing evidence indicates that renewable energy investment can promote local employment, but the magnitude and persistence of these effects vary with technology, project stage, and regional conditions; some employment opportunities may also arise outside the host locality (Fabra et al., 2024; Scheifele & Popp, 2025). Reviews further emphasize differences between construction and installation and operation and maintenance in job numbers, skill requirements, and employment duration (Hanna et al., 2024). These characteristics make dynamic analysis important for understanding local employment returns from renewable energy investment.

Employment benefits also depend on labor-market structure and regional economic linkages. Employment and wage gains differ across education and skill groups, some economic benefits are realized through business activity and public expenditure, and changes in total employment depend on local economic capacity to absorb investment (Gavard et al., 2025; Gilbert et al., 2024). Occupational skill matching and the spatial allocation of projects further shape where employment opportunities arise, while prioritizing local job creation can involve different economic costs from allowing energy facilities to be located across regions (Greenspon & Raimi, 2024; Vanatta et al., 2022). Growth in renewable capacity is therefore not simply proportional to employment benefits in host counties; these returns also depend on local industrial capacity, labor mobility, and regional specialization.

From a land economics perspective, land-market adjustment and employment returns from solar development may follow different time paths. Solar facilities generally require long-term land use, potentially producing lasting changes in local agricultural rental markets, while construction-related labor demand is concentrated in project implementation. As projects move from construction to operation, land demand remains, whereas employment growth may weaken. These differences in adjustment mean that local economic effects include both recurring changes in land-use costs and stage-specific labor-market benefits. An integrated dynamic analysis of agricultural cash rents and employment can therefore clarify differences in the adjustment of land and labor markets during solar expansion.

2.3. Land Structure and Spatial Effects

The land-market and employment effects of solar expansion depend on existing agricultural production conditions and land-use structure. The feasibility of combining farming and solar production on the same land varies with facility configuration, crop type, solar conditions, and farming practices. Different technological arrangements can change competition and complementarity between energy production and agriculture (Gomez-Casanovas et al., 2023; Mamun et al., 2022). Crop yield responses to shading also vary substantially, highlighting the importance of agricultural production characteristics and land-use practices when evaluating solar development (Laub et al., 2022). Pre-development land cover, the cropland share, and agricultural production structure can therefore help explain the relationship between energy development and farming across regions.

Land conditions also affect the economic feasibility of energy development through agricultural operating decisions. Returns from combining agriculture and solar production depend jointly on farm type, operating scale, technology, and regional conditions, while

investment and adoption decisions vary across operators (Feuerbacher et al., 2021; Feuerbacher et al., 2022). Agricultural operators may be more sensitive to land supply and rent changes where farming depends more heavily on rented land. Where cropland accounts for a larger share of land, energy development and agricultural production are more closely connected through land allocation. Local manufacturing and related services can also influence project construction, equipment supply, and industrial linkages, producing regional differences in employment returns.

Land-market adjustment also reflects the decisions of economic actors, institutional arrangements, and social acceptance. Agricultural operators and energy industry participants assess combined land use in terms of investment costs, agricultural returns, technical conditions, and coordination of local interests (Morash & Pavao-Zuckerman, 2026; Pascaris et al., 2021). Technical characteristics, agricultural value, and community impacts are also closely related to acceptance and adoption (Torma & Aschemann-Witzel, 2023). As energy development expands from initial pilots to broader deployment, learning across industries, regulatory coordination, and market conditions influence project implementation (Pascaris et al., 2023), while farmers' expected returns, social norms, and willingness to innovate further shape land-use decisions (Wagner et al., 2024). Long-term land arrangements also allocate costs and benefits among economic actors, making landownership, leasing relationships, and farming interests important institutional contexts for understanding local solar development effects (Vezzoni, 2025).

The relationship between regional economic structure and land governance also has a spatial dimension. The siting and implementation of utility-scale solar projects involve local land-use planning, coordination of community interests, and changes in energy landscapes (Spangler et al., 2025). Demand for leased land, construction procurement, and labor mobility can cross county boundaries, allowing renewable energy investment to affect neighboring land and labor markets. In the presence of spatial interference, comparisons between treated and neighboring exposed areas need to account for their different economic linkages and exposure paths (Xu, 2026).

Local solar development effects thus depend on the land endowments and industrial base of host counties and may also spread to surrounding areas through cross-county factor movements. Land rental dependence, the cropland share, and prior project-site land use shape the conditions for land competition, while manufacturing capacity affects the ability to retain local employment benefits. Economic linkages between counties further shape the spatial distribution of land-market and employment effects. Together, these factors provide the

economic basis for analyzing regional heterogeneity and spatial spillovers from utility-scale solar expansion.

2.4. Research Hypotheses

The literature suggests that utility-scale ground-mounted solar expansion affects agricultural rental and labor markets primarily through competition over land use and local investment activity. Solar development provides a new productive use for land, potentially changing the supply and market price of land available for agriculture. Construction and operation affect local employment through labor demand at different project stages. Existing land structure and the industrial base shape the magnitude of these adjustments, while economic linkages across counties may transmit project effects to neighboring areas. Based on these mechanisms, this study proposes four hypotheses.

H1: Land Rent Effects. Utility-scale ground-mounted solar entry increases local real agricultural cash rents, with relatively persistent effects following commissioning.

H2: Employment Dynamics. Utility-scale ground-mounted solar entry promotes local employment growth, but the effects are concentrated in the initial period after commissioning and gradually weaken during operation.

H3: Regional Heterogeneity. The economic effects of solar entry depend on land and industrial structure: rent responses are stronger where land rental dependence, the cropland share, and pre-development cropland cover are higher, while employment responses are stronger where the manufacturing base is stronger.

H4: Spatial Spillover Effects. Utility-scale ground-mounted solar entry generates positive spillovers to agricultural cash rents and employment in neighboring areas through cross-county land and labor market linkages.

These hypotheses form the theoretical framework of the study. **Figure 1** shows the main paths through which solar entry affects farmland rents and local employment through land competition and construction, together with the moderating roles of land and industrial structure and transmission to neighboring counties. The framework connects land-market adjustment, employment dynamics, and spatial effects, providing a common economic basis for the empirical analysis.

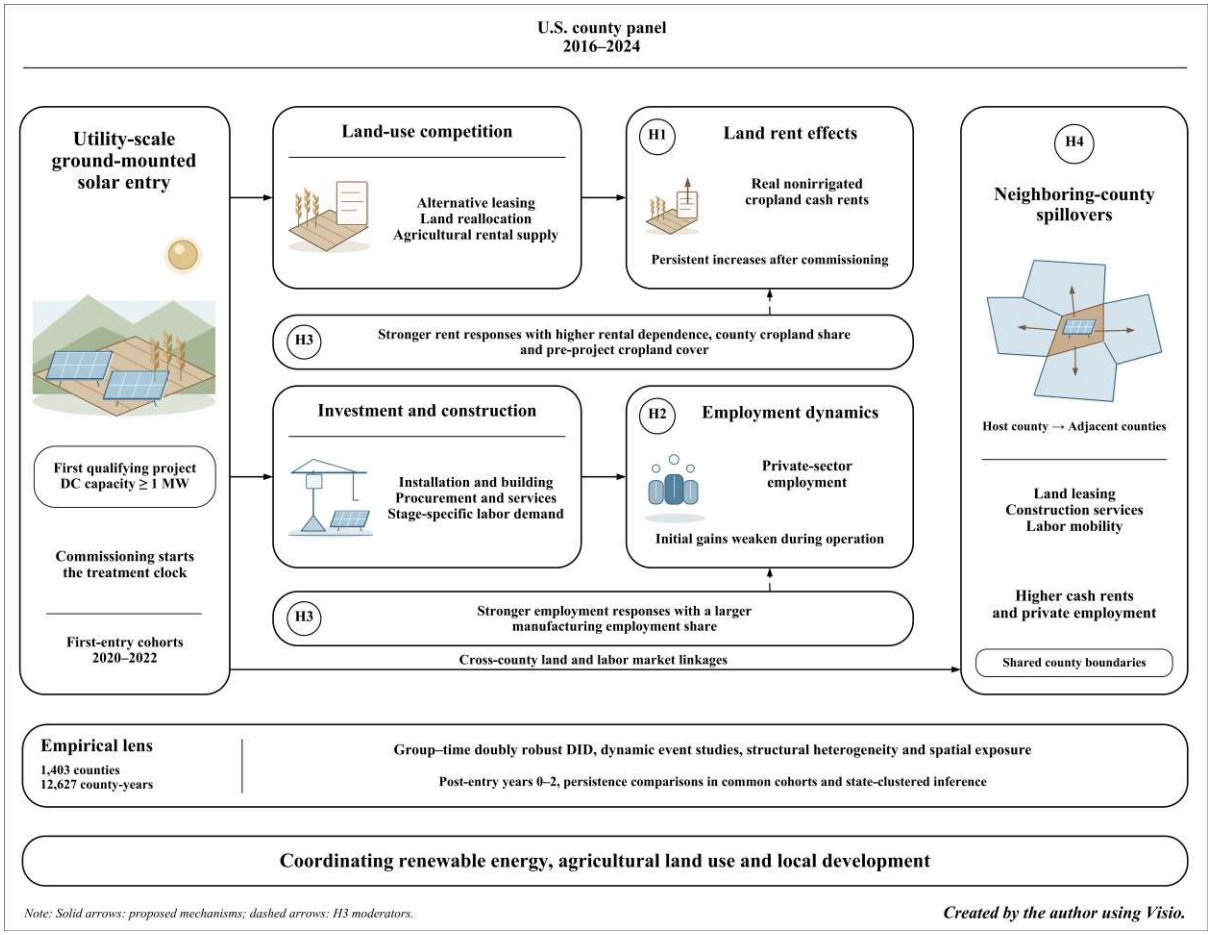


Figure 1. Research framework: land costs and local returns.

3. Data and Methods

3.1. Data and Variables

This study constructs a county-level panel for the contiguous United States covering 2016–2024, combining utility-scale ground-mounted photovoltaic facilities, agricultural land rents, local employment, and county economic characteristics to examine land market adjustment and employment dynamics associated with solar expansion. Facility locations, boundaries, mounting types, and commissioning years are obtained from the U.S. Large-Scale Solar Photovoltaic Database (USPVDB; Fujita et al., 2023), with capacity and commissioning information cross-checked against the U.S. Energy Information Administration's EIA-860 records. Agricultural cash rents come from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA NASS). Private-sector employment, construction employment, average annual pay, and establishments are obtained from the U.S. Bureau of Labor Statistics' Quarterly Census of Employment and Wages (BLS QCEW). County population, education, and farm characteristics come from the U.S. Census Bureau and the

2017 Census of Agriculture, while annual temperature and precipitation data are obtained from NOAA.

The main outcomes are real nonirrigated cropland cash rents ($LnRent$) and private-sector employment ($LnEmp$). Construction employment ($LnConstr$), real average annual pay ($LnPay$), and private establishments ($LnEstab$) capture additional local economic responses. All outcomes enter the estimations in natural logarithms, and monetary variables are expressed in 2024 U.S. dollars. The treatment is the first entry of utility-scale ground-mounted solar ($Solar\ Entry$), defined as the commissioning of a county's first qualifying ground-mounted project with a direct-current capacity of at least 1 MW. Treatment status remains equal to one after entry.

Controls comprise eight county characteristics measured in the 2017 baseline year: population density, educational attainment, manufacturing employment share, cropland share, rental dependence, mean farm size, irrigation dependence, and grain and oilseed specialization. Annual temperature and precipitation account for differences in weather conditions. Neighboring-county solar exposure and installed capacity per unit of baseline cropland are also constructed for the spatial spillover and nonlinearity analyses, respectively. **Table 1** presents variable definitions and data sources.

Table 1. Variable Definitions and Data Sources.

Variable	Definition and Measurement	Data Source
	Outcomes and Solar Exposure	
$LnRent$	Log of real nonirrigated cropland cash rent; levels in USD per acre.	USDA NASS
$LnEmp$; $LnConstr$	Logs of annual average private employment and construction employment (NAICS 23).	BLS QCEW
$LnPay$; $LnEstab$	Logs of real annual pay and private establishments.	BLS QCEW
Solar Entry (G, D)	First strict ground-mounted project with DC capacity ≥1 MW; D is absorbing after entry.	USPVDB; EIA-860
Neighbor Exposure (S)	At least one adjacent county has entered.	Census adjacency; USPVDB
Capacity Intensity (Q)	AC MW per 1,000 acres of 2017 county cropland.	EIA-860; USDA Census of Agriculture
	Baseline County Characteristics	
Population Density	Population per km² of county land; log(1 + density) in estimation.	U.S. Census
College Share	Share of residents aged 25+ with a bachelor's degree or higher.	ACS 2013–2017
Manufacturing Share	Private manufacturing employment / total private employment.	BLS QCEW 2017
Cropland Share	Cropland area / county land area, using consistent units.	USDA Census of Agriculture; Census boundaries

Variable	Definition and Measurement	Data Source
Rental Dependence	Rented operating acreage / total farm operating acreage.	USDA Census of Agriculture
Mean Farm Size	Operating acres / number of farms; log in estimation.	USDA Census of Agriculture
Irrigation Share	Irrigated acreage / total farm operating acreage.	USDA Census of Agriculture
Grain and Oilseed Specialization	NAICS 1111 farms / all farms.	USDA Census of Agriculture
	Weather and Site Characteristics	
Temperature; Precipitation	Annual mean temperature (°C) and annual precipitation (mm).	NOAA
Pre-Project Cropland Cover	Cropland pixel share within first-entry project polygons, measured two years before operation.	USDA CDL; USPVDB polygons

Note: Baseline year: 2017; monetary values are in 2024 USD.

3.2. Sample and Land Use

The analysis identifies counties in the contiguous United States where the first qualifying ground-mounted solar project entered during 2020–2022 and constructs a control group using historical project records. Sample selection considers commissioning dates, the completeness of baseline covariates, consistent county boundaries, and prior solar exposure. The final sample comprises 1,403 counties and 12,627 county-year observations, including 186 counties in the first-entry cohorts and 1,217 counties without qualifying entry. **Table 2** details the selection process and cohort composition.

Table 2. Sample Selection and Treatment Cohorts.

Sample Selection Criteria	Counties	County-Year Observations
Sequential Sample Selection		
Contiguous U.S. county frame	3,108	27,972
Retain G = 0 or entry in 2020–2022	2,170	19,530
Require all eight baseline covariates	1,432	12,888
Require stable geographic definitions	1,432	12,888
Exclude timing conflicts and earlier exposure	1,403	12,627
Treatment Cohorts		
2020 Entry Cohort	81	729
2021 Entry Cohort	67	603
2022 Entry Cohort	38	342
Never-Treated Controls	1,217	10,953
Final Main Sample	1,403	12,627

Note: 2016–2024 panel; 43 state clusters. G = 0 denotes no qualifying entry in the project data.

Solar entry dates and project scales vary substantially across U.S. regions. First commissioning years and cumulative installed capacity are matched to county boundaries to characterize the location of renewable energy development. Figure 2 maps the first-entry

cohorts and 2024 installed capacity per unit of baseline cropland, illustrating the spatial distribution of energy investment.

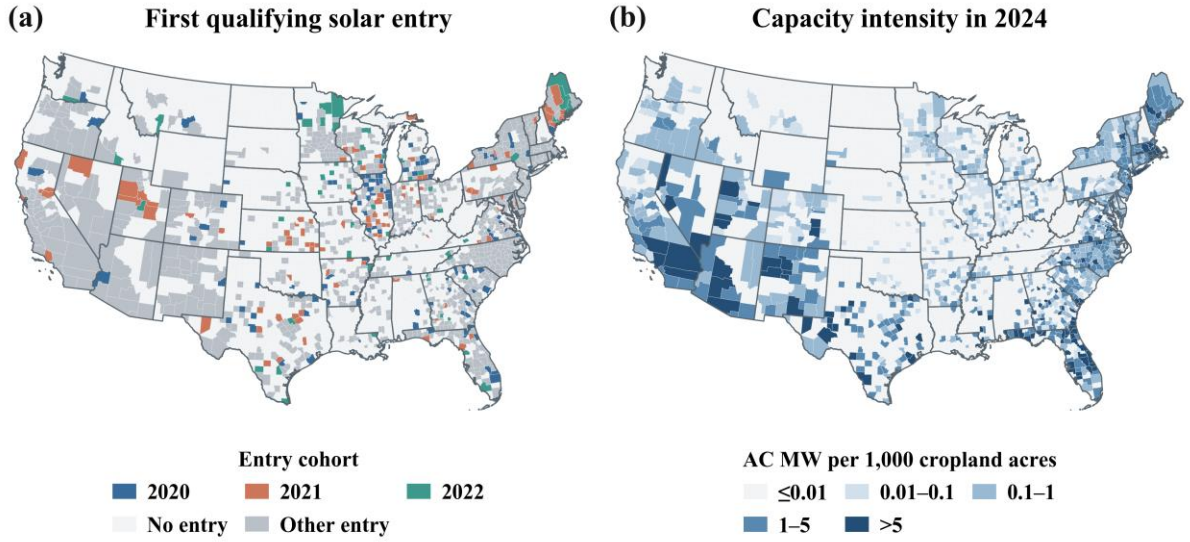


Figure 2. Solar entry and capacity intensity: **(a)** first qualifying entry across contiguous U.S. counties; **(b)** 2024 operating capacity (MWac per 1,000 acres of 2017 cropland). Other entry denotes cohorts outside 2020–2022.

Pre-development land use is directly relevant to the allocation of land between energy development and agriculture. USPVDB project boundaries are spatially matched to the USDA Cropland Data Layer (CDL), using land cover two years before commissioning to calculate land-cover shares and land area per unit of installed capacity. **Figure 3** presents historical land cover for a representative project, land-cover composition across entry cohorts, and land footprints by prior land-cover type. These spatial characteristics inform the analysis of land competition and heterogeneous economic effects.

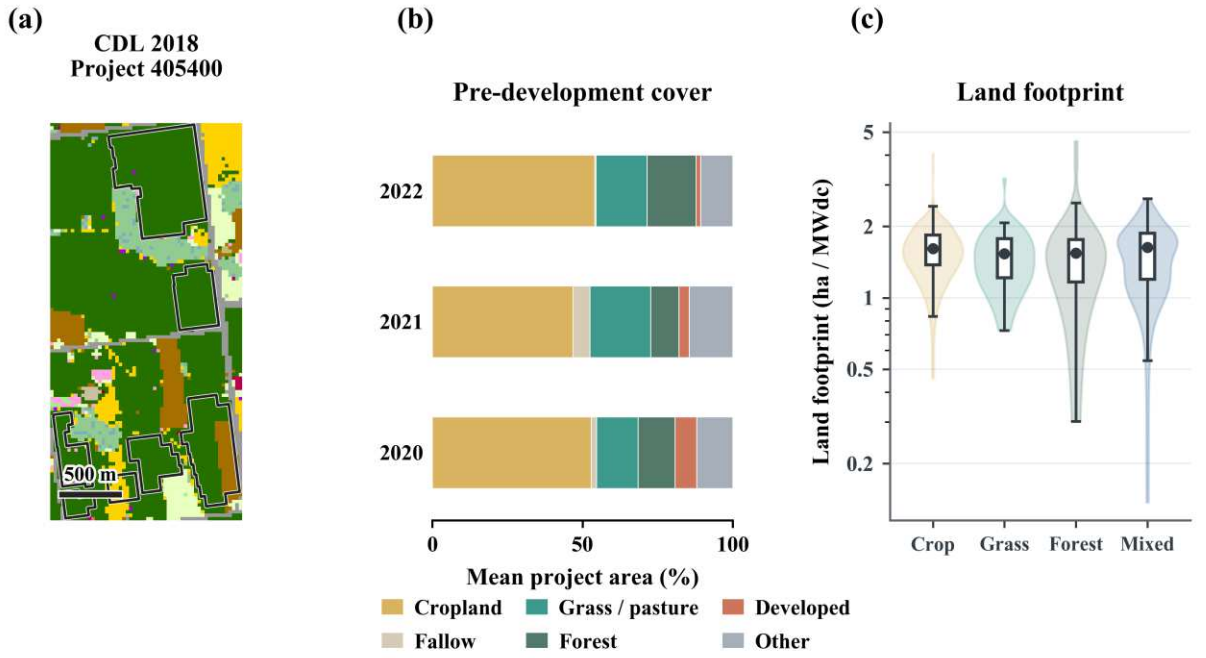


Figure 3. Pre-development land cover and land footprint: **(a)** CDL cover two years before entry, with project boundaries; **(b)** mean project-level cover shares by cohort; **(c)** hectares per MWdc by dominant cover (≥50%), on a log scale.

3.3. Descriptive Statistics

Table 3 reports descriptive statistics for the main economic outcomes and baseline county characteristics, including sample sizes, means, standard deviations, and quantiles. Standardized mean differences (SMDs) compare initial characteristics between treated and control counties, while covariate balance after inverse probability tilting is also reported. These comparisons characterize the sample used to estimate average treatment effects.

Table 3. Descriptive Statistics and Covariate Balance.

Variable	N	Mean	SD	P25	P75
Summary Statistics of Outcomes					
Cropland Cash Rent (USD/acre)	12,627	110.09	94.79	40.83	156.88
Private Employment (jobs)	12,627	25,279.07	86,285.75	2,613.17	15,832.74
Construction Employment (jobs)	12,627	1,563.46	5,903.92	139.52	947.65
Real Annual Pay (USD)	12,627	51,176.54	10,999.23	44,308.70	55,401.58
Private Establishments (count)	12,627	1,833.27	5,390.96	284.73	1,284.12
Baseline County Characteristics					
Population Density (persons/km²)	1,403	43.04	95.76	7.25	35.79
College Share (%)	1,403	20.35	8.08	14.69	23.47
Manufacturing Share (%)	1,403	16.89	11.59	7.78	23.67
Cropland Share (%)	1,403	32.68	27.41	8.73	55.18
Rental Dependence (%)	1,403	37.98	15.32	25.96	49.88
Mean Farm Size (acres)	1,403	503.38	651.25	164.50	529.00
Irrigation Share (%)	1,403	6.07	13.27	0.18	4.45

Variable	N	Mean	SD	P25	P75
Grain and Oilseed Specialization (%)	1,403	18.84	21.07	1.40	35.40

Covariate Balance

Variable	Treated Mean	Control Mean	Raw SMD	Weighted |SMD|
Population Density (persons/km²)	52.76	41.56	0.480	<0.001
College Share (%)	21.80	20.13	0.186	<0.001
Manufacturing Share (%)	17.05	16.87	0.018	<0.001
Cropland Share (%)	36.23	32.14	0.220	<0.001
Rental Dependence (%)	41.28	37.48	0.358	<0.001
Mean Farm Size (acres)	371.98	523.46	−0.087	<0.001
Irrigation Share (%)	7.07	5.91	0.115	<0.001
Grain and Oilseed Specialization (%)	22.85	18.22	0.290	<0.001

Note: Monetary values are in 2024 USD. Covariates refer to 2017. SMDs use transformed covariates; IPT-weighted absolute SMDs < 0.001.

Figure 4 summarizes the annual distribution of first solar entry and the paths of farmland rents and private-sector employment for fixed treated and control groups. Both economic indicators are indexed to 2016 to illustrate changes in energy investment and local economic activity over the study period and provide descriptive context for the dynamic analysis.

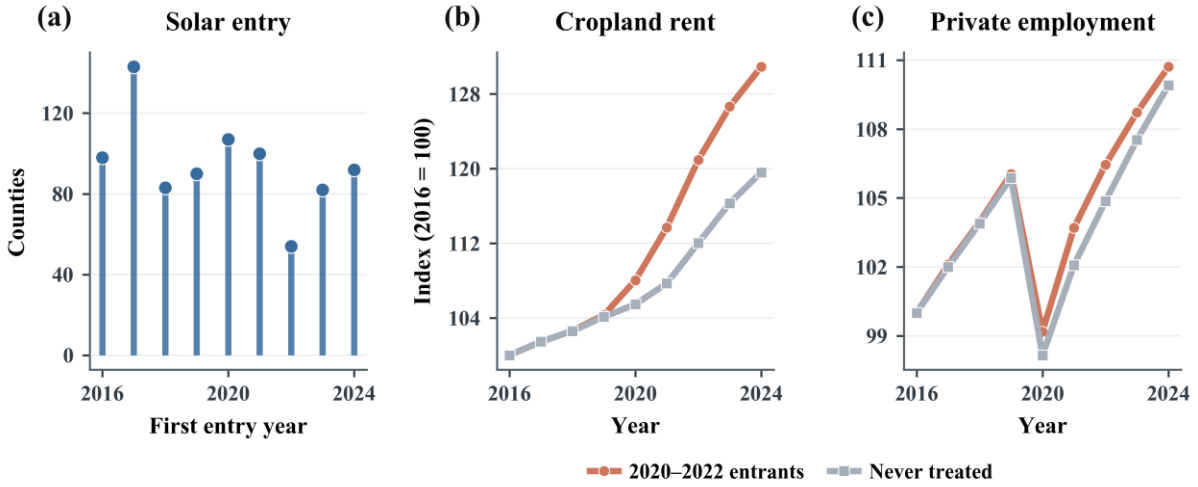


Figure 4. Solar entry and economic trends: **(a)** annual first entries across contiguous U.S. counties; **(b)** rent and **(c)** employment indices for fixed treated/control groups (186/1,217 counties), based on mean logs (2016 = 100).

3.4. Empirical Strategy

3.4.1. Average Treatment Effects

To identify the local economic effects of utility-scale ground-mounted solar entry, the analysis first estimates a two-way fixed-effects specification (M1) with county and state-by-

year fixed effects, controlling for persistent local characteristics and common state-level shocks:

$$Y_{it} = \beta D_{it} + \mu_i + \lambda_{s(i),t} + \boldsymbol{X}_{i0}^{\top}\boldsymbol{\gamma}_t + \boldsymbol{W}_{it}^{\top}\boldsymbol{\delta} + \varepsilon_{it} \quad (1)$$

Here, Y_{it} is the economic outcome for county i in year t; D_{it} is the solar-entry indicator, equal to one in the first commissioning year and thereafter and zero otherwise; and β is the coefficient on treatment in the fixed-effects regression. County fixed effects, μ_i, absorb time-invariant local characteristics. The state-by-year fixed effects are denoted by $\lambda_{s(i),t}$, where $s(i)$ identifies the state containing county i. The vector $\boldsymbol{X}_{i0}$ contains the eight baseline characteristics, with year-specific coefficient vector $\boldsymbol{\gamma}_t$. The vector $\boldsymbol{W}_{it}$ includes temperature and precipitation, $\boldsymbol{\delta}$ denotes their coefficients, and ε_{it} is the error term.

Research on staggered treatment emphasizes defining treatment-effect comparisons and aggregation in terms of treatment cohorts and event time (Goodman-Bacon, 2021; Roth et al., 2023; Sun & Abraham, 2021). To accommodate differences in entry timing and treatment effects across counties, the main identification strategy (M2) combines the group-time framework (Callaway & Sant'Anna, 2021) with the doubly robust estimator (Sant'Anna & Zhao, 2020). Treatment-probability weighting and a model for untreated outcome changes jointly estimate average treatment effects for each entry cohort in each year:

$$\widehat{ATT}^{DR}(g,t) = \sum_{i \in \mathcal{J}_{gt}} \left(\widetilde{w}_{i,gt}^{T} - \widetilde{w}_{i,gt}^{C}\right)\left[\Delta Y_{i,gt} - \widehat{m}_{0,gt}\left(\boldsymbol{X}_{i0}, \Delta \boldsymbol{W}_{i,gt}, s(i)\right)\right] \quad (2)$$

Here, g denotes the county's first solar-entry year and t is the comparison year; $\mathcal{J}_{gt}$ is the eligible sample for the corresponding group-time comparison; and $\widehat{ATT}^{DR}(g,t)$ is the doubly robust average treatment effect. The change in the outcome relative to the second year before commissioning is denoted by $\Delta Y_{i,gt} = Y_{it} - Y_{i,g-2}$, while $\Delta \boldsymbol{W}_{i,gt}$ denotes the corresponding change in weather variables. The untreated outcome change estimated using control counties is represented by $\widehat{m}_{0,gt}(\cdot)$. The terms $\widetilde{w}_{i,gt}^{T}$ and $\widetilde{w}_{i,gt}^{C}$ are the normalized treated and control weights, respectively.

Treatment probabilities are estimated from the eight baseline characteristics using inverse probability tilting (Graham et al., 2012), while the outcome-change model additionally includes weather changes and state indicators. The second year before commissioning serves as the main reference period, allowing anticipation in the year immediately before commissioning and selecting eligible controls accordingly. Effects over post-entry years 0–2 are then aggregated across the 2020–2022 cohorts using weights proportional to the numbers of treated counties. The doubly robust estimates constitute the main results, with the fixed-effects specification providing a methodological benchmark.

3.4.2. Dynamics and Persistence

Ground-mounted solar development combines long-term land use with construction activity concentrated in particular stages, potentially generating different adjustment paths for rents and employment. A dynamic event study (M3) is constructed from the group-time treatment effects to examine responses before and after entry:

$$\widehat{\theta}_k = \sum_{g \in \mathcal{G}} \omega_g \, \hat{\tau}(g, g+k), \qquad k = -4, \ldots, 2, \quad \theta_{-2} = 0 \tag{3}$$

Here, $k = t - g$ is event time relative to the first commissioning year; $\mathcal{G}$ is the set of 2020–2022 treatment cohorts; and ω_g denotes normalized cohort weights based on treated-county counts. The estimate $\hat{\tau}(g, g+k)$ is the effect for cohort g at event time k. It represents an average treatment effect after entry and a comparison of trends or anticipation relative to the reference period before entry. The aggregated dynamic effect is denoted by $\hat{\theta}_k$.

The reference period is $k = -2$. Event times $k = -4, -3$ are used to assess pre-treatment trends, $k = -1$ is used to examine anticipation, and estimates at $k = 0,1,2$ trace the post-entry dynamics of rent and employment effects.

Persistence is further examined using the 2020 and 2021 cohorts, which share a common post-treatment observation window. Post-entry years 0–1 define the early period and years 2–3 define the later period. Average effects in the two periods and their difference are estimated using the same cohorts and comparison windows, ensuring a consistent sample for comparing the persistence of rent and employment responses.

3.4.3. Spatial Spillovers

Solar-related land demand, construction activity, and labor mobility create links across counties, potentially extending economic effects to neighboring areas. A spatial exposure indicator (M4) based on shared county boundaries distinguishes exposure arising from own-county and neighboring-county entry:

$$S_{it} = \mathbb{I}\left(\sum_{j \neq i} a_{ij} \, D_{jt} > 0 \right), \qquad E_{it} = (D_{it}, S_{it}) \tag{4}$$

Here, S_{it} denotes neighboring-county solar exposure for county i in year t. The adjacency-matrix element a_{ij} equals one when counties i and j share a boundary and zero otherwise. The term D_{jt} represents the solar-entry status of neighboring county j. The function $\mathbb{I}(\cdot)$ is an indicator, and E_{it} denotes joint own-county and neighboring-county exposure.

The indicator defines four exposure states: unexposed (0,0), own-county entry only (1,0), neighboring-county entry only (0,1), and joint exposure (1,1). The group-time doubly

robust approach is applied to estimate rent and employment effects associated with own-county and neighboring-county entry, using counties that remain on an unexposed path as the comparison group.

To improve comparability across spatial effects, the analysis uses a common main post-treatment window and retains cohort comparisons with sufficient within-state controls and treated counties. Estimates for the different exposure paths characterize economic responses in host and neighboring counties, informing the spatial distribution of returns to energy investment.

3.4.4. Capacity Intensity and Nonlinearity

Land demand and economic responses may vary with the scale of solar development. Development intensity is measured by cumulative operating capacity per unit of baseline cropland. A fixed-effects restricted cubic spline specification (M5) estimates nonlinear associations between capacity intensity and economic outcomes:

$$Y_{it} = \alpha_i + \lambda_{s(i),t} + \sum_{r=1}^{R} \rho_r B_r[\ln(1 + Q_{it})] + \boldsymbol{X}_{i0}^{\top}\boldsymbol{\Gamma}_t + \boldsymbol{W}_{it}^{\top}\boldsymbol{\psi} + u_{it} \quad (5)$$

Here, Q_{it} is the ratio of cumulative operating photovoltaic AC capacity in county i and year t to its 2017 baseline cropland area, measured in MWac per 1,000 acres. The term $B_r(\cdot)$ denotes the restricted cubic spline basis function indexed by r, R is the number of basis functions, and ρ_r is the corresponding coefficient. County and state-by-year fixed effects are denoted by α_i and $\lambda_{s(i),t}$, respectively. The coefficient vectors $\boldsymbol{\Gamma}_t$ and $\boldsymbol{\psi}$ correspond to the baseline-characteristic interactions and annual weather variables, and u_{it} is the error term.

The spline uses $\ln(1 + Q_{it})$ as its argument, with knots at the 10th, 50th, and 90th percentiles of the positive capacity-intensity distribution and zero capacity as the reference for prediction contrasts. Fitted differences across intensity levels, 95% confidence intervals, and a joint test of the nonlinear terms characterize the conditional relationships between development scale, farmland rents, and local employment, extending the analysis of energy-facility land intensity and its economic implications.

3.5. Inference and Robustness

Identification relies on conditional parallel trends, common support, and a consistent definition of treatment timing. Inference is clustered at the state level to accommodate common economic shocks and temporal dependence among counties within the same state. The sample contains 43 state clusters. The dynamic event study uses 999 state-level multiplier bootstrap draws to construct 95% simultaneous confidence bands, evaluates pre-treatment trends and

anticipation through joint tests, and applies the Holm correction across multiple outcomes. Combining pre-treatment trend diagnostics with sensitivity analysis provides complementary assessments of the identifying conditions (Roth, 2022).

Robustness checks vary the control-group definition, reference year, cohort weights, post-treatment observation window, and project-capacity threshold. Alternative estimators, pre-entry placebo tests, and leave-one-state-out analyses further assess the stability of the average treatment effects.

Sensitivity analysis of trend deviations provides a complementary assessment of the parallel-trends condition (Rambachan & Roth, 2023). A bias envelope under specified linear trend deviations evaluates the main estimates across different magnitudes of departure:

$$CI(\delta) = [\hat{\tau} - c\hat{\sigma} - 3\delta,\ \hat{\tau} + c\hat{\sigma} + 3\delta] \quad (6)$$

Here, $\hat{\tau}$ is the average treatment effect over post-entry years 0–2, $\hat{\sigma}$ is its state-clustered standard error, c is the critical value for the specified confidence level, and δ is the permitted magnitude of the annual linear differential trend between treated and control counties. The main post-treatment window is, on average, three years from the $g-2$ reference period, so 3δ is used to construct the sensitivity interval.

The empirical design centers on doubly robust staggered DID, supported by fixed-effects comparisons, dynamic analysis, spatial exposure, and capacity-intensity estimation. Together, these approaches examine land market adjustment and local employment responses to utility-scale solar expansion through average effects, persistence, regional heterogeneity, and spatial transmission.

4. Results

4.1. Baseline Effects on Rents and Employment

We first examine the average effects of utility-scale ground-mounted solar entry on farmland rents and local employment. **Table 4** shows that, under the preferred doubly robust DID specification, real nonirrigated cropland cash rents increase by an average of 7.12% and private-sector employment by 1.26% over years 0–2 after commissioning; both effects are significant at the 1% level. Unadjusted DID and two-way fixed-effects estimates are also positive, indicating consistency across estimation specifications. Real average annual pay and the number of private establishments increase by approximately 0.77% and 0.78%, respectively, suggesting that solar entry is also accompanied by an expansion in labor compensation and local business activity.

These results reflect the joint effects of energy development on land and labor markets. Utility-scale solar facilities provide a long-term use for land beyond agricultural production, potentially increasing its value in alternative uses and affecting agricultural operating costs through changes in the supply of rentable land. At a reference rent of USD 65.34 per acre, a 7.12% increase corresponds to approximately USD 4.65 in additional annual rental expenditure per acre. Landowners may benefit from higher land-use values, while farmers who rely on rented land face higher production costs. At the same time, growth in employment, pay, and business activity reflects the contribution of energy investment to the local economy. Solar development therefore affects both land-use costs and local economic returns. The baseline results provide initial support for **H1** on rising farmland rents and **H2** on employment growth.

Table 4. Baseline Treatment Effects.

Estimator	(1) LnRent	(2) LnEmp	(3) LnPay	(4) LnEstab
Unadjusted Group-Time DID	0.0743*** (0.0081)	0.0154*** (0.0025)	0.0111*** (0.0013)	0.0099*** (0.0021)
DR-DID (Preferred)	0.0687*** (0.0060)	0.0125*** (0.0015)	0.0077*** (0.0008)	0.0078*** (0.0015)
TWFE Benchmark	0.0702*** (0.0050)	0.0102*** (0.0011)	0.0080*** (0.0006)	0.0075*** (0.0009)
Eligible Panel Observations	12,627	12,627	12,627	12,627
Eligible Counties	1,403	1,403	1,403	1,403
Treated Counties	186	186	186	186
Never-Treated Counties	1,217	1,217	1,217	1,217
State Clusters	43	43	43	43

Note: State-clustered SEs in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Group-time DID averages years 0–2; TWFE uses the full panel. DR-DID adjusts for baseline covariates, weather, and state indicators.

4.2. Dynamic Responses

Utility-scale ground-mounted solar projects involve long-term land use and distinct phases of construction, so farmland rents and employment may follow different time paths. **Figure 5** presents dynamic treatment effects before and after solar entry. Pre-commissioning estimates are generally close to zero. Joint tests for event years −4, −3, and −1 yield *p*-values of 0.252 for farmland rents and 0.220 for employment; year −1 is a period in which anticipatory responses may occur. After commissioning, the farmland rent effect rises gradually from 0.0534 log points in the commissioning year to 0.0812 log points in year 2. By contrast, the private-sector employment effect declines from 0.0201 to 0.0059 log points over the same period, indicating markedly different adjustment paths.

This dynamic divergence reflects the different economic characteristics of land and labor as inputs to energy development. Solar projects generally require land for an extended

period. Once land is allocated to energy production, its value in alternative uses and nearby agricultural rental conditions may remain affected, allowing farmers' land-use costs to continue adjusting after commissioning. In contrast, labor demand for engineering, equipment installation, and infrastructure construction is concentrated in the initial implementation phase. Additional labor demand gradually weakens as facilities enter stable operation.

Land market adjustment and local employment returns from solar expansion therefore do not occur on identical schedules. Long-term land use may generate persistent changes in rents, whereas employment growth associated with construction investment is more concentrated in particular project phases. These findings support **H1** on the persistent increase in farmland rents and **H2** on the gradual decline in employment effects. They also reveal a dynamic difference between land costs and local economic returns during the energy transition.

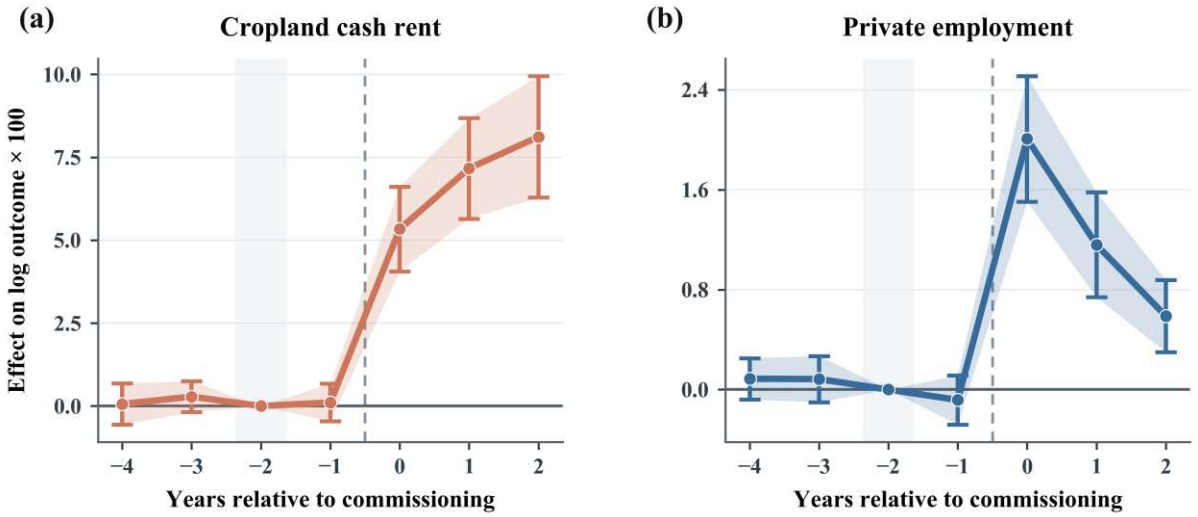


Figure 5. Dynamic treatment effects: **(a)** farmland rents; **(b)** private employment. Shading and error bars show 95% simultaneous bands for the 2020–2022 cohorts; reference year = −2. Reported *p*-values jointly test event years −4, −3, and −1.

4.3. Cohort Effects and Persistence

To examine economic responses across entry years, **Table 5** reports average treatment effects for the 2020–2022 solar entry cohorts. Farmland rent effects are 0.0679, 0.0704, and 0.0677 for the three cohorts, respectively, while private-sector employment effects are 0.0124, 0.0127, and 0.0125. Their similar signs and magnitudes indicate consistency in the main economic relationships across entry cohorts.

The persistence analysis uses the 2020 and 2021 cohorts, which share a common observation window, to compare persistence between the early and later post-commissioning periods. The farmland rent effect rises from 0.0627 in years 0–1 to 0.0838 in years 2–3, an increase of 0.0211 log points. The employment effect declines from 0.0157 to 0.0042, a

decrease of 0.0115 log points. Both differences are significant at the 1% level. These results further demonstrate that land market adjustment and local employment growth differ in persistence.

As solar facilities enter stable operation, land remains allocated to energy production, potentially creating longer-term adjustments in agricultural land use and rental markets. Local employment growth becomes more moderate as construction activity is completed. For agricultural operators, changes in rents may continue to affect production budgets and land rental decisions, whereas employment gains are more concentrated in the initial investment period. These results further support **H1** and **H2**, showing that the difference in timing between land costs and employment returns is stable across treatment cohorts.

Table 5. Cohort Effects and Persistence.

Cohort / Period	Treated Counties	(1) LnRent ATT	(2) LnEmp ATT
Cohort-Specific Effects (Years 0–2)			
2020	81	0.0679*** (0.0084)	0.0124*** (0.0027)
2021	67	0.0704*** (0.0065)	0.0127*** (0.0011)
2022	38	0.0677*** (0.0069)	0.0125*** (0.0020)
Pooled	186	0.0687*** (0.0060)	0.0125*** (0.0015)
Persistence within Common Cohorts			
Early Period (0–1)	148	0.0627*** (0.0061)	0.0157*** (0.0021)
Later Period (2–3)	148	0.0838*** (0.0088)	0.0042*** (0.0012)
Later − Early	148	0.0211*** (0.0033)	−0.0115*** (0.0014)

Note: SEs and significance as in Table 4. Persistence uses 148 treated counties (2020–2021 cohorts); difference SEs retain cross-period covariance.

4.4. Robustness Checks

We first assess baseline covariate balance between treated and control counties. **Figure 6a** shows initial differences in population density, cropland share, and rental dependence, among other characteristics. Inverse probability tilting substantially reduces the standardized mean differences in all eight baseline covariates. **Figure 6b–c** further presents farmland rent and employment effects under alternative estimation specifications, with the main results generally retaining similar signs and magnitudes. Because solar siting is closely related to local land conditions and economic structure, adjustment for baseline characteristics improves comparability between treated and control counties.

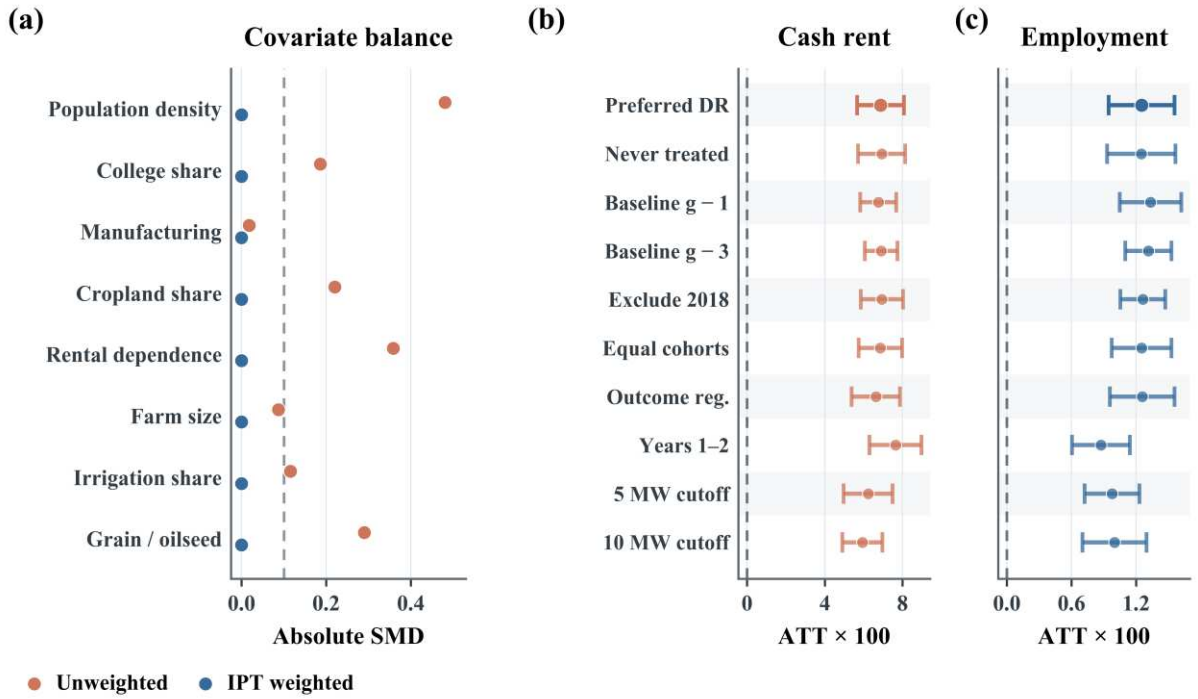


Figure 6. Covariate balance and robustness: **(a)** absolute SMDs of transformed covariates (dashed line = 0.1); **(b)** rents; **(c)** employment. Error bars show 95% pointwise intervals. "Exclude 2018" and $g - 3$ specifications use the 2021–2022 cohorts.

Table 6 examines robustness to the choice of controls, reference year, cohort weights, treatment window, and project capacity threshold. Both main effects remain positive when controls are restricted to counties that never experience entry, the reference year is changed, or alternative estimators are used. Raising the project threshold to 5 MW and 10 MW produces farmland rent effects of 0.0624 and 0.0594 and employment effects of 0.0098 and 0.0100, respectively. Pre-commissioning placebo estimates are close to zero, and the main effects remain stable when individual states are excluded. Under an annual linear trend deviation of 0.003 log points, the lower sensitivity bounds remain positive for both outcomes.

The results across estimation conditions show that the rent and employment changes following solar entry do not depend on a single project threshold, regional sample, or estimator. The consistent positive responses in land and local labor markets strengthen the empirical support for **H1** and **H2** and provide a basis for examining regional differences and spatial transmission.

Table 6. Robustness and Sensitivity.

Specification / Diagnostic	(1) LnRent	(2) LnEmp
Alternative Specifications		
Baseline DR-DID	0.0687*** (0.0060)	0.0125*** (0.0015)

Specification / Diagnostic	(1) LnRent	(2) LnEmp
Never-Treated Controls	0.0693*** (0.0060)	0.0125*** (0.0016)
No Anticipation (g − 1)	0.0676*** (0.0046)	0.0133*** (0.0014)
Earlier Baseline (g − 3; 2021–2022)	0.0690*** (0.0042)	0.0132*** (0.0011)
Excluding 2018 Baseline (2021–2022)	0.0694*** (0.0054)	0.0126*** (0.0010)
Equal Cohort Weighting	0.0687*** (0.0056)	0.0125*** (0.0014)
Outcome Regression	0.0663*** (0.0062)	0.0126*** (0.0015)
Years 1–2 after Entry	0.0764*** (0.0066)	0.0087*** (0.0013)
5 MWdc Project Threshold	0.0624*** (0.0062)	0.0098*** (0.0013)
10 MWdc Project Threshold	0.0594*** (0.0051)	0.0100*** (0.0015)
Identification Diagnostics		
Pre-Entry Joint Test (−4, −3, −1), p	0.252	0.220
Holm-Adjusted Joint-Test p	0.659	0.659
Pre-Entry Placebo ATT	−0.0003 (0.0030)	−0.0004 (0.0007)
Linear Trend-Bias Bound (δ = 0.001)	[0.0537, 0.0838]	[0.0065, 0.0186]
Linear Trend-Bias Bound (δ = 0.003)	[0.0477, 0.0898]	[0.0005, 0.0246]
Leave-One-State-Out ATT Range	0.0629—0.0703	0.0111—0.0132
Maximum Leave-One-State-Out p	<0.001	<0.001

Note: Inference as in Table 4. The 2021–2022 variants use 105 candidate treated counties; higher thresholds exclude prior small-project entrants. Holm covers five outcomes. Placebo: g − 4 vs. g − 2; bounds: Equation (6); leave-one-state-out: 43 states.

4.5. Construction and Local Economic Activity

Solar investment involves engineering, equipment installation, and related services, with local economic effects emerging through different industries and business activities. **Figure 7** presents dynamic responses in construction employment, real average annual pay, and the number of private establishments. Construction employment increases markedly around commissioning and subsequently declines, whereas real average annual pay and establishment counts adjust more gradually and retain positive effects in later years. These differences reflect the concentrated labor demand associated with construction and the more gradual adjustment of other local economic activities.

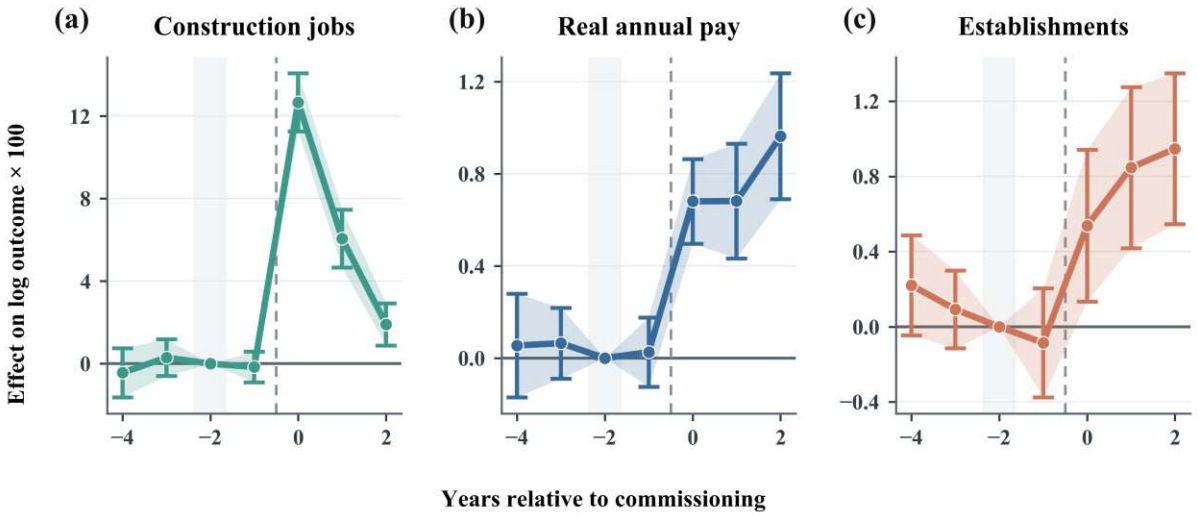


Figure 7. Dynamic local economic responses: **(a)** construction employment; **(b)** real average annual pay; **(c)** private establishments. Cohorts, reference year, simultaneous 95% bands, and joint-test definitions follow Figure 5.

Table 7 shows an average construction employment effect of 0.0688 in years 0–2 after commissioning, corresponding to approximately 7.12% growth, substantially above the relative increase in total private-sector employment over the same period. Within the common treatment cohorts, the construction employment effect declines from 0.0941 in the early period to 0.0133 in the later period, a difference of −0.0807 log points. Meanwhile, the effect on real average annual pay increases from 0.0064 to 0.0091, and the effect on private establishment counts rises from 0.0076 to 0.0116.

The initial expansion and subsequent decline in construction employment indicate that renewable energy investment creates concentrated demand for construction labor, while pay and business activity follow different persistence patterns. In counties with equipment installation, engineering services, and supporting industrial capabilities, solar construction may also stimulate related businesses through procurement and supply-chain links. Local economic returns therefore extend beyond the number of additional jobs to changes in labor compensation and business activity. These results provide further support for **H2** on the phase-specific nature of employment effects.

Table 7. Local Economic Responses.

Estimate / Period	(1) Construction Employment	(2) Real Annual Pay	(3) Establishments
Average ATT (0–2)	0.0688*** (0.0047)	0.0077*** (0.0008)	0.0078*** (0.0015)
Anticipation Period (−1)	−0.0016 (0.0030)	0.0003 (0.0006)	−0.0009 (0.0011)
Early Period (0–1)	0.0941*** (0.0058)	0.0064*** (0.0007)	0.0076*** (0.0017)
Later Period (2–3)	0.0133*** (0.0049)	0.0091*** (0.0010)	0.0116*** (0.0018)
Later − Early	−0.0807*** (0.0040)	0.0028*** (0.0007)	0.0039*** (0.0008)
Joint-Test p (−4, −3, −1)	0.081	0.750	0.161
Holm-Adjusted Joint-Test p	0.406	0.750	0.643
Treated Counties	186	186	186
Common-Cohort Treated Counties	148	148	148

Note: Log outcomes; inference as in Table 4. Early/later comparisons use the 2020–2021 cohorts and retain covariance. Joint tests include year −1; Holm covers five outcomes.

4.6. Heterogeneity Analysis

The economic effects of utility-scale solar development also depend on existing land resources and industrial structure. **Figure 8** compares counties with different levels of rental dependence, cropland share, manufacturing employment share, and pre-project cropland cover. Rent responses are stronger where agricultural land use is more concentrated and rental dependence is higher, while employment growth is greater where the manufacturing base is stronger. These patterns link the economic effects of renewable energy investment to the structure of local land markets and industrial conditions.

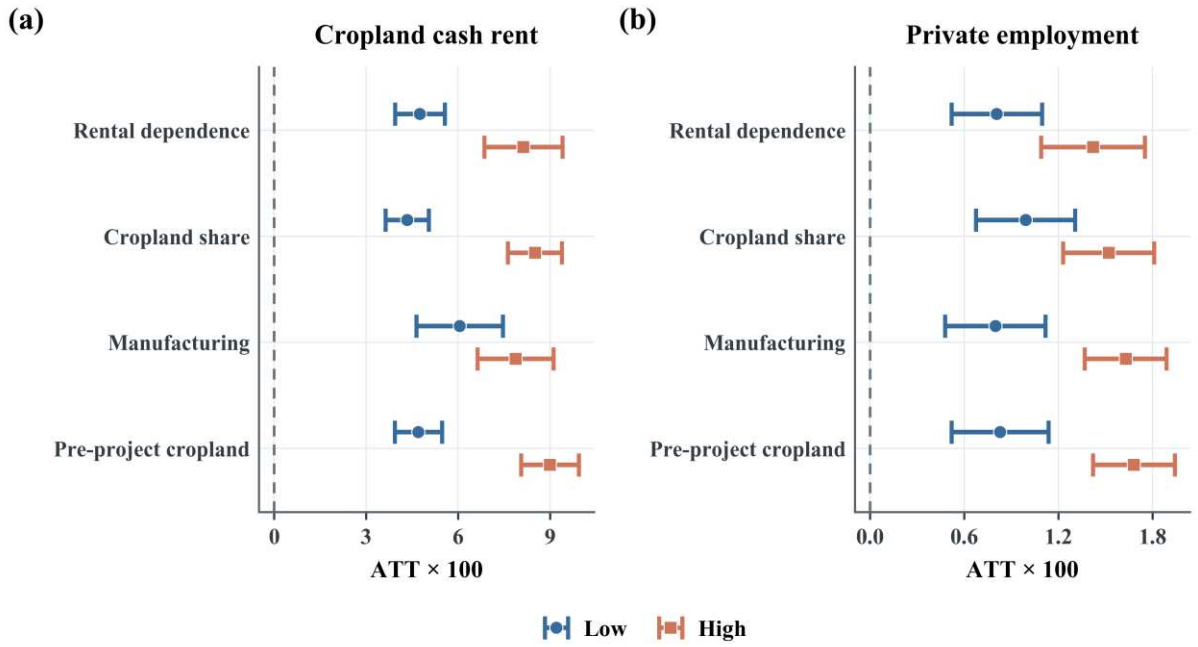


Figure 8. Heterogeneous treatment effects: **(a)** farmland rents; **(b)** private employment. Blue/red denote low/high groups; error bars show 95% state-clustered pointwise intervals. Independent splits use sample medians, except project cover, which uses the treated-county median.

Table 8 further reports subgroup estimates and between-group differences. The rent effect is 0.0813 in counties with high rental dependence, compared with 0.0475 in the low-dependence group. It reaches 0.0851 in the high-cropland-share group, compared with 0.0434 in the low-share group. Counties with greater pre-project cropland cover have a rent effect of 0.0900, also above the 0.0471 estimate for the low-cover group. All corresponding between-group differences are statistically significant. Where agricultural rental markets are more active and land is more intensively used for farming, cash rents may more readily reflect land-use competition arising from solar development. For farmers who rely on rented land, these differences indicate that the impact of energy development on land costs varies substantially across regions.

For employment, the treatment effect is 0.0163 in counties with a stronger manufacturing base, compared with 0.0080 in those with a weaker base, a difference of 0.0083 log points. A stronger industrial base may improve local capacity to benefit from energy investment through equipment installation, material supply, and related services. Land resource conditions thus influence the magnitude of rent adjustment, while industrial structure shapes local employment returns. These results support **H3** on heterogeneity by land and industrial structure and indicate that renewable energy siting should account for both agricultural land conditions and local industrial development.

Table 8. Heterogeneous Effects.

Outcome / Statistic	Low ATT	High ATT	High − Low	Difference p-value
Rental Dependence				
LnRent	0.0475*** (0.0040)	0.0813*** (0.0063)	0.0338 (0.0070)	<0.001
LnEmp	0.0081*** (0.0014)	0.0142*** (0.0016)	0.0061 (0.0021)	0.006
Candidate Treated Counties	74	112	—	—
Cropland Share				
LnRent	0.0434*** (0.0035)	0.0851*** (0.0044)	0.0417 (0.0054)	<0.001
LnEmp	0.0099*** (0.0016)	0.0152*** (0.0014)	0.0053 (0.0024)	0.032
Candidate Treated Counties	75	111	—	—
Manufacturing Share				
LnRent	0.0605*** (0.0070)	0.0787*** (0.0062)	0.0182 (0.0069)	0.012
LnEmp	0.0080*** (0.0016)	0.0163*** (0.0013)	0.0083 (0.0017)	<0.001
Candidate Treated Counties	93	93	—	—
Pre-Project Cropland Cover				
LnRent	0.0471*** (0.0038)	0.0900*** (0.0047)	0.0429 (0.0056)	<0.001
LnEmp	0.0083*** (0.0015)	0.0168*** (0.0013)	0.0085 (0.0017)	<0.001
Candidate Treated Counties	93	93	—	—

Note: Inference as in Table 4. Cutoffs (in group order): 0.362, 0.225, 0.147, 0.703. Counts precede support checks; the pre-project cropland cover groups share 1,217 controls. Difference SEs retain shared-control covariance; p-values are unadjusted.

4.7. Spillovers to Neighboring Counties

Utility-scale solar development may affect neighboring areas through land rental demand, construction activity, and labor mobility. **Figure 9a** shows spatial exposure across selected Midwestern U.S. counties, while **Figure 9b–c** compares rent and employment effects under ordinary entry, own-only entry, and neighbor-only entry paths. Links between county land markets and labor mobility may extend a project's economic effects beyond its host county, changing land-use costs and employment opportunities in nearby areas.

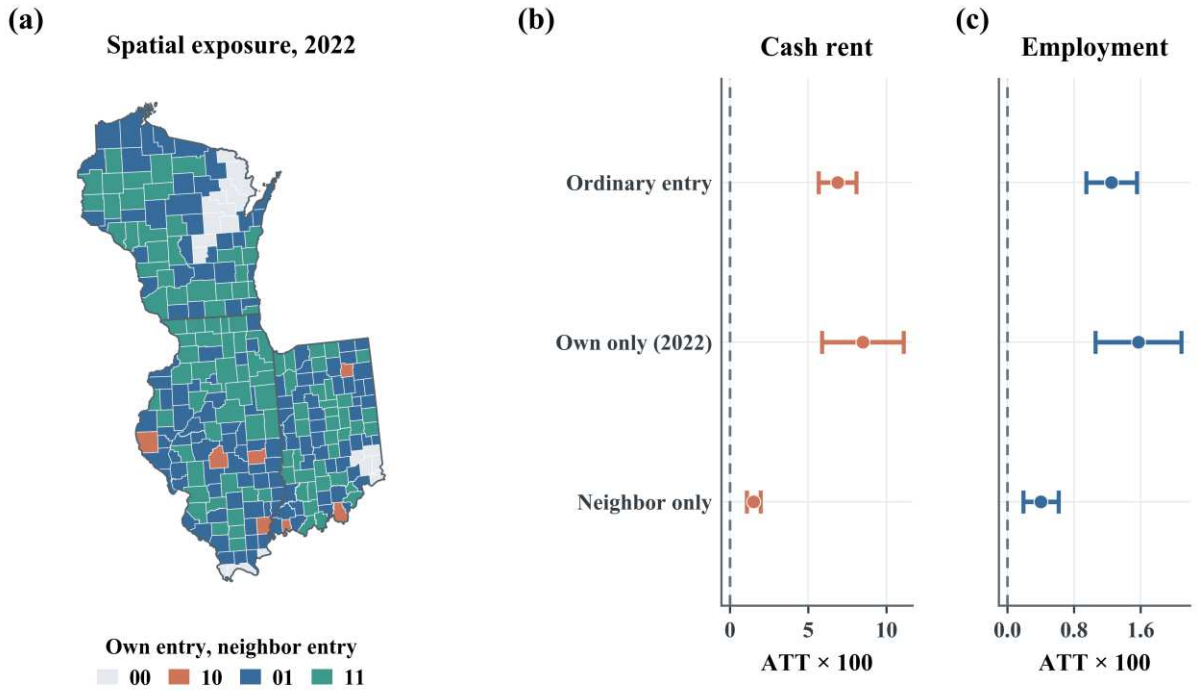


Figure 9. Local and neighboring-county effects: **(a)** 2022 exposure states in Illinois, Indiana, and Wisconsin (own, neighboring); **(b)** rent and **(c)** employment ATT with 95% state-clustered intervals. Paths have different target populations; own-only estimates use seven counties.

Table 9 shows farmland rent and employment effects of 0.0152 and 0.0040 under the strict neighbor-only entry path, corresponding to increases of approximately 1.53% and 0.40%, respectively; both are statistically significant. Under the own-only entry path, the rent and employment effects are 0.0849 and 0.0157. These estimates are based on seven eligible treated counties in the 2022 cohort and provide a supplementary comparison across spatial exposure paths. Positive neighboring-county responses suggest that land demand and economic activity arising from energy development may spread through regional factor markets.

These spatial links imply that land costs and economic returns may be distributed across different counties. Host counties accommodate direct land requirements, while surrounding areas may be affected through labor supply, construction services, or agricultural rental-market links. Employment returns and changes in land costs within an individual county may therefore not align fully. These findings support **H4** on positive spillovers to neighboring counties and highlight the importance of coordinating energy facility siting and land resources across county boundaries.

Table 9. Local and Neighboring-County Effects.

Outcome / Statistic	(1) Ordinary Entry	(2) Own Only	(3) Neighbor Only
	Log Farmland Rent		
ATT	0.0687***	0.0849***	0.0152***
	(0.0060)	(0.0130)	(0.0021)
	Log Private Employment		
ATT	0.0125***	0.0157***	0.0040***
	(0.0015)	(0.0026)	(0.0011)
Treated Counties	186	7	153
Supported Cohorts	2020–2022	2022	2020–2022

Note: ATT averages years 0–2; inference as in Table 4. Clean paths exclude the other exposure through g + 3 and use unexposed controls. Own-only estimates (seven counties) are exploratory; target populations and controls differ across paths.

4.8. Capacity Intensity and Nonlinear Relationships

Beyond whether a solar project enters a county, the scale of development may shape the extent of land market and local economic adjustment. **Figure 10** presents nonlinear relationships between installed capacity per unit of baseline cropland and farmland rents and private-sector employment. Fitted differences in both outcomes increase over the low-to-moderate intensity range, then level off and decline somewhat at higher intensities. This pattern indicates nonlinear links between the scale of solar development and land and labor markets.

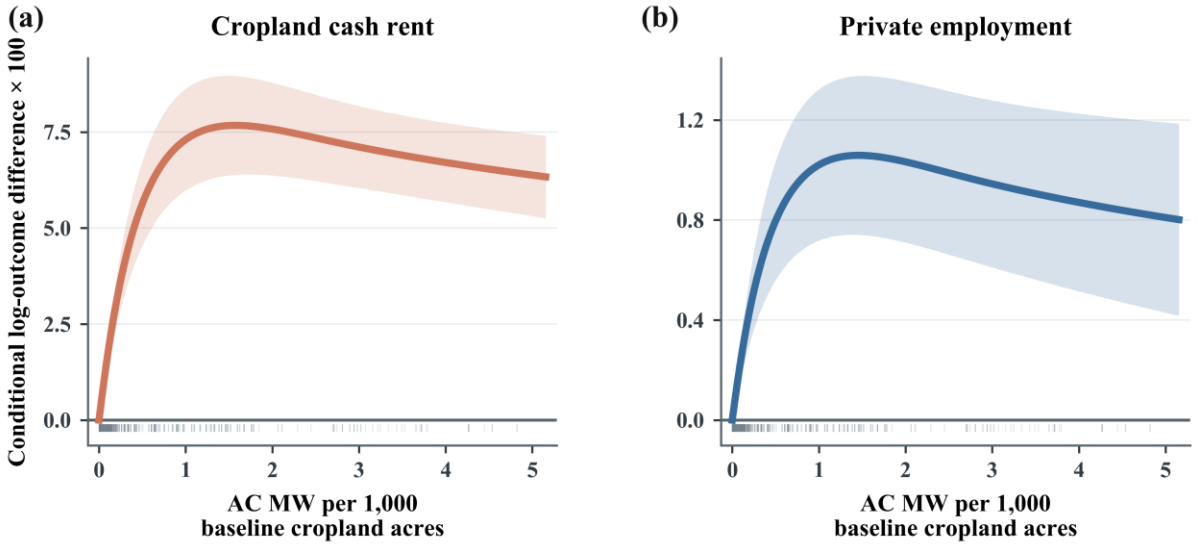


Figure 10. Capacity intensity and economic outcomes: **(a)** farmland rents; **(b)** private employment. Curves show conditional associations relative to $Q = 0$, with 95% state-clustered pointwise intervals. Splines use $\log(1 + Q)$, plotted on the Q scale through the positive-intensity P95; rugs mark positive observations.

Table 10 reports estimates at the 10th, 50th, and 90th percentiles of capacity intensity. Relative to zero installed capacity, the conditional log differences in farmland rents are 0.0013, 0.0181, and 0.0721, respectively; the corresponding employment differences are 0.0002, 0.0026, and 0.0096. Both joint tests of nonlinearity yield p-values below 0.001. The

associations of installed capacity with land demand and local economic activity strengthen as capacity intensity increases, but the rate of increase becomes more moderate at higher intensities.

These findings reflect different responses of land and labor markets to the scale of energy development. Larger solar facilities typically require more land allocation, while local employment growth also depends on construction phases, operating requirements, and the capacity of local industries to accommodate investment. Expanding installed capacity therefore need not generate proportional employment growth. The nonlinear relationships between development intensity and economic outcomes further indicate that renewable energy planning should account for land supply, agricultural operating conditions, and local industrial structure. This analysis provides supplementary associational evidence related to **H1** and **H2** from the perspective of development scale and deepens the understanding of energy development and land resource allocation.

Table 10. Capacity Intensity and Nonlinear Associations.

Capacity Level / Statistic	MWac per 1,000 Acres	(1) LnRent	(2) LnEmp
P10	0.0069	0.0013 [0.0010, 0.0015]	0.0002 [0.0001, 0.0002]
P50	0.1067	0.0181 [0.0144, 0.0217]	0.0026 [0.0018, 0.0033]
P90	2.7697	0.0721 [0.0613, 0.0830]	0.0096 [0.0063, 0.0129]
Nonlinearity Test, p	—	<0.001	<0.001
County FE	—	Yes	Yes
State × Year FE	—	Yes	Yes
Baseline Controls × Year	—	Yes	Yes
Weather Controls	—	Yes	Yes
Observations	—	12,627	12,627
Counties	—	1,403	1,403
Positive-Intensity County-Years	—	787	787

Note: Conditional associations relative to Q = 0; brackets show 95% state-clustered intervals. Knots: P10, P50, and P90 of positive log(1 + Q).

5. Discussion

5.1. Land Costs and Local Returns

This study reveals different adjustment paths for land markets and local employment during utility-scale solar expansion. The farmland rent effect strengthens with time since commissioning, whereas employment growth is concentrated in the initial years and subsequently weakens. This difference is closely related to the distinct characteristics of land

and labor inputs in energy development. Solar facilities typically require long-term land use, which may persistently change the value of alternative land uses and agricultural leasing conditions, while labor demand for construction and equipment installation is more concentrated. Land costs and employment gains therefore follow different adjustment paths, and understanding local economic effects requires considering the responses of both factor markets.

The estimated average increases in farmland rents and employment are 7.12% and 1.26%, respectively. At a reference rent of USD 65.34 per acre, the rent effect corresponds to approximately USD 4.65 per acre annually. A higher value of land use may increase landowners' returns while raising production costs for agricultural tenants. Employment growth benefits the local economy through labor demand and related business activity. The initial expansion in construction employment, together with subsequent changes in real annual pay and the number of establishments, further illustrates the varied timing and forms of energy investment benefits. These findings indicate that the local economic value of solar development depends on investment scale, land costs, employment persistence, and the distribution of returns among economic actors.

5.2. Spatial Planning and Land Governance

Land resources and the existing industrial base jointly shape the local economic effects of utility-scale solar development. Counties with greater dependence on rented land, higher cropland shares, and more cropland cover before project development exhibit stronger farmland rent responses. This pattern indicates that agricultural land use and leasing arrangements influence land competition during renewable energy development. Changes in land use may affect agricultural operating costs more directly where rented farming is prevalent. Counties with a stronger manufacturing base experience larger employment gains, highlighting the importance of local supply chains and the capacity of labor markets to capture investment benefits. Solar siting should therefore account for regional land endowments and industrial conditions to coordinate land allocation between energy development and agricultural production.

The spatial exposure results further suggest that the economic effects of solar development can extend beyond the host county. Solar entry in neighboring counties is positively associated with farmland rents and employment, consistent with transmission through land leasing, construction activity, and labor market connections. Host counties and surrounding areas may consequently face different land costs and receive different forms of

economic benefits. This spatial pattern means that energy siting concerns both local land-use efficiency and the regional allocation of land resources, industrial activity, and employment opportunities. Coordination across county boundaries in land governance and infrastructure is therefore an important component of aligning renewable energy expansion with local economic development.

5.3. Policy Implications

First, solar siting should be coordinated more closely with agricultural land-use planning. Project assessments should incorporate land cover before development, cropland availability, and agricultural leasing conditions. Subject to energy development and grid connection requirements, planners should prioritize comparisons of available sites with fewer conflicts with agricultural production and coordinate the space allocated to solar facilities and farming. In areas with high dependence on rented land, attention should be given to changes in agricultural cash rents around projects. Long-term land-use negotiations, disclosure of leasing information, and arrangements that coordinate agricultural operators' interests can improve the distribution of energy development benefits and agricultural land-use costs.

Second, renewable energy investment should deliver stronger long-term local economic returns. Local governments can align training in construction, equipment maintenance, and related technical skills with project construction and operating needs. Supporting local firms' participation in engineering services and supply chains can connect construction-stage employment opportunities with sustained industrial activity. Given the transmission of land market and employment effects across county boundaries, neighboring jurisdictions can also coordinate project siting, agricultural land protection, workforce training, and infrastructure development. Integrating land allocation with local industrial development can improve the overall economic benefits of energy investment and support sustainable regional land use.

6. Conclusions

Utility-scale solar expansion reshapes agricultural land markets and local economic activity, with effects that differ in timing and persistence. Evidence from 1,403 U.S. counties during 2016–2024 indicates that solar entry increases real cropland cash rents by an average of 7.12% and private-sector employment by 1.26% during the commissioning year and the following two years. Rent effects become stronger over time, whereas employment gains are concentrated around commissioning and gradually diminish. The pronounced initial response

in construction employment further reflects the stage-specific labor demand associated with solar investment.

Local land and industrial conditions also shape these economic responses. Rent increases are more pronounced in counties with greater dependence on rented farmland, higher cropland shares, and more extensive pre-development cropland cover. Employment gains, meanwhile, are stronger in counties with established manufacturing bases, highlighting the importance of local industrial capacity in capturing investment benefits. Positive spillovers to neighboring counties further suggest that land market adjustments and employment opportunities extend beyond project locations, creating spatial differences in the distribution of economic costs and returns.

Overall, the divergent dynamics of farmland rents and employment highlight the importance of balancing renewable energy development with agricultural land-use needs and long-term local economic benefits. Integrating solar siting decisions with farmland protection, equitable leasing arrangements, workforce development, and regional coordination can promote more sustainable land allocation. Future research incorporating parcel-level lease contracts and firm-level employment records could further clarify how the economic benefits of solar expansion are distributed among landowners, agricultural operators, and local communities.

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