

Solar photovoltaic adoption and poverty alleviation: experience from rural China

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ONLINE APPENDIX

A. The scale of PPAPs by different solar resource areas and station types

There are four types of PPAP power stations in China: household, village, joint-village, and centralized. The household PPAPs (of scale about 3–5 kW) are generally built on roofs of households or in open yards, with their property rights and profits all owned by households. The village (of scale about < 300 kW) and joint-village PPAPs (of scale < 6000 kW) are usually built on vacant lands or barren hills of each village or between villages; the property rights are owned by villages. The power generation income is part of the collective economy of villages and is allocated to poor households. The centralized PPAPs (with larger PV scale and different grid connection modes) are generally established on large areas of vacant land or barren hills in a county, and built by joint ventures between enterprises and the government. The profits are distributed according to the investment proportion, with part donated to poor villages. Overall, centralized and village-level PV plants are operated and maintained by commercial investment enterprises in cooperation with government-appointed PV enterprises and financing institutions. The daily PV maintenance of household PV systems is technically less difficult, poor households can participate in the cleaning and maintenance of PV modules through public service positions set up by village collectives after receiving training.

In this study, we consider the household, village, and joint-village PV power stations as distributed PV and the centralized power stations as centralized PV based on their average project construction scale per household. For village-level PV stations (including household), the corresponding project scale for each poverty alleviation target is about 5 kW; For centralized PV stations, it is about 25 kW (NEA of China, 2014).

Table A1. The scale of PPAPs by different solar resource areas

Solar resource areas	Power station types	Construction scale (MW)	Poverty alleviation scale (MW)	Number of helped poor households (thousand)	Construction scale per household (kW)	Poverty alleviation scale per household (kW)
I	Household	1.70	1.70	0.57	3.00	3.00
	Village	59.95	59.95	12.32	4.87	4.87
	Joint-village	343.43	343.43	57.16	6.01	6.01
	Centralized	253.00	72.14	10.31	24.55	7.00
II	Household	45.57	45.57	12.43	3.67	3.67
	Village	547.75	547.75	93.40	5.86	5.86
	Join-village	2,416.23	2,416.23	411.24	5.88	5.88
	Centralized	2,580.97	704.43	102.74	25.12	6.86
III	Household	458.25	458.25	126.01	3.64	3.64
	Village	3,357.10	3,357.10	821.77	4.09	4.09
	Joint-village	3,828.23	3,828.23	764.12	5.01	5.01
	Centralized	7,885.82	2,240.11	333.91	23.62	6.71
Sum		21,778.01	14,074.89	2,745.99	115.30	62.58

Notes: The table are collected and calculated by the authors from the website of the NEA of China. By matching the solar resource area with the county code of PPAPs, we accounted for the construction and poverty alleviation details of PPAPs by different resource areas. Poverty alleviation scale refers to capacity designated for poverty targeting. Revenue calculations use this metric exclusively. Unlike village- or household-level distributed systems, whose entire installed capacity is used for poverty alleviation, centralized PPAP projects involve a higher level of participation from social enterprises. A significant portion of the electricity revenues is retained by these enterprises, with only a small share allocated for poverty alleviation (NEA of China, 2018).

B. Variables descriptive statistics and the three batches of PPAP subsidies catalogue

Table A2. Descriptive statistics

Panel A: Variable descriptive statistics						
Variables	Mean	Std. Dev.	p25	Median	p75	N
Rural per capita income (thousand yuan)	5.93	0.25	3.68	5.15	6.94	5,086
PPAPs implementation (Dummy)	0.15	0.36	0	0	0	5,086
Industrial structure (%)	0.45	0.17	0.33	0.45	0.57	5,086
Fiscal expenditure-to-revenue ratio (%)	5.85	5.19	2.64	4.38	6.97	5,086
Sunlight hours (h)	2347.26	2368.59	2094.19	2337.78	2591.32	5,086
Grain production (Thousand t)	289.33	368.33	83.26	173.57	338.00	5,086
Education level (%)	0.12	0.07	0.09	0.11	0.13	5,086
Panel B: Three batches of subsidies catalogue of PPAPs published by the government						
Power station types	Number of power stations	Constructi on scale (MW)	Poverty alleviation scale (MW)	Number of helped poor households (Thousand)	Poverty alleviation scale per household (kW)	
Household	137,506	505.52	505.52	139.01	3.62	
Village	32,999	3,964.80	3,964.80	927.49	6.55	
Joint-village	8,618	6,587.89	6,587.89	1,232.52	7.63	
Centralized	530	10,719.79	3,016.68	446.96	6.85	
Sum	179,653	21,778.00	14,074.89	2,745.98	5.13	

Notes: Panel A presents averages and t-value for a test of the equality between the two groups for all variables in the sample (treatment and control groups). The treatment group refers to counties that implement PPAPs, while the control group refers to other counties in the same province that do not implement PPAPs. Panel B presents the statistical information on the three batches of PV subsidy catalogue data for PPAPs.

C. Balance test and robustness tests

Table A3. Balance test (Baseline year)

	Control group (1)	Treatment group (2)	Diff. (3)	Cond. Diff. (4)
<i>Panel A. Selection criteria</i>				
The logarithm of GDP	13.336 (0.045)	12.499 (0.065)	0.838*** (0.000)	
Fiscal expenditure-to-revenue ratio (%)	3.896 (0.146)	8.538 (0.547)	-4.643*** (0.000)	
Sunlight hours (h)	2341.428 (21.1)	2430.698 (25.3)	-89.270*** (0.010)	
<i>Panel B. County characteristics</i>				
Industrial structure (%)	0.504 (0.010)	0.404 (0.013)	0.100*** (0.000)	-0.011 (0.016)
Grain production (Thousand tons)	12.066 (0.077)	11.729 (0.103)	0.337*** (0.010)	0.025 (0.122)
Education level (%)	0.141 (0.006)	0.133 (0.004)	0.008 (0.393)	0.002 (0.010)

Notes: Table A3 presents county-level characteristics for treated counties and untreated counties (columns 1 and 2) in the baseline year. Columns 3 and 4 report the unconditional and conditional differences (on selection criteria variables and province fixed effects) and p-values (in parentheses) between the treatment and control groups.

Table A4. Robustness check

Dependent variable: Log (Rural per-capita disposable income)		
Specifications	DID	PSM-DID
PPAPs implementation (Dummy)	0.049*** (0.007)	0.048*** (0.009)
Industrial structure (%)	0.077** (0.029)	0.057 (0.037)
Fiscal expenditure-to-revenue ratio (%)	-0.306 (0.172)	-0.394 (0.211)
Log (Sunlight hours)	0.169*** (0.025)	0.205*** (0.040)
Log (Grain production)	0.016* (0.008)	0.017* (0.007)
Education level (%)	-0.006 (0.017)	0.053 (0.097)
Fiscal expenditure-to-revenue ratio	0.000	0.000
*Time trend	(0.000)	(0.000)
County FE	Y	Y
Year FE	Y	Y
N	5,071	3,670
With-in R^2	0.897	0.860

Notes: Coefficients for constants are not reported. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Robust standard errors in parentheses are clustered at the county level.

Table A5. Robustness tests

Panel A: Altering the control group with non-poverty-stricken counties		
	Observations	Coefficients on PPAPs implementation (Dummy)
No control variables	4,577	0.056*** (0.008)
Including all control variables	4,577	0.054*** (0.008)
Panel B: Excluding other confounding control observations		
	Observations	Coefficients on PPAPs implementation (Dummy)
No control variables	4,041	0.054*** (0.006)
Including all control variables	4,041	0.052*** (0.006)
Panel C: Replacing the control group with “Not Yet Treated” group.		
	2,807	0.040** (0.014)
	2,807	0.041** (0.014)
Panel D: Bacon Decomposition		
	Weight	Estimate
Earlier Treated vs. Later Control	0.018	−0.004
Later Treated vs. Earlier Control	0.014	−0.010
Treated vs. Never Treated	0.968	0.040
Difference-in-Difference		0.038
Panel E: Driscoll and Kraay (1998) standard errors		
	Observations	Coefficients on PPAPs implementation (Dummy)
No control variables	5,086	0.053*** (0.009)
Including all control variables	5,086	0.052*** (0.009)
Panel F: A permutation test by randomly assigning treatment groups		
Observed β	Simulated $\beta > \text{Observed } \beta$	Number of Randomization Iterations
0.052	0	500

Notes: All control variables and two-way fixed effects in column 3 of Table 2 are controlled in the second rows of Panel A, Panel B, and Panel D of Table A5. Panel C reports the three components of Bacon Decomposition results: Among them, the later Control counties are used as controls for earlier treated counties; the earlier Control counties are used as controls for later treated counties. The Bacon decomposition is not able to include covariates at present, thereby we do not incorporate controls in the model of Panel C. Standard errors in parentheses are clustered at the county level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A6. Placebo test

Dependent variable: Log (Rural per-capita disposable income)		
Specifications	(1)	(2)
Panel 1: Assume 2009–2011 had PV policy implementation, the sample period is up to 2014		
PPAPs implementation (Dummy)	–0.003 (0.007)	–0.011 (0.006)
Control variables	N	Y
County FE	Y	Y
Year FE	Y	Y
N	3,095	3,095
Within R^2	0.000	0.104
Panel 2: Assume 2010–2012 had PV policy implementation, the sample period is up to 2014		
PPAPs implementation (Dummy)	–0.001 (0.006)	–0.006 (0.006)
Control variables	N	Y
County FE	Y	Y
Year FE	Y	Y
N	3,095	3,095
Within R^2	0.000	0.102
Panel 3: Assume 2011–2013 had PV policy implementation, the sample period is up to 2014		
PPAPs implementation (Dummy)	0.010 (0.006)	0.004 (0.005)
Control variables	N	Y
County FE	Y	Y
Year FE	Y	Y
N	3,095	3,095
Within R^2	0.001	0.102

Notes: Standard errors are clustered at the county level in parentheses. Coefficients for constants are not reported. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

D. Cost-benefit calculations

Table A7. PV electricity price and subsidy in different solar resource areas for PPAPs

PV types	Solar resource area	2014	2015	2016	2017	2018	2018.05	2019.07	2020.06
Centralized PV	I	1	0.9	0.8	0.65				
(Benchmarking	II	1	0.95	0.88	0.75				
Feed-in Tariff)	III	1	1	0.98	0.85				
Distributed PV	Equal in								Remain unchanged
(subsidies for	all solar	0.42	0.42	0.42	0.42				
residents)	regions								

Notes: According to the annual equivalent utilization hours, China can be divided into three types of solar resource areas. Class I area refers to areas where the annual equivalent utilization hours exceed 1,600 hours. 1,400–1,600 hours are classified as class II areas, and 1,200–1,400 hours are classified as class III areas (NEA, 2020). In this paper, the number of annual effective sunshine hours is set to 1,600, 1,300, and 1,100 hours respectively for calculation (MOF of China, 2020).

Table A8. Households' revenue from PPAPs

Types of PV	Electricity consumption modes	Calculation methods	Revenue (billion yuan)
Centralized PV	All for the national grid	$Q_C \times P_C$	2.86
	Mode 1: All for self-use	$(P_1 + S_1) \times Q_D$	12.35
Distributed PV	Mode 2: Spontaneous self-use, surplus for the national grid	$P_1 \times Q_1 + P_2 \times Q_2 + S_1 \times Q_D$	
	Mode 3: All for the national grid	$(P_2 + S_1) \times Q_D$	10.32
Sum			13.12–15.21

Notes: Different areas use different benchmarking electricity prices by solar resource areas. P_C is the benchmarking feed-in tariff of centralized PV price as shown in Table A7. Q_C and Q_D are the total amount of power generated by centralized PV and distributed PV respectively, which are obtained by multiplying generation hours and the installed size of PV power generation for poverty alleviation. Q_1 and Q_2 are the total amount of residential self-use PV power generation, and the total amount of remaining grid-connected PV power generation respectively, which are also obtained by a similar calculation. P_1 is the local residential electricity price using the national average residential electricity price, i.e. 0.542 yuan /kWh (State Grid, 2020). P_2 is the on-grid electricity price using the average nationwide on-grid electricity price for desulfurized coal-fired power, i.e. 0.37 yuan /kWh. S_1 is the subsidies to distributed PV, i.e. 0.42 yuan /kWh as shown in Table A7.

Table A9. The environmental costs and benefits of PPAPs based on the existing research

Resource	Types of PV	Evaluation object	Results (costs)	Environmental costs of PPAPs (billion yuan)	
				China carbon price (50 yuan/t)	EU carbon price (100 euro/t)
(Peng <i>et al.</i> , 2013)	Thin film PV systems	CO ₂	10.5–50 g CO ₂ eq./kWh	0.009–0.041	0.129–0.617
	Mono-Si PV systems	CO ₂	29–45 g CO ₂ eq./kWh	0.024–0.037	0.358–0.555
(Kumar <i>et al.</i> , 2020)	100 MW	CO ₂	15.6 g CO ₂ /kWh	0.013	0.192
Resource	Types of PV	Evaluation object	Results (benefits)	Environmental benefits of PPAPs (billion yuan)	
				China carbon price (50 yuan/t)	EU carbon price (100 euro/t)
(Green Peace, 2017)		CO ₂	0.067 yuan/kWh	1.103	16.524
		Environmental benefit	0.096 yuan/kWh	1.581	

Notes: Table A9 calculates the environmental costs and benefits of PPAPs using the electricity generated by PV plants from the three batches of PPAP subsidy catalogue data and the environmental costs and benefits per unit of PV panels derived from existing studies. Among them, the external CO₂ costs and benefits of PPAPs are calculated using the current carbon price of 50 yuan/t in China's carbon trading market and the EU carbon price of 100 euro/t, respectively. The external environmental benefit of PPAPs, which includes external environmental impacts such as PM_{2.5}, SO₂, NO_x, dust emissions, and CO₂ emissions from coal production, transportation, and coal-fired power generation, is calculated based on the result of 0.096 yuan/kWh from Green Peace (2017).

E. Figures

E1. The operation process of PPAPs

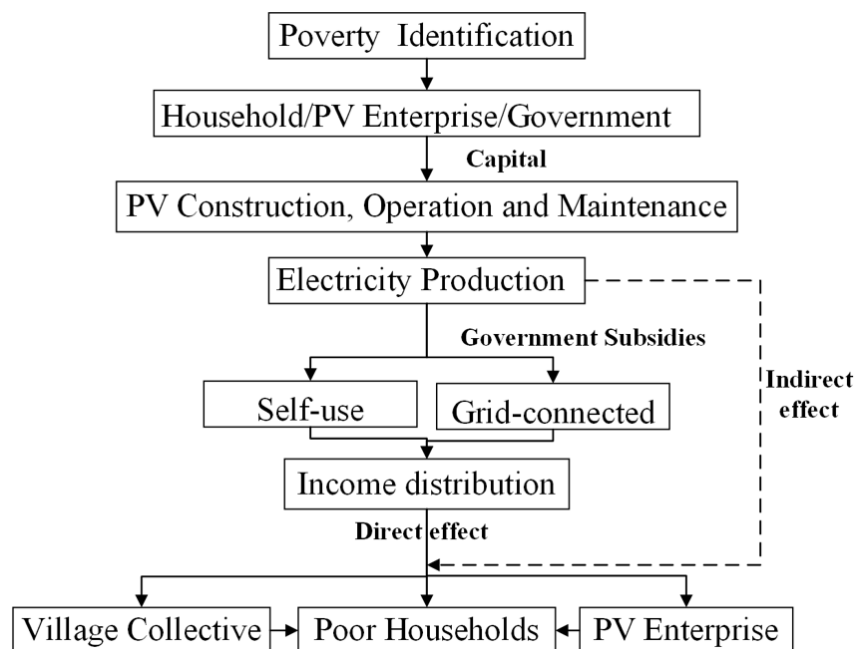


Figure A1. Operation process of PPAPs.

Notes: The first step of PPAPs is to identify poverty alleviation targets according to the nationally registered poor villages and poor households. Then it is to carry out targeted PPAPs on a voluntary basis, mainly by generating electricity for self-use or selling excess electricity to the grid or providing certain public service jobs. The Chinese government has set higher electricity price subsidy quotas for distributed and centralized PPAPs than for general PV power generation projects. The subsidy amount has remained unchanged since 2017. Indirect effect denotes unobservable welfare effects such as increased productivity and improved quality of life due to PV-generated electricity. PPAPs have generated a variety of income distribution mechanisms according to different investment and financing methods. PV enterprises participating in investment and construction will get a certain income and donate part of the income for poverty alleviation. Local governments (including village collectives) will also receive profits, part of which will be used as village collective funds to set up public welfare positions, public welfare undertakings, incentive bonus, emergency funds, PV maintenance, etc., and the other part will be directly distributed to poor households. The general property rights and income of household solar PV are directly owned by poor households.

E2. The regional distribution of PPAPs

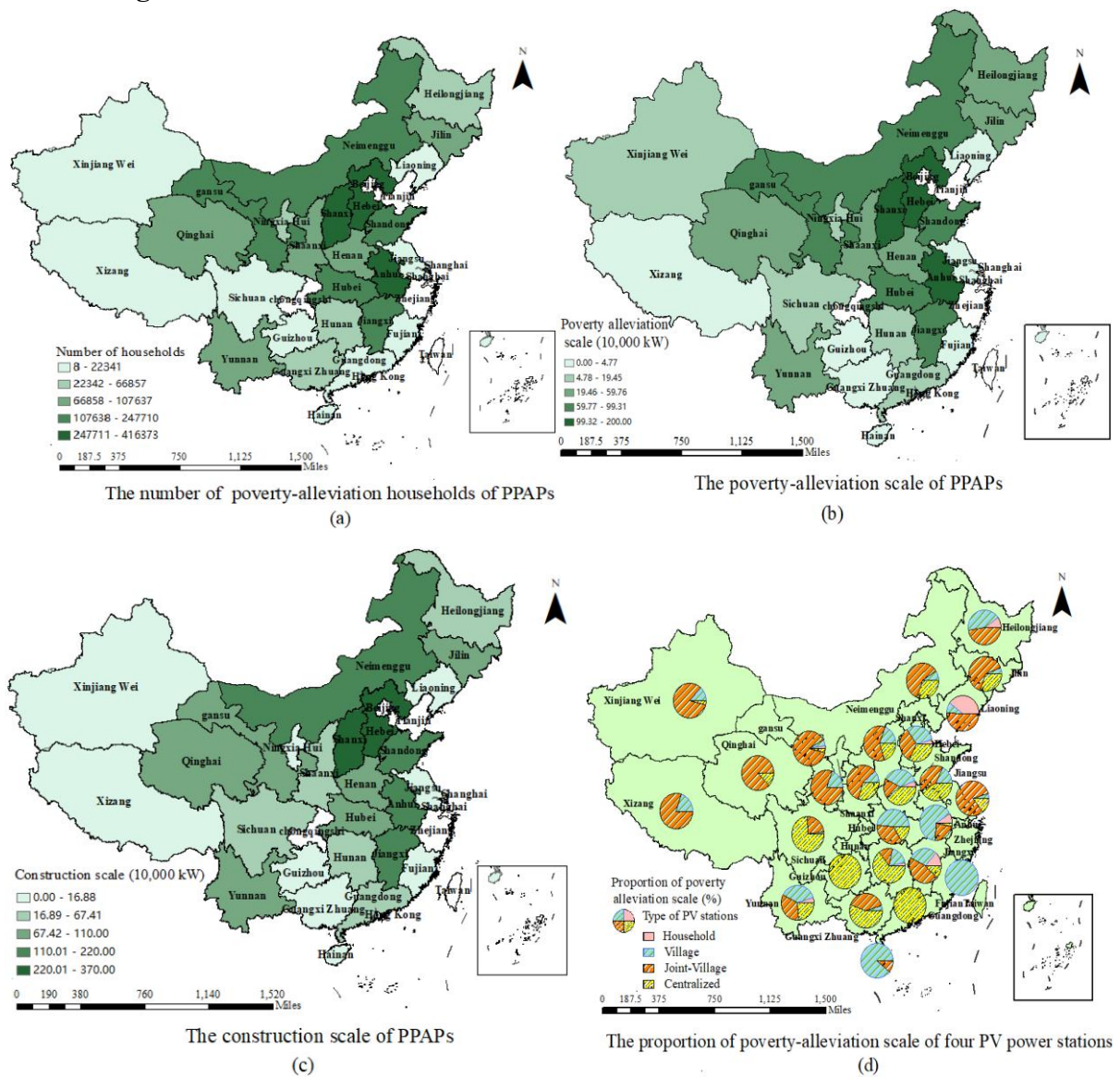


Figure A2. Regional distribution of China's PPAPs.

Notes: Hebei, Shanxi, and Anhui exhibit the largest PV construction scale, poverty-alleviation scale, and number of beneficiary households, with a scale exceeding 2 million kW (panels (a)–(c)). As for the poverty-alleviation scale of the four types of PV power stations in different regions (panel (d)), PPAPs appear great regional differences due to solar radiation intensities and poverty alleviation needs. In general, the joint-village power stations were the first choice in northern regions. The scale of centralized PV projects was large and mainly concentrated in southwestern regions. Although the construction scale of household PV power stations was tiny, the number of stations was the largest. Village PV power stations were mainly located in central and eastern areas with scarce land resources. The figure is a schematic map and does not imply the definite boundaries. The difference between the poverty-alleviation scale Figure A2 (b) and the construction scale Figure A2 (c) is that the former refers to the PV power generation scale used to help the poor, and the latter refers to the actual construction scale of PV power stations.

E3. The geographical distribution of the treatment and control counties

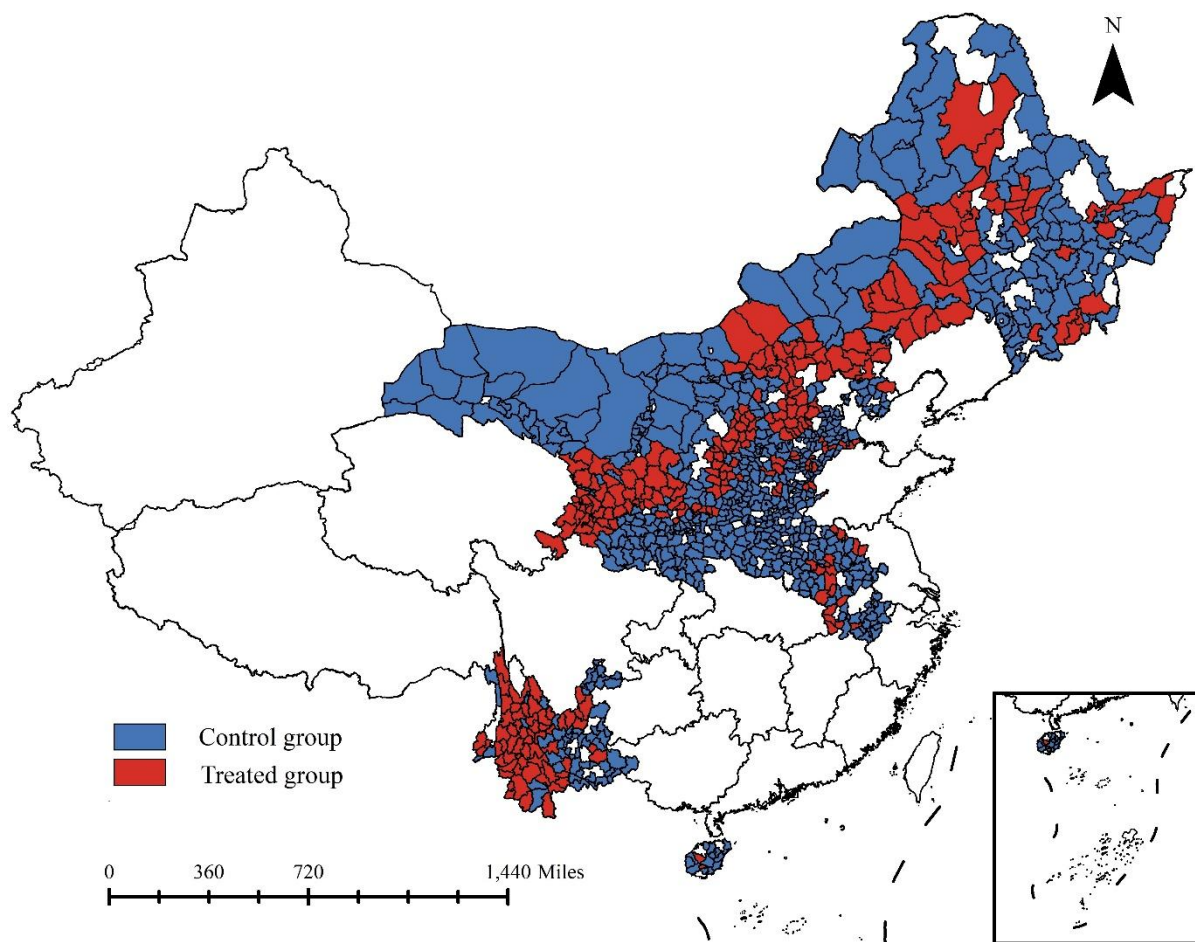


Figure A3. Geographical distribution of the treatment and control counties.

Notes: The figure is a schematic map and does not implicate the definite boundaries. It demonstrates that the treated PPAP counties (Treated group in red color) are located in the eastern (Jilin, Heilongjiang, Hebei, and Hainan), central (Henan, Shanxi, and Anhui) and western (Shaanxi, Gansu, Ningxia, Inner Mongolia and Yunnan) regions of China. The blue-colored control counties (Control group) surround and intermingle with the red treated counties in many locations, suggesting that their location and geographic conditions may be close and comparable.

E4. Parallel trend test

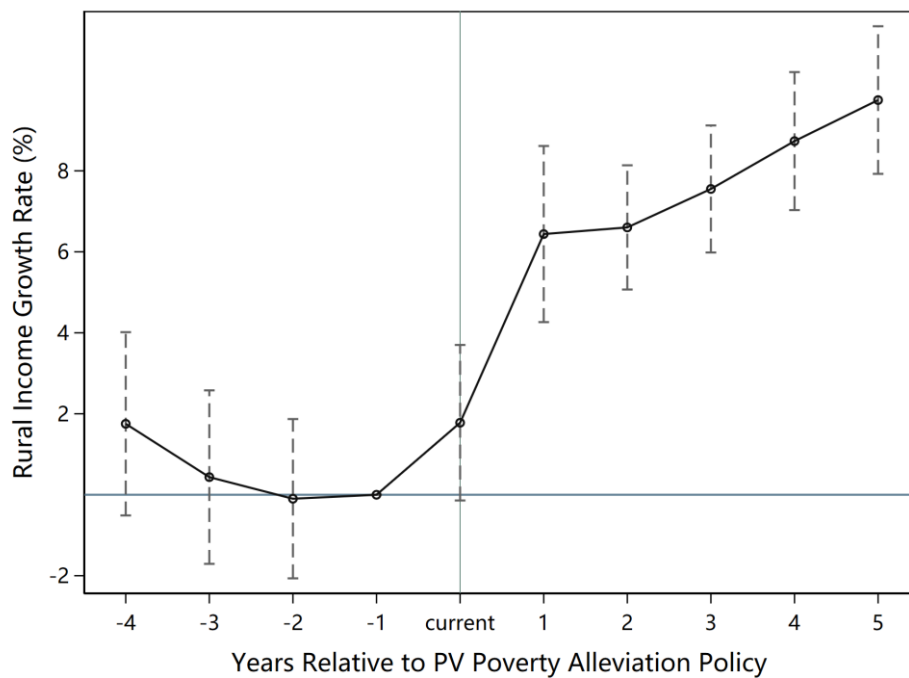


Figure A4. Parallel trend test by altering the control group with non-poverty stricken counties.

Notes: The figure demonstrates the pre-treatment parallel trend assumption and post-treatment estimated effect of PPAPs by altering the control group with non-poverty stricken counties. The dots indicate point estimates of the event variable, and the vertical lines indicate their 95% confidence intervals.

E. Permutation test

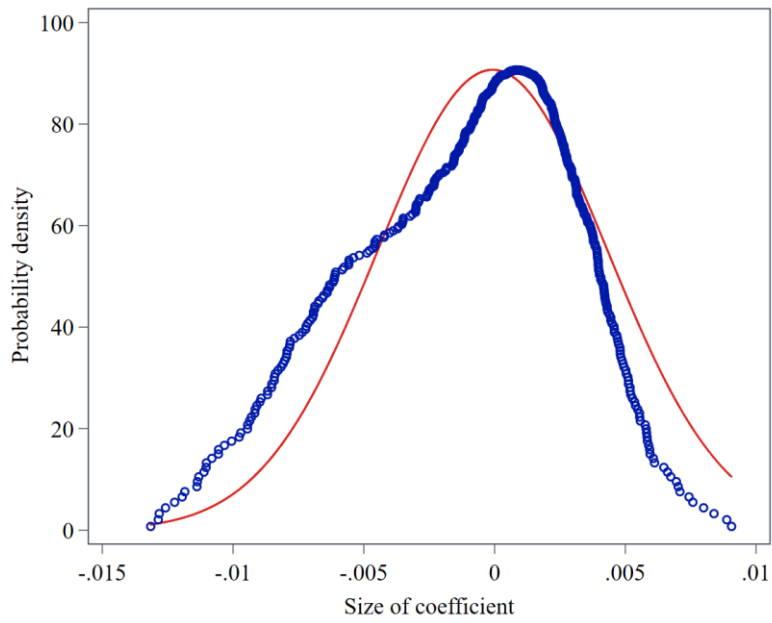


Figure A5. Distribution of estimated coefficients of the permutation test.

Notes: Figure A5 shows that the distribution of estimates from randomly drawn treatment status is located around zero, and the true point estimate is located outside the whole distribution of the 500 placebo estimates, indicating that the findings are not likely to be driven by an over-rejection problem.

References

Green Peace (2017) *Synergies of Wind Photovoltaic and Power Generation in China*.

Available at <https://www.greenpeace.org.cn/news/> (accessed 27 April 2022) (in Chinese).

Kumar NM, Chopra SS and Rajput P (2020) Life cycle assessment and environmental impacts of solar PV systems. In *Photovoltaic Solar Energy Conversion*. Academic Press, pp. 391-411.

MOF of China (2020) Supplementary Notice on Matters Related to the Opinions on Promoting the Healthy Development of Electricity Generation from Non-water Renewable Sources . Ministry of Finance of China. Available at http://jjs.mof.gov.cn/zhengcefagui/202010/t20201015_3604104.htm (accessed 27 April 2022) (in Chinese).

NEA of China (2014) Notice on the Issue of the Implementation of Photovoltaic Poverty Alleviation Projects Work Plan. National Energy Administration of China. Available at http://zfxgk.nea.gov.cn/auto87/201411/t20141105_1862.htm (accessed 27 April 2022) (in Chinese).

NEA of China (2018) Qinghai: Photovoltaic Power Generation Brings Stable Income. National Energy Administration of China. Available at https://www.nea.gov.cn/2018-12/03/c_137648009.htm (Accessed 8th July 2025) (in Chinese).

NEA of China (2020) Hundred Questions and Answers on Photovoltaic Poverty Alleviation (Trial Version 2) National Energy Administration of China. Available at http://nrra.gov.cn/art/2020/2/27/art_46_113101.html (accessed 27 April 2022) (in Chinese).

Peng J, Lu L and Yang H (2013) Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and Sustainable Energy Reviews* **19**, 255–274.

State Grid (2020) *National Grid Report Card on Reducing Electricity Costs 2016–2019*. Available at <https://news.bjx.com.cn/html/20200526/1075686.shtml> (accessed 27 April 2022) (in Chinese).