Journal of World Economy
ISSN 2709-3999
www.pioneerpublisher.com/jwe
Volume 2 Number 4 December 2023

Cost–Benefit Analysis of China's Whole County PV Program: A Case Study of Julu County, Hebei Province

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doi:10.56397/JWE.2023.12.03

Abstract

Solar photovoltaics' rising efficiency is increasingly considered the key to achieving carbon neutrality targets in various countries. The Chinese government implemented a variety of regulations from both the supply and demand sides to assist in the development of distributed photovoltaics in the second decade of the twenty-first century. The whole county-wide photovoltaic promotion project, announced in 2021, is regarded as one of the most important new energy development projects in China in the coming years. The paper examines the cost and benefits of a pilot whole-county distributed photovoltaics project in Julu County, Hebei Province, from the perspectives of different stakeholders. The analysis shows that as China enters the era of grid parity, the whole county's distributed photovoltaics programme still exhibits robust economic, social, and environmental performance in locations with abundant solar resources. And different business models have a significant impact on the distribution of interests among stakeholders. The goal of this paper is to offer effective policy recommendations for promoting the development of distributed new energy beyond urban areas.

Keywords: cost-benefit analysis, rooftop PV, Whole County Program, economic benefit, environmental benefit, decarbonization

1. Introduction

Since the signing of the Paris Agreement, an increasing number of nations have put forth ambitious carbon peak and carbon neutrality targets. These countries include Thailand (Pongthanaisawan et al., 2023), China (Zhao et al., 2022), and Switzerland (Li et al., 2020), etc. Considering that carbon dioxide emissions from the combustion of fossil fuels are the primary drivers behind the escalating atmospheric carbon dioxide concentrations (Raupach & Canadell, 2010), it is evident that the adoption of renewable energy sources in lieu of fossil fuels has emerged as a vital technological solution in the pursuit of carbon neutrality objectives. As indicated in Lazard's 2021 levelized cost of energy (LCOE) report (LAZARD, 2021), the average unsubsidized LCOE per megawatt-hour (MWh) for photovoltaic (PV) power generation exhibited a remarkable decrease from $359/MWh in 2009 to $36/MWh in 2021, as depicted in Figure 1. This reduction is notably below the costs associated with coal-fired power generation ($108/MWh), nuclear power generation ($167/MWh), and geothermal power generation ($75/MWh). Professor Gregory F. Nemet (2019) attributed this impressive trajectory in the affordability of solar energy to several key factors throughout its developmental timeline. These include the pioneering technological innovations in the United States during the 1970s, the substantial expansion of markets in Japan and Germany starting from the 1980s, and the substantial upscaling of production by Chinese solar energy enterprises upon entering the 21st century. This growth can be attributed to a unique combination of high-risk entrepreneurial ventures, proactive government support that allocated substantial resources to these enterprises, and a significant number of orders secured through international trade with Western nations in the early stages. Over the years spanning from 2000 to 2016, Chinese PV companies impressively expanded their production scale by a factor of 500 (Jefferson, 2019). By 2021, China had established itself as the dominant player across all stages of solar panel manufacturing, encompassing the production of polysilicon ingots, wafers, cells, and modules, contributing to more than 80% of the global output (IEA, 2022). From a demand perspective, China exhibited a resounding commitment to renewable energy by incorporating 106 GW of new solar PV capacity in 2022, representing 44% of the world's total addition (REN21, 2023). Moreover, from 2012 to 2022, China amassed a cumulative solar installed capacity exceeding 400 GW, accounting for approximately 35% of the world's accumulated installed capacity (REN21, 2023). In light of China's predominant role in both the production and demand aspects of solar PV power, an in-depth exploration of the latest PV policies in China bears great significance. Such an investigation not only facilitates comprehension of the process by which PV energy becomes more affordable but also sheds light on the broader energy transition journey, where renewable energy takes precedence over fossil fuels. Ultimately, this insight informs the feasibility of carbon neutrality goals for various nations.

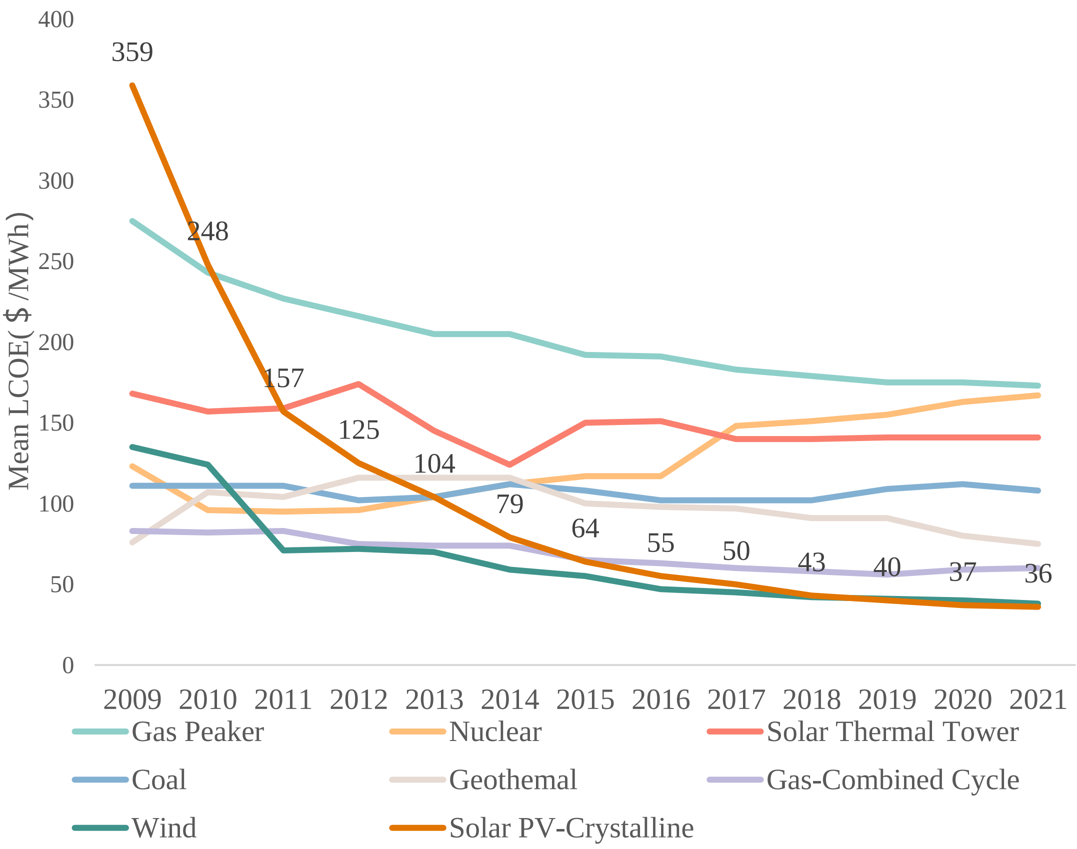

Figure 1. Selected Historical Mean Unsubsidized LCOE Value

Owing to the pressing demand for land resources (van de Ven et al., 2021), the substantial transmission losses incurred when transmitting electricity from distant PV projects to densely populated regions (Ito et al., 2005), and the significant share of residential energy consumption in the overall energy usage (Goldstein et al., 2020; Nejat et al., 2015), numerous countries are redirecting their focus in solar development from centralized PV power stations to distributed rooftop PV installations (Xie et al., 2022). This paradigm shift is exemplified by China, where distributed PV additions constituted over 60% of the newly installed solar capacity in 2022 (David et al., 2023). The burgeoning capacity of distributed PV systems has emerged as the principal catalyst in the advancement of PV power generation in China. In September 2021, the National Energy Administration of China unveiled a comprehensive program listing 676 pilot counties slated for the implementation of the whole county PV initiative. The primary aim of this initiative is to accelerate the expansion of rooftop distributed solar capacity in Chinese counties (National Energy Administration of China, 2021a). This program has garnered widespread recognition as the pivotal driving force behind the surge in China's solar capacity over recent years (Hove, 2023).

In the context of global governments' heightened efforts to achieve carbon neutrality targets and facilitate the transition to sustainable energy sources, it has become increasingly imperative to assess both the costs and benefits associated with China's current promotion policies for key rooftop PV systems. This paper endeavors to address the following essential questions: What are the environmental, economic, and social implications in terms of costs and benefits arising from the Chinese whole county PV program, and how do they vary from the perspectives of different stakeholders? The answers to these questions hold the potential to furnish invaluable theoretical underpinnings for the Chinese government. Such insights can aid in steering the energy transition process, facilitating a comprehensive understanding of variances in energy efficiency at a geographical level, and charting a course toward achieving carbon peak and carbon neutrality objectives. Additionally, the findings will serve as a reference not only for other nations but especially for those with a substantial rural population. These countries can draw upon the lessons learned from China's approach to deploying rooftop distributed PV promotion policies as part of their strategies for energy decarbonization.

The subsequent sections of this paper are organized as follows: Section 2 comprises a comprehensive review of the literature, providing insights into the existing body of knowledge on the subject matter. Section 3 delves into our methodology and data, including the construction of a robust cost-benefit analysis model. Section 4 presents the empirical results derived from our analysis, and Section 5 offers a concise conclusion, summarizing key findings from the empirical study and providing relevant policy recommendations.

2. Literature Review

2.1 Research on Chinese Rooftop Distributed PV Projects

Previous research has primarily concentrated on assessing the impact of distributed rooftop PV systems in terms of their economic and environmental performance. The economic ramifications of such systems are often evaluated by quantifying changes in key economic indicators, while their environmental effects are predominantly assessed through the application of the life cycle assessment method. Li et al. (2018) employed the economic indicators of net present value (NPV) and simple payback period to gauge the economic performance of rooftop solar PV installations across 14 households within five distinct climate zones in China. Zhao and Xie (2019) utilized NPV, internal rate of return, and payback period to construct an evaluative framework for analyzing the economic performance of industrial and commercial rooftop distributed PV systems in the provinces of Ningxia, Qinghai, Shandong, Zhejiang, and Sichuan in China. Their analysis concluded that rooftop PV systems in the northern region of Ningxia exhibited the highest profitability. Duman and Güler (2020) evaluated the economic benefits of a 5KW household PV system in Turkey using economic indicators such as the discounted payback period, IRR, and profitability index, calculated through the HOMER GRID software. In terms of environmental impact, Nugent and Sovacool (2014) reviewed 23 recent solar PV studies, revealing that the average greenhouse gas emissions during the life cycle of solar PV systems amounted to 49.9g CO_2/KWH. They suggested that the majority of carbon emissions from PVs occur during the construction and fabrication stages. The Asia-Pacific Economic Cooperation (APEC) energy working group conducted comprehensive full lifecycle assessments of several PV projects in multiple APEC countries. They determined the impact of different lifecycle stages of these distributed PV projects on greenhouse gas emission growth and pollution emissions (APEC Energy Working Group, 2019). Guo et al. (2019) employed the life cycle assessment method to calculate the carbon footprint of a 1KW PV system in China. Their calculations indicated that, in regions with abundant solar energy and an average annual effective illumination time of 3000 hours, a typical 1KW Chinese PV power generation system would reduce carbon emissions by 23.684 tons of carbon dioxide during its entire lifecycle.

Before the Chinese government discontinued subsidies for rooftop distributed PV systems and the implementation of the grid parity policy in 2021, previous studies concerning China's rooftop distributed PV policies predominantly cantered on alterations in feed-in tariff and subsidy policies. In a study conducted by Tu et al. (2019), the impact of steadily decreasing feed-in tariff rates on the profitability of PV power plants in China was examined. Additionally, the study assessed the feasibility of introducing a carbon pricing mechanism to address the resulting financial challenges. Among the limited literature addressing the promotion of whole county PV projects across entire counties, Zhang et al. (2023) presented a case study involving a county-wide promotion initiative in Heilongjiang Province, China. This study scrutinized the project's advantages by assigning monetary value to its environmental benefits and incorporating these values into the economic evaluation metrics. Hove (2023) investigated the economic advantages of integrating heat pumps into specific regions of PV projects within the framework of the whole county PV project. The findings of this research indicated that the combination of heat pumps and PV systems yielded the most substantial benefits in the central and northern regions of China.

2.2 Cost-Benefit Analysis

Cost–benefit analysis (CBA) is a systematic approach for assessing both the positive and negative impacts of a given system. When applied to new energy systems, CBA can be conducted from various viewpoints, including those of new energy system customers, utilities, total resources, non-participating customers, and government-related perspectives. A notable illustration of this is the evaluation of the Net Energy Metering (NEM) electricity pricing mechanism. In the case of Nevada, the government formerly conducted a comprehensive cost-benefit analysis of the NEM program, considering five key aspects: installed customers, uninstalled customers, utilities, total energy costs, and social benefits (Energy And Environmental Economics, 2014). In California, the Energy + Environmental Economics company carried out a similar analysis to assess the costs and benefits of a NEM program, focusing on the perspectives of taxpayers and utilities (California Public Utilities Commission, 2013). When it comes to PV systems, Pikas et al. (2017) explored the costs and benefits associated with constructing Nearly Zero Energy Buildings (nZEB) for both private and public entities. Their analysis involved modeling the required PV capacities, net present cash flows, subsidies, and job generation. Chaianong et al. (2019) quantified the benefits and costs of distributed rooftop PV power generation for power companies and taxpayers under various conditions, shedding light on the economic implications of such systems.

The existing body of literature provides a robust theoretical foundation for this study; nevertheless, there are notable gaps and limitations: (1) In terms of research content, there is a scarcity of scholarly works that have analyzed Chinese rooftop distributed PV systems within the same comprehensive cost-benefit analysis framework. (2) Regarding the research object, the whole county promotion policy, recognized as the world's most extensive rooftop distributed PV promotion initiative in recent years, has received disproportionately limited attention in previous research efforts. (3) In terms of research methodology, a limited number of prior studies have delved into the holistic analysis of the costs and benefits associated with rooftop PV projects.

This paper makes a substantial contribution in three primary dimensions. Firstly, it stands as the pioneering work to comprehensively analyze China's county-wide promotion policies, taking into account various perspectives, including economic, environmental, and societal aspects, all within the framework of a cost-benefit analysis. Secondly, it conducts a detailed examination of the entire lifecycle of rooftop distributed PV systems, using the Life Cycle

Theory as the analytical foundation. This approach considers the often-overlooked carbon emissions footprint of PV modules throughout their entire lifespan. Lastly, the paper employs a practical case study of a pilot county in Hebei Province to explore the existing business models for rooftop distributed PV systems in China, providing an insightful assessment of their respective costs and benefits from the diverse viewpoints of different stakeholders.

3. Method and Data

3.1 Case Description

Julu County, situated in the southern region of Hebei province within Xingtai city (as depicted in Figure 2), enjoys ample solar resources, with solar radiation levels spanning from 5000 to 5850 MJ/m^2 (Bai, 2012). Historically, Hebei province, being the largest steel production base in China, predominantly relied on coal-fired power generation to sustain its industrial operations (WorldBank, 2019). However, with the pressing concerns of air pollution and the imperative to align with the Chinese government's ambitious target of carbon neutrality by 2060 (Wang et al., 2021), Hebei Province has been diligently working to transition its energy consumption structure from fossil fuels to renewable sources (Lv et al., 2022). In this context, solar PV emerges as a pivotal element in the province's energy transformation efforts, with plans to incorporate 32 million kilowatts of new PV capacity between 2021 and 2025 (Seetao, 2021). Notably, the whole county PV initiative has been identified by Hebei province as a significant strategy for advancing rooftop distributed PV installations. For this study, we have chosen the Julu County program as a representative case among the 37 pilot programs in Hebei Province for our analysis (Hebei Development and Reform Commission, 2021).

Figure 2. The location map of the Julu County

According to the official development plan, the entire county has set ambitious targets for the installation of rooftop distributed PV systems, with a total planned capacity of 220 MW. Of this capacity, 20 MW will be allocated for commercial and industrial distributed PV systems, to be installed on the roofs of public service and management organizations' buildings, including public schools and hospitals. These installations will be grid-connected, operating under a "self-use first and the surplus generation feeds into the grid" model. This mode entails that the rooftop PV systems prioritize fulfilling the electricity needs of the respective public buildings, with any excess energy being exported to the transmission and distribution grid. The expected 20 MW capacity for commercial and industrial rooftop distributed PV systems primarily comprises twenty 100 kW industrial and commercial rooftop distributed PV power plants. Within the commercial and industrial PV power plant business model (refer to Figure 3), the investment company initially acquires ownership of these distributed industrial and commercial PV power stations through its initial investment. The construction and subsequent operation of these distributed rooftop PV systems are carried out by equipment construction and operation companies, with the associated costs being covered by the investment company. Once the industrial and commercial distributed PV power stations commence electricity generation, they will sell the produced electricity to the public service and management organizations at a discounted rate, in exchange for renting the rooftop space. Any surplus electricity will be sold to the power grid company. All revenue generated from the sale of electricity by the distributed PV power plants will be attributed to the investment company.

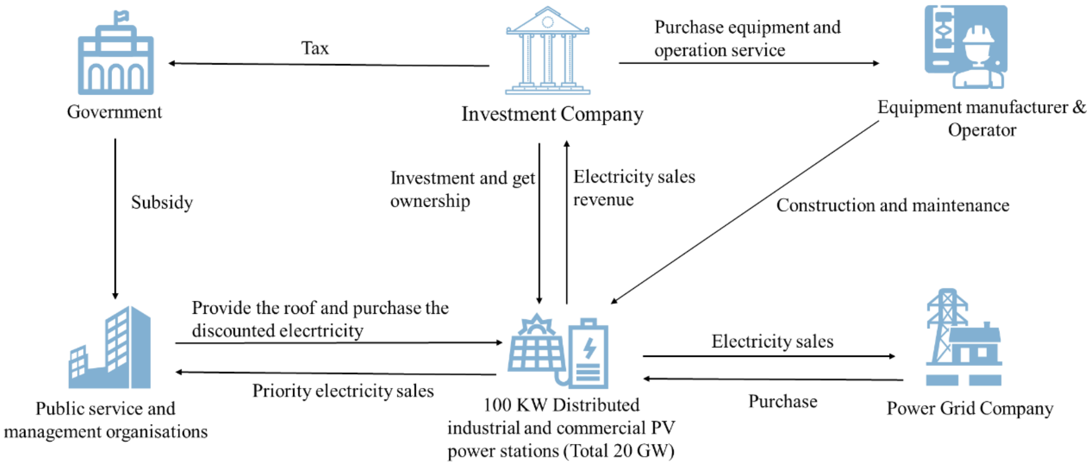

Figure 3. The business model for the industrial and commercial distributed PV system

Furthermore, as part of the initiative, ordinary residents are expected to contribute by installing a total of 200 MW of distributed PV systems on their rooftops, utilizing the "all generation to the grid mode". Under this mode, all the electricity generated by these rooftop distributed PV systems will be sold directly to the power grid company. The planned 200 MW capacity is primarily envisioned to consist of over sixty 30 kW household rooftop distributed PV power plants, with each 30 kW household rooftop distributed PV power station being installed on the roof of individual households. The official development plan for the household-distributed PV program offers ordinary residents two distinct options, providing them with decision-making authority. In the first option, referred to as the "roof rental mode" (illustrated in Figure 4), investment companies continue to secure rooftop space from ordinary residents by renting their rooftops. In return, the investment company compensates each household with an annual rent of 1120 Chinese yuan for the use of their roof space. Following the commencement of electricity generation by the household distributed PV systems, all the electricity generated is sold to the power grid company. Investment companies are responsible for managing electricity sales revenue and covering equipment and operating costs.

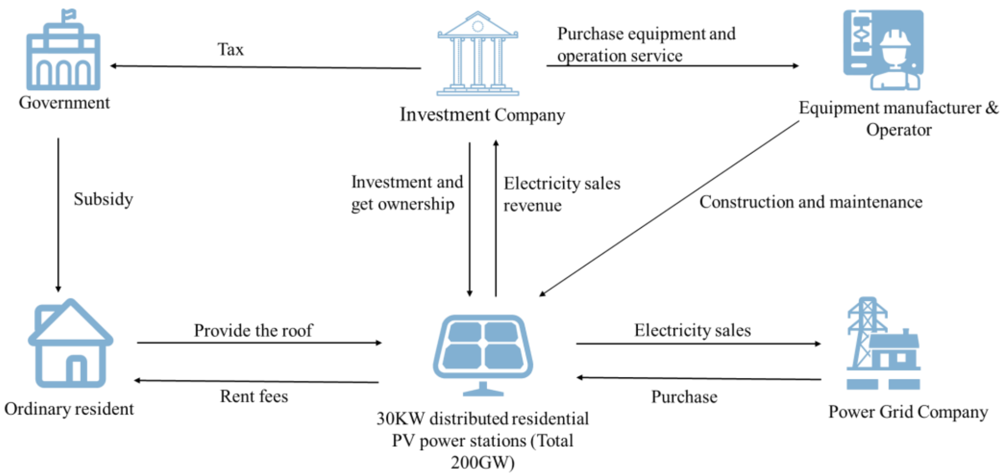

Figure 4. The business model for the "roof rental mode"

Another mode introduced is the "roof financing loan mode" (as depicted in Figure 5). According to the official development plan, ordinary residents gain ownership of 30 kW rooftop household distributed PV power plants by availing themselves of ten-year, 100% loans from banks. These loans are used to pay distributed PV contractors for the completion of grid-connected power generation. The revenue generated from selling electricity is then utilized to repay the full amount of the finance loan, in addition to covering operating and maintenance expenses for the first ten years following the commencement of electricity generation from the rooftop residential distributed power station. In the event of a surplus, it is allocated to ordinary residents; conversely, in the case of a deficit, it must be supplemented by the ordinary residents. Subsequently, the revenue generated from electricity sales via household distributed PV systems, with the exception of operation and maintenance costs, will be the sole possession of ordinary residents.

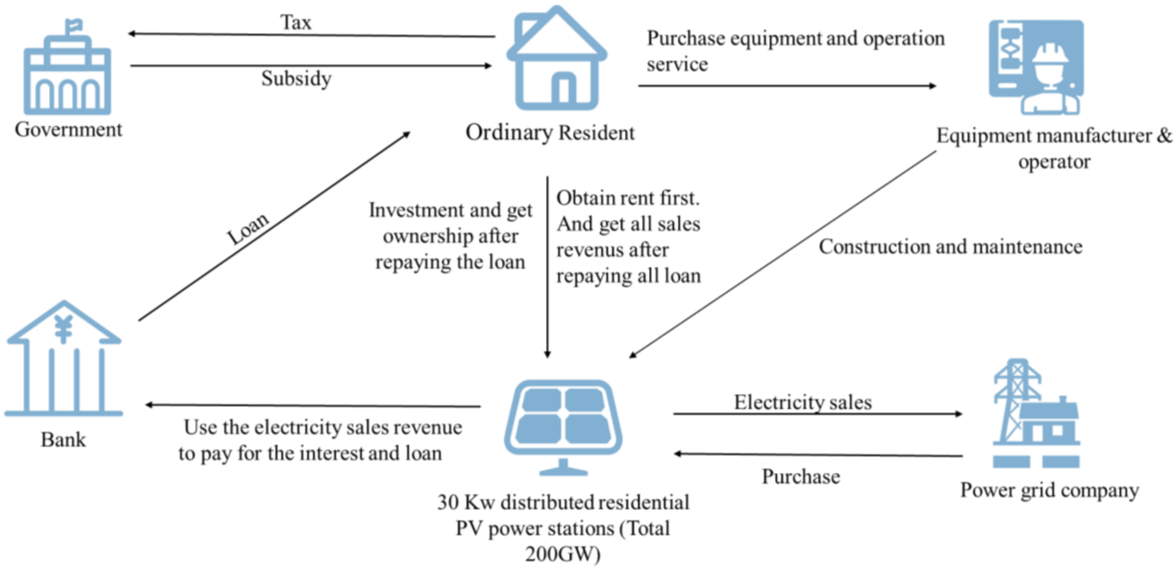

Figure 5. The business model for the "roof financing loan mode"

3.2 Model Construction

This paper will conduct a comprehensive analysis of the costs and benefits associated with each of these modes, considering five distinct aspects. The following table 1 provides explanations of costs and benefits from these five perspectives.

Table 1. Cost Benefit result interpretation

	Benefits		Costs
Public Service and Management Organizations	Discounted electricity price		The noise and visual pollution
Ordinary Resident	"roof rental mode"	Rent revenue	The noise and visual pollution
	"roof financing loan mode"	Electricity sales revenue	Loans and interest, operation and maintenance expenses
Investment Company	Electricity sales revenue		Equipment and construction fees, taxes, operation and maintenance fees
Government	Tax revenue Energy security and diversification Employment Growth Research and development		Subsidy and feed-in tariff expenses Tax preferential expenses

Society	Pollutants and carbon emissions from the same generation capacity of thermal power	Pollution and carbon emissions generated during the lifecycle of PV power plants

The analysis from these five perspectives will be integrated with relevant indicators (Figure 6). To assess the benefits for public service and management organizations and ordinary residents, cash flow and discount cash flow will be employed as measurement tools. Meanwhile, the cost and benefit for the investment company will be evaluated using indicators such as the internal rate of return, discount cash flow, and investment payback period. In the context of government considerations, the analysis will encompass the Shannon-Weiner index, tax revenue, increased job opportunities, and augmented research and development investment. Lastly, to gauge the environmental benefits of distributed PV systems, the reduction in pollutants and carbon emissions in comparison to thermal power generation will serve as critical metrics.

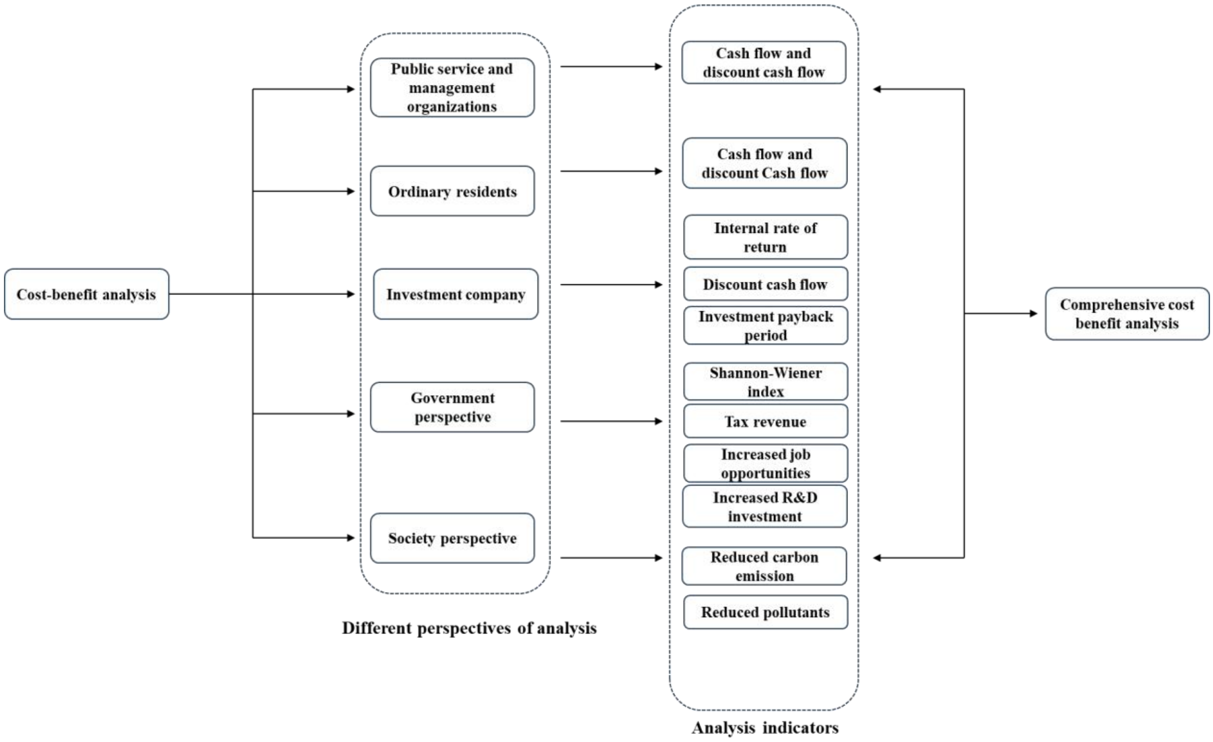

Figure 6. The analysis framework for this paper

3.3 Parameter Setting and Data Source

3.3.1 Solar Radiation

Julu County is geographically located between approximately 37.07 to 37.25 degrees north latitude and 114.5 to 115.12 degrees east longitude. Data from the NASA Prediction of Worldwide Energy Resource indicates that Julu County experiences an average of approximately 4.25 hours of peak sunlight daily, with an annual total of around 1551.25 peak sunlight hours. As depicted in the figure 7 below, radiation levels in the region tend to remain high from April to July, while they decrease notably from November to March.

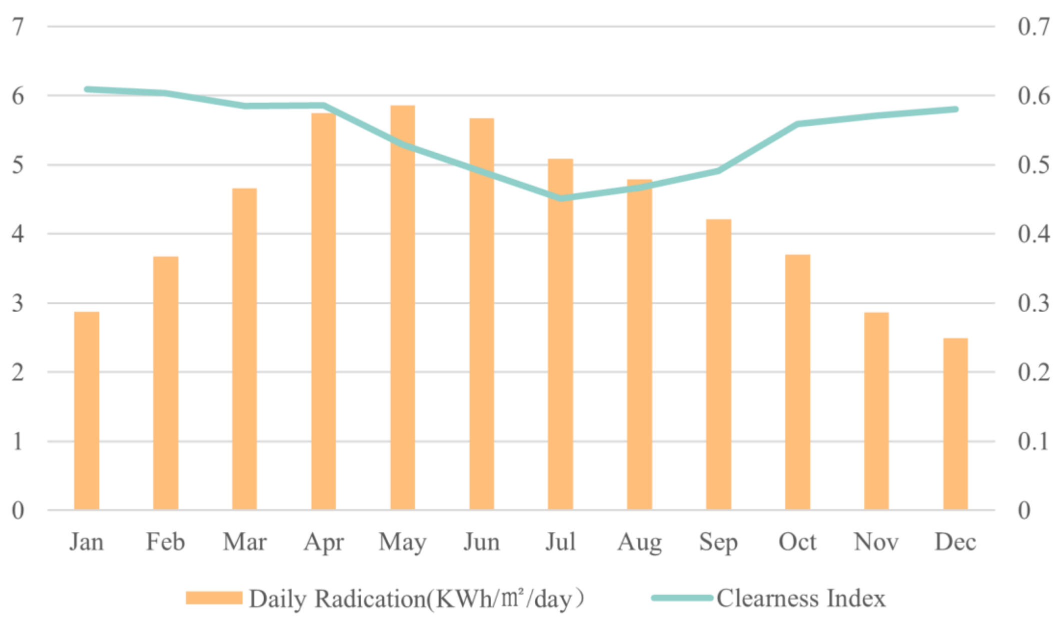

Figure 7. Monthly average Solar Global Horizontal Irradiance (GHI) Data in Julu County

3.3.2 PV System Parameters

According to the official development plan, both the 30 kW and 100 kW distributed PV systems are designed to employ the same 535 WP monocrystalline silicon module, implying an identical power generation efficiency assumption. Based on data from the China PV Industry Association (China Photovoltaic Industry Association, 2023), the initial investment cost for distributed PV systems in China's industrial and commercial sector stood at 3.74 yuan/W as of 2022. Additionally, the annual operation and maintenance cost for all distributed PV systems is estimated at 0.048 yuan/W. Furthermore, according to research by Zhongtai Securities (Lei, 2022), the initial investment cost for household distributed PV systems in China as of 2022 is 3.3 yuan/W. The official development plan specifies that the annual average system efficiency loss of distributed solar systems should not exceed 2.5% in the first year, and it should not surpass 0.7% annually until the PV systems reach the end of their 25-year operational lifespan. Therefore, for this study, it is assumed that all distributed PV systems have a projected lifespan of 25 years, with an initial system efficiency loss of 2.5% in the first year, followed by an annual efficiency loss of 0.7% in the subsequent 24 years.

Apart from the efficiency losses attributed to equipment aging due to prolonged service life, it's worth noting that various components of grid-connected solar systems, including inverters and AC grid connections, can introduce additional efficiency losses (Lupangu & Bansal, 2017). Efficiency losses in the distributed PV system for this project can manifest at different stages, encompassing the matching efficiency loss of PV modules, temperature-related efficiency loss in PV modules, efficiency reduction due to surface dust accumulation on PV modules, losses arising from unavailable solar radiation, direct current losses, inverter inefficiencies, and losses related to alternating current grid connections (See in Table 2). Consequently, the overall technical efficiency involved in converting solar-generated electricity from ideal sunlight conditions into electricity integrated into the power grid is determined by the cumulative impact of these various efficiency losses:

$$97.5\% \times 96\% \times 95\% \times 97\% \times 99.5\% \times 98.4\% \times 95.07 = 81.28\%$$

Table 2. Efficiency of Different Stages in Distributed PV Systems

Stages	Efficiency
Matching efficiency of PV modules	97.5%
Temperature efficiency of PV modules	96%
Surface dust efficiency of PV modules	95%

Unavailable solar radiation efficiency	97%
Direct Current loss efficiency	99.5%
Inverter efficiency	98.4%
Alternating current grid connection efficiency	95.07%
Total efficiency	81.28%

3.3.3 Subsidy Policy

China's distributed PV subsidy policies encompass a hierarchy of national, provincial, and prefecture-level city subsidies and principally consist of two policy types: fiscal subsidies and feed-in tariffs. The feed-in tariff system offers a per-kilowatt-hour rate exceeding that of grid electricity. Initially, Chinese feed-in tariff subsidies were distributed based on the richness of the country's solar energy resources. These resources were classified into four tiers based on their abundance, as detailed in Table 2. Between 2013 and 2020, China's national-level distributed PV subsidy policies provided varying feed-in tariff standards according to the classification of solar energy resource regions, accompanied by fiscal subsidies, as shown in Table 3 (Jiangxi Provincial Meteorological Center, 2008).

Table 3. Classification of Solar Energy Abundance in China

China's solar energy resource richness level				
Class	Resource Code	Annual Total Radiation (MJ/m^2)	Annual total radiation (kwh/m^2)	Annual total radiation (MJ/m^2)
Richest area	I	≥ 6300	≥ 1750	≥4.8
Rich area	II	5040~6300	1400~1750	3.8~4.8
Relatively rich area	III	3780~5040	1050~1400	2.9~3.8
General area	Ⅳ	< 3780	< 1050	< 2.9

In the wake of a surge in construction volumes, the disparity in subsidy funds has continued to widen, leading to issues and delays in subsidy disbursement (Chen & Wang, 2022). To gain insights into the progression of national-level distributed PV subsidy policies in China from 2013 to 2022, we compiled official documents from the Chinese government, summarizing the evolution of these policies, as presented in Table 4. Over this period, the Chinese government has gradually phased out financial subsidies and electricity price subsidies at the national level. In 2021, all subsidy policies, with the exception of the 0.03 yuan per kilowatt-hour subsidy for household distributed PV, were terminated. Starting in 2022, the central government ceased providing subsidies and transitioned to implementing grid parity.

Table 4. Evolution of Distributed PV Subsidy Policies at the National Level in China

Year Period	Subsidy Standard
2013-2015	Kilowatt-hour fiscal subsidy: 0.42; The feed-in tariffs for three types of electricity price areas: 0.9, 0.95, 1 yuan/KWh
The whole year of 2016	Kilowatt-hour fiscal subsidy: 0.42; The feed-in tariffs for three types of electricity price areas: 0.8, 0.88, 0.98 yuan/KWh
The whole year of 2017	kilowatt-hour fiscal subsidy: 0.42; The feed-in tariffs for three types of electricity price areas: 0.65, 0.75, 0.85 yuan/KWh
From January 1, 2018	kilowatt-hour fiscal subsidy: 0.37; The feed-in tariffs for three types of electricity price areas: 0.55, 0.65, 0.75 yuan/KWh
From May 31, 2018	0.32 kilowatt-hour fiscal subsidy; The feed-in tariffs for three types of electricity price areas: 0.5, 0.6, 0.7 yuan/KWh

From 2021	Newly filed industrial and commercial distributed projects: Internet access at parity; Newly-built household project: total electricity: 0.03 yuan/kWh
From 2022	All kinds of newly filed distributed PV projects: Internet access at parity

Due to the discontinuation of both fiscal subsidies and feed-in tariff incentives, the countywide promotion project in Julu County no longer qualifies for any national-level subsidies in China. Additionally, Hebei Province and Xingtai City have also terminated the distributed PV subsidy policy post-2018. As a result, the countywide promotion project in Julu County is ineligible for any fiscal subsidies, and the cost of electricity sold to the grid stands at 0.3644 yuan per kilowatt-hour, based on Hebei Province's benchmark electricity price for desulfurization. This necessitates the achievement of grid parity for the project. Furthermore, according to the project plan, the current comprehensive electricity price for public buildings in Xingtai City is 0.52 yuan per kilowatt-hour. However, the discounted electricity rate, applicable to public buildings post-completion of industrial and commercial distributed PV, is set at 0.442 yuan per kilowatt-hour.

3.3.4 Tax Policy

Despite the withdrawal of fiscal subsidies and electricity price support for distributed PV systems, the Chinese government continues to offer tax incentives to distributed PV power station owners. Based on research by Yuan et al. (2014) and Zhang et al. (2023), along with policy documents from the Chinese State Taxation Administration (State Taxation Administration, 2014) (State Taxation Administration, 2022), we have compiled the latest information on taxes and associated tax rates applicable to the distributed PV power generation project in Julu County (refer to Table 5). For individuals selling electricity generated from distributed PV power plants, the tax obligations primarily include value-added tax, income tax, and additional levies such as urban maintenance and construction tax, surtax on education expenses, and surtax on local education expenses. For household owners of distributed PV power stations who qualify as small-scale taxpayers, no value-added tax is required if their monthly electricity sales income does not exceed 150,000 yuan, and income tax is calculated according to personal income tax regulations. General taxpayers with annual value-added tax sales exceeding 5 million yuan can enjoy an exemption from income tax for the first three years and a 50% reduction for the subsequent three years.

Table 5. The main taxes and tax rates in Julu County's whole county distributed PV power generation project

Categories of tax		Tax rate	
Value added tax		Small scale taxpayers	General taxpayers
		3% (monthly electricity sales exceed 15K, if not the tax rate is 0%)	13%
Income tax		Individual income tax	Corporate income tax
		Sales income, applicable to progressive tax rate of 5% to 35%	25% (Exemption from the first to third years, 50% reduction from the fourth to sixth years)
Urban maintenance and construction tax		Value added tax amount × 5%	
Surtax on education	Surtax on education expense	Value added tax amount × 3%	
	Surtax on local education expense	Value added tax amount × 2%	

3.3.5 Discount Rate and Interest Rate

The interest rate in this article is determined based on the recently published benchmark interest rate of the People's Bank of China. The one-year loan interest rate stands at 3.55%, and the repayment method is structured as equal principal and interest.

4. Results

4.1 The Power Generation of the Project

According to Wen and Qiu (2018) research, the total power generation of distributed PV over a 25 year lifespan can be calculated using formulas:

$$L=\sum_{n=1,2,3\ldots25}^{n} W \times t \times \mu \times (1-r)^n$$

Where L is the total power generation and the unit is kWh; W is the total installed power and the unit is watt; t is the annual peak sunshine and the unit is hours; μ is the comprehensive efficiency of the PV system and has a fixed value of 81.28%; r is the annual decay rate, and n represents the year number. Utilizing the data and the equation above, the estimated 200 MW of household distributed PV power generation is depicted in Figure 8. Over the 25-year lifespan of household distributed PV, the average annual power generation amounts to approximately 224684539.2 kWh, resulting in a total power generation of 5617113480 kWh.

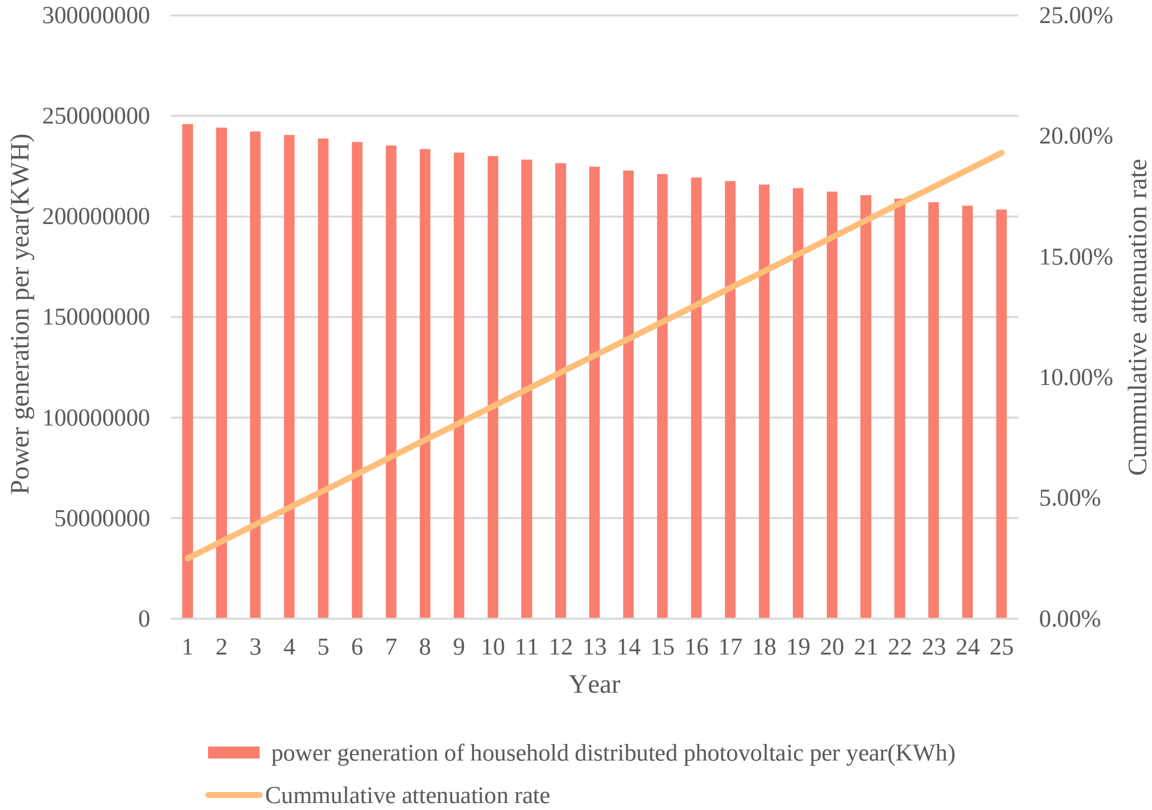

Figure 8. 200MW Household Distributed PV Annual Power Generation Estimation

Our estimated 20MW industrial and commercial distributed PV system power generation is shown in Figure 9 below. During the 25-year lifespan of household distributed PV, the average annual power generation is approximately 22468453.92 kWh, with a total power generation of 561711348 kWh.

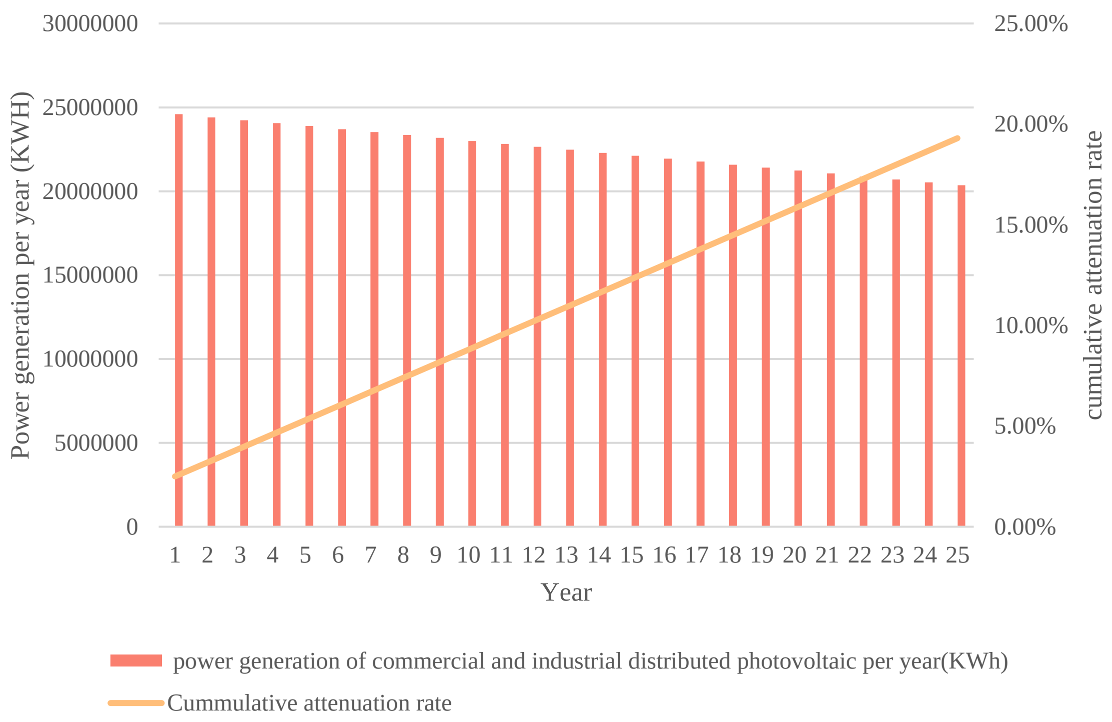

Figure 9. 20MW Industrial & Commercial Distributed PV Annual Power Generation Estimation

Considering that in the "roof financing loan mode", each ordinary resident household obtains ownership and benefits from their own 30 kW distributed household rooftop PV system through loans. Taxes are calculated based on the income earned by each household. Additionally, we have computed the power generation of the 30 kW household distributed rooftop power plant. Our estimated 30KW household distributed rooftop PV system power station is shown in Figure 10 below. During the 25-year lifespan of household distributed PV, the average annual power generation is approximately 33702.68088 kWh, with a total power generation of 842567.022 kWh.

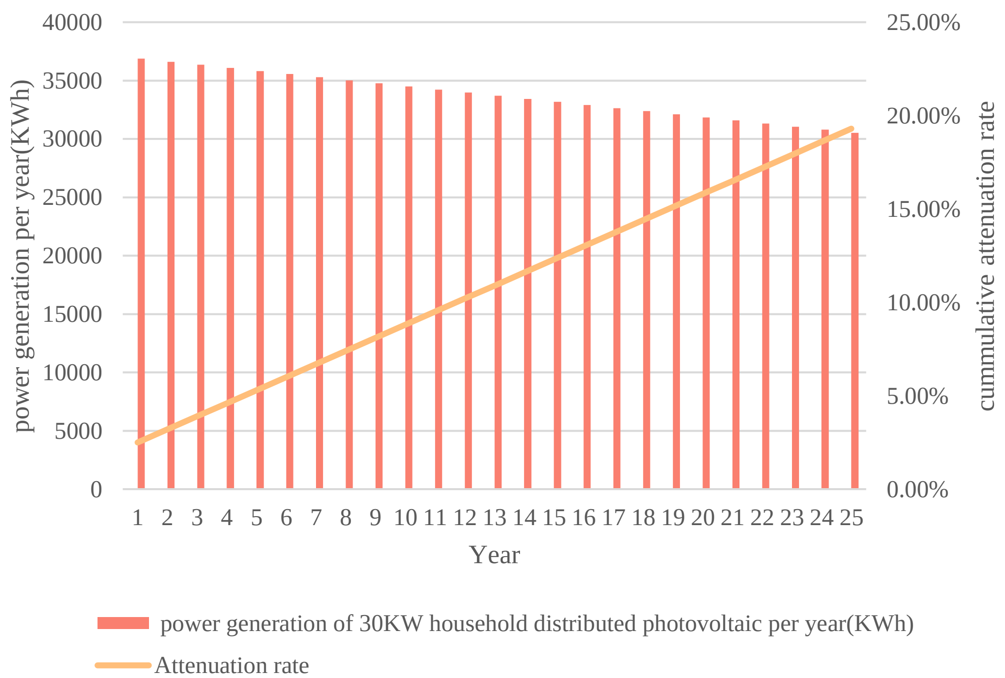

Figure 10. 30KW Household Distributed PV Annual Power Generation Estimation

4.2 Result from the Perspective of Public Service and Management Organizations

For industrial and commercial users renting rooftops, the primary cost factor is associated with the noise and visual impact during the construction of distributed PV systems (Tawalbeh et al., 2021). According to the 2021 Statistical Yearbook of Hebei Province (Hebei Provincial Bureau of Statistics, 2022), the electricity consumption of public services and management organizations in Xingtai City comprises 4.71987% of the city's total electricity consumption. Based on this percentage, we can calculate that the electricity demand of public service and management organizations in Julu County is 42,703,023.825 kilowatt-hours per year. This figure surpasses the annual electricity generation of the 20 MW industrial and commercial distributed PV power generation system, which means that all the electricity generated by this system will be sold to public service and management institutions. For public service and management organizations, the primary benefit arises from the lower electricity prices offered by industrial and commercial distributed PV systems compared to the grid, resulting in cost savings for industrial and commercial residents. As of 2022, the grid electricity price for industrial and commercial users is 0.52 yuan/kWh, while the discounted electricity price provided by distributed PV systems is 0.442 yuan/kWh, saving 0.078 yuan per kWh for public service and management organizations. As shown in Figure 11 below, the annual electricity cost savings decrease as the annual power generation efficiency of industrial and commercial distributed PV declines. Over the 25-year service period of industrial and commercial distributed PV systems, the 20 MW industrial and commercial distributed PV system will save a total of 43,813,485.14 yuan for public service and management organizations.

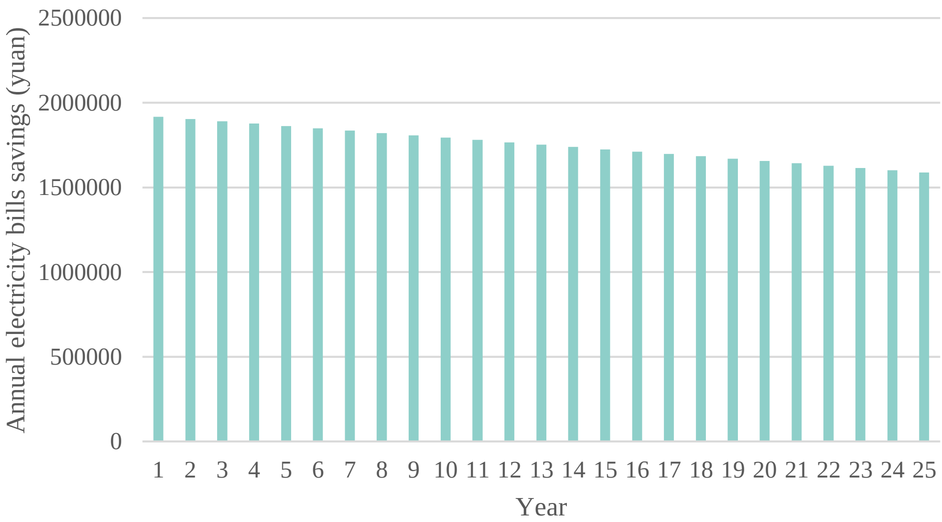

Figure 11. Total annual electricity savings for public service and management organizations

4.3 Result from the Perspective of Ordinary Residents

Similar to the public service and management organizations, the primary concern for ordinary residents is the potential sound and visual disturbance during the construction and maintenance of PV systems. Residents have two options to choose from. In the "roof rental mode", the annual rent for each 30 kW household distributed PV system is 1,120 Chinese yuan. The total 200 MW household distributed PV system comprises approximately 6,667 30 kW household distributed PV systems, resulting in a total annual rent of 7,467,040 yuan and a cumulative total of 186,676,000 yuan over 25 years. Given that the average annual income for households from renting roofs is only 1,120 yuan, which does not meet the threshold for personal income tax, income tax is not applicable.

If we calculate the discount cash flow of rent using the current benchmark interest rate (3.55%), the discount cash flows are illustrated in Figure 12, and the NPV for all ordinary residents amounts to 126,748,291.4 yuan.

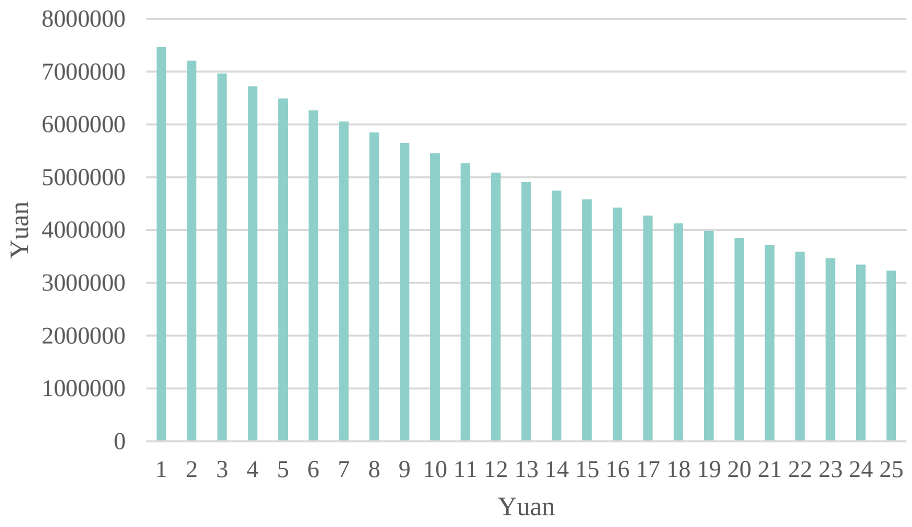

Figure 12. The discounted cash flow if all ordinary residents choose the "roof rental mode"

In the "roof financing loan mode", ordinary users primarily benefit from electricity sales revenue once the loan is repaid. Based on previously compiled data, the initial investment for a 30KW household distributed PV system is approximately 99,000 yuan, with an annual operation and maintenance cost of around 1,440 yuan per system. It's worth noting that the electricity sales income for each household falls below the personal income tax threshold, so tax considerations are not necessary when calculating the cash flow for ordinary residents opting for the "roof financing loan mode". The cash flow and discounted cash flow of a 30KW household distributed PV system are presented in Figure 13 below, resulting in an NPV of 82,862.24 yuan per ordinary resident household.

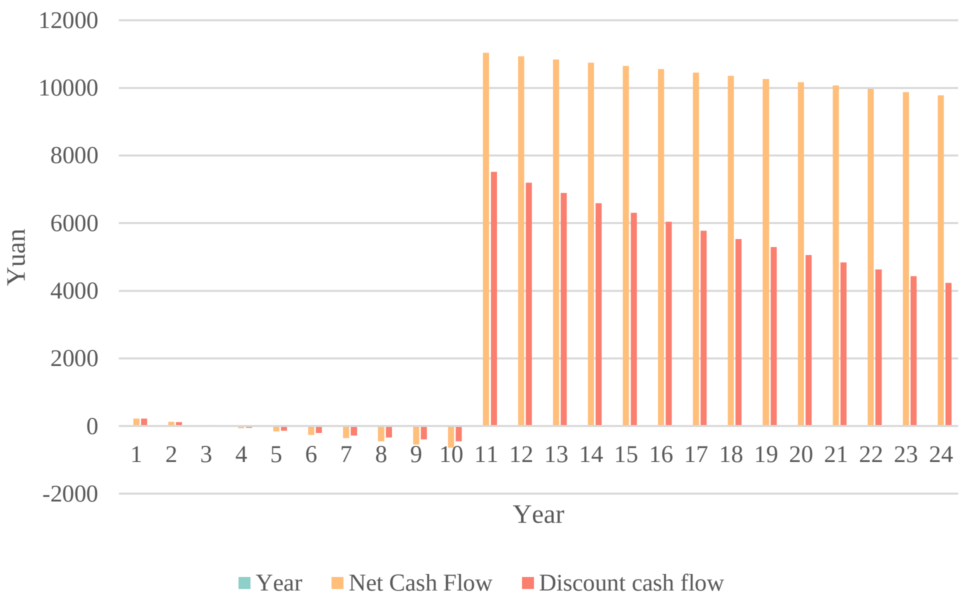

Figure 13. 30KW household distributed PV system cash flow

If all ordinary residents choose the "roof financing loan mode" instead of the "roof rental mode", the comprehensive cash flow and discounted cash flow of ordinary residents are shown in the following Figure 14. And the total NPV for all ordinary residents amounts to 552414919.9 yuan.

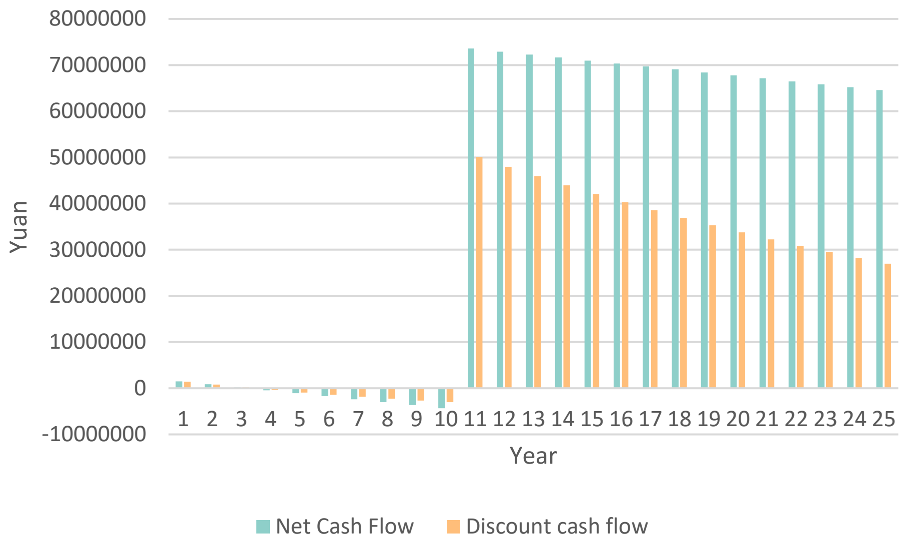

Figure 14. cash flow and discount cash flow if all ordinary residents choose the "roof financing mode"

By comparing Figure 14 and Figure 12, it becomes evident that opting for the "roof financing mode" yields significantly greater economic benefits for ordinary residents compared to the "roof rental mode". The decision between these two modes lies with ordinary residents. Below, we present the cash flow scenario in which 50% of ordinary residents choose the "roof financing mode", while the remaining 50% opt for the "roof rental mode". The total NPV for all ordinary residents in this scenario amounts to 337,408,952.6 yuan.

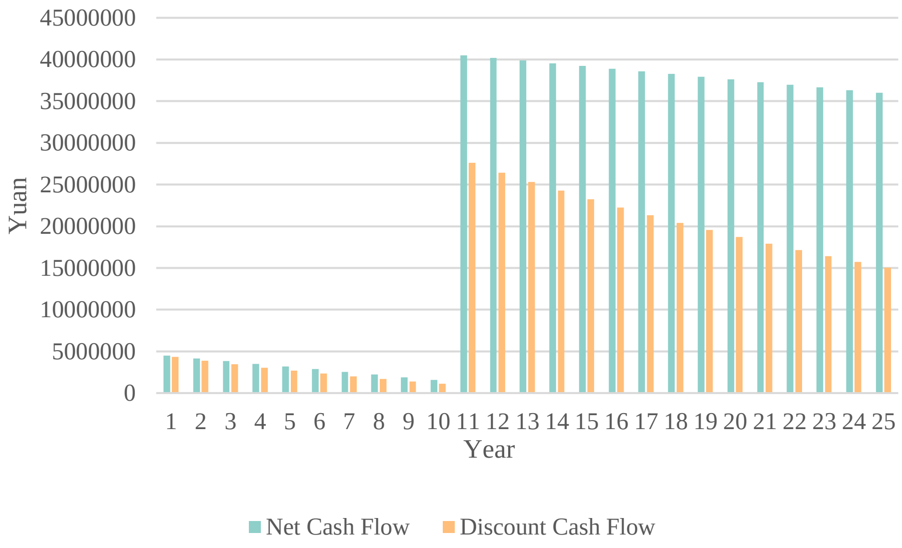

Figure 15. cash flow and discount cash flow if 50% ordinary residents choose the "roof financing mode" and 50% choose the "roof rental mode"

4.4 Result from the Perspective of Investment Company

Similar to ordinary households, the economic benefits for investment companies also depend on the proportion of different modes chosen by ordinary households. Here, we outline the economic benefits and costs for investment companies in three scenarios: when all ordinary users choose the "roof financing mode", when all choose the "roof rental mode", and when both modes are evenly split at 50% each.

Considering that cost-benefit analysis for investment companies primarily revolves around investment return issues, we introduce two additional investment benefit indicators alongside NPV to enhance the analysis.

(1) Internal rate of Return

$$\frac{r-i_1}{i_2-i_1}=\frac{NPV_1}{NPV_1-NPV_2}$$

$$\sum_{i=1}^{t}\frac{NCF_i}{(1+r)^i}-C=0$$

(2) Investment Payback Period

$$TP = y_{npv\geq 0} - 1 + \frac{|NPV_{y_{npv\geq 0-1}}|}{y_{NPV}}$$

If all ordinary households choose the "roof financing mode", which is the most profitable choice for them, the investment company's costs primarily include the purchase and construction of distributed PV systems for 20MW industrial and commercial households, subsequent maintenance and operation expenses, as well as taxes. The investment company gains ownership of the 20MW industrial and commercial distributed PV system, with the main benefit being the revenue from electricity fees sold to ordinary residents. The detailed cash flow is presented below. The total discounted cash flow (after tax) amounts to 6039116.055 yuan (as shown in Figure 16). The investment payback period is 17 years and 29.11 days, with an internal rate of return of 8.57%.

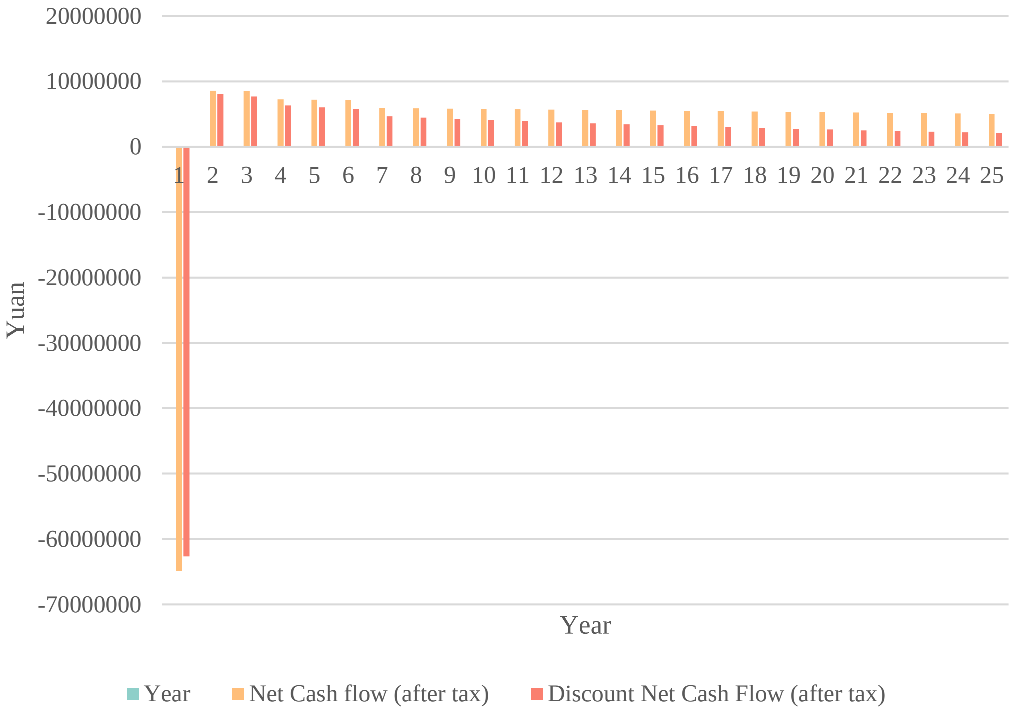

Figure 16. The cash flow and discount cash flow for investment company under the situation that all ordinary residents choose the "roof financing mode"

If 50% of ordinary residents choose the "roof financing mode" and 50% of ordinary residents choose the "roof rental mode", the investment company gains ownership of 20MW industrial and commercial distributed PV systems and 100MW household distributed PV systems. The primary revenue sources are electricity sales revenue from the 100MW household distributed PV systems to the power grid and electricity sales revenue from the 20MW industrial and commercial distributed PV systems to ordinary households. The cash flow is illustrated in the following Figure 17. The total discounted net cash flow (after tax) amounts to 134955568.3 yuan. The investment payback period is 14 years and 255.27 days, with an internal rate of return of 7.44%.

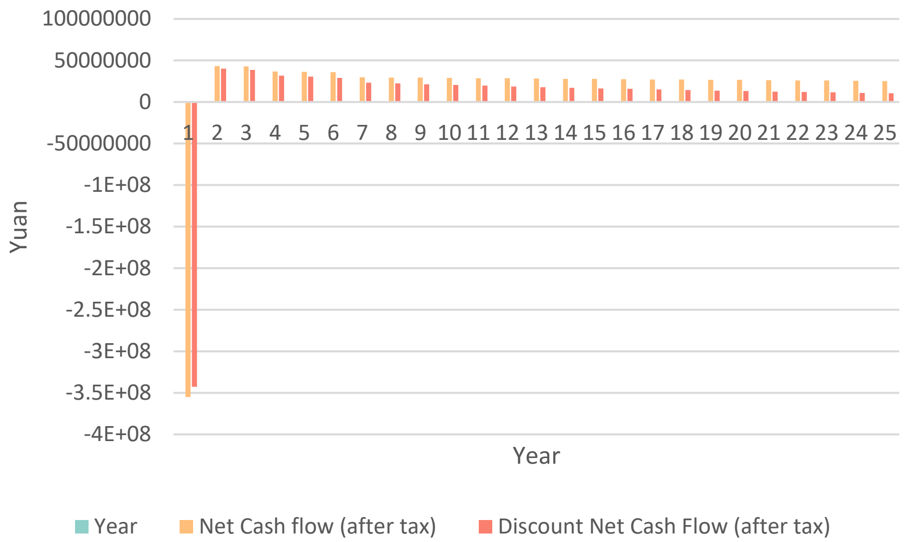

Figure 17. The discount cash flow and cash flow for investment company under the situation that 50% ordinary residents choose the "roof financing mode" and 50% choose the "roof rental mode"

If all 100% of ordinary residents choose the "rooftop current mode", the investment company can obtain the ownership of all 200 MW household distributed PV systems and 20MW commercial and industrial distributed PV systems. The detailed cash flow before tax and after tax is shown below. The total discounted cash flow (after tax) is 237605496.5 yuan. The investment payback period is 14 years 322.23 days, with an internal rate of return of 7.33%.

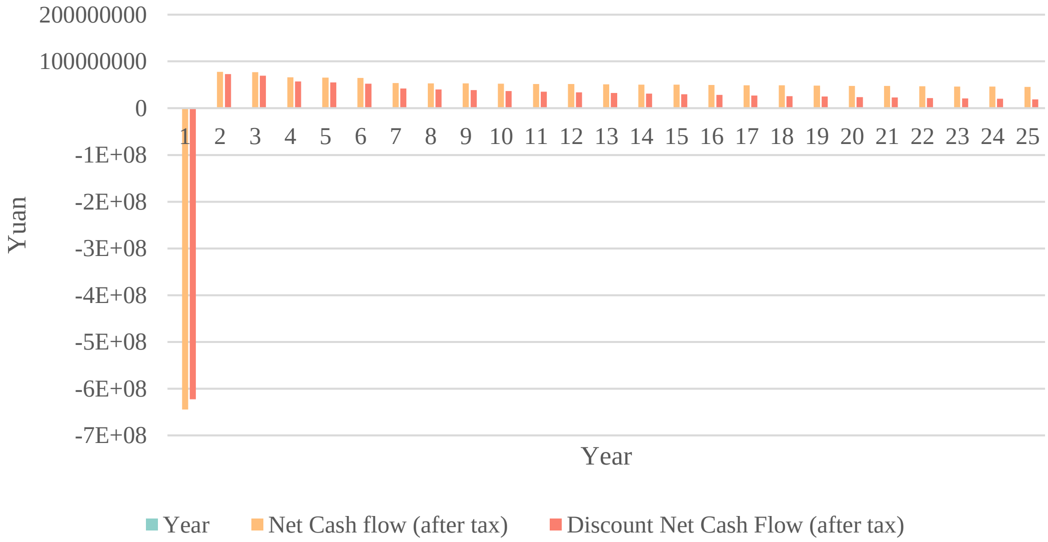

Figure 18. The discount cash flow under the situation that all ordinary residents choose the "roof financing mode"

4.5 Result from the Perspective of Government

For the government, costs primarily involve tax exemption policies. Benefits include tax revenue, job creation, energy security, and the research and development investment that the Whole County Programs can contribute to the industry's development.

4.5.1 Benefit: Tax Revenue

Ordinary residents play a pivotal role as taxpayers when they invest in household-distributed PV power stations. Typically, the monthly electricity sales income from 30 KW household distributed PV systems falls below the thresholds for personal income tax and value-added tax, effectively exempting ordinary resident households from taxation. However, when an investment company undertakes ownership of power plants, it necessitates consolidating the monthly electricity sales from residential power plants for taxation purposes. The extent of tax revenue garnered by the government is intricately linked to the percentage of ordinary residents opting for the "roof rental mode". In this context, we present the government's tax revenue under varying scenarios: 0%, 50%, and 100% of ordinary residents choosing the "roof rental mode" (see in Figure 19). When all ordinary residents opt for the "roof rental mode", the government can collect income tax on all household-distributed PV sales from investment companies. This results in significantly greater tax revenue in comparison to scenarios where fewer residents choose the "roof rental mode".

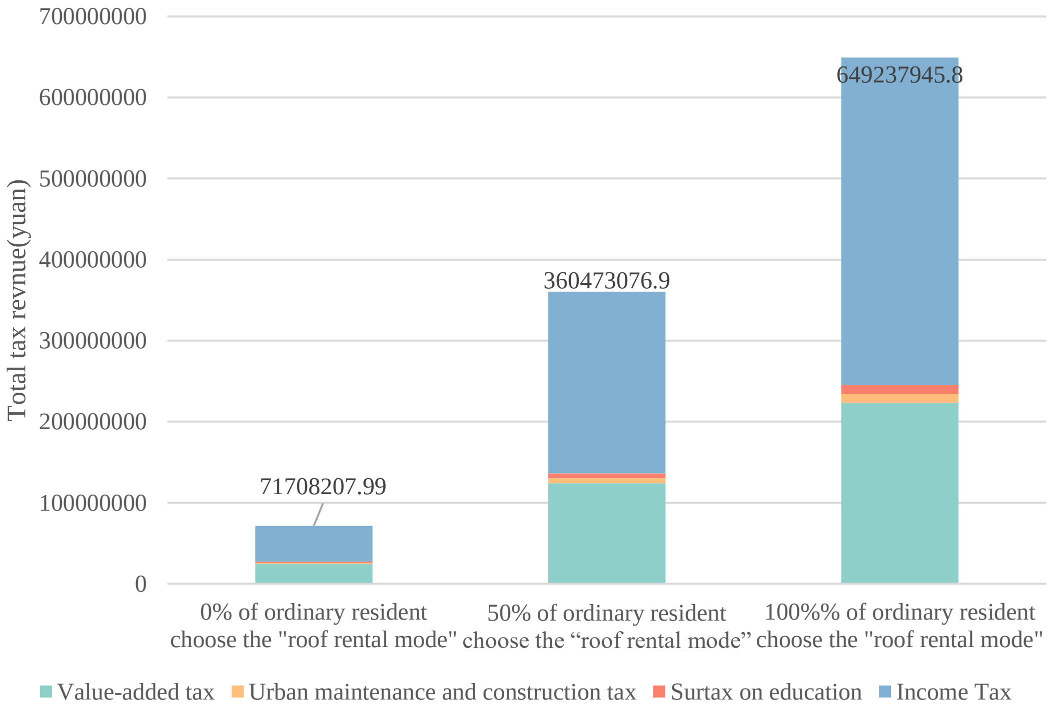

Figure 19. The tax revenue and its composition received by the government when different percentage of ordinary residents choose "roof current mode"

4.5.2 Benefit: Energy Security

The outbreak of the Russia-Ukraine crisis in early 2022 has heightened concerns regarding energy security in many countries and has spurred an increased demand for renewable energy to foster energy diversification (Hosseini, 2022). The Shannon-Wiener diversity index (SWI) is an indicator employed to investigate diversity within the local flora of a plant community. However, it has also found utility in numerous prior studies for evaluating the diversity of energy systems (Ranjan & Hughes, 2014; Sun & Ren, 2021). In this study, we utilize this index to gauge the impact of the Whole County Program on the diversity of electricity generation in China. The Shannon–Weiner index formula is shown below:

$$\text{SWI}=-\sum_{i=1}^{n} S_i \times ln_{S_i}$$

where n is the number of energy varieties in the energy consumption system, S_i is the ratio of energy consumption i. SWI reflects the diversity of the electricity generation structure.

According to Hua and Lin (2021) research, the promotion of the Whole County Distributed PV Program involves 676 counties in China, with a total installed capacity of approximately 140GW. These 676 counties are primarily situated in regions with ample and comparatively abundant sunshine in China *(National Energy Administration of China, 2021b)*. Based on our estimation, if these 676 Whole County Programs are able to connect to the grid for power generation as intended, their collective operational lifespan can yield a total of 3,928,811,040,000 kWh of electricity. Furthermore, the newly added average annual power generation is approximately 157,152,441,600 kWh (refer to Figure 20).

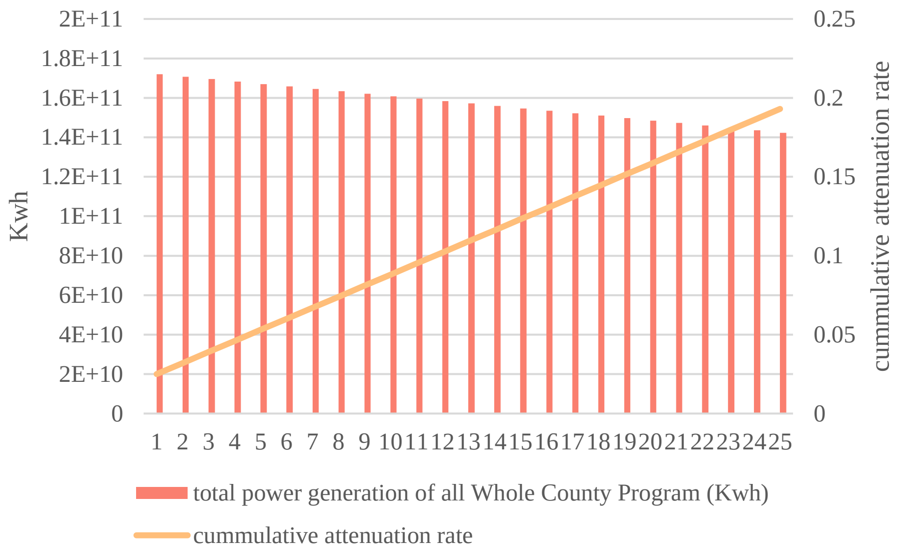

Figure 20. 140GW Whole County Distributed PV Annual Power Generation Estimation

According to data from the China Bureau of Statistics, China's total electricity power generation in 2022 amounted to 8848.71 billion kilowatt hours, including 58887.9 kilowatt hours of thermal power generation, 13522 kilowatt hours of hydroelectric power generation, 4177.8 kilowatt hours of nuclear power generation, 7626.7 kilowatt hours of wind power generation, and 4272.7 kilowatt hours of solar power generation. The Shannon-Wiener diversity index of China's electricity power generation structure in 2022 was calculated as 1.0598. If the 676 Whole County Programs commence electricity generation, they can contribute an additional 1,571.52-billion-kilowatt hours of solar power annually. Consequently, the Shannon-Wiener diversity index (SWI) for China's electricity generation structure will increase from 1.0598 to 1.0915.

4.5.3 Benefit: Job Creation

According to the official development plan, the initial two years of the Whole County Promotion Project in Julu County are expected to create approximately 2,250 jobs, and from the 3rd year to the 25th year, there will be a stable workforce of 100 maintenance and operation personnel. From a macroeconomic standpoint, in alignment with Qian's 2019 research, a distributed PV penetration exceeding 60% in China has the potential to foster the creation of over 7 million jobs.

4.5.4 Benefit: Promote the Development of Relevant Technologies

Participation in the Whole County Distributed PV Programs can indirectly lead to increased research and development (R&D) investments in PV manufacturing. On average, Chinese PV manufacturing companies allocate around 5% of their sales revenue to R&D initiatives. Considering the total sales revenue of 220MW distributed PV equipment in Julu County amounts to approximately 734,800,000 yuan, the indirect R&D investment contribution to China's PV industry would be 734,800,000 * 0.05 = 36,740,000 yuan. With 676 Whole County Programs in operation, the cumulative indirect R&D investment for the Chinese PV industry is estimated at roughly 24,836,240,000 yuan.

4.5.5 Cost: Tax Exemption Policies

Given the conclusion of the Chinese government's subsidy policy, the primary financial consideration for distributed PV systems now revolves around tax incentives. Notably, the Chinese government has introduced tax incentives to support the development of distributed PV systems. These incentives encompass an exemption from income tax for investment companies during the initial three years of their investment, followed by a 50% reduction in income tax for the subsequent three years.

The tax exemptions under different scenarios are as follows:

0% of ordinary residents choose "roof rental mode": 8395642.996 yuan.

50% of ordinary residents choose "roof rental mode": 42275034.533 yuan.

100% of ordinary residents choose "roof rental mode": 76154426.08 yuan.

4.6 Result from the Perspective of Society

As shown in the figure below, a total of 6178824828 kWh will be generated by 220MW in 25 years lifespan.

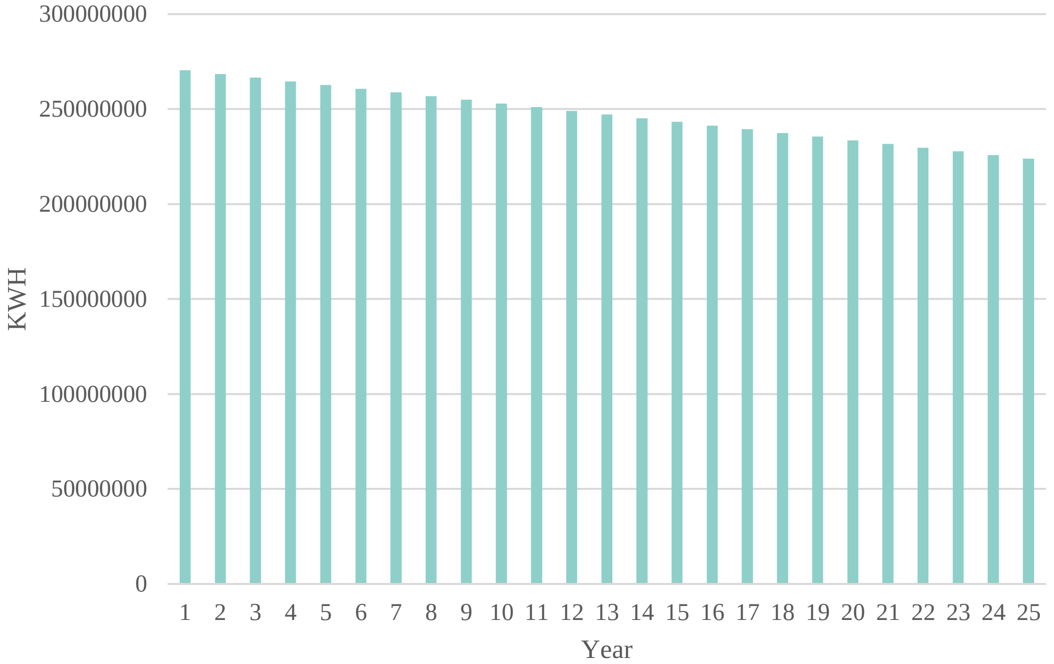

Figure 21. Total power generation of 220 MW distributed PV system in Julu County

As per the 2022 annual development report of China's power industry published by the China Electricity Council (CHINA ELECTRICITY COUNCIL, 2022), China's thermal power plants exhibited a standard coal consumption of 301.5g/Kwh in 2021, leading to carbon dioxide emissions of approximately 828g/Kwh per unit of thermal power generation. Moreover, the emissions of smoke, sulfur dioxide, and nitrogen oxides per unit of thermal power generation stood at 22 mg/Kwh, 101 mg/Kwh, and 152 mg/Kwh, respectively. Considering that PV production and operation do not generate smoke pollution, sulfur dioxide, and nitrogen oxides, the adoption of a 220MW distributed PV power generation system in Julu County is anticipated to reduce waste smoke pollution by 135934146.216g, sulfur dioxide emissions by 624061307.628g, and nitrogen oxides emissions by 939181373.856g during its 25-year lifecycle when compared to traditional thermal power generation. Furthermore, based on data from China's dual carbon information disclosure platform for the electromechanical industry, the carbon footprint of China's monocrystalline silicon PV modules across their entire life cycle, from production and operation to recovery, is estimated at approximately 10 g CO2e/kWh. In comparison to the 828g/Kwh carbon emissions associated with thermal power generation, the 220MW distributed PV project in Julu County is projected to reduce approximately 5054278.709 tons of carbon emissions over its 25-year lifespan.

5. Conclusion and Policy Recommendations

Developing distributed PV energy holds immense significance in advancing energy diversification, mitigating environmental degradation, and accelerating decarbonization efforts. In a country like China, characterized by a substantial non-urban population and a well-established solar product supply chain, the large-scale implementation of distributed solar PV systems in counties serves to alleviate energy shortages while simultaneously bolstering the income of non-urban communities and fostering growth in the domestic PV industry. This paper centers its analysis on the comprehensive county-wide promotion project in Julu County, located in Hebei Province, China. By dissecting the stakeholders involved in the current business model, and by assessing the project's cost-effectiveness from multiple vantage points, the following key findings emerge: (1) Given the prevailing technological landscape and product pricing, the whole county promotion project exhibits robust economic performance in regions endowed with ample solar energy resources. NPV and discounted cash flow analyses consistently illustrate favorable economic outcomes across the lifecycle of distributed PV systems, considering the interests of both investing entities and households alike. (2) When considering the factors influencing economic viability, it becomes apparent that, in the era of grid parity, the economic feasibility of these Whole County Promotion projects hinges not only on geographical location, technical conditions, product costs, and operation and maintenance expenses but is also notably shaped by local coal-fired electricity prices, tax policies, and roof rental rates. (3) Beyond economic implications, the county-wide promotion projects wield substantial societal and environmental benefits. These encompass reductions in pollutants and carbon emissions, advancements in energy diversification, and the generation of employment opportunities that resonate throughout the entire lifecycle of these initiatives.

Based on the findings of this paper, the following policy recommendations are made to promote the development of whole-county PV power generation.

(1) Promote Technological Advancements and Innovation: The continual enhancement of distributed PV conversion efficiency over the past decade underscores its pivotal role in realizing the economic benefits of PV power generation and reducing reliance on fossil fuels. The Chinese government should persist in fostering technological research and development in the PV sector. This can be achieved through various means, including offering financial incentives such as tax exemptions to enterprises that allocate substantial investments toward research and development initiatives. Additionally, allocating national leading funds to support the development of cutting-edge PV technologies is essential to stay at the forefront of the industry.

(2) Address Discrepancies in Revenue Models: The paper highlights significant disparities in the revenue models of distributed PV systems provided by local governments in China, particularly in the context of residential choices between the "roof financing loan mode" and the "roof current mode". Residents opting for the "roof financing loan mode" tend to reap considerably greater benefits compared to those choosing the "roof current mode". Conversely, for governments and investment companies, the reverse holds true. The economic disparity in the output of distributed PV systems resulting from these different business models may engender disputes and potential deception among stakeholders. It is imperative to address these issues and strive for a more equitable distribution of economic benefits among all parties. Moreover, thorough investigation and risk assessment of the financial implications associated with the "roof financing loan mode" are necessary to mitigate potential financial risks and ensure the sustainability of these projects.

(3) Mitigate High Initial Investment Costs and Promote Sustainable Incentives: The shift into the subsidy-free era in China introduces considerable challenges and risks, particularly pertaining to the high initial investment costs associated with county-level distributed power generation projects. At present, the Chinese government predominantly incentivizes demand through tax benefits. However, it is imperative to explore and implement more streamlined and accessible authentication mechanisms for green electricity certificates and carbon credits. This entails a vision of gradually establishing robust and dependable markets for green electricity, green certificates, and carbon emissions trading specific to distributed PVs. By doing so, we can foster the growth of these markets, thereby enhancing their vitality and ensuring a sustainable future for the industry. These mechanisms will serve to incentivize investment, spur innovation, and expedite the adoption of distributed PV solutions while reducing the dependence on government subsidies.

On the other hand, this paper has certain limitations that provide intriguing avenues for future research. Firstly, the research scope of this study is confined to one of the 676 pilot counties within the Whole County Promotion Project. Variations in market size, policy parameters, and solar energy resources exist among different countries in China. Therefore, future research can enhance its comprehensiveness by expanding the study to a more diverse array of counties, taking into account these disparities, which would facilitate a more precise assessment of economic and environmental aspects and yield a more refined project benefit analysis. Secondly, forthcoming research can better quantify the cost-effectiveness of county-level distributed PV projects in various social and environmental domains, such as energy diversification, light pollution, sound pollution, and others. This approach will enable a more comprehensive and intuitive cost analysis and evaluation, providing a holistic understanding of the societal and environmental impacts of county-level distributed PV projects. Addressing these limitations and delving into these areas for future research will contribute to a more robust and comprehensive comprehension of the potential and implications of county-level distributed PV projects in China and beyond.

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