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Community-based energy revolution: An evaluation of China's photovoltaic poverty alleviation Program's economic and social benefits☆

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A B S T R A C T

We use a unique micro dataset from the period of 2014–2021 to evaluate China's Photovoltaic Poverty Alleviation (PVPA) program. By employing a difference-in-differences strategy, we find that the community-based PVPA stations distributed in China are anti-poverty facilities that can reconcile equity and efficiency. The PVPA program not only significantly increases the total income of treated households, but also reduces the within-village inequality and encourages off-farm labor supply. Heterogeneity analysis suggests that the effect of PVPA is more substantial for households with a high dependency ratio and in villages where officials are well-educated. The benefit-cost ratio of a village-level PVPA station is greater than one, indicating that the community-based PVPA program is cost-effective.

1. Introduction

Poverty reduction and clean energy are two of the 2030 Sustainable Development Goals proposed by the United Nations. The climate goals of the Paris Agreement also impose limits on peak carbon emissions by 2030 and require an increase in the proportion of non-fossil energy among primary energy consumption to 20%. However, it is difficult to determine how economic growth be sustained without exacerbating social inequity or causing environmental pollution. As the largest developing country and leading carbon emitter, China has made great efforts to reconcile these goals. The Targeted Poverty Alleviation (TPA) program initiated in 2013 is the largest anti-poverty campaign in China. The Photovoltaic Poverty Alleviation (PVPA) program was introduced into the TPA program in 2015. By the end of 2019, the PVPA installed capacity reached 26.36 million kilowatts and nearly 4.15 million households in rural areas benefited directly from the program.[1] PV, as a type of clean energy, do not emit any greenhouse gas into the environment and are ideal for addressing climate change concerns. Additionally, the revenue generated from the implementation of PV can help poor people living close to PVPA stations escape poverty.

The environmental benefits of solar energy have been widely recognized by researchers (Tsoutsos et al., 2005; Sweerts et al., 2019; Creutzig et al., 2017). However, empirical analysis of the economic and social benefits of poverty-targeted PV stations, particularly community-based stations, is insufficient. Community-based stations have become the major mode of PVPA projects since 2017 (Li et al., 2018), covering over 4.15 million impoverished households.[2] This type of PVPA project is characterized by a moderate scale and decentralization at the village level. The revenues generated by PVPA stations are managed and distributed by village committees. How a decentralized decision-making process affects the efficiency and equity of poverty alleviation is a classical research question of great significance to both researchers and policymakers.

The objective of this study is to investigate the economic and social benefits of community-based PVPA programs using micro data. Several empirical studies have evaluated the effects of PVPA in terms of fighting poverty, all of which have found that PVPA has a positive impact on economic wellbeing (Zhang et al., 2019, poverty index; Zhang et al., 2020, disposable income; Liu et al., 2021, economic conditions, social capital, livelihood capital; Liao et al., 2021, income and welfare level; Huang et al., 2021, income and living standards). However, we still lack answers to questions such as what are the social benefits of PVPA programs, how good targeting accuracy is at the village or household levels, and the mechanisms by which PVPA helps the poor from a micro

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[1] National Energy Administration: http://www.nea.gov.cn/2020-10/30/c_139478911.htm.
[2] National Energy Administration: http://www.nea.gov.cn/2022-06/03/c_1310612901.htm.

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perspective.

To capture the essence of China's PVPA program and overcome the empirical challenges encountered in previous studies, we use a unique dataset collected from one representative county in the central region of China. This dataset combines village-level, household-level, and project-level administrative data covering a relatively long period from 2014 to 2021. By linking these three types of data, we can identify which villages have installed PVPA stations and which households are the actual beneficiaries of PVPA. A clean data structure with variations in both time and treatment status allows us to employ a difference-in-differences (DID) identification framework to evaluate the medium- and long-term impacts of PVPA on household and village wellbeing.

Empirical analysis indicates that the PVPA program significantly enhances the total family income of treated families by 6.5%. Increase in off-farm labor supply and transfer income are two possible mechanisms. PVPA program also has positive effects on village wellbeing, with a remarkable decrease in income inequality and weak evidence of collective economy expansion. Heterogeneity analysis shows that PVPA has a more substantial effect on households with a high dependency ratio, and on villages if government officials are younger and better educated.

We also find the medium-scale PVPA stations at the village level are cost-effective. The benefit-cost ratio is 1.28, implying that the socio-economic and ecological benefits of PVPA already outweigh the costs. If we further consider PVPA's social benefits in terms of increasing labor supply and promoting social equality, the benefit-cost ratio is even higher.

Our study not only has strong policy implications but also contributes to several heated research debates. First, reconciling the sustainable development goals (SDG) of poverty reduction and clean energy is challenging for numerous developing countries. China's PVPA program represents a potential solution. The PVPA program is a cost-effective program that generates revenue from natural endowments. Because China comprehensively solved the problem of electricity access for people living in remote and rural areas in 2015 (National Energy Administration), the direct goal of community-based PVPA stations is not to achieve electricity access, but to provide additional resources in areas where access to electricity is limited (Cook, 2005; Lenz et al., 2017; Joshi et al., 2019). Additionally, we demonstrate that PVPA projects with proper policy design can effectively increase labor supply and reduce Gini coefficients. This can alleviate concerns regarding welfare dependence and deteriorative social inequality arising from earlier anti-poverty projects.

Another concern conveyed in earlier literature is whether community-based poverty alleviation programs can precisely target the poor. Decentralization in decision-making can improve both the targeting and impact of anti-poverty projects, but empirical evidence remains mixed (Bardhan and Mookherjee, 2005; Wang and Yao, 2007). Such policies may not necessarily benefit the poor for various reasons, including elite exclusion, poor people having a low capacity to take advantage of public investment, or lack of participation in decision-making (Park and Wang, 2010). However, we find that the PVPA program performs very well at targeting the vulnerable and closing income inequality. The unique design and implementation of PVPA, including targeting at the household level, information transparency, frequent screening, and providing welfare positions, rather than direct cash transfer, can explain its positive effects. PVPA provides a good example for policymakers to design policies that reconcile efficiency and equity.

Finally, this study broadens the research horizon of PVPA projects. Appendix A compares our study with existing ones from several perspectives. In contrast to previous studies mainly focus on economic benefits (Zhang et al., 2019, 2020; Liu et al., 2021; Liao et al., 2021; Huang et al., 2021), our study further investigates the social impact of PVPA projects in boosting labor supply and reducing within-village inequality. In addition, our study extends to village-level analysis while majority of earlier literatures focus on the household well-being, except for Zhang et al. (2019, 2020) conducted analysis at county level. The village-level analysis is necessary since a considerable portion of PVPA revenues is spent in an aggregate manner. Exploring the policy effect on village-level welfare positions and collective economy can help us to better understand how the revenue is spent and why poor hosueholds can benefit from PVPA. Both promoting income of the poor and achieving common prosperity are crucial development goals of PVPA and other TPA programs. Village-level analysis with Gini coefficient of income as the dependent variable can capture the redistributive effect of PVPA projects. At last, our study covers a considerably long period that makes medium-term evaluations and cost-benefit analysis of PVPA projects plausible. To the best of our knowledge, this stuy is among the few incorporating both economic benefits and ecological benefits of community-based PVPA stations into a cost-benefit analysis framework.

The remainder of this paper is organized as follows. Section 2 provides a brief introduction to China's institutional background and develops testable hypotheses. Section 3 describes the dataset and empirical strategy adopted in this study. Section 4 reports our empirical results and Section 5 presents cost-benefit analysis. Section 6 summarizes.

2. Institutional background and hypothesis development

2.1. TPA in China

TPA is the largest anti-poverty campaign in China. It was initiated in 2013 and had successfully lifted over 90 million people out of extreme poverty by 2020. Compared to earlier anti-poverty campaigns in China, the TPA has the following three distinct features.

First, the target unit was shifted to the household. Household income is the main, but not sole identification criterion. TPA has an evident inclination to help the vulnerable, particularly households suffering from diseases, disabilities, and natural disasters. Poor households in rural China have been officially registered by the government, and demographic characteristics and economic indicators such as education, labor supply, annual income, and asset value are tracked every year.

Second, China's TPA is a "Big Push" strategy based on comprehensive policy tools. Registered poor households are entitled to various pro-poor assistance programs, including infrastructure investments, cash transfers, agricultural subsidies, vocational training, migration bonuses, microcredit, household renovation, and resettlement.

Third, information friction during TPA implementation was significantly reduced. The list of registered poor households and beneficiaries of any type of assistance in a village must be discussed and disclosed. Furthermore, each household is assigned to a coordinator, who is typically a government official that is responsible for information transmission and distribution (Zhang et al., 2021). These policies guarantee that every poor household fully understands the benefits to which they are entitled.

2.2. The pro-poor nature of PVPA projects

In 2015, PVPA was determined to be one of the 10 TPA projects that makes full use of solar energy in poor areas and simultaneously increases the income of poor households.[3] Compared to typical photovoltaic stations, PVPA installations have distinct pro-poor features.

First, PVPA targets the poorest areas. We plot the correlation between provincial GDP in 2018 and the cumulative installed capacity of PVPA in Fig. 1. The negative correlation between GDP and PVPA capacity indicates that less-developed districts installed more PVPA capacity. This finding is consistent with empirical evidence from various sources. Liao and Fei (2019) analyzed PV-based program targeting using

[3] Administrative measures for PV power stations for poverty alleviation, accessed via http://www.gov.cn/xinwen/2014-10/18/content_2767377.htm?from=androidqq.

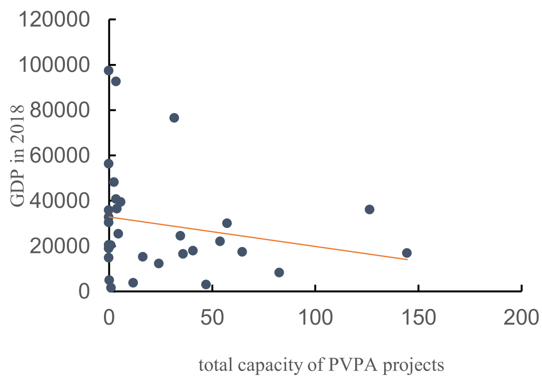

Fig. 1. Correlation between GDP and Accumulative Installed Capacity of PVPA Stations at the Provincial Level. Note: Provincial GDP and the accumulative installed capacity of PVPA stations were measured in 2018. Data were collected from the Provincial Statistical Yearbook and National Energy Administration.

a spatial approach from a national perspective and found that PVPA mainly targets counties that are poorer and endowed with greater solar radiation. Based on project-level data from 22 provinces, Han et al. (2020) also found that PVPA targets areas where GDP and household savings are relatively low. Nationally designated poor counties and poor villages are the main targets of PVPA projects. Almost all the pilot PVPA projects are initiated in poverty-stricken counties, and approximately 65% of village-level PVPA stations are located in poverty-stricken villages.

Second, PVPA projects receive more subsidies than other types of power projects, as well as more subsidies than typical PV stations. Governments subsidize the electricity price of PV power and provide additional subsidies for PVPA projects. The average on-grid price of a PVPA power station is 0.85 yuan/kWh in our sample county, whereas the prices of typical PV stations, and traditional hydropower and thermal power were 0.75 yuan/kWh and less than 0.4 yuan/kWh, respectively, in 2018.[4]

Third, the PVPA program has been prioritized in connection to the grid. Local grid companies are responsible for the construction of PVPA stations and for making suitable plans for PV power grid connection and accommodation.

Both additional price subsidies and grid connection priority imply strong support from the central government and National Energy Administration for the PVPA program. By the end of 2019, the National PVPA Subsidy Catalog had covered 4.15 million poor households. The share of PVPA has increased to 4.2% of the total accommodation capacity of PV stations, exhibiting rapid growth in recent years.

It should be noted that there is no large-scale construction plan of village-level PVPA stations after 2019, but the central government and relevant ministries continued to subsidize the on-grid price of PVPA stations.[5] From a more general perspective, even the working priorities of county governments and village governments gradually switch from poverty reduction to rural revitalization since 2021, there is a five-year transitional period, during which period majority of TPA programs receive sustained support. The above policy changes indicate that PVPA stations already built would continue to benefit poor households within the village.

2.3. Operations and revenue management of community-based PVPA stations

Based on inherent endowment differences and regional disparities, multiple PVPA patterns are adopted across the nation, namely household-based, community-based, and centralized stations in order of small to large scale. Community-based stations have become a major mode of PVPA projects since 2017 (Li et al., 2018). It is worth noting that China's PVPA program, particularly with regard to village-level stations, does not aim to improve access to electricity for the poor. According to the National Energy Administration, in 2015, China had effectively solved the problem of access to electricity for people without electricity in remote rural regions. Therefore, all of the electricity generated by village-level PVPA stations is fed directly into the grid.

According to *Measures for the Administration of Income Distribution for Village-level Photovoltaic Poverty Alleviation Power Stations*,[6] PVPA installations represent property owned by villages. Revenue should be used to provide welfare positions, make cash transfers, and subsidize village development. Village committees are responsible for developing revenue-sharing schemes. Such schemes must be discussed at a village representative conference and consent must be obtained from the majority.

PVPA mainly benefits poor households through revenue generation and sharing, similar to Bangladesh's pattern (Biswas et al., 2004). Bangladesh has established decentralized rural PV stations to help landless farmers. The Bangladeshi government re-assigned existing subsidies from the centralized power system to decentralized rural power companies, which significantly increased the income of one-third of landless farmers.

All PVPA stations considered in our study are community-based stations. Our sample county is representative of the central areas of China and is characterized by medium-sized PV projects and a medium level of poverty. Based on mixed information sources, including interviews with local governments, administrative records, and national policies, we summarize the PVPA operation and revenue-sharing pattern in a sample below.

First, operations, management, and revenue sharing are decentralized to a village committee. A village-level PVPA power station is constructed by the government and PV management companies, and owned by the village collective. The single-household PV program is not suitable for rural houses in our sample county because installing solar panels on roofs is relatively difficult and each household must finance a portion of the construction fees, which is infeasible for poor households facing severe financial constraints. Centralized PV power stations (which are widely adopted in Qinghai Province according to Liao et al., 2021) were not constructed in our sample county because this type of PV project is discouraged in eastern and central districts with limited land resources.

Second, only the poorest households are registered as direct beneficiaries of PVPA projects because one village-level PVPA power station has an average capacity of only 57 kW. The list of PVPA beneficiaries must be discussed at a village democratic conference and released to the public. Anyone who objects to the list appeals to the village committee. The poorest households mainly refer to those with limited capacity to make a living on their own, including disabled or elderly individuals who cannot earn off-farm wages or undertake agricultural production.

Third, PVPA projects can benefit poor households in several ways. A large proportion of generated revenue is used to subsidize programs such as welfare positions, cash transfers, and village development. Welfare positions are provided in the form of cleaners, forest rangers, security guards and so on. Welfare work is characterized by (1) closeness to home, meaning all work is performed within the village; (2) only meeting the basic living standard, where the monthly wage varies from

[4] National Development and Reform Commission: https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171222_960932.html?code=&state=123.

[5] According to National Development and Reform Commission: *Notice on matters related to the feed-in tariff policy for photovoltaic power generation in 2020*, the on-grid price for village-level PVPA stations (including joint village PVPA stations) that meet the relevant management regulations of national photovoltaic poverty alleviation projects remains unchanged. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202004/t20200402_1225031.html.

[6] The National Rural Revitalization Administration: http://www.nrra.gov.cn/art/2018/1/4/art_50_76181.html.

500 RMB to 1000 RMB; and (3) a low workload with low skill requirements that even weak laborers can fulfill. A portion of PVPA revenue is further distributed to the poorest households via direct cash transfers. Finally, the remaining revenue can be used to develop a collective economy or invest in village infrastructure. We have attached the detailed revenue-sharing schemes of the four villages in the sample county in Appendix B, all of which allocate a considerable portion of revenue (70%–80%) to welfare positions and cash transfers, with the remaining portion funding collective investment.

2.4. Hypothesis development

Fig. 2 illustrates the potential mechanisms by which PVPA helps the poor. We focus on the income-augmenting effect and equality-promoting effect, which can be interpreted as economic and social benefits of PVPA projects. Based on the revenue sharing schemes discussed earlier, we develop the following testable hypotheses. The first three hypotheses discuss how the PVPA projects benefit households, while the last three focus on how the PVPA projects affect village-level wellbeing.

First, PVPA projects can affect off-farm labor supply in opposite ways. On the one hand, the construction and maintenance of PVPA stations entail local employment opportunities. The welfare positions and development of collective economy funded by PVPA revenue also boost local work vacancies. On the other hand, if PVPA projects increase non-labor income at the same time, then treated households may reduce labor supply as their demand for leisure is higher. We still posit a positive impact of PVPA projects on labor supply even the total effect could be undetermined.

Hypothesis I. The PVPA projects would increase off-farm labor supply and labor income.

Another crucial way to distribute PVPA revenue is making direct cash transfer to the eligible households. Each eligible PVPA household should receive at least 3000 RMB/year to meet the minimum national criteria. Therefore we make the following hypothesis.

Hypothesis II. The PVPA projects would increase transfer income.

As PVPA projects increase both labor income and transfer income of treated families. Then it is natural to hypothesize the total family income also increases. The third hypothesis concerning household wellbeing is as follows.

Hypothesis III. The PVPA projects would increase the total family income.

How does PVPA project enhance household well-being and living standard has been tested in earlier studies. However, the village-level analysis is rare. A considerable portion of PVPA revenues is spent on purchasing public services and developing collective economy. Thus PVPA is expected to affect villages' wellbeing in the following ways.

Providing welfare positions is one of the major policy tools to motivate impoverished people and guarantee their living standards. Almost all the revenue sharing schemes we have read include offering welfare positions. Then it is reasonable to infer the number of welfare positions would increase in PVPA villages.

Hypothesis IV. The PVPA projects would increase the number of welfare positions.

Even developing collective economy is not the major goal of PVPA projects, the policy allows for investment in collective economy if the funding requirements of welfare positions and cash transfer are already met. We assume the size of collective economy would expand as PVPA projects can provide extra fund.

Hypothesis V. The PVPA projects would boost the development of collective economy.

The PVPA projects mainly target the poorest households in the village, for example, the welfare positions are offered to weak labors, the selection criteria of PVPA beneficiaries have an apparent preference of low-income families and disabled people. Therefore households in extreme poverty should benefit more from PVPA projects. We hypothesize the income inequality within village would be decreased.

Hypothesis VI. The PVPA projects would reduce within-village inequality.

3. Data and identification strategy

3.1. Data

The data we analyze are drawn from County X, which is a nationally designated poor county located in the middle part of China. County X is a representative sample of poverty-stricken counties in terms of economic development and solar energy endowment. In Appendix C, we demonstrate that several of the main socioeconomic indicators of County X, including the proportion of the secondary industry, population density, savings per capita, and fixed asset investment per capita, are comparable to the national average. County X's solar energy resources are also at an average level for the central region of China. Since community-based stations are the major mode of PVPA and PVPA mainly targets the nationally designated poor areas, empirical analysis using our sample county have potentials to be applied and generalized to other places.

We merge three datasets for our main analysis. The village-level data consists of 17 townships and 205 villages in County X, 73 of which are nationally designated poor villages.[7] Village characteristics include population, number of households, average net income per capita, the scale of the village collective economy, infrastructure, and driving distance to the county government. Outcome variables such as the number of welfare positions and the Gini coefficient of total income could be accessed easily for the period from 2014 to 2021. However, records on the scale of the village collective economy and the Gini coefficient for other types of income are incomplete.

The household data used in this study comprise a longitudinal dataset covering more than 1200 registered poor households and nearly 4300 poor individuals from 2014 to 2021. Ample information could be obtained from government administrative records, including demographic characteristics, income from different sources, labor supply, and household assets.

PVPA project-level data are also collected from an administrative dataset. According to the *2017 Photovoltaic Poverty Alleviation Work Promotion Plan*, County X is a national designated poor county on the list of Henan Province's pilot projects. County X initiated PVPA projects in 2017 that expanded to more villages in 2018. Approximately one-quarter of poor households are listed as direct PVPA beneficiaries. By the end of 2018, there are 103 PV projects across the entire county, covering 179 villages and 1119 poor households.[8]

The characteristics of the PVPA stations are summarized in Table 1. On average, the capacity of one PVPA installation is 56.01 kW and the power generation per year is 71,605 kWh. One PVPA station directly benefits 11.6 poor households. The average capacity per household is approximately 5.02 kW, which meets minimum policy requirements.[9]

Based on our calculations, the average annual PVPA revenue shared

[7] The iIdentification of nationally designated poor villages initiated in 2001 uses a weighted poverty index based on multiple indicators. Nationally designated poor villages are entitled to a large amount of public investment programs (Park and Wang, 2010).

[8] Most PVPA stations are independently owned by one village, but some are concentrated in one village or jointly owned by several villages.

[9] Notice of the Poverty Alleviation Office and The State Council of the National Energy Administration on the compilation of the 13th Five-Year Plan for Photovoltaic Poverty Alleviation: http://zfxxgk.nea.gov.cn/auto87/201708/t20170808_2839.htm.

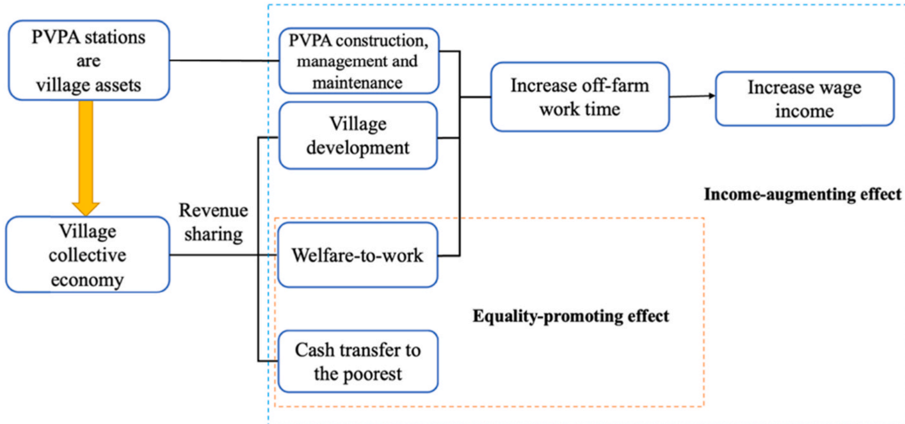

Fig. 2. Operation and Revenue-Sharing Patterns of Community-based PVPA Stations in China. Note: This pattern is based on policies of the central government, revenue-sharing schemes of multiple villages, and author interviews with local governments.

Table 1
Summary statistics of PVPA projects in county X.

	Unit	Mean
Project capacity	kW	56.01
Number of households covered		11.64
Capacity per household	kW	5.02
Electricity generation per station	kWh/year	71,605
Revenue from electricity generation per station	Yuan	60,864

Note: These statistics are based on the administrative records of 103 PVPA stations in County X.

by each listed household (approximately 5228 yuan) is equivalent to one-fourth of their net income in 2016, indicating that the PVPA subsidy constitutes a considerable portion of poor household income. The construction and operation of village-level PVPA projects have become standardized on a national scale. The supporting policies for solar PV and PVPA projects ensure low risk. Although solar irradiation varies over time and by environment, our sample county is a representative county in the central region of China and our findings have universal implications.

The three datasets described above can be precisely matched using unique household and village identifiers.

3.2. Targeting accuracy of PVPA

Targeting accuracy is a crucial dimension for evaluating anti-poverty projects. Policies failing to cover poor people or extending to non-poor people will enlarge existing inequality. In contrast to earlier studies that examined targeting accuracy at the county level (Liao and Fei, 2019; Han et al., 2020), we evaluate the targeting accuracy of PVPA at the village and household levels.

3.2.1. Village-level targeting accuracy

There are a total of 205 villages in our sample county, 26 of which neither have PVPA stations nor poor households, so they are dropped

Table 2
Targeting accuracy.

Panel A: Village level					
	PVPA village First round	PVPA village Second round	Non-PVPA village	first-second	PVPA-nonPVPA
Population	1668.05 (118.746)	1534.73 (60.685)	1394.71 (129.517)	133.3135 (139.462)	172.96* (91.782)
Households	484.23 (38.122)	426.41 (17.403)	374.48 (17.625)	57.8149 (40.795)	64.567** (26.333)
Farmland (*mu*)	1025.22 (66.552)	1121.04 (129.709)	965.56 (74.498)	−95.81763 (275.038)	135.033 (160.774)
Income per capita of poor households	7932.117 (353.609)	7371.511 (168.859)	6687.709 (194.148)	560.6057 (392.533)	847.19** (261.199)
Distance to county (km)	31.44 (3.018)	25.88 (11.243)	24.09 (1.614)	5.564** (2.807)	2.724 (1.933)
Poverty headcount rate	20.61% (0.017)	17.69% (0.009)	12.02% (0.011)	2.92% (0.022)	6.49%*** (0.014)
Gini coefficient	0.223 (0.007)	0.225 (0.008)	0.210 (0.058)	−0.001 (0.012)	0.015* (0.035)
Collective economy (10,000 Yuan)	2.134 (0.262)	2.034 (0.239)	2.09 (7.203)	0.100 (0.517)	0.036 (0.708)
N	22	101	56		
Panel B: Household level					
	Group 1 Eligible households in PVPA village	Group 2 Ineligible households in PVPA village	Group 3 Households in non-PVPA village	Group 1-Group 2	Mean (Group 1, Group 2)- Group 3
Disable ratio	0.139 (0.008)	0.098 (0.002)	0.131 (0.005)	0.041*** (0.007)	−0.029*** (0.005)
Dependency ratio	0.402 (0.009)	0.384 (0.003)	0.426 (0.007)	0.018* (0.010)	−0.039*** (0.007)
Farmland (*mu*)	2.210 (0.039)	2.275 (0.015)	2.233 (0.029)	−0.065 (0.045)	0.034 (0.032)
Education of family head	6.678 (0.094)	7.123 (0.031)	6.526 (0.068)	−0.445*** (0.095)	0.549*** (0.069)
Net income per capita	3110.583 (67.473)	3678.712 (26.757)	3294.241 (44.033)	−568.130*** (80.151)	322.69*** (55.710)
N	1119	8616	2332		

Notes: Village level analysis uses 2017 administrative records because that is earliest information we access. Household level analysis uses 2015 administrative records. 1 mu equals to 0.067 ha. Standard deviations are presented in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

from our analysis framework. The first wave of PVPA stations covers 22 villages in 2017 and the second wave covers 101 additional villages in the subsequent year. The remaining 56 villages have poor households, but no PVPA stations. We compare the baseline characteristics of the first- and second-wave villages to the non-PVPA villages in Panel A of Table 2 to highlight which types of villages are the targets of PVPA. Baseline characteristics include population, number of households, farmland area, income per capita of poor households, distance to county, poverty headcount rate, Gini coefficient, and collective economy scale. Compared to non-PVPA villages, PVPA villages generally have a significantly higher poverty headcount rate (12% and 18%, respectively), are more populated, and have a higher Gini coefficient. It is noteworthy that the average income of poor households in PVPA villages is higher than that of non-PVPA villages. This means that the breadth of poverty, rather than the depth of poverty, plays a more dominant role in governmental decisions. Within-PVPA village comparisons indicate that first-wave PVPA villages are farther away from the county government and have even higher poverty headcount rates.

The pre- and post-treatment differences in the outcome variables of these three groups are presented in Panel A of Table 3. The number of welfare positions increases significantly in both PVPA and non-PVPA villages, but the increase is more significant in PVPA villages. The Gini coefficient of income is stable in PVPA villages, but increases in non-PVPA villages. The collective economy expands more rapidly in PVPA villages, even though differences in the Gini coefficient and collective economy between PVPA and non-PVPA villages are not statistically significant at the 10% level.

3.2.2. Household-level targeting accuracy

According to *Administrative Measures for PV Power Stations for Poverty Alleviation*, PVPA power stations are aimed at increasing the income of a population in extreme poverty, particularly for families suffering from weak labor. Families with weak labor find it difficult to earn money on their own. A total of 1199 households and 3949 poor individuals are listed as direct PVPA beneficiaries in county X, who are eligible for revenue sharing. In Panel B of Table 2, we summarize the baseline characteristics of the three groups, which are eligible households in PVPA villages, non-eligible households in PVPA villages, and households in non-PVPA villages.

First, compared to non-eligible households in PVPA villages, households on the PVPA list have a significantly higher disability ratio, a higher dependency ratio, fewer educated household heads, and are poorer in terms of income per capita. The within-village comparison results are consistent with the goals of PVPA projects for targeting the poorest households. Second, households in PVPA villages are wealthier than their counterparts in non-PVPA villages on average. This is mainly because PVPA projects target villages with a larger number of impoverished households, rather than areas where the extent of deprivation is deeper.

The before and after comparison in Panel B of Table 3 reveals that net income per capita, wage income per capita, and off-farm labor supply exhibit a remarkable increase for all three groups. Although the increment in the income of treated households in PVPA villages is smaller in absolute value compared to the other two groups, the percentage change relative to the baseline level is the most significant. The rise in off-farm labor supply as measured by employment months in one year is the largest in the treated households in PVPA villages. These findings suggest that PVPA projects improve both the income and self-sufficiency of poor households.

3.3. Identification strategy

We empirically test the impact of the PVPA program by employing a two-way fixed DID framework. Because the implementation of the PVPA program is a phase-in process, we use a time-varying DID strategy to identify the causal impact of PVPA on household wellbeing. As is shown in Appendix D, we only focus on PVPA villages for household-level regression. Households registered as PVPA beneficiaries are treatment group, while non-registered households in PVPA villages are control group. We further include households in non-PVPA villages as control group in the robustness check.

The household-level regression is performed as follows:

$$Y_{ivt} = \beta_0 + \beta_1 PVPA_{ivt} + \boldsymbol{X}_{ivt}^{'}\boldsymbol{\beta_2} + \varepsilon_i + \mu_t + \lambda_{ivt} \tag{1}$$

The explanatory variable Y_{ivt} is the outcome variable for household i in village v in year t, including the off-farm labor supply, income from various sources, and wage rate. The variable $PVPA_{ivt}$ is a dummy variable equal to one if poor households are registered as beneficiaries of the PVPA program in year t. X is a series of household time-varying control variables. Following previous lieteratures on poverty reduction program (Walle, 2003; Wan and Zhou, 2005; Zhang et al., 2021), we control for variables potentially correlated with the treatment status and outcome variables, including the education level of the household head (*headedu*), household head age (*headage*) and its square term (*headage*^{2}), and dependency ratio. ε_i is the household-level fixed effect and μ_t is the year-fixed effect. λ_{ivt} is the error term, which is assumed to be independently and identically distributed.

To estimate the effects of PVPA on village wellbeing, we use the following village-level regression model. All the PVPA villages are treatment group and non-PVPA villages are control group.

$$Z_{vt} = \alpha_0 + \alpha_1 PVPA_{vt} + \boldsymbol{W}_{vt}^{'}\boldsymbol{\alpha}_2 + \varepsilon_v + \mu_t + \rho_{vt}, \tag{2}$$

where Z_{vt} is the outcome variable of village v in year t, including the number of welfare positions, collective economy scale, and income Gini coefficient. The main independent variable is $PVPA_{vt}$, which is a village-level dummy variable representing whether the village participated in the PVPA program in year t. W_{vt} is a series of time-varying village characteristics, including the number of impoverished individuals to proxy village average income level (Shen and Yao, 2008), and land per capita to proxy village agricultural endowment (Benjamin and Brandt, 1997; Wan, 2004; Wan and Zhou, 2005; Shen and Yao, 2008). ε_v is the village-level fixed effect and μ_t is the year-fixed effect. ρ_{vt} is the error term.

The regressions above are clustered at the household and village levels. The common trend assumption used to validate the DID results is discussed in Section 4.3.

4. Results

4.1. PVPA's treatment effect on household wellbeing

Table 4 reports the estimation results for the effect of PVPA on household wellbeing. The outcome variables we are interested in are net income per capita, off-farm labor supply, wage income per capita, transfer income per capita, and off-farm wage rate. Off-farm labor supply, which is measured by working months in the past year, is reported at the individual level. However, all sources of income are reported at the household level, so we calculate the household-level total labor supply and use aggregate income to compute the income per capita and wage rate. We do not know the work location of off-farm labor supply, meaning we are unable to test the treatment effect on migration.

As shown in Column (1), the overall treatment effect of PVPA on family income is positive. For PVPA beneficiaries, the program can increase net income per capita by 6.5%, indicating that PVPA is an effective method for eliminating poverty. To investigate how PVPA generates income increases, we further estimate the treatment effect on labor supply, wage income, wage rate, and transfer income. The sample size reported in Column (2) (3) (5) are smaller because income data by different sources are missing in some years.

The impact of PVPA on labor supply could be ambiguous. On one hand, both newly created welfare positions funded by PVPA and PVPA

Table 3
Summary statistics of key outcome variables before and after treatment.

Panel A: Village level

	Number of welfare work positions			Gini coefficient			Collective economy (Yuan)		
	First round PVPA	Second round PVPA	Non-PVPA	First round PVPA	Second round PVPA	Non-PVPA	First round PVPA	Second round PVPA	Non-PVPA
Pre-treatment	0.015	0.358	0.295	0.213	0.191	0.187	0.67	1.92	1.91
	(0.015)	(0.065)	(0.077)	(0.007)	(0.004)	(0.005)	(0.202)	(0.469)	(0.742)
Post-treatment	2.234	2.270	1.214	0.208	0.195	0.196	4.08	3.96	2.59
	(0.418)	(0.198)	(0.157)	(0.004)	(0.002)	(0.004)	(0.458)	(0.372)	(0.915)
Difference	2.219***	1.912***	0.920***	−0.005	0.004	0.009	3.414***	2.039***	0.680
	(0.500)	(0.212)	(0.175)	(0.008)	(0.004)	(0.006)	(0.507)	(0.660	(1.165)
Difference in difference									
first-second	0.307*** (0.528)			−0.0085 (0.010)			1.375 (1.216)		
PVPA-nonPVPA	1.056*** (0.309)			−0.0076 (0.007)			1.723 (1.138)		

Panel B: Household level

	Net income per capita			Wage income per capita			Off-farm employment months		
	Group 1 Eligible households in PVPA village	Group 2 Ineligible households in PVPA village	Group 3 Households in non-PVPA village	Group 1 Eligible households in PVPA village	Group 2 Ineligible households in PVPA village	Group 3 Households in non-PVPA village	Group 1 Eligible households in PVPA village	Group 2 Ineligible households in PVPA village	Group 3 Households in non-PVPA village
Pre-treatment	3993.50 (53.129)	4815.77 (21.97)	4253.51 (33.77)	2477.10 (51.11)	3509.93 (21.76)	2708.30 (34.82)	4.43 (0.08)	5.26 (0.03)	4.16 (0.05)
Post-treatment	10998.22 (84.26)	12262.47 (32.40)	11928.04 (67.34)	7546.82 (131.73)	9458.46 (52.10)	8675.70 (112.19)	9.61 (0.12)	9.24 (0.04)	8.37 (0.08)
Difference	7004.72*** (103.68)	7446.70*** (40.14)	7674.53*** (75.77)	5069.72*** (122.28)	5948.53*** (48.81)	5967.40*** (93.09)	5.18*** (0.15)	3.98*** (0.05)	4.21*** (0.10)
Difference in difference									
Group 1-Group 2	−441.98*** (121.01)			−878.81*** (145.26)			1.20*** (0.18)		
Group 1,2-Group3	−279.72*** (85.39)			−125.66 (106.08)			−0.10 (0.12)		

Notes: Panels A and B display the before-and-after treatment change in village-level and household-level outcomes. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 4
Impact of PVPA projects on household wellbeing.

	(1)	(2)	(3)	(4)	(5)
	ln_netinc_per	ln_wage_per	ln_transfer_per	month_tot	ln_wagerate
PVPA household	0.0655*** (0.0122)	0.263*** (0.0644)	0.219*** (0.0282)	1.237*** (0.165)	−0.137*** (0.0265)
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
Household-fixed effect	Yes	Yes	Yes	Yes	Yes
Time-variant controls	Yes	Yes	Yes	Yes	Yes
Constant	8.534*** (0.128)	6.540*** (0.691)	8.317*** (0.291)	−5.477*** (1.190)	6.852*** (0.205)
Control group mean for the post period	13182.67	11592.85	2154.72	9.71	3955.32
Observations	77,378	57,128	57,249	77,394	37,007
R^2	0.794	0.263	0.274	0.175	0.313

Note: The treatment and control groups are eligible and non-eligible households in PVPA villages. Time-variant control variables include education level of the household head, age and age squared of the household head, and dependency ratio. All dependent variables are constructed at the household level. Net income includes income from all sources. *Month_total* is the aggregate household off-farm employment month per year. The wage rate is obtained by dividing the household aggregate wage income by the aggregated labor supply. The sample size reported in Column (2) (3) (5) are smaller because income data by different sources are missing in some years.Control means are not reported in log form. Robust standard errors in parentheses are clustered at the household level. ***p < 0.01, **p < 0.05, *p < 0.1.

construction-related jobs increase employment by driving up the labor demand curve. On the other hand, direct cash transfer increases non-labor income, further increasing demand for leisure and reducing the labor supply. As reported in the fourth column of Table 4, the overall effect of PVPA on household off-farm labor supply is 1.237, indicating that PVPA increases the average duration of off-farm work for the treated group by 1.2 months per year compared to the counterparts in the control group. Because the average off-farm labor supply per household in the control group is 9.7 months, these results indicate that PVPA increased the labor supply by 12.7%. A positive sign indicates that the labor demand effect plays a dominant role. Our first hypothesis is supported. Another explanation for the employment-augmenting effect is that labor supply has long been depressed in rural areas and poor people have the desire to work, but as a result of credit constraints or a lack of information, they fail to take off-farm work (Bryan et al., 2014). PVPA projects can remove credit constraints and fill the information gap. However, because we do not know exact workplace details, it is difficult to identify whether poor households take on-site welfare positions, work in counties, or even migrate to other provinces.

Next, we test the treatment effect on income from various sources. Unsurprisingly, PVPA increases family wage incomes, which is consistent with the results for off-farm labor supply with the wage incomes of treated families increasing by 26.3%.

In the last column, we also report how PVPA affects the wage rate as a test of the intensive margin. The average wage rate, which is calculated by dividing household total wage income by household total off-farm working months, is reduced among PVPA households. This indicates that new labor market entrants have a lower wage rate than existant wage earners. Since PVPA targets the most vulnerable groups (e.g., welfare positions are provided to the elderly and disabled), it is reasonable that new entrants have lower productivity than existing wage earners.

The third column in Table 4 demonstrates that PVPA also increases the transfer income of treated families by 22%, capturing the other income-augmenting channels of PVPA. The positive impact on transfer income supports our second hypothesis.

In general, we find a significant pro-poor effect of PVPA, which is in line with previous studies such as those by Zhang et al. (2020), Liu et al. (2021), Liao et al. (2021), and Huang et al. (2021). The empirical findings generally support the third hypothesis concerning the overall effect of PVPA projects on household income. What distinguishes our study from the existing literature is that we are able to test income-boosting channels based on household-level data. PVPA mainly works by boosting the off-farm labor supply and increasing cash assistance. One critique of anti-poverty subsidies is that they increase welfare dependency (Ellwood and Summers, 1986) and create disincentives to work. Although the PVPA project is an anti-poverty program including direct cash transfers, its overall effect on labor supply is positive, implying a high level of self-sufficiency and sustainability.

4.2. PVPA's treatment effect on village wellbeing

We wish to determine how PVPA affects villages as a whole. To evaluate the socioeconomic effects of PVPA projects on village wellbeing, we focus on several village-level indicators, namely the availability of welfare positions, Gini coefficients of different sources of income, and the scale of the collective economy. The treatment status and all outcome variables are constructed at the village level. Table 5 presents the regression results.

First, one can see that the number of welfare positions is significantly increased in PVPA villages, which is consistent with the revenue-sharing scheme and the positive effect on off-farm labor supply at the household level. Our fourth hypothesis concerning number of welfare positions receives support. The collective economy also grows in PVPA villages, although the coefficient is not statistically significant at the 10% significance level, lending weak support to the fifth hypothesis. In Section 4.3, by employing an event study strategy, we highlight a significant increase in the collective economy three years after PVPA implementation. This indicates that PVPA has a lagged impact on the stimulation of local industrial development.

In the third column, we replace the dependent variable with the Gini coefficient constructed from the income of all poor households. The Gini coefficient of PVPA villages is significantly lower than that of non-PVPA villages at the 10% significance level, indicating that PVPA has a distributional effect in terms of narrowing inequality among the poor. Our last hypothesis concerning PVPA projects' distributive effect holds. It should be noted that although we do not have information on non-poor household income, the inequality between poor and non-poor households should be further reduced because most of China's TPA projects are exclusive to registered poor households.

In the final two columns in Table 5, we construct another two measures of inequality based on the Gini coefficients of all types of transfers and other types of transfers. Other types of transfers are a subset of all types of transfers and mainly refer to cash transfers made by villages. Because these two variables were not collected every year, the sample sizes were much smaller. However, PVPA consistently reduces inequality in the transfer of income.

Analysis at the village level indicates that PVPA not only has an economic benefit in terms of income augmentation but also has a social benefit in terms of promoting equality. Our findings are contrary to previous literature (Park and Wang, 2010), which indicates that rich people benefit more from community-based poverty alleviation programs. Its implementation process can explain why PVPA does a better job at reducing inequality than community-based anti-poverty programs. Based on the requirements for frequent information disclosure, both the list of beneficiary households and revenue-sharing scheme must

Table 5
Impact of PVPA projects on village wellbeing.

	(1)	(2)	(3)	(4)	(5)
	Number of Welfarework	ln_Collective	Gini of net income	Gini of transfer	Gini of other transfer
PVPA village	0.876*** (0.155)	0.0717 (0.0471)	−0.0145* (0.00757)	−0.00268 (0.0201)	−0.0329* (0.0172)
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
Village-fixed effect	Yes	Yes	Yes	Yes	Yes
Constant	0.000 (0.0557)	0.0633 (0.0472)	0.159*** (0.00407)	0.441*** (0.0419)	0.602*** (0.0542)
Control group mean for the post period	1.21	2588.57	0.196	0.487	0.591
Observations	1432	644	1412	476	1058
R^2	0.618	0.242	0.189	0.058	0.104

Note: The treatment and control groups are PVPA and non-PVPA villages, respectively. Net income includes income from all sources. Other transfer income is a portion of the transfer income that mainly refers to transfers made by the village. The control mean in Column (2) is reported in yuan. Robust standard errors in parentheses are clustered at the village level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

be discussed publicly and consent must be obtained from village representatives. Therefore, the targeting of PVPA projects is more precise than that of previous projects. Furthermore, there are policy constraints for revenue-sharing decisions. For example, the majority of PVPA revenue must feed directly into listed poor households, and villages are encouraged to offer welfare positions, all of which guarantee that poor households have priority and capacity to take advantage of PVPA.

4.3. Robustness checks

4.3.1. Parallel trends test

A common trend is the key assumption of DID analysis. We adopt an event study design and plot the coefficients of interactions between treatment status and time relative to treatment (Fig. 3). The year before the construction of PVPA stations is considered the reference year. The pre-treatment coefficients in various regressions exhibit no significant differences from the reference year. The post-treatment period coefficients exhibit a positive time trend for household off-farm labor supply, wage income, and village welfare positions, and a negative time trend for village Gini coefficients. This evidence supports the common trend assumption and reduces concerns that PVPA treatment effects are driven by differential pre-treatment trends.

This event study design also provides hints regarding when PVPA comes into effect and what roles different mechanisms play. PVPA has an immediate positive impact on household labor supply and transfer income per capita. However, an increase in the provision of welfare positions and expansion of the collective economy is not observed until PVPA stations are established for three years. This disparity in timing implies that expenditure on PVPA revenue prioritizes schemes that directly benefit poor households, including cash transfer, followed by the development of a collective economy. However, welfare work alone cannot explain the growing labor supply that occurs immediately following the establishment of PVPA stations. Therefore, it can be concluded that PVPA projects must stimulate off-farm labor supply in other ways such as creating construction-related vacancies or encouraging out-migration.

4.3.2. Redefining control groups

We include households in non-PVPA villages as a control group (Table 6). Even if the localities of PVPA projects are chosen endogenously, households in non-PVPA villages have characteristics comparable to those of treated households in PVPA villages (see Panel B of Table 1). All household-level analyses using the new sample are consistent with the main results reported in Table 4.

4.3.3. Propensity score matching (PSM)

Based on concerns that eligible households and ineligible households may be systematically different, we performe PSM within PVPA villages, where each eligible household in the treatment group is matched with its 10 nearest neighbors in the same village with replacement. We set the value of the caliper to 0.01 to obtain PSM estimators. We use a logistic regression model to predict the propensity for treatment. The predictors consist of per capita net income, highest family member education level, disability ratio, dependency ratio, age of household head, arable land area, forest land area, and household size in 2016. The mean bias after matching is reduced from 11.2 to 5.1, indicating that the treated and control groups are balanced. We also match PVPA villages with non-PVPA villages using predictors of the total population, total arable land area, total forest area, net income per capita of poor households, and distance from the county government in 2017[10]. The mean bias of the village sample after matching is reduced from 64.5 to 9.4.

Table 7 presents the PSM estimators. The coefficients are based on the average treatment effect of the treated with standard errors adjusted for clustering. The treatment effect on net income per capita is reduced to 1.15%, which is insignificant at the 10% significance level. The impact of PVPA on off-farm labor supply, wage income, transfer income, and wage rate becomes slightly smaller. However, the main finding that PVPA increases off-farm labor supply and transfer income remains robust.

Overall, we obtain robust results from the village-level PSM estimators. Consistent with Table 4, the PSM estimators indicate that PVPA villages provide more welfare positions and have smaller Gini coefficients. One can also see a marginally significant impact on the collective economy, where the scale of the collective economy in PVPA villages is 9.5% larger than that in non-PVPA villages.

The estimation results reported above confirm that the positive effects of PVPA in terms of improving household and village-level wellbeing observed in Tables 4 and 5 are not merely driven by observable factors that group villages into PVPA villages or non-PVPA villages.

4.3.4. Excluding resettlement samples

Because China's TPA is a "Big Push" anti-poverty program incorporating comprehensive projects, it is of particular interest to estimate the pure effect of PVPA projects. Most TPA policies have universal coverage, including health insurance and education subsidies. However, the resettlement program, which involves short-distance movement from villages to towns, covers 18% of the sample population and has a significant effect on income and labor supply (Zhang et al., 2023). We exclude 1450 households that participated in resettlement and re-estimated the baseline regressions in Table 8. Our finding that PVPA increases household labor supply and income remains robust.

4.3.5. Placebo test

We run placebo tests by randomly assigning treatment status to households and villages. Then we re-estimate Equations (1) and (2) using the assigned treatment status. After repeating the re-assignment 1000 times, we draw the distribution of t values of β_1 and α_1 in Fig. 4.

[10] Earlier records of village characteristics are not available. We had to use information from 2017 as a baseline, implicitly assuming that some characteristics are time invariant or exhibit little variation between 2016 and 2017.

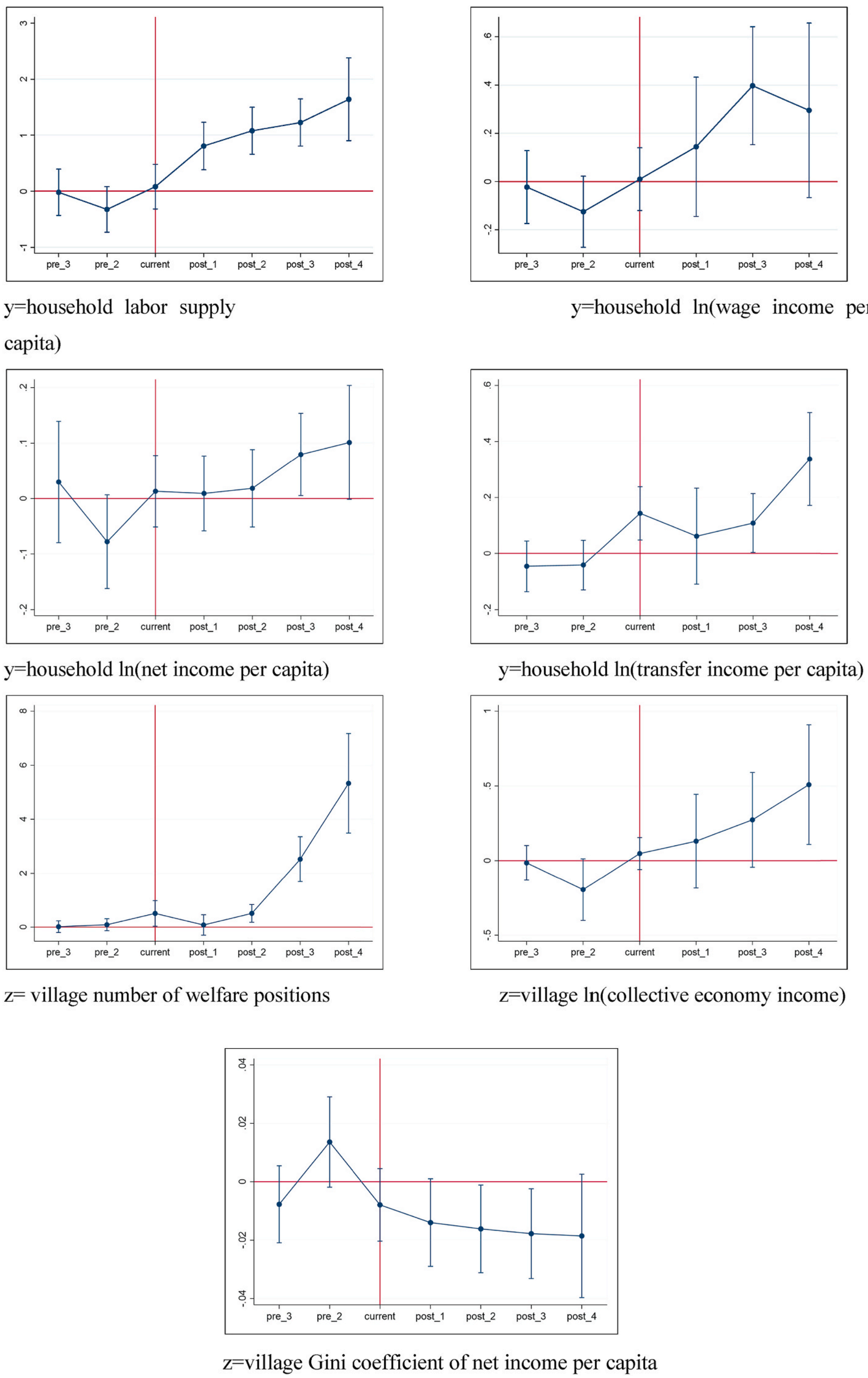

Fig. 3. Parallel Trends Test Results. Note: We used the event study method to test common pre-trend assumptions. The regression models are $y_{ivt} = \beta_0 + \sum \beta_{1t} PVPA_{iv} \times time_{it} + X'_{ivt}\boldsymbol{\beta_2} + \varepsilon_i + \mu_{it} + \lambda_{ivt}$ and $z_{vt} = \alpha_0 + \sum \alpha_{1t} PVPA_v \times time_{vt} + W'_{vt}\boldsymbol{\alpha_2} + \varepsilon_v + \mu_t + \rho_{vt}$. $time_{it}$ and $time_{vt}$ are vectors of time dummies relative to PVPA implementation. The coefficients and confidence intervals of β_{1t} and α_{1t} are reported.

It is clearly demonstrated that the distribution of t values is bell-shaped with the mean at zero, regardless of what outcome variables we employ. We cannot reject the hypothesis that the mean of coefficients is indifferent from zero, which implies that the income-augmenting and equality-promoting effects of PVPA are not driven by accident.

4.3.6. Discussion of PVPA stations' construction timing

The PVPA stations in County X were built in two rounds in 2017 and 2018. Table 1 shows that the first-round and second-round PVPA villages are slightly different from each other, as the project priotized investment in poorer and more distant areas. To investigate whether the empirical findings are driven by observations in certain rounds, we re-estimate Equations (1) and (2) using first-round samples and second-round samples separately. Table 9-Panel A presents the household-level estimation results that constrain samples to first-round PVPA villages and second-round PVPA villages only. Both samples yield consistent empirical findings with Table 4. The control group in village-level analysis is still non-PVPA villages, but we replace the treatment group

Table 6
Redefined control group.

	(1)	(2)	(3)	(4)	(5)
	ln_netinc_per	*ln_wage_per*	*ln_transfer_per*	*month_tot*	*ln_wagerate*
PVPA household	0.0494*** (0.0121)	0.225*** (0.0642)	0.216*** (0.0279)	1.202*** (0.164)	−0.141*** (0.0263)
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
Household-fixed effect	Yes	Yes	Yes	Yes	Yes
Time-variant controls	Yes	Yes	Yes	Yes	Yes
Constant	8.510*** (0.115)	6.101*** (0.615)	8.222*** (0.258)	−6.687*** (1.052)	7.032*** (0.197)
Control group mean for the post period	12262.47	9458.45	1836.23	9.23	3511.08
Observations	95,793	70,539	70,816	95,819	44,756
R^2	0.792	0.258	0.273	0.175	0.310

Note: The treatment group is eligible households in PVPA villages, while the control group includes non-eligible households in PVPA villages and poor households in non-PVPA villages. All the other specifications are the same as Table 4. Robust standard errors in parentheses are clustered at the household level. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 7
PSM estimates.

Panel A: Household level					
	(1)	(2)	(3)	(4)	(5)
	ln_netinc_per	ln_wage_per	ln_transfer_per	month_tot	Ln (wagerate)
PVPA household	0.0115 (0.0150)	0.197** (0.0776)	0.169*** (0.0379)	1.151*** (0.211)	−0.163*** (0.0346)
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
Household-fixed effect	Yes	Yes	Yes	Yes	Yes
Time-variant controls	Yes	Yes	Yes	Yes	Yes
Constant	8.381*** (0.188)	5.038*** (1.127)	8.535*** (0.571)	−10.25*** (2.747)	1375 (1392)
Control group mean for the post period	12330.85	9510.14	2018.04	9.13	3517.65
Observations	22,595	16,929	16,957	22,603	10,927
R^2	0.807	0.256	0.298	0.183	0.169
Panel B: Village level					
	(6) *Number of Welfarework*	(7) *Ln(Collective)*	(8) *Gini of net income*	(9) *Gini of transfer*	(10) *Gini of other transfer*
PVPA household	0.753*** 0.753***	0.0954* (0.0516)	−0.00729 (0.00793)	−0.0235** (0.0109)	−0.0217 (0.0189)
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
Village-fixed effect	Yes	Yes	Yes	Yes	Yes
Constant	−4.637** (2.011)	−0.463 (0.480)	0.164*** (0.0497)	0.506*** (0.0336)	0.447*** (0.0512)
Control group mean for the post period	1.21	2.63	0.21	0.49	0.58
Observations	393	485	483	483	483
R^2	0.729	0.755	0.296	0.201	0.147

Note: In Panel A, eligible households are matched with ineligible households in the same village. Predictors include per capita net income, family member highest education level, disability ratio, dependency ratio, age of household head, arable land area, forest land area, and household size in 2016. In Panel B, PVPA villages are matched with non-PVPA villages. Predictors include the total population, total arable land area, total forest area, net income per capita of poor households, and distance from the county government in 2017. Robust standard errors in parentheses are clustered at the household and village levels. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 8
Excluding resettlement samples.

	(1)	(2)	(3)	(4)	(5)
	ln_netinc_per	*ln_wage_per*	*ln_transfer_per*	*month_tot*	*ln(wagerate)*
PVPA household	0.0550*** (0.0132)	0.222*** (0.0697)	0.242*** (0.0280)	1.012*** (0.168)	−0.126*** (0.0279)
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
Household-fixed effect	Yes	Yes	Yes	Yes	Yes
Time-variant controls	Yes	Yes	Yes	Yes	Yes
Constant	8.590*** (0.144)	7.007*** (0.723)	8.329*** (0.338)	−7.281*** (1.361)	6.431*** (0.227)
Control group mean for the post period	13256.08	11526.82	2282.32	9.62	3929.49
Observations	65,461	48,629	48,743	65,476	30,931
R^2	0.783	0.244	0.264	0.177	0.318

Note: Unlike in Table 4, we excluded 1450 households that participated in the resettlement program. Robust standard errors in parentheses are clustered at the household level. ***p < 0.01, **p < 0.05, *p < 0.1.

with first round PVPA villages and second round PVPA villages (see Table 10-Panel B). Even the village-level analysis are slightly different between row three and row four, coefficients are generally of the same sign. The above tests suggest that the PVPA's treatment effects is not driven by PVPA stations built in certain rounds.

4.4. Heterogeneity analysis

We test the heterogeneous impacts of PVPA according to family characteristics, village status, and village governance, as shown in Table 10.

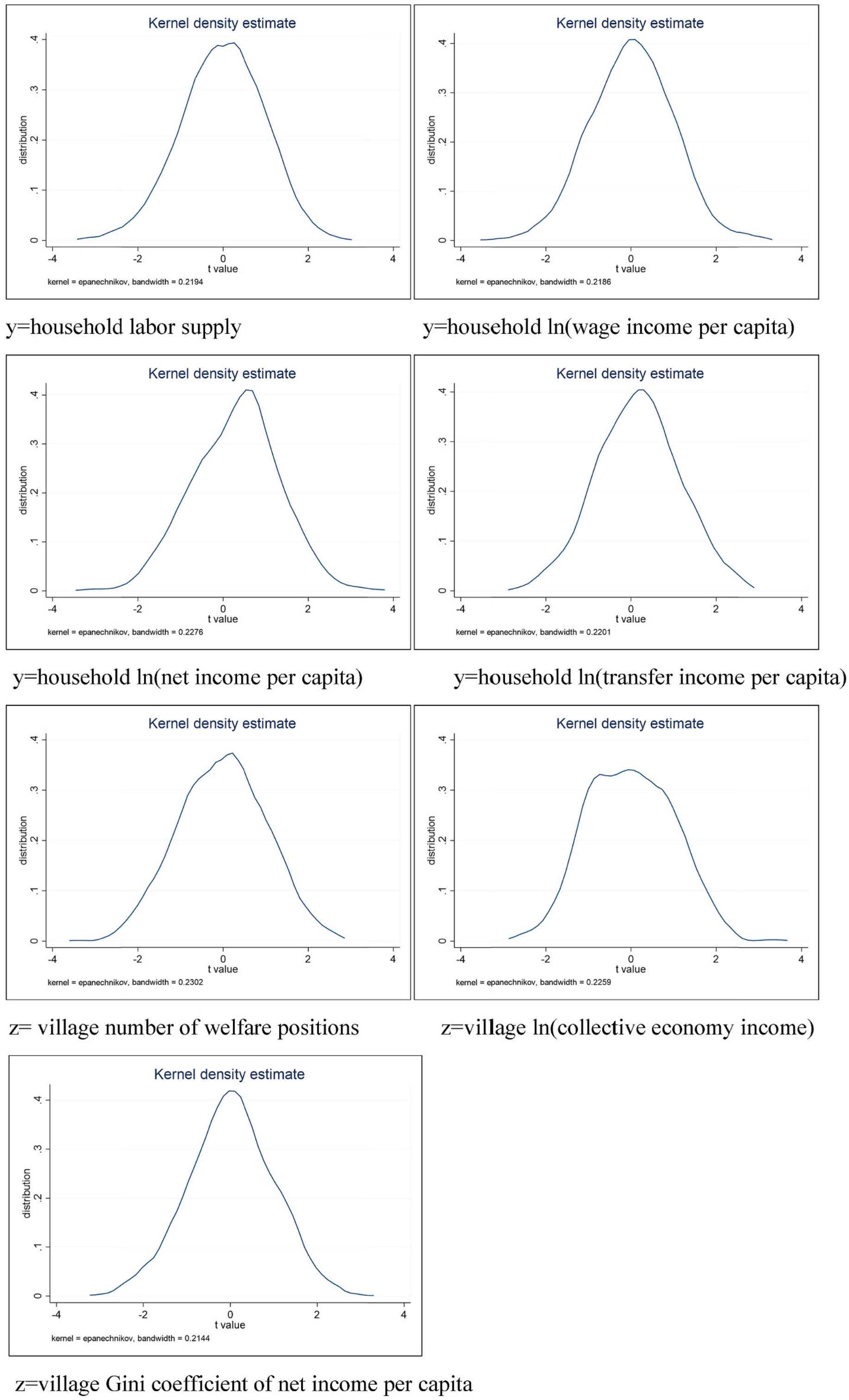

Fig. 4. Placebo Test. Note: The above figures plot the distribution of t values of β_1 and α_1 in Equations (1) and (2) after the rearrangement of treatment status to households or village.

First, we split households into high- and low-dependence-ratio groups considering that households with weak labor may be prioritized in policies. One can see a more substantial effect on net income, wage income, and transfer income per capita among the high-dependence-ratio group in Panel A, which is consistent with the PVPA program goal of reaching the most vulnerable people. Off-farm labor supply increases significantly for both subgroups, but unsurprisingly, the increase is significantly larger for the low-dependency-ratio group. Regarding the wage rate, although PVPA's effect is negative for both groups, reflecting the fact that the new labor market entrants are less productive, the drop is smaller for the high-dependency subgroup. These heterogeneities imply that even though the high-dependency group works less, they receive a higher wage rate.

Second, we examine whether nationally designated poor villages are relevant to the effects of PVPA projects. Nationally designated poor villages have a high deprivation level (Park and Wang, 2010). Although

Table 9
Robustness check by constuction timing.

Panel A: Household-level Analysis					
	ln_netinc_per	*ln_wage_per*	*ln_transfer_per*	*month_tot*	*Ln(wagerate)*
PVPA stations built in 2017	0.0747*** (0.0206)	0.136 (0.117)	0.320*** (0.0519)	1.345*** (0.296)	−0.198*** (0.0472)
PVPA stations built in 2018	0.0624*** (0.0147)	0.323*** (0.0761)	0.173*** (0.0328)	1.204*** (0.196)	−0.115*** (0.0316)
Panel B: Village-level Analysis					
	Number of Welfarework	*ln_Collective*	*Gini of net income*	*Gini of transfer*	*Gini of other transfer*
PVPA stations built in 2017	1.152*** (0.257)	0.355** (0.165)	−0.0280** (0.0127)	−0.00313 (0.0201)	−0.0665 (0.0403)
PVPA stations built in 2018	0.994*** (0.159)	0.0726 (0.0442)	−0.00678 (0.00824)	0.00680 (0.0110)	−0.00959 (0.0165)

Note: Panel A reports household-level estimation results using first round PVPA villages and second round PVPA villages. Panel B uses reports village-level estimation results using first round PVPA villages and second round PVPA villages as treatment group. The other specifications in Panel A and B are the same as Tables 4 and 5. Robust standard errors in parentheses are clustered at household level. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 10
Heterogeneity analysis.

Panel A: Family characteristics					
	ln_netinc_per	*ln_wage_per*	*ln_transfer_per*	*month_tot*	*Ln(wagerate)*
Low dependency ratio	0.0372** (0.0177)	0.181** (0.0896)	0.186*** (0.0397)	1.616*** (0.257)	−0.178*** (0.0365)
High dependency ratio	0.0972*** (0.0168)	0.347*** (0.0926)	0.239*** (0.0395)	0.960*** (0.208)	−0.0892** (0.0382)
Panel B: Village status					
	ln_netinc_per	*ln_wage_per*	*ln_transfer_per*	*month_tot*	*Ln(wagerate)*
Poor village	0.0908*** (0.0130)	0.340*** (0.0684)	0.255*** (0.0304)	1.275*** (0.178)	−0.132*** (0.0282)
Non-poor village	0.0304 (0.0347)	0.0348 (0.186)	0.132* (0.0764)	1.463*** (0.445)	−0.121 (0.0752)
Panel C: Village governance					
	Number of welfare workers	*Ln(collective)*	*Gini of net income*	*Gini of transfer*	*Gini of other transfer*
Average age ≤ 50	0.627** (0.251)	0.160*** (0.0434)	0.00268 (0.0117)	0.00399 (0.0145)	−0.00181 (0.0190)
Average age>50	1.155*** (0.201)	0.0236 (0.0789)	−0.0239** (0.00952)	−0.00907 (0.0150)	−0.0644** (0.0260)
Average edu ≤ 11	0.812*** (0.264)	−0.0204 (0.0678)	−0.0119 (0.0101)	0.00223 (0.0165)	−0.0181 (0.0282)
Average edu>11	0.885*** (0.189)	0.138** (0.0620)	−0.00814 (0.0102)	−0.00633 (0.0132)	−0.0453** (0.0203)

Notes: We split the samples by dependency ratio and whether the village was a nationally designated poor village and re-estimated the regressions in Table 4. The coefficients of PVPA households are reported in panels A and B. We then split the samples by village governance as measured by the average age and average years of schooling of the village committee, and re-estimated the regressions in Table 5. The coefficients of PVPA villages are reported in Panel C.

household-level anti-poverty policies are identical for poor households living in poor villages and non-poor villages, poor villages are eligible for a larger amount of infrastructure investment. Panel B of Table 10 indicates that the work-augmenting effect is comparable between poor and non-poor villages. However, PVPA has a better effect in terms of improving net income, wage income, and transfer income in poor villages. One possible explanation is that anti-poverty policies in poor villages are more intensive and consistent. Therefore, each policy tends to have a better effect.

Third, it is interesting to investigate how village governance affects program effectiveness. Because village-level PVPA stations are village-owned assets and the authority to make revenue-sharing schemes is decentralized to the village committee, the characteristics of the village committee may play a non-negligible role. We considered the average age and education level of village officials as measures of governance. Generally, PVPA villages with committee members older than 50 years are more likely to provide welfare positions and are more successful at reducing income inequality. However, the augmenting impact of the PVPA program on the collective economy is larger, both economically and statistically, with a younger village committee. This heterogeneity could reflect village official preferences or comparative advantages in village governance, where older officials place more emphasis on reaching the poorest people and younger officials are better at stimulating local industrial development. In terms of village official education level, PVPA's effect is more significant on the collective economy in villages with better-educated officials. We also test the heterogeneous impacts of village governance on household wellbeing, but do not report the estimation results to save space. The effects of PVPA on households tend to be consistent, regardless of the village official characteristics. One possible explanation is that the design and implementation of revenue-sharing schemes are consistent across villages, meaning treatment effects are generally consistent.

5. Cost-benefit analysis

5.1. Benefits analysis

We conduct a cost-benefit analysis of village-level PVPA projects. Table 11 reports the estimates and sources of important parameters. The benefits of PVPA projects include the current value of economic and ecological benefits (see Equation (3)).

$$Benefit = social\ benefit + ecological\ benefit = \sum_{t=1}^{20} \frac{power\ generation\ \ revenue_t}{(1+r)^t} + \sum_{t=1}^{20} \frac{carbon\ \ revenue_t}{(1+r)^t} \tag{3}$$

We equalize the economic benefit of a PV station to the fiscal revenue generated by a single station. The median capacity of County X's 103 PVPA stations is 59.4 kW. We use two methods to estimate the yearly electricity generated from one median PVPA station. The first estimate is based on capacity and natural endowment. The second is based on the actual volume calculated from the 16 PVPA stations. Both methods provide an estimate of 71,605 kWh per year, indicating that the endowment is fully used. By multiplying the estimated electricity generated from one station per year by the on-grid price per kWh, we obtained the economic benefit per station per year, which is 60,864

Table 11
Cost-benefit analysis of community-based PVPA stations.

Benefit analysis		
Capacity of one PVPA power station (kW)	59.4	Median of 103 PVPA stations in County X
Total electricity generated per station (kWh/year)	71605.45	Author calculation based on 16 PVPA stations
On-grid price per kWh (yuan)	0.85	National Development and Reform Commission
Economic benefit per station per year (yuan)	60864.63	= 71605.45 × 0.85
Ecological benefit per station per year (yuan)	3223.23	Carbon revenue = thermal power station emissions for generating the same volume of electricity times carbon price (50 yuan/ton)
Lifespan (year)	20	Zhang et al. (2018)
Discount rate	6%	Rodrigues et al. (2017); Bai et al. (2021)
NPV of total benefits (yuan)	¥735,071.21	NPV of economic benefit + NPV of ecological benefit
Cost analysis		
Capital cost per watt (yuan)	7205	Author calculation
Total capital cost per station (yuan)	425,095	Capital cost = cost per watt × capacity
Estimated connection cost per station (yuan)	96,367	Author calculation based on 76 stations
Operating and maintenance fee (yuan)	3043	The costs (MOLS; n) of PV modules are assumed to be 5% of the electricity generation income (Bai et al., 2021).
Land area per station (Mu)	2	Author calculation
Rental per mu (Yuan)	800	Author calculation
Land cost per station (yuan)	1600	Land cost = land area × rent
Lifespan (year)	20	Zhang et al. (2018)
Discount rate	6%	Rodrigues et al. (2017); Bai et al. (2021)
NPV of total costs (yuan)	¥574,719.50	
Benefit-cost ratio	1.28	= benefit NPV/cost NPV

yuan.

Ecological benefits are a non-negligible component of evaluating PVPA projects because solar power is a clean and renewable energy source with positive spillovers. The annual amount of electricity generated per PV station is 71,605 kWh. To generate the same volume of electricity as a PVPA station, a thermal power station needs to consume standard coal equivalent to 21.4758 tce, which yields an estimated ecological benefit of 3223 yuan. The carbon price was derived from China's carbon trading market and is equal to 50 yuan per ton.[11]

In the analysis above, we adopt the following arbitrary assumptions. First, we use current revenue to predict future revenue, explicitly assuming that both the electricity generated and on-grid price are constant over time. Second, we follow Zhang et al. (2018) in allowing the expected lifespan of one PVPA station to be 20 years. Third, both benefits and costs are discounted to the initial year at a discount rate of 6% (Rodrigues et al., 2017; Bai et al., 2021).

As illustrated in Panel A of Table 11, the estimated net value of the total benefit of one PVPA station is 731,837 yuan.

5.2. Analysis of costs

The costs of a PVPA station consist of construction cost, connection cost, current value of operating and maintenance fees, and land cost incurred each year (see Equation (4)). We use the bills from 103 PVPA projects in our sampled county and parameters from the existing literature to estimate the cost of one average village-level PVPA power station.

$$Cost = capital\ cost + connection\ cost + \sum_{t=1}^{20}(1+g)^t \frac{operating\ and\ maintenence\ fee_t + land\ cos\ t_t}{(1+r)^t} \quad (4)$$

The construction and connection costs are one-time fixed investments. The average fixed construction investment was 7205 yuan/kW as estimated from 103 PVPA stations in County X. The connection cost is estimated from 76 PVPA stations because information on the other stations was not available. The bulk of connection and accommodation costs are spent on cable lines, overhead lines, electricity channels, and other civil and constructional engineering projects. The average connection cost per watt is negatively correlated with capacity, implying that the marginal cost of connection is diminishing. We use the ordinary least squares method to derive the nonlinear relationship between cost and capacity.[12] The total connection cost of a median-size PVPA station is reported in Panel B of Table 11.

Next, we let the yearly operating and maintenance fee be equal to 5% of fiscal revenue based on the findings of Bai et al. (2021).

Land cost is not a large portion of the total cost because a village-level PVPA project occupies only 2 *mu* of land (approximately 0.133 ha). The market rental rate is largely affected by distance to the town and transportation convenience. According to our interviews with local government officials, the land rent varies from 200 to 800 yuan/mu, so we consider the highest rental rate of 800 yuan/mu as a proxy for land cost.

The financial cost of a PVPA station is also minimal, so we did not include the financial cost in our calculation. According to the *Measures of Photovoltaic Poverty Alleviation Power Station Management* issued in 2018,[13] village-level PVPA power stations must be financed by government or personal donations. Because debt is prohibited, the interest expense incurred is close to zero. In contrast, financial expenses are non-negligible for large-scale PV power stations located in northwest China (Ouyang and Lin, 2014). Yan et al. (2019) also pointed out that owners of small PV stations with poor credit must accept relatively high loan interest rates.

The estimated net present value (NPV) of the cost of a village-level PVPA station was 574,719 yuan.

5.3. Benefit-cost ratio

Based on the calculations above, the NPV of the benefits and costs are 731,837 Yuan and 574,719 Yuan per station, respectively. The benefit-cost ratio is 1.27, which is slightly higher than 1, implying that village-level PVPA stations are cost effective.

However, we may still have underestimated the benefit-cost ratio of PVPA stations for the following reasons. First, our sample county is located in a type-III resource district[14] and its endowment is at the lowest level. In type-I and type-II areas, even if the on-grid price is lower, centralized stations have larger capacities and lower construction costs. Therefore, they are expected to have a higher benefit-cost ratio. Second, the cost of solar PV modules, which accounts for the largest proportion

[11] The carbon price in the national carbon market was derived from the Shanghai Environment and Energy Exchange: https://www.cneeex.com/. The carbon price fluctuates between 50 yuan/ton and 60 yuan/ton. We considered the lowest value for cost-benefit analysis.

[12] The estimated regression model is $Conection = 3.966 - 0.0489 capacity + 0.000159 capacity^2$

[13] National Energy Administration: http://www.gov.cn/xinwen/2018-04/10/content_5281311.htm.

[14] Cities are classified into three types of resource districts according to solar endowment. Type-III districts have the lowest level of endowment. National Development and Reform Commission: https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171222_960932.html?code=&state=123.

of construction costs, is decreasing rapidly. The learning rate of solar PV modules in China has been estimated to be 25% (Zou et al., 2016). Considering that solar modules account for 40% of the total cost (our calculation; La De La Tour et al., 2011), the benefit-cost ratio will increase further in the future. Third, we did not consider the social benefits of PVPA stations in terms of promoting equality and encouraging self-sufficiency in the analysis presented above. The overall benefit-cost ratio is expected to be much higher if social benefits are considered.

6. Conclusion and policy implications

This study evaluates the economic and social benefits of the village-level PVPA program in China. The PVPA program, which began in 2015, has become an important policy for achieving poverty reduction and clean energy SDGs. The evaluation of PVPA projects is crucial for three reasons. First, solar power, as a clean energy source with zero carbon emissions, is an energy source that can potentially help China meet the goals of the Paris Agreement. Second, small-to-medium-scale PV power stations are suitable for poor areas because they are environmentally friendly and do not require complex conditions. A large proportion of nationally designated poor counties are ecological protection zones in which the development of the manufacturing sector encounters many restrictions. The PVPA program can meet both economic development and environmental protection goals. Third, current supporting policies provide a large amount of PV subsidies for poverty-stricken areas. Therefore, this program has strong policy implications.

The sample county considered in this study is a typical case of a village-level PVPA project that can serve as a representative case for nationally designated poor counties. Compared with earlier literatures, the innovation of our findings lies in two aspects. On the one hand, our findings are consistent with previous studies that we document a significant impact on poverty alleviation. But we also extend their findings by focusing on the pro-equality effect of PVPA projects. Not all the community-based investment can benefit the poor, because poor people may lack capacities to utilize those opportunities. The poverty alleviation program documented in Park and Wang (2010) is one such example. But we find PVPA projects did a good job in targeting the poor and disclosing income disparity, mainly because the selection of eligible households is strict, and the revenue sharing schemes are applicable to poor people.

On the other hand, several studies have highlighted the high cost of building PVPA stations and difficulties in running PVPA projects (Ouyang and Lin, 2014; Fu et al., 2018; Yan et al., 2019; Zhao and Wang, 2019). However, none of them have conducted a cost-benefit analysis. To the best of our knowledge, our study is among the few that quantify PVPA's cost and benefit, directly showing that building PVPA stations is a cost-effective way to alleviate poverty.

Our findings not only contribute to the academic research but also have strong policy implications. It's suggested that PVPA projects could be a potential solution to achieve poverty reduction and environmental protection simultaneously in places where the solar endowment is rich. Another lesson we can draw from PVPA projects is providing local employment opportunities is a suitable way to help weak labors. Third, as a number of policies are implemented in a decentralized way, the ability of village officials are important.

Our study has potential limitations. It only exploits information in one county over an eight-year period. Analysis with broader geographical coverage and longer time span are necessary. Arising from the geographical coverage concern, another limitation of this study is it only examines the impact of the community-based PVPA projects, but multiple patterns exist. A thorough comparison between different PVPA patterns, which are centralized, community-based, and household roof stations, is obligatory to understand the socioeconomic benefits and environmental consequence of PVPA projects. Third, the social benefits of PVPA projects in boosting equality and encouraging labor supply is not quantified in the cost-benefit analysis yet. At last, even we have tried to explore mechanisms of PVPA projects, further detailed information is needed, for example, who actually took the welfare positions, and whether the treated households worked in local market or migrated to other places.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A

Table A1
Comparison between Literatures and Our Study

	Sampling frame	Sample size	Data source	Time span	Panel data	Method	Outcome variables
Zhang et al. (2019)	30 pilot counties in 6 provinces	30 counties	China County Statistical Yearbook	2014–2016	Yes	OLS	County level multidimensional poverty index
Zhang et al. (2020)	211 pilot counties and control group	963 counties	China County Statistical Yearbook	2013–2016	Yes	DID	County level disposable income
Liu et al. (2021)	Six national poor counties in six provinces	781 households	Self-collected household surveys	2013–2017	Retrospective panel	DID	Household capital
Liao et al. (2021)	Nine villages in two prefectures in Qinghai Province	Unknown	Self-collected household surveys	2018	No	OLS	Household income, energy transition
Huang et al. (2021)	Three poverty-stricken villages in the northwestern part of China	300 households	Self-collected household surveys	2016–2017	Unknown	OLS	Household income and living standard
Our study	One poverty-stricken county in the middle part of China	12,067 households and 179 villages	Administrative records provided by the county government	2014–2021	Yes	DID	Household income, labor supply; Village income inequality, collective economy, welfare position

Appendix B

Table A2
Examples of Village Revenue-Sharing Schemes

Village	PVPA stations	Scheme
A	There are three stations, the capacities of which are 36 kw, 60 kw, and 60 kw. The yearly revenue is 30,000 to 60,000 RMB.	Approximately 20% of revenue is used for maintenance and repair with the remaining 80% for poverty reduction. Sharing schemes are discussed in the village representative conference. The cash transfer is normally between 300 and 600 RMB per person. There are three welfare positions and monthly wages range from 500 to 700 RMB. Temporary welfare positions such as infrastructure construction are also subsidized.
B	The station capacity is 50 kw and the station is funded by county fiscal expenditure. The yearly revenue is 40,000 RMB.	Four welfare positions are provided at a monthly wage rate of 500 RMB. Approximately 30% of revenue is spent on maintenance and welfare positions, and the remaining 70% is distributed among 19 listed households. Households on the list and sharing scheme are discussed in the village representative conference and are made public to all villagers.
C	The station capacity is 50 kw and the station is funded by county fiscal expenditure. The yearly revenue is 30,000 to 40,000 RMB.	The PVPA project covers 17 households. Sharing schemes are discussed in the village representative conference. PVPA revenue finances welfare positions at a yearly income of 6000 RMB.
D	There are two stations, the capacities of which are 35 kw and 39 kw. The revenue is 50,000 to 60,000 RMB.	There are two welfare positions, the yearly wages of which are 4000 RMB and 5000 RMB. Approximately 80% of revenue is spent on the listed poor households with the other 20% spent on village construction and PVPA station maintenance. The cash transfer scheme is discussed in the village representative conference and is typically between 300 and 500 RMB per person.

Note: The PVPA station sharing schemes in County X were collected by the authors.

Appendix C. Representativeness of County X

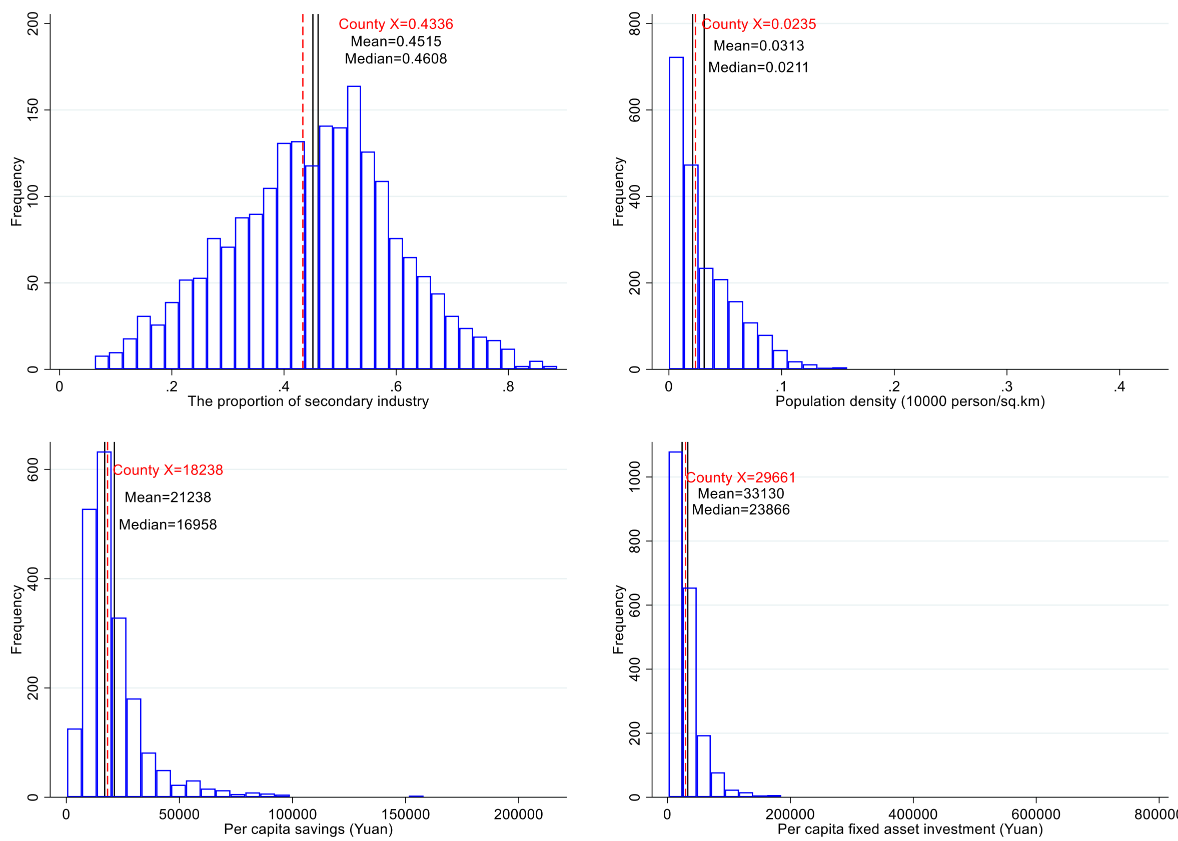

Fig. A1. Distribution of Economic Indicators of All Nationally Designated Poor Counties in 2014. Data source: China County Statistical Yearbook, National Bureau of Statistics, and provincial statistical yearbooks. The national mean, median, and level of County X are marked by spikes.

Table A3
Annual Lighting Times of Zhengzhou, Wuhan, Hefei, and Xinyang

Province	Henan	Hubei	Anhui	Henan
City	Zhengzhou	Wuhan	Hefei	Xinyang
Jan.	117.1	86.3	105.7	114
Feb.	170.1	109.2	123.9	99
Mar.	165.5	102.9	144.9	114
Apr.	199.4	160.4	184.5	156

(*continued on next page*)

Table A3 (*continued*)

Province	Henan	Hubei	Anhui	Henan
May	272.3	192.1	207.3	128
June	214.7	106.4	146.2	129
July	213.5	263.4	215.3	161
Aug.	179.7	173.7	121.8	169
Sept.	146.7	117.2	89.3	168
Oct.	80.2	103	95	213
Nov.	177.9	121.9	112.3	190
Dec.	178.5	125.5	129.6	99
Total	2115.6	1662	1675.8	1740

Note: Zhengzhou, Wuhan, and Hefei are the major cities in the central region of China. Xinyang is the city in which our sample county is located. Data source: China Statistical Yearbook.

Appendix D

Table A4
Illustration of Treatment Group and Control Group

		Pre 2014–2016	Post_1 2017	Post_2 2018–2021	Equation (1)	Equation (2)
First round PVPA villages	Eligible	N	Y	Y	Treatment	Treatment
	Ineligible	N	N	N	Control	
Second round PVPA villages	Eligible	N	N	Y	Treatment	Treatment
	Ineligible	N	N	N	Control	
Non-PVPA villages	NA	N	N	N		Control

Note: This table illustrates the treatment group and control group in Equations (1) and (2). In Equation (1) namely the household-level analysis, poor households eligible for PVPA revenue sharing are treatment group while poor households in PVPA villages ineligible for PVPA revenue are control group. In Equation (2) namely the village-level analysis, PVPA villages are treatment group and non-PVPA villages are control group. In Section 4.3.2, we further include all the poor households in non-PVPA villages as control group.

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