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Distributed photovoltaic adoption in rural Shandong, China: status, challenges, and influential factors

Zheng Zhen[1], Pengfei Zhang[2], Jiaxing Cao[3], Fan Su[4], Lu Tong[5], Yue Qi[6], Yuankang Li[7], Wendong Wei[5,7]

[1]College of Smart Energy, Shanghai Jiao Tong University, Shanghai 200030, China.
[2]Institute of Blue and Green Development, Shandong University, Weihai 264209, Shandong, China.
[3]School of Public Affairs, Zhejiang University, Hangzhou 310058, Zhejiang, China.
[4]School of Public Policy and Management, Tsinghua University, Beijing 100084, China.
[5]School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
[6]Research Center, State-Owned Assets Supervision and Administration Commission of the State Council, Beijing 100053, China.
[7]SJTU-UNIDO Joint Institute of Inclusive and Sustainable Industrial Development, Shanghai Jiao Tong University, Shanghai 200030, China.

Correspondence to: Dr. Pengfei Zhang, Institute of Blue and Green Development, Shandong University, No. 180, Wenhua West Road, Weihai 264209, Shandong, China. E-mail: 202120993@mail.sdu.edu.cn; Dr. Wendong Wei, School of Environmental Science and Engineering, Shanghai Jiao Tong University, No. 800, Dongchuan Road, Shanghai 200240, China. E-mail: wendongwei@sjtu.edu.cn

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Abstract

Distributed photovoltaic systems (distributed PV) enable rural households to replace traditional energy sources, reduce their household carbon footprint, and generate additional income. Due to the multiple benefits, China increasingly prioritizes developing distributed PV in its rural areas. However, the overall status, primary challenges of distributed PV in rural China, and how regional social and economic factors contribute to adoption choices of distributed PV remain largely uninvestigated. Here, we aim to provide insights into the above issues and offer a basis for policy recommendations that can facilitate the adoption of distributed PV, drawing from Shandong Province's experience. This study is based on a survey conducted in 2023, encompassing a total of 169 households across 36 villages in Shandong Province. Our results show that 43% of the households have embraced distributed PV with various system standards employed. We also find that rural households in Shandong Province encounter challenges engaging in distributed PV systems, such as inadequate policy support, significant heterogeneity of policy promotion among villages, a predominant emphasis on construction rather than management, and an extended payback period. We suggest that future attention should be paid to households that have not experienced extreme weather events and those that have not yet engaged in related low-carbon environmental activities. Local village officials should take the lead in spearheading policy promotion activities to enhance villagers' awareness and enthusiasm. Besides, efforts should be directed towards guaranteeing the availability of high-quality distributed PV systems with consistent standards.

Keywords: Distributed photovoltaic system, rural households, face-to-face survey, policy implication, Shandong Province

INTRODUCTION

The escalating climate change crisis has underscored the urgency of developing renewable energy, such as photovoltaics[1]. Among various photovoltaic technologies, the distributed photovoltaic system (distributed PV) is a promising solution[2,3]. Compared to the centralized photovoltaic system, the distributed PV offers several distinct advantages, including lower investment costs and reduced strain on the local grids[4]. Consequently, distributed PV has been recognized as a crucial way to achieve the goals of the Paris Climate Agreement[5]. Germany, for instance, implemented the *Renewable Energy Sources Act* in 2000, which included national subsidies to support the adoption of distributed PV[6]. The US and Japan have adopted similar subsidy policies to bolster the expansion of distributed PV[7].

The Chinese government has placed significant emphasis on developing distributed PV in its rural areas, where substantial rooftops and solar resources are available[8]. It is estimated that if distributed PV was universally applied in all rural households, these systems could provide up to 1.55 times China's annual electricity demand for non-production purposes[9]. In addition to the benefits of distributed PV in reducing carbon emissions, China regards it as an effective means to increase household income through electricity sales. Both the Photovoltaic Poverty Alleviation projects and the Rural Revitalization Strategy have highlighted the importance of promoting distributed PV in rural areas[10], and considerable subsidies have been provided to support the adoption of distributed PV, leading to a rapid increase in installed capacity across rural China[11,12]. In 2022, the growth in distributed PV reached 51.11 million kilowatts in China, accounting for 58.5% of the country's newly added photovoltaic capacity[13].

However, several challenges arise when advancing distributed PV in China's rural areas. The high installation costs and extended payback periods have limited rural residents' willingness to adopt such photovoltaic equipment[14]. This problem has also been observed in other countries, such as the United States[15] and Ireland[16]. Moreover, various cooperation modes exist in distributed PV adoption, which may inevitably bring obstacles to balancing the interests of different stakeholders and eventually influence the installation of such photovoltaic systems in rural China[17,18]. Previous efforts for promoting distributed PV in rural China mainly rely on governmental subsidies[19], while scant attention has been paid to measures through community relations and other socioeconomic factors[20,21]. Consequently, more comprehensive strategies are required to foster the development of distributed PV in China's rural areas[22].

Existing studies have investigated the influence of many factors on the installation of distributed PV, such as household characteristics, income level, environmental awareness, technique features, socioeconomic status, and policy incentives[22-24]. For example, Sommerfeld *et al.* investigated the influence of demographic variables on distributed PV adoption, indicating that home ownership was a major influencing factor[25]. Kurata *et al.* focused on the demographic and socioeconomic factors affecting family adoption of photovoltaic systems, and they confirmed that household income positively influenced their decision on distributed PV adoption, while the presence of a smoker had a negative impact[26]. In the context of Tehran, Bashiri and Alizadeh[27] found that environmental concerns and related knowledge positively influenced individual adoption of distributed PV, while a decrease in income negatively affected adoption rates. Agir *et al*. examined the opportunities and challenges of photovoltaics in rural areas from the perspective of farmers[28]. They revealed that mutual mistrust between stakeholders considerably declined households' willingness to adopt distributed PV. Kabir's research indicates that a comprehensive understanding of the impacts of energy or environmental projects on stakeholders and enhancing cooperation and communication among them are crucial for successful implementation[29]. Furthermore, Wu *et al*. developed a research framework encompassing the entire life cycle of rural distributed PV to identify obstacles to distributed PV adoption[30]. They indicated that imperfect policies, shrinking subsidies, exorbitant investment, and poor equipment quality jeopardized the development of rural distributed PV. However, existing studies have primarily focused on foreign countries, and there is a limited exploration of the overall development status, driving factors, and challenges of distributed PV in rural China, as well as how regional-specific factors contribute to adoption choices.

In this study, by conducting a household survey in Shandong Province, China, we uncover the critical aspects concerning the development of distributed PV in rural areas of Shandong Province, which contributes to a more in-depth understanding of the development of distributed PV in China and provides insights into its future development. Our survey covered 184 households from 36 villages in Shandong Province. The remainder of this study is organized as follows. Section 2 introduces our research methods, including survey design and data. Section 3 presents the current situation and challenges of distributed PV in Shandong Province. Section 4 discusses the results and implications for fostering distributed PV in rural China. Section 5 shows the conclusions of this study.

METHODS AND DATA

In this study, we have developed a research framework to guide our investigation [Figure 1]. This framework provides a structured roadmap that outlines the main components and stages of our research process.

Study area

This study employs survey data collected from questionnaires for rural households and village committees in Shandong Province, China, in 2023. Located in eastern China, Shandong Province has abundant solar radiation resources and PV development potential[24]. In 2021, Shandong Province ranked first in China in total installed PV capacity, with 14.92 million kilowatts of distributed PV connected to the grid[31]. This survey covered all prefecture-level cities in Shandong Province, except for Weihai, Liaocheng, and Laiwu (with a total coverage rate of 82.4%). At least one village in each city was included in this survey. The village locations are displayed in Figure 2.

Questionnaire design

Our research team drafted the questionnaire, which has been revised based on suggestions provided by experts with extensive experience in rural surveys. To avoid possible misunderstandings and assess the effectiveness of the face-to-face household survey, our team conducted a small-scale pilot survey including village committees of four villages and ten households. The household survey includes information on demographic variables, household energy consumption, related perceptions, distributed PV installation, and use status. The village committee survey involves basic village information, village energy consumption, related policies, and the development of distributed PV.

Survey and sampling method

The survey included questionnaires for farmers and village committees to understand the installation of Distributed PV in households and villages, respectively. Respondents were randomly selected from among

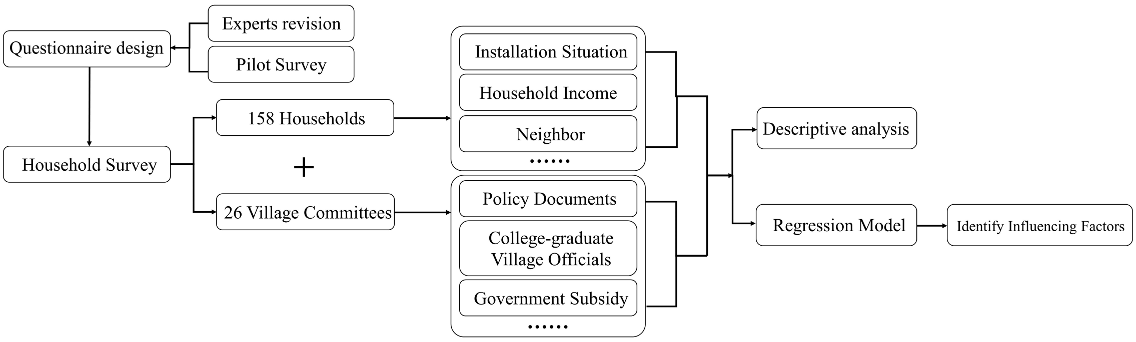

Figure 1. Research framework of this study.

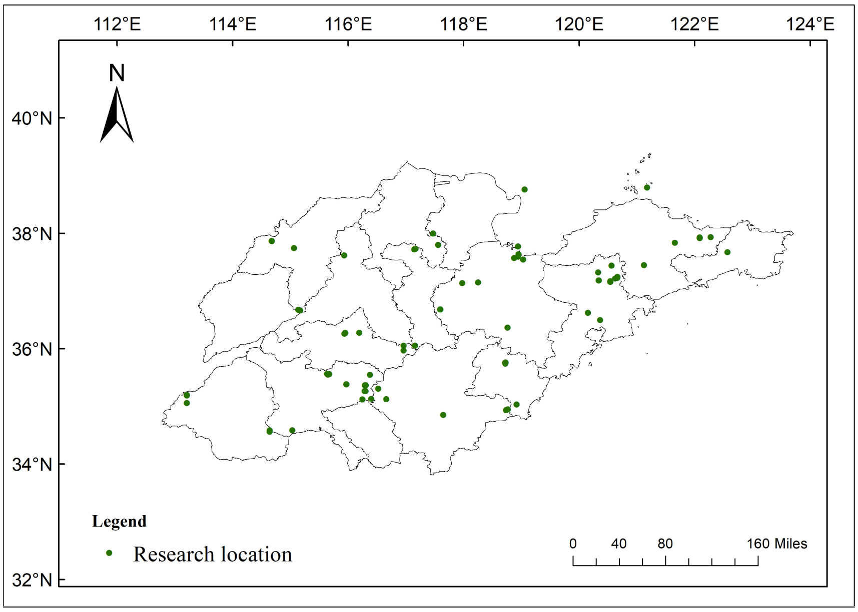

Figure 2. Survey site distribution.

the villages to ensure that the results represented the entire region. Specifically, all respondents were from that village. Respondents were also informed about their households as a whole. Due to the extensive geographical coverage and limitations imposed by socioeconomic factors, we dedicated two months, specifically from January to February 2023, to complete this survey.

There are three crucial points to note regarding our methodology. First, we conducted face-to-face interviews, which is a highly reliable method for obtaining a comprehensive set of information. This approach allows us to observe the specific conditions of PV systems in each household, underlying our construction of the information base for the rural households, the subject of our analysis. Second, we developed and administered questionnaires to rural households and village committees. This dual approach enables us to integrate information from the household and village levels, helping us to pinpoint problems in the promotion of distributed PV in rural China with a cross-supporting picture with villagers' information. Lastly, all of our interviewees were locals from Shandong Province. They were familiar with regional dialects and customs and trained in the intricacies of PV equipment, survey methodologies, and questionnaire implementation. This expertise ensured the collection of high-quality data and information in our study. The survey was distributed to 158 farmers and 26 village committees across 14 cities and 36 villages in Shandong Province. Of the 184 distributed questionnaires, 169 were valid (15 families did not complete the questionnaires).

Model setting

Logit regression uses a maximum likelihood approach to form a best-fit equation or function, which maximizes the probability that a given regression coefficient will classify the observations into the appropriate category[32]. In our research, the dependent variable (*Install*) is binary, representing the decision of the families about whether they install distributed PV or not. Thus, we apply the Logit model to analyze the decision of each family, which has been widely applied in analyzing the determinants of decision-making[33,34].

In this study, the installation of distributed PV in a household is a binary variable (1 for installed and 0 for not installed). The probability of a household i installing distributed PV, $Pr(Installi=1|X)$, can be written as follows:

$$Pr(Install_i = 1|X) = g(\beta_0 + \beta_1 X + e) \qquad (1)$$

$$g(x) = \frac{e^x}{1+e^x} \qquad (2)$$

where X is a vector of explanatory variables including low-income subsidies and poverty alleviation subsidies, household income, household electricity consumption, and neighborhood installation. β_0 is a constant term and β_1 is a vector of coefficients. e is a constant term. We have also incorporated the village-level variables into the model, including PV promotion by village committees and the experience of impoverished villages. This allows us to gain insights into factors influencing villagers' decisions to install distributed PV. The data and code used in this empirical analysis are available upon a reasonable request.

RESULTS

Overview of survey results

Table 1 presents partial results of the survey questions. To illustrate the current development of distributed PV effectively, we analyzed the results regarding installation status (including installation rate, types, and modes), challenges, and affecting factors, respectively.

Installation status of distributed PV

Photovoltaic equipment types

Several critical parameters, such as the photovoltaic installation mode, panel type, and equipment tilt angle, are significantly associated with the success of distributed PV promotion[35]. These factors directly impact household PV systems' power generation and revenue and are pivotal to the promotion of renewable energy. Depending on the type of residential roof, common rooftop photovoltaic models include tilt roof photovoltaic and horizontal roof photovoltaic[36]. The horizontal roof photovoltaic design considers the house's geographic conditions and the orientation and inclination angle of photovoltaic equipment, to enhance power generation efficiency. In recent years, a flat-to-slope photovoltaic mode has been diffused and adopted. This mode involves arranging the photovoltaic modules on a flat roof at a certain tilt, transforming the original flat roof into a tilted one. As a result, both the photovoltaic power generation and housing storage space increase. The data from rural households in Shandong Province reveals that 50.8% of

Table 1. Selected characteristics of the interviewed households and villages

Item	Definition	Response	No. of respondents	Percentage/%
Installation situation	Whether distributed PV is installed	Installed	61	42.66
		Not installed	82	57.34
Household income (Unit: 1,000 yuan)	Annual income situation	0-50	66	46.15
		50-100	55	38.46
		100-200	17	11.89
		200-300	4	2.80
		over 300	1	0.70
Neighbor	Is there a neighborhood with distributed PV	Installed	104	82.54
		Not installed	22	17.46
Subsidies	Is there any government subsidy	Yes	45	31.47
		No	98	68.53
College	Does the village cadre include college-graduate village officials or selected students	Yes	8	30.77
		No	18	69.23
Policy install	Are there policy documents to support or guide the development of PV technology	Yes	10	38.46
		No	16	61.54

households use the tilted roof photovoltaic mode, while 29.5% and 32.8% of households use horizontal roof and flat-to-slope photovoltaic modes, respectively [Figure 3A].

Furthermore, 86.9% of photovoltaic equipment consists of high-efficiency monocrystalline silicon or polycrystalline silicon modules [Figure 3B], contributing to a total annual power generation of 1.132 million kilowatt-hours. Among the surveyed households, 15.2% generate power of 10,000 kilowatt-hours or less and 6.5% exceed 50,000 kilowatt-hours annually [Figure 3C]. The power generation efficiency of distributed PV equipment can be affected by excessively small or large tilt angles of photovoltaic panels. Generally, the recommended tilt angle for photovoltaic equipment is equal to the regional latitude. Shandong Province is situated within the latitude range of 30-40° N, but our survey shows that 39.0% of the photovoltaic equipment has an inclination angle between 30-50°, and 57.6% has an inclination angle of less than 30° [Figure 3D]. Therefore, it is necessary to optimize the installation inclination angle for the distributed photovoltaic equipment.

Adoption modes for distributed PV

According to our survey, there are three kinds of adoption modes for distributed PV, namely resident-led mode, enterprise-led mode, and village-led mode [Figure 4].

54.1% of the households choose the resident-led mode, where both enterprises and households play a significant role. Under this installation mode, residents seek installation services from enterprises, and residents bear the costs and benefits. This mode offers residents full autonomy in using distributed PV, but it also places significant economic pressure on them. Compared to the other two modes, there is a higher likelihood of encountering challenges in ensuring regular on-site maintenance of photovoltaic devices and equipment.

41.0% of the households adopt the enterprise-led mode, which can be further divided into two types. One is where residents bear the installation costs and enjoy the electricity generation returns, and the other is

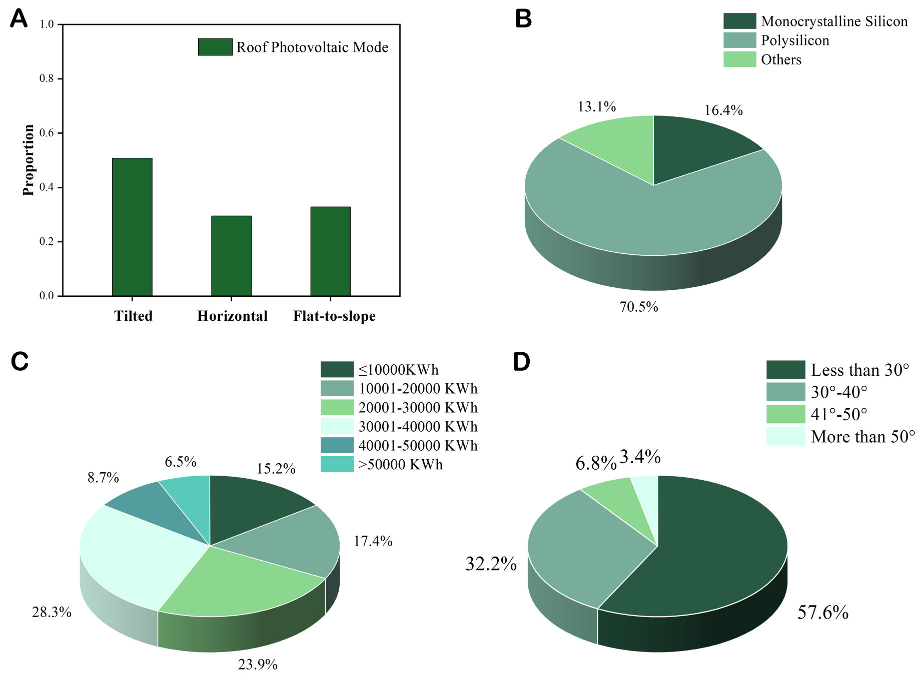

Figure 3. Descriptive statistical results of rooftop photovoltaic models (A), photovoltaic module types (B), annual power generation (C), and the tilt angle of photovoltaic equipment (D).

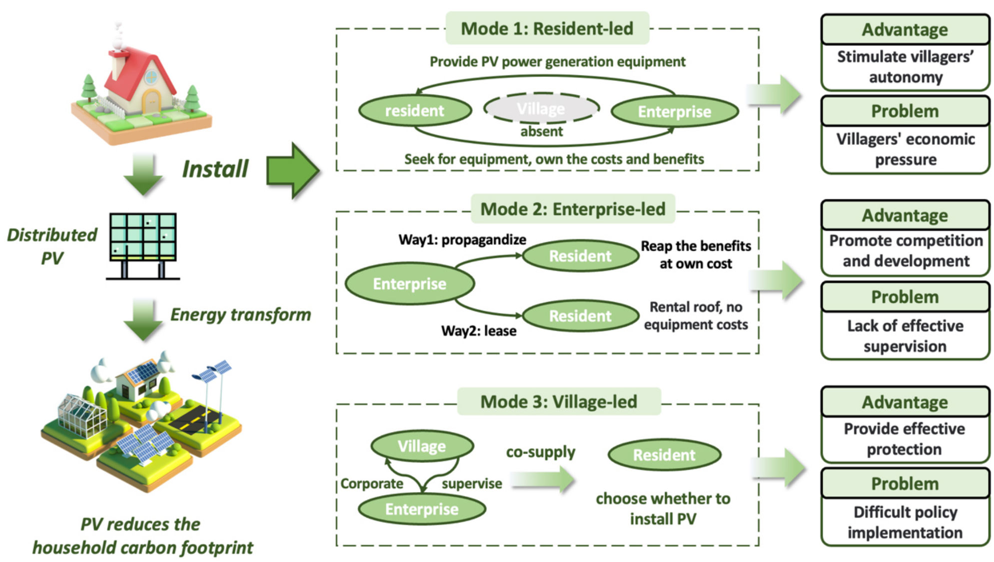

Figure 4. Different modes of photovoltaic installation and their pros and cons.

where enterprises rent residents' rooftops, cover the installation costs, and enjoy the electricity generation benefits. In the first case, due to the lack of government supervision and intervention, the returns from distributed PV may be overstated, and there is a risk of keeping long-term maintenance services.

The village-led mode accounts for only 4.9%. In this mode, the village committee coordinated and integrated the needs, and the enterprise provided installation and maintenance services. With the cooperation of village committees and enterprises, the cost and risk of residents' participation were significantly reduced. This model accounts for only a tiny part of the installed distributed PV. The village committees must take the initiative to understand the photovoltaic-related policies and promote implementation.

Installation rate

Within the surveyed households, 42.7% have installed and utilized the distributed photovoltaic system. 80.3% of these households handled the installation through direct contact with enterprises. Among the households that have installed distributed PV, 49.2% of the households leased their rooftops to enterprises and received a fixed annual subsidy. In comparison, 50.8% of the households chose the mode of "self-use first and the rest of the generation to the grid" or "all generation to the grid" .

Regarding installation costs, 41.0% of the users stated that the installation cost of photovoltaic equipment is fully covered, 11.5% of them spent 30,000-50,000 yuan, and 27.9% bear a cost of more than 80,000 yuan. Among the village councils interviewed, 26.9% received energy transition targets from superior authorities, and 38.5% received the target of carbon peaking and carbon neutrality. 42.3% of villages benefited from clear photovoltaic policy support, with 45.5% under the "whole county photovoltaic" scheme. Meanwhile, 38.5% of the village councils confirmed receiving financial subsidies for photovoltaic installations.

Satisfaction

Previous studies show that the high satisfaction of rural households with distributed PV is often based on high subsidies and high power reliability[37], and installation costs and power generation revenues are the main factors affecting residents' willingness to install distributed PV and satisfaction[15,16]. Among the households that have installed distributed PV, 18.0% are unsatisfied, and only 21.3% are satisfied [Figure 5A]. The villagers' primary concerns regarding installing photovoltaic equipment include diminishing subsidies, elevated installation costs, and a limited understanding of the related policies. Additionally, some enterprises fail to provide proper maintenance and supervision after the installation. According to the survey results, 25.2% of villagers reported a lack of awareness regarding policies related to photovoltaic installation. Additionally, 51.7% mentioned that local government departments or enterprises did not conduct follow-up visits or provide regular maintenance for photovoltaic equipment in the previous year [Figure 5B]. It's evident that there is room for improvement in the current practices of installing and maintaining distributed PV systems.

Challenges of distributed PV development

Insufficient policy promotion

Results show that the transmission rate of photovoltaic policy-related documents to the village-level administrative units is less than 50%. Furthermore, 53.8% of the village committees have never publicly publicized photovoltaic-related policies and 34.6% of the village committees do not participate in the process of villagers purchasing and using photovoltaic equipment [Figure 5C]. This also leads to the lack of a comprehensive understanding of distributed PV systems for households by villagers. In our survey, 64.4% of the villagers said that they did not understand the relevant policies on the installation of such systems, only 11.2% of the villagers had familiarity with the relevant policies [Figure 5D], and 31.2% of the villagers learned the relevant information through the dissemination by the village committee or enterprises. In addition, during the installation process, 88.52% of the villagers said that the village committee did not participate at all or rarely participated in the specific installation process. 30.4% of the villagers who did not

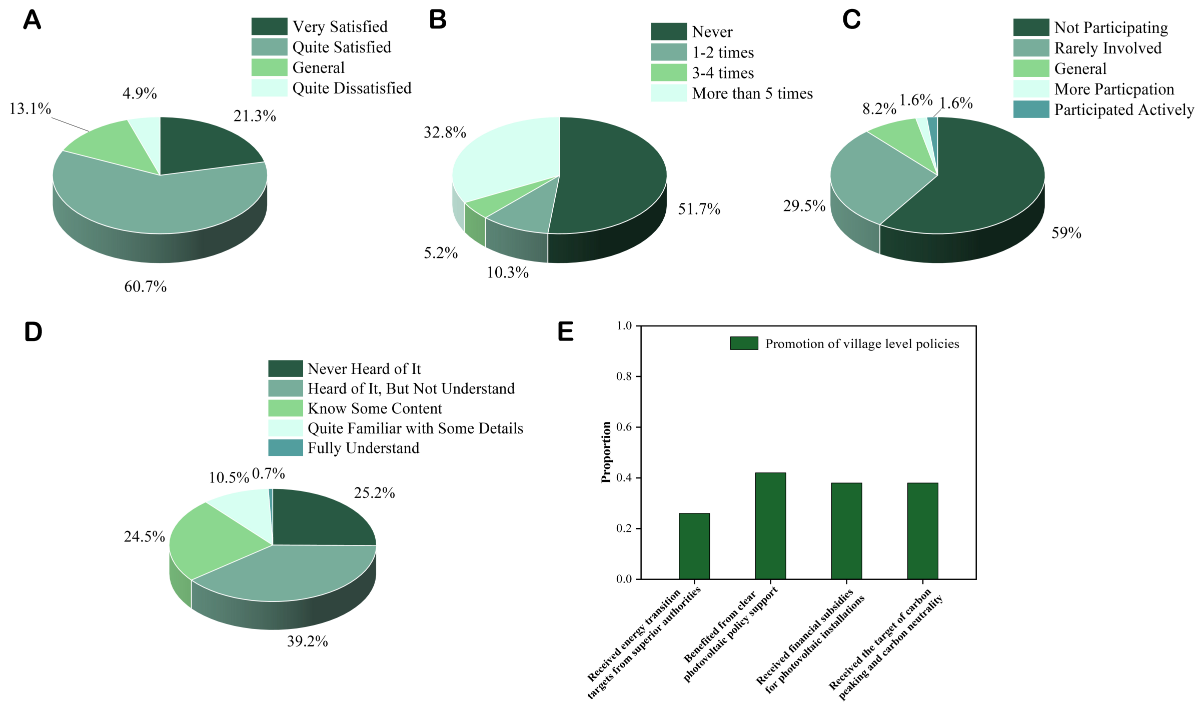

Figure 5. Descriptive statistical results of satisfaction with photovoltaic (A), maintenance frequency in the previous year (B), participation of village committees (C), installation policy awareness (D), promotion of village level policies (E).

install the distributed PV system admitted their confusion about the actual situation, which caused them to hesitate to a large extent.

Regional disparities in installation

Due to regional differences in policy communication, local promotion, and other factors, the development of distributed PV for rural households varies greatly between towns and villages. Previous studies have shown that policy tools and publicity guidance positively affect farmers' willingness to adopt clean energy[38], and our research results also reflect the impact of such factors on photovoltaic installation in different villages and towns. On the one hand, the effectiveness of PV-related policies on local communication is different, which may lead to differences in the number and type of policy guidance received by each village and village committee, resulting in differences in the actual PV installation situation. According to the survey results, the average photovoltaic penetration rate of villages and towns with clear documents guiding the development of village photovoltaic and the provision of residential photovoltaic subsidies reached 5.6% and 5.4%, respectively, while the average photovoltaic penetration rate of villages and towns without relevant subsidies or documents is only 1.6% and 0.7% [Figure 5E].

Table 2 lists the policy communication and propaganda of the village committee of typical villages. It can be seen that the more complete the photovoltaic-related policy documents of the villages and towns, the higher the proportion of photovoltaic installation. On the other hand, there are also differences in the policy publicity of village committees in different regions. In villages where village committees engaged in public advocacy - a practice observed in 46.2% of the sample - the photovoltaic installation rate reached 5.8%, higher than the average across all sampled villages, reflecting that the propaganda of village committees bears the potential to foster photovoltaic systems adoption. As shown in Table 2, through typical villages, we can intuitively find that villages that take more measures in policy promotion and advocacy are more likely to increase the installation of PV in villages.

Table 2. PV installation percentage and promotion policy of representative villages

Representative villages	Whether there is a PV-related policy	Whether there is a policy to provide PV subsidies	Whether there are energy transition indicators required	Whether the village committee promoted PV	Installatio percentage (%)
Village 1	○	○	○	○	0
Village 2	○	○	●	○	0
Village 3	○	○	○	○	25.0%
Village 4	●	○	○	○	33.3%
Village 5	○	●	○	▲	50.0%
Village 6	○	●	○	▲	55.0%
Village 7	●	●	●	▲	80.0%
Village 8	●	●	●	●	90.9%
Village 9	●	●	○	▲	100.0%

○: No, ●: yes, ▲: the villagers' response is inconsistent with the village committee.

Overlooked maintenance

The survey results show that the lack of government and enterprise in the operation and maintenance of photovoltaic equipment is severe, resulting in the frequent failure of photovoltaic equipment. 34.6% of village committees are not involved in villagers' purchase and use of photovoltaic systems, and more than half of the village committees said that photovoltaic enterprises never revisit for annual maintenance. Moreover, even a few village committees had no record or understanding of the revisit of the enterprises. At the same time, 49.2% of the interviewed households reflected that the enterprises never revisited to inspect the photovoltaic module equipment in the previous year.

19.7% of the villagers said they had encountered photovoltaic failure, ranging from 1 to 5 times. 24.5% of the villagers were dissatisfied with the current installation and use of photovoltaic equipment, demanding the government strengthen supervision, enterprises to ensure regular maintenance, *etc*. Strengthening the cooperation between government and enterprises to improve the lack of maintenance of photovoltaic equipment can effectively reduce the frequency of equipment failure, enhance customer satisfaction, and promote the healthy development of the photovoltaic industry.

High costs and long payback periods

Despite promoting distributed PV systems, the progressively declining subsidies for new energy and photovoltaics impose a significant barrier[39]. The high cost of installing such systems, with its extended payback period, places a notable financial burden on villagers, thereby hindering its widespread adoption. On the one hand, with the high installation cost of photovoltaic equipment, villagers are under tremendous pressure to take out loans. According to the research results, 34.6% of the villages in the sample had been national or provincial poverty-stricken villages, 9.8% of the villagers need loans to purchase photovoltaic equipment, of which 66.7% of photovoltaic loans for three years or more, which brings additional economic pressure on the villagers. On the other hand, the photovoltaic income shrinks, and the payback period becomes longer. 84.6% of villagers hope to recover the installation cost within five years. In fact, in recent years, photovoltaic subsidies have continued to retreat. In Shandong Province, the photovoltaic feed-in tariff decreased by 0.35 yuan/kWh in 2018 compared to 2013; among the villagers interviewed, 65.5% reported annual incomes of less than 5,000 yuan from their installed family photovoltaic power generation systems, while 49.2% indicated that the cost of installing photovoltaic equipment was 50,000 yuan or more.

In the absence of additional government subsidies, most families have difficulty in recovering costs within a predetermined period.

Factors affecting photovoltaic installation for rural households

Given the above findings, we have identified several obstacles to the policy promotion of rural household photovoltaic installation. However, we must consider other factors associated with the installation of such systems and quantify their impact. Understanding these factors will enrich our knowledge of the current advancement of distributed photovoltaics in rural China, thus paving the way for further policy measures and reduction of the carbon footprint of rural households.

This paper integrates household and village-level variables in the Logit model. Table 3 presents the logit regression with *Install* as an explained variable. The first column presents the logit regression of *Install* on family level characteristics; the second column presents the logit regression of *Install* on village level characteristics; the third column includes all family and village level explanatory variables; the fourth column further uses heteroscedasticity-robust standard errors based on the third column. To present a more intuitive understanding of the influence of different factors, we list the odds ratio and corresponding confidence interval estimations of different variables in the final column.

Household-level factors

At the household level, the factors that significantly influence the installation of photovoltaics in rural households are the experience of extreme weather and participation in other low-carbon environmental policies. This suggests that even though household photovoltaic systems can help people to be more resilient to extreme weather to some extent, they do not appear to do so based on the results of the survey of households in Shandong Province, where households that have experienced extreme weather leading to electricity problems are more reluctant to install photovoltaic systems than those that have not experienced extreme weather, with installation rates of only 9% (β = -2.392, odds ratio = 0.09, $P < 0.01$). This also poses challenges for installing photovoltaic equipment and adapting rural households to extreme weather conditions[40,41]. Households that had participated in policies such as coal-to-gas and coal-to-electricity conversions showed a higher motivation to install photovoltaic equipment, with a 20.17 times higher installation ratio compared to households with no experience in low-carbon policy participation (β = 3.004, odds ratio = 20.17, $P < 0.001$). It suggests that existing energy retrofit policies have spillover effects on future local low-carbon transitions in addition to the critical role they already play and that high levels of public policy engagement can drive community-wide energy transitions[42].

However, our study reveals that household income and social norms are not significant factors in installing photovoltaic equipment, which diverges from the conclusions of previous studies[20,43]. The face-to-face household surveys conducted in our research appear to provide new insights that contrast with the existing literature. As two villagers told us:

"As you can see in our village, rich families do not want to install, and the poor have no money to afford this equipment and dare not install it. If the good things are already rolled out, it is not our turn." (Interview ID: 20230206SDJN0108)

"Many households in our village have installed, but some enjoy the minimum living guarantee, so when the village cadres told them to install this, they soon agreed. However, if you want a family like mine to do it, I don't necessarily want even if all others have installed (such systems)." (Interview ID: 20230214SDRZ0105)

Table 3. Effects of household level and village level variables on installation

	(1) Family	(2) Village	(3) Family & village	(4) Family & village	(5) Odds ratio
Weather	-0.339		-2.392**	-2.392**	0.09
	(-0.61)		(-2.29)	(-2.15)	[0.01, 0.81]
Activities	1.677***		3.004***	3.004***	20.17
	(2.79)		(2.88)	(2.71)	[2.29.177.77]
Neighbor	1.762**		1.397	1.397	4.04
	(2.40)		(1.23)	(0.91)	[0.20, 82.92]
Income	-0.205		0.491	0.491	1.63
	(-0.66)		(0.84)	(0.83)	[0.51, 5.18]
Subsidies	0.049		0.708	0.708	2.03
	(0.10)		(0.86)	(0.93)	[0.46, 8.98]
Consumption	-0.475		-0.285	-0.285	0.75
	(-1.32)		(-0.40)	(-0.53)	[0.26, 2.14]
Publicity		0.764	0.714	0.714	2.04
		(1.34)	(0.82)	(0.79)	[0.35, 12.08]
Collage		-1.871**	-4.012**	-4.012***	0.02
		(-2.29)	(-2.28)	(-3.03)	[0.00, 0.24]
Poverty		-0.383	0.211	0.211	1.23
		(-0.63)	(0.20)	(0.18)	[0.13, 11.93]
Policy envprotect		0.453	1.214	1.214	3.37
		(0.73)	(1.21)	(1.10)	[0.38, 29.59]
Policy install		-0.020	1.970	1.970	7.17
		(-0.03)	(1.63)	(1.50)	[0.55, 93.71]
Plan		0.623	-1.030	-1.030	0.36
		(0.80)	(-0.78)	(-0.81)	[0.03, 4.35]
Notice		-0.182	-0.146	-0.146	0.86
		(-0.30)	(-0.11)	(-0.12)	[0.09, 8.68]
Constant	-0.611	-0.880	-5.770	-5.770	0.00
	(-0.22)	(-1.34)	(-1.06)	(-1.26)	[0.00, 25.35]
Observations	122	105	89	89	89
House structure FE	YES		YES	YES	YES
Energy type FE	YES		YES	YES	YES
Robust Std. Err.				YES	YES
Pseudo R-squared	0.188	0.115	0.389	0.389	0.389

***P < 0.001, **P < 0.01 (two-tailed tests), column 5 is 95%CI. Consumption is treated logarithmically.

This is a microscopic interpretation of the regression results and a further reflection of the current problem of insufficient publicity of distributed photovoltaic policies. Promoting their active participation in understanding relevant knowledge may be more effective for these households than subsidies, as highlighted by the theory of planned behavior, attitude, and subjective self-regulation of new energy, which are more likely to drive their adoption and other low-carbon behaviors.

Village-level factors

Additionally, we found that implementing policies such as photovoltaic poverty alleviation and whole-county photovoltaics at the village level did not significantly increase the installation of household photovoltaics by rural households. Previous studies have shown that photovoltaic poverty alleviation can improve rural energy poverty[44], increase the cleanliness and energy affordability of farmers' energy consumption, and promote rural energy transformation[10].

Meanwhile, village committees, as representatives of grassroots power in rural China, have played an important role in waste separation[45] and bioenergy promotion[46]. However, their efforts in photovoltaic poverty alleviation and countywide photovoltaic pilots have not significantly increased the installation rate of distributed PV among villagers. The possible explanation for this phenomenon may lie in the abovementioned phenomenon: A majority of households (95.1%) that install distributed PV opt for the resident-led or enterprise-led modes, while a mere 4.9% choose the village-led mode.

The variable of "college-graduate village official" has a significant negative impact. The estimated results of the Logit model show that, holding other variables constant, the installation rate of distributed PV in villages with college-graduate village officials is only 2% of those without such officials (β = -4.012, odds ratio = 0.02, P < 0.001). The possible reason may be that non-local officials in rural China may find it challenging to gain the trust of local residents, especially when implementing policies that may cause conflicts of interest[47]. A limited term of office is not enough for them to integrate into the existing local network based on blood and clan[48].

DISCUSSION

Over the past decade, China has allocated substantial financial resources for the development of distributed PV in rural areas, leading to remarkable increase in installed capacity of distributed PV systems. However, further efforts are still needed to promote the development of distributed PV in rural China. In this study, we investigated the status, challenges, and influential factors of distributed PV adoption in rural areas of Shandong province. Compared to previous research, we have some new findings, including that household income and social norms do not have a significant impact on distributed PV adoption. Results show that households that had participated in earlier energy retrofitting actions, such as coal-to-gas and coal-to-electricity conversions, have a higher motivation to install distributed PV systems. Our study also reveals that having well-defined policy objectives can effectively stimulated the growth of distributed PV. In addition, establishing national-level installation standards for distributed PV is needed, which can help prevent quality issues that may arise due to commercial interests.

Our findings highlight the pivotal role of access to finance in facilitating rural households to invest in distributed PV systems, as the initial costs can be substantial. Several measures can be utilized, such as government subsidies, low-interest loans, and innovative financing models. In particular, streamlining the loan approval process through financial institutions like banks can enhance the accessibility of loans for households. In addition, it is essential to strengthen the maintenance of photovoltaic equipment by companies to ensure the smooth operation of distributed PV systems. Actually, the adoption mode, maintenance, and equipment quality are interconnected and should be considered collectively. Summarizing the experiences of pilot programs and gathering user feedback on various modes, product suppliers, and service providers, can assist households in making decisions when installing distributed PV systems.

This study proposes a phased approach. The initial priority should be the promotion of distributed PV in households that have participated in government-related policies and have not been adversely affected by extreme weather. This strategy is preferred over targeting economically well-off households or villages. It also requires that local village committees first acquaint themselves with related policies and knowledge and dispatch local people who share close relationships with villagers to guide the installation process so that villagers can obtain low-carbon energy through distributed PV systems while improving their life quality with minimum financial burdens.

The government needs to consistently refine its promotion policy for distributed PV for rural households. This entails comprehensive planning and the establishment of related promotion standards, along with pilot villages, to facilitate its implementation at the village level. These pilot programs should encompass grid-connected standards, enterprise access standards, equipment operation standards, and performance evaluations. It is especially crucial to establish an appropriate subsidy standard, as previous studies have highlighted that reduced subsidies can considerably decline households' willingness to install distributed PV[16]. Ultimately, the government's focus should be on ensuring the efficient and stable operation of photovoltaic systems, optimizing the cost burden on households, supervising the operation of relevant enterprises and the provision of maintenance service, assessing the performance of village-level photovoltaic initiatives, and establishing a long-term low-carbon management mechanism.

Photovoltaic companies should take the initiative to raise their standards and actively engage in formulation of industry standards to support organized market participation. These companies shall prioritize the provision of regular maintenance service, foster robust partnerships with relevant village committees, ensure the consistent operation of the equipment, and base their market expansion efforts on the satisfaction of users.

For the village committees, it is necessary to carry out in-depth policy advocacy by thoroughly understanding the photovoltaic policies of the higher-level governments, including various environmental protection and low-carbon initiatives. They should align the promotion with local customs to resonate with villagers. In addition, village committees should fully understand the actual needs of residents and promote the development of distributed PV systems to help them achieve multiple economic and low-carbon benefits, thereby improving their life quality.

For rural households, it is essential to acquire knowledge related to PV systems and actively engage in low-carbon and environmental protection activities that align with their needs, which has positive associations with their distributed PV adoption intention[49]. They should also be cautious about incurring excessive financial burdens resulting from photovoltaic loans and prioritize regular inspection and maintenance to ensure the optimal functioning of their photovoltaic systems.

Notably, as the share of intermittent renewable energy sources such as wind and solar increases in the power system, maintaining stability in the electricity grid becomes challenging. Therefore, as Shandong develops distributed PV, it is important to enhance the flexibility of the power system. One strategy is to encourage a significant number of coal-fired power plants within the province to participate in flexibility supply through the implementation of the recently proposed capacity-based pricing mechanism by the National Development and Reform Commission. Additionally, electrochemical energy storage holds great potential; however, its current costs remain high. Moreover, collaborating with businesses and employing demand-side response methods can also provide flexibility to the power system.

Our study is subject to several limitations. One main limitation is that the findings and suggestions drawn from our survey conducted in Shandong Province may not be applicable to other regions, as there are significant variations in photovoltaic resources, economic development, and lifestyle across different regions in China. Another limitation is that we did not consider the installation year of distributed PV systems in households, which could introduce uncertainties to our results. The costs and government subsidies associated with installing distributed PV systems can vary from year to year, influencing households' decisions regarding the adoption of distributed PV. Moreover, constrained by factors such as personnel costs and research funding, the sample size in this study was relatively small, thereby limiting our capacity to conduct a more in-depth analysis of the heterogeneity of distributed photovoltaic adoption across regions. To further enhance our understanding of the development of distributed PV in China, it will be necessary to conduct surveys that include more regions and details regarding household distributed PV systems in future studies.

CONCLUSION

Promoting the development of distributed PV is a critical strategy to reduce household carbon footprint and an essential measure to achieve carbon neutrality in China. This study aims to ascertain the development status, promotion model, and problems of distributed PV in rural China through an extensive household survey in Shandong Province and provide corresponding policy recommendations.

While China has made substantial progress in renewable energy development, including PV, with some villages demonstrating high installation rates of distributed PV, our household survey in Shandong Province reveals that more comprehensive policies are required to foster the development of distributed PV in China's rural areas. Implementing these policies depends on efficient coordination among higher-level governments, local village committees, enterprises, and villagers. In addition, high-quality standard policy documents for distributed PV are a prerequisite for addressing various challenges of distributed PV in rural areas. Moreover, it is vital to consider the impacts of family and village heterogeneity on households' installation behavior.

DECLARATIONS

Author contributions

Writing - original draft, visualization, software, methodology, investigation, formal analysis, data curation: Zhen Z
Writing - review & editing, methodology, investigation, formal analysis: Zhang P
Writing - review & editing, supervision, resources, investigation: Cao J
Supervision, software, methodology: Su F
Writing - review & editing, methodology, investigation: Tong L
Investigation, formal analysis, data curation: Qi Y
Investigation, formal analysis: Li Y
Conceptualization, writing - review & editing: Wei W

Availability of data and materials

The data and code used in this study are available upon a reasonable request.

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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