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Evaluating the economic and environmental impacts of distributed photovoltaic policy: Insights from county-level data in China

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ABSTRACT

Distributed photovoltaic (DPV) construction has a positive effect on environmental protection and energy security, and a notable significance in promoting economic development and improving people's livelihoods. However, existing research lacks empirical evidence assessing the integrated implementation effects of DPV construction policy. To bridge this knowledge gap, this study employs a difference-in-differences model to investigate the effects of DPV construction policy in China, covering 1766 county-level administrative regions in China from 2011 to 2019. The findings reveal that DPV construction effectively combines the dual benefits of emissions reduction and economic growth. On average, DPV construction reduces local carbon emissions by approximately 6.21% and increases per capita GDP by around 3.22% compared with the control group. Analysis of the underlying mechanisms indicates that DPV construction has several key impacts. First, it facilitates the transformation of resource-dependent cities, resulting in emissions reduction. Second, it generates economic development opportunities in rural areas with abundant solar energy resources, enabling regions to convert resource advantages into economic benefits. This study yields significant practical evidence and provides valuable insights for advancing the synergistic development of economic growth and low-carbon environmental protection using DPV.

1. Introduction

The transition from fossil fuels to clean energy is essential for advancing sustainable development and is a central focus of the United Nations' global energy transformation goal (Wang and Zhen, 2024b). The climate goals of the Paris Agreement also limited peak carbon emissions to 2030, calling for an increase in the share of nonfossil fuel energy in primary energy consumption to 20%. With rapid economic development, China faces the dual pressure of energy and environment. China's ambition to achieve carbon neutrality by 2060 has attracted worldwide attention in recent years. As a strategic emerging industry in China, clean energy has been growing in scale and is key to building a new energy system in China. Solar energy is a crucial complementary energy source that produces no pollutants during conversion, making it one of the cleanest energy alternatives. Numerous studies have evaluated and emphasized the richness of solar energy resources in China (Wang et al., 2021); (Wang et al., 2021), demonstrating that the national solar energy resource potential is between 5400.00MJ/m^2–8245.05 MJ/m^2, with an average value of 6429.05 MJ/m^2, denoting favorable conditions for the deployment of photovoltaic (PV) power generation (Zhang, H. et al., 2020).

Distributed photovoltaic (DPV) construction, as a low-carbon and environmentally friendly energy solution, has been widely promoted for its role in mitigating global carbon emissions (Zhang, A.H. et al., 2022). Compared to centralized PV, DPV offers several advantages, including a smaller carbon footprint, lower investment costs, and a shorter construction period. It can be widely installed on residential and factory rooftops, idle land, and other available spaces, facilitating decentralized emission reductions. The primary advantage of DPV construction is its short energy transmission distance, which provides users with alternative clean energy options. Additionally, the short transmission distance can reduce residents' energy costs and provide complementary income to solar panel hosts. Overall, DPV policies are pivotal for economic growth and carbon emission reduction. They are essential for decreasing dependence on traditional fossil fuels and advancing the green, low-carbon transformation of the economy. Therefore, it is essential to systematically evaluate the effectiveness of distributed PV policies to provide empirical evidence for their improvement and adjustment,

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thereby promoting the sustainable development of renewable energy.

Scholars in several developing countries, including China, have focused on studying photovoltaic construction and the formulation and implementation of related policies. China's large-scale PV construction efforts began with the PV poverty alleviation policy, followed by the introduction of various distributed photovoltaic policies, which led to rapid growth in national PV construction. The PV poverty alleviation policy is a characteristic new energy application policy in China, and related studies have primarily focused on the economic effects of the policy (Li et al., 2020; Liu et al., 2021). First, the microhousehold survey and interview data used in these studies are subjective, introducing potential bias and uncertainty. Second, spatial scale limitations may affect the applicability of study results across different geographic regions. Third, previous studies have focused on small-scale PV projects in individual cities or towns; therefore, the results are not generalizable enough to support the development of large-scale PV projects on a national scale. Fourth, most existing studies have focused on individual impacts of PV on the economy, society, and environment, neglecting to establish an integrated research framework. The combined effects of PV project construction remain largely unexplored.

Building on this foundation, this study uses China's photovoltaic poverty alleviation projects (PPAP) pilot policy as a starting point and employs Difference-in-Differences (DID) models to estimate the emissions reduction and economic growth effects of large-scale DPV construction in China. The study analyzes 1766 county-level administrative regions in China over the period from 2011 to 2019. The main contributions of this study are summarized as follows.

First, this study takes DPV construction as the research object to systematically assess the effect of DPV construction policy in China. Although previous studies have recognized the importance of clean energy production to socioeconomic development, most research has focused on the total amount of new energy generated, and few have examined DPV as a niche area. This study innovatively uses the PPAP pilot to examine the policy effects of large-scale DPV construction in China, analyzing both the economic and environmental impacts in detail and expanding the existing research perspectives in the field of new energy.

Second, this study integrates the economic and environmental dimensions to enhance the empirical assessment of PV policy effects. Recently, there has been limited research on the effects of energy-economic policies, with fewer studies addressing their synergistic impacts. Therefore, from a depth-of-research perspective, this study explores DPV construction policy through the dual lenses of carbon emissions and economic growth, offering empirical evidence for promoting the synergistic advancement of economic growth, energy conservation, and emissions reduction. Regarding empirical data, this study utilizes panel data from China's county-level administrative regions, producing more objective, generalizable, and realistic results.

Third, this study investigates the internal mechanisms of emissions reduction and economic growth effects of DPV construction policy, focusing on the transformation of cities' resources and resource advantages. This approach addresses the gaps in existing studies on DPV construction policies. This study integrates the transformation of resource-based cities, natural resource advantages, and low-carbon economic growth into a unified framework for analyzing DPV construction policy. It offers empirical support for the strategic promotion of resource-based cities' transformation and the rational planning of PV industry configurations. The mechanism analysis offers valuable insights into the policy impacts of DPV construction and provides guidance for advancing the transformation and upgrading of resource-based cities, as well as promoting the synergistic and sustainable development of China's economy and environment.

The remainder of this paper is structured as follows. Section 2 presents the literature review. Section 3 describes the methodology. Section 4 details the study's empirical analysis. Section 5 reports the mechanisms analysis, and Section 6 includes conclusions and limitations.

2. Literature review

2.1. Economic benefits of DPV construction

DPV construction was initially designed to integrate regional poverty reduction with the development of clean energy industries, leading to a growing body of research on its economic effects (Olczak et al., 2022; Zander et al., 2024). Economic effect studies, discussed below, have examined cost savings, energy poverty alleviation, rural economic development, and improvements in social wellbeing.

DPV construction, as an energy engineering project that integrates renewable energy development with rural revitalization, has garnered significant academic attention for its economic benefits. PV technology has emerged as a clean, low-carbon, and cost-competitive energy source in many countries, with research on cost savings and energy poverty alleviation being a central focus (Bhattarai et al., 2018). Li et al. (2023) empirically examined the impact of PV poverty alleviation policies on household energy poverty using panel data from China's 2010–2018 tracking survey. Their findings indicate that these policies have positively contributed to alleviating energy poverty. The widespread adoption of PV technology and supportive industrial policies has alleviated energy poverty, largely due to the significant reduction in energy costs enabled by the application of new energy technologies (Sharif and Mithila, 2013). As a result, countries worldwide, including the United States, Germany, France, and Turkey, are actively promoting PV technology programs and policies (Kilic and Kekezoglu, 2022; Nuñez-Jimenez et al., 2023; Yadav et al., 2020). Jin et al. (2024) used a numerical simulation methodology to conduct a solar energy cost-benefit analysis, showing that the adoption of renewable energy in large shopping malls reduces energy costs and increases corporate profits.

Notably, China's DPV construction is based on the strategy of poverty alleviation, contending that the development of the PV industry can effectively drive rural economic development and enhance social welfare, reducing the urban–rural gap (He et al., 2023; Liu et al., 2023). Zhang, Y. et al. (2020) investigated PPAP counties and found that PV poverty alleviation projects increased per capita disposable income by approximately 7%–8%, with PV strategies positively influencing rural economic development. Yasmeen et al. (2023) examined the impact of PV power on income inequality, finding that PV power increased household income and reduced regional income inequality. However, recent studies have raised questions about the positive effects of PV construction on rural revitalization and social wellbeing. Li et al. (2020) argued that the distribution of solar poverty alleviation projects in rural China has been inefficient, weakening their effectiveness in narrowing the urban–rural gap. Additionally, some scholars have argued that PV construction in rural areas should be cautiously evaluated based on practical, region-specific experiences to avoid overestimating its positive effects on rural revitalization and social wellbeing (Bai et al., 2021; Zhang, M. et al., 2021; Zhang, Q. et al., 2021).

2.2. Environmental benefits of DPV construction

PV construction is an effective method for advancing energy transitions, addressing climate change, and achieving large-scale emissions reductions through the extensive collection and conversion of solar energy. DPV construction, in particular, has gained wider adoption due to its flexibility and broad applicability (Chowdhury et al., 2014). Existing research on the environmental impacts of DPV construction has primarily focused on carbon emissions reduction and the improvement of energy structures.

PV energy, as a form of clean energy, has a significantly lower impact on air quality and climate change compared to traditional power generation systems, making PV construction a potent tool for reducing greenhouse gas (GHG) emissions. DPV construction is considered clean during its operational phase and directly contributes to carbon emissions reduction (Fu et al., 2015). Jaeger-Waldau et al. (2020) argued that cumulative PV capacity in the EU and UK must be increased to 455–605 GW to achieve a 55% reduction in GHG emissions, highlighting the significance of PV construction in national emissions reduction targets. Zhang, L. et al. (2022) developed a system dynamics model to analyze carbon emissions reduction in the PV industry, concluding that China's PV sector could contribute 14.7% toward carbon neutrality by 2060. However, several studies have also emphasized that energy consumption and emissions throughout the lifecycle of PV panels must be considered (Dong et al., 2024; Sonter et al., 2020; Wang and Zhen, 2024a). Sajid and Bicer (2021) argued that PV systems cannot be regarded as fully eco-friendly, zero-emissions systems, as their entire lifecycle carbon footprint offsets the zero-emissions goal. Furthermore, the overall environmental impact of PV construction remains a topic of considerable debate. Wang et al. (2022) assessed the environmental impact of domestic energy consumption in rural households, using PV poverty alleviation areas as a case study. The study found that although China's large-scale PV poverty alleviation program has successfully alleviated poverty, its impact on the ecological footprint, including energy transitions for the rural poor, remains insufficient. The study also concluded that while PV systems can help reduce poverty by lowering energy consumption in rural areas, their overall impact on energy consumption and the environment remains minimal.

Second, studies have shown that DPV construction positively impacts the energy structure, promoting regional ecological sustainability and advancing economic development by optimizing energy consumption patterns. D'Adamo et al. (2022) argued that solar PV systems play a crucial role in protecting ecosystems, assisting countries in transforming energy structures, achieving energy independence, and fostering a cleaner future. Kyere et al. (2024) used a qualitative analysis to show that the global proliferation of home-based DPV solar energy systems has become a significant source of low-carbon energy. The widespread adoption of PV has become a key component of global energy restructuring, enabling emerging economies to foster sustainable economic transitions through energy technology innovation. Liu et al. (2023) found that large-scale DPV construction in China has significantly accelerated energy transitions among rural households, based on panel data from China's Rural Poor Household Monitoring System.

Overall, a cleaner energy mix is essential for sustainable development, and DPV construction is now a major strategy for mitigating global climate change and advancing sustainable development. Existing studies have primarily examined the economic and environmental impacts of new energy development. Among these, DPV construction has gained significant attention as a key strategy for promoting clean energy use in China. Most studies indicate that DPV construction offers substantial economic benefits, providing theoretical support for the clean energy transition and economic growth. Regarding environmental impact, studies widely acknowledge that clean energy use plays a positive role in reducing carbon emissions and alleviating environmental pressure. Furthermore, DPV, as the leading clean energy source, holds significant potential in balancing regional economic growth with environmental protection.

While existing research on the economic and environmental impacts of new energy development has been extensive, it often adopts a macro-level approach, focusing on new energy as a whole, without considering the unique characteristics of DPV construction or the effects of related policies. Overall, existing studies lack a comprehensive framework that links economic and environmental factors to the broader impacts of DPV construction policies. To address this gap, the study develops a comprehensive theoretical framework for evaluating DPV construction policies, considering both economic and environmental perspectives (Fig. 1). This framework systematically assesses the policy effects in China and provides empirical evidence for global clean energy utilization.

3. Methodology

3.1. Model setting

China's large-scale DPV construction was initially launched through the PPAP policy, with successive batches of pilot areas established over the years. To accurately assess the impact of DPV construction policies, this study adopts the methodologies used in previous research by Fan and Zhang (2021) and Lu and Zhou (2023). The study constructs a DID model to evaluate the emissions reduction and economic growth effects of DPV construction, focusing on the dimensions of carbon emissions

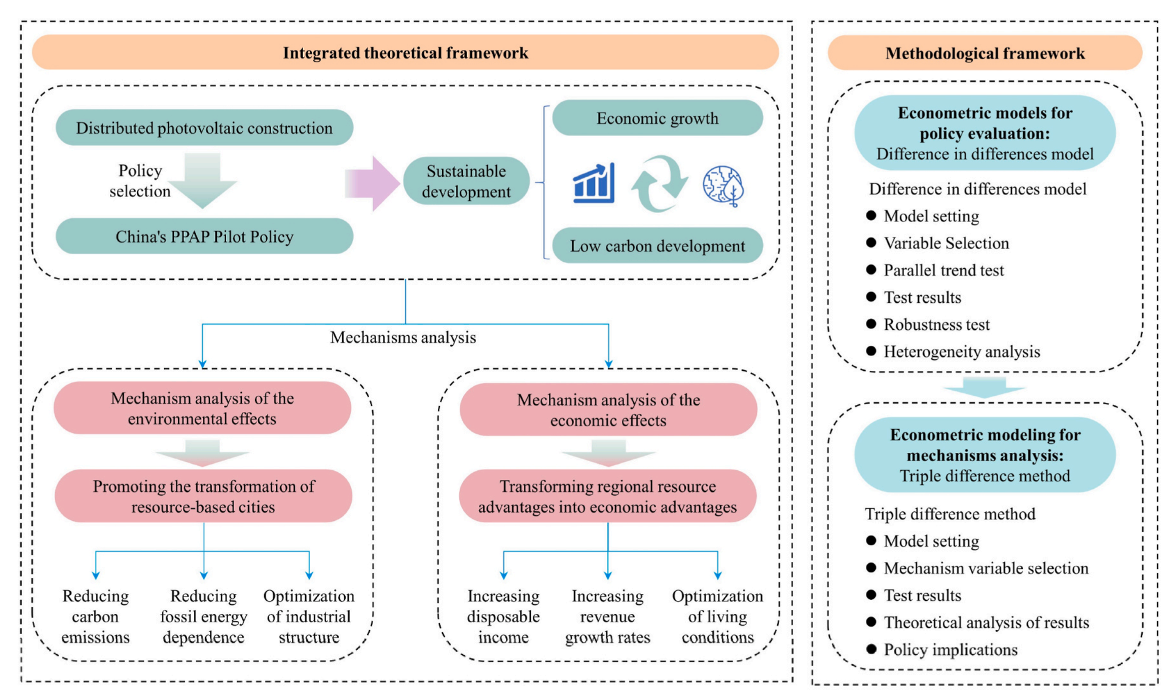

Fig. 1. Integrated research framework.

reduction and economic development. The specific model settings are as follows:

$$y_{i,t} = \alpha_0 + \alpha_1 did_{i,t} + \beta \boldsymbol{Z}_{i,t} + \gamma_t + \tau_i + \varepsilon_{i,t} \tag{1}$$

where the explanatory variables ($y_{i,t}$) include economic growth rate (*GDPR*) and carbon emissions (CO_2). $did_{i,t}$ is the core independent variable, and $did_{i,t} = treat_i \times post_t$ is a dummy variable that takes a value of 1 if county i was a PPAP pilot area in year t and otherwise 0. When $y_{i,t}$ references regional carbon emissions, if coefficient α_1 of $did_{i,t}$ is significantly less than 0, it indicates that DPV construction significantly reduced local carbon emissions, confirming the emissions reduction effect. When $y_{i,t}$ references the regional *GDPR*, if coefficient α_1 of $did_{i,t}$ is significantly greater than 0, it indicates that DPV construction had a significant driving effect on local economic growth, confirming the economic growth effect. $\boldsymbol{Z}_{i,t}$ denotes a set of control variables; γ_t denotes time fixed effects, controlling for influences that vary over time; τ_i denotes county fixed effects, controlling for individual factors that affect the explanatory variables but do not vary over time; and $\varepsilon_{i,t}$ denotes the error term.

DPV systems development has two primary objectives. First, development policies seek to convert regional resource advantages into economic benefits while addressing wealth inequality through the comprehensive utilization of solar energy resources. Second, policies promote the transition to a low-carbon economy in resource-rich regions by reallocating investments towards new energy development. To further explore the mechanisms underlying the emissions reduction and economic growth effects of DPV construction, and drawing on the design concepts proposed by Lu and Zhou (2023), this study develops the following triple-difference models:

$$T_{i,t} = \phi_0 + \phi_1 did_{i,t} + \phi_2 did_{i,t} \times City_i + \beta \boldsymbol{Z}_{i,t} + \gamma_t + \tau_i + \varepsilon_{i,t} \tag{2}$$

$$R_{i,t} = \varphi_0 + \varphi_1 did_{i,t} + \varphi_2 did_{i,t} \times Sun_i + \beta \boldsymbol{Z}_{i,t} + \gamma_t + \tau_i + \varepsilon_{i,t} \tag{3}$$

where $T_{i,t}$ denotes the emissions reduction effect, which is measured by carbon emissions, energy consumption, and industrial structure, and $R_{i,t}$ denotes the economic growth effect, which is measured by per capita household disposable income in rural areas, per capita housing area in rural areas, and the growth rate of farmers' per capita income. $did_{i,t} \times City_i$ and $did_{i,t} \times Sun_i$ denote the triple difference estimators, $City_i$ is a dummy variable for whether area i is a resource-based city, and Sun_i is a dummy variable for whether area i is a solar resource-rich area. The coefficient estimate ϕ_2 represents the emissions reduction effect of DPV construction, where if ϕ_2 is significantly less than 0, it indicates that compared with other cities, resource cities achieve greater emissions reduction through DPV construction, confirming that resource cities realized energy transition through DPV construction. The coefficient estimate φ_2 represents the economic growth effect of DPV construction, where if φ_2 is significantly greater than 0, it indicates that DPV construction has transformed the advantages of solar resource-rich areas into economic and social benefits.

3.2. Index selection and variable explanation

3.2.1. Dependent variable

The dual carbon strategy—achieving peak carbon emissions by 2030 and carbon neutrality by 2060—serves as a key guiding principle for China's ongoing economic and social development. Given that carbon emissions currently serve as the primary benchmark for regulating domestic fossil fuel energy consumption (Kirikkaleli and Adebayo, 2021), and considering the feasibility of available sample data, this study draws from the insights of Yu et al. (2022), using county-level carbon emissions (CO_2) as a proxy variable to quantify the emissions reduction effect. In addition, this study also examines carbon emissions according to different energy types, using carbon emissions data from the Emissions Database for Global Atmospheric Research (EDGAR, https://edgar.jrc.ec.europa.eu/) (denoted as CO_2_sub) for robustness testing (Cheng et al., 2023; Lekaki et al., 2024).

Conversely, China's economic growth objectives have transitioned from a focus on accelerated, quantity-driven growth to an emphasis on high-quality-oriented development. Consequently, in alignment with the fundamental requirements of this high-quality economic development paradigm, referencing the insights of Beck et al. (2010), this study uses the growth rate of per capita GDP (*GDPR*) as the proxy variable for economic growth effects. Nighttime lighting is strongly associated with regional economic development and is widely used in research (Marbuah et al., 2021; Wan et al., 2023). To ensure robustness, this study uses nighttime lighting data (*GDP_sub*) as a robustness test, replacing *GDPR*.

3.2.2. Independent variable

PPAP policy implementation marked the beginning of large-scale DPV construction in rural China, and this study identifies the pilot counties referencing relevant documents concerning PPAP pilots from the National Energy Administration and the Poverty Alleviation Office of the State Council. This study was conducted at the county level; however, some data were missing for certain regions in the China County Statistical Yearbook, such as Qinghai, Xinjiang, and Tibet. As a result, after excluding counties with missing data, the study identified 204 policy pilot counties as the treatment group. These pilot counties were primarily located in Eastern, Central, and Northwestern China. To ensure comprehensive regional representation, 1562 non-pilot counties were included as the control group in the study.

The pilot PPAP counties during the sample period are identified as the DPV construction treatment group ($treat_i = 1$); otherwise, they are included in the control group ($treat_i = 0$). $post_t$ is the time dummy variable for PPAP implementation. $post_t$ is a time dummy variable of PPAP, where when year $\geq$ pilot year, $post_t = 1$; otherwise $post_t = 0$. The crossmultiplication term $did_{i,t}$ ($did_{i,t} = treat_i \times post_t$) is the core explanatory variable of this study.

3.2.3. Control variables

To ensure the comparability of the treatment and control groups, it is essential to include various other factors that may influence the model in addition to the impact of DPV construction to control for the interference of such exogenous variables. Referencing Li et al. (2016), Wang (2013), and Zhang, Y. et al. (2020), this study introduces the following control variables. Industrial development (*ind*): This variable represents the proportion of value added in secondary and tertiary industries, which is employed to control for the impact of industrial development in the county. Savings (*sav*): This variable is the natural logarithm of the balance of residents' savings deposits to account for regional savings. Financial situation (*pub*): This variable reflects the ratio of public financial expenditure to income to control for the regional financial circumstances. Education level (*edu*): The number of students enrolled in general secondary schools as a proportion of the total population controls for the regional education level. Financial development (*fin*): This variable quantifies the balance of loans from financial institutions as a proportion of the regional GDP to control for regions' financial development level. Social welfare (*wel*): This variable uses the natural logarithm of the number of beds in various social welfare adoptive units to control for regional social welfare level.

Table 1 presents a detailed description of the variables mentioned above.

3.3. Sample selection and data sources

This study constructs a panel dataset of annual observations from 2011 to 2019 at the county level to comprehensively assess the policy effects of DPV construction. As of 2019, 2846 county-level administrative units existed in China, and the sample in the study includes 1766 county-level administrative units after excluding counties with missing

Table 1
Description of variable indicators.

Variable Type	Variable Name	Variable Symbol	Variable Description
Dependent variable	Carbon emission	CO_2	Carbon dioxide emissions
	Economic growth	*GDPR*	Growth rate of per capita GDP
Independent variable	Piloting of PPAP	*did*	Policy variable
Control variables	Industrial development	*ind*	Proportion of value added in secondary and tertiary industries
	Savings	*sav*	The natural logarithm of the balance of residents' savings deposits
	Financial situation	*pub*	Ratio of public financial expenditure
	Education level	*edu*	Number of students enrolled in general secondary schools as a percentage of the total population
	Financial development	*fin*	Loan balances of financial institutions as a ratio of GDP
	Social welfare	*wel*	The natural logarithm of the number of beds in various social welfare adoptive units

data.

The sources of data for the study's variables in the study are as follows. County-level carbon emissions data used in the explanatory variables are sourced from China Emission Accounts & Datasets (https://www.ceads.net/). As noted, this study also uses CO_2 emissions data from EDGAR for robustness testing. Data on per capita GDP are obtained from the China County Statistical Yearbook, and data for the remaining variables are acquired from the China Economic Database (https://www.ceicdata.com.cn/). This study applied linear interpolation for some of the missing data to fill in the blanks. We also considered the distribution of solar radiation resources; however, given that China does not disclose solar irradiance data at the county level, our data are obtained from the China Meteorological Administration, which collects data from more than 700 meteorological stations across the country.

This comprehensive data collection approach ensures a robust and rigorous analysis of the policy effects of DPV construction across county-level administrative districts in China during the specified period. Table 2 presents the descriptive statistics of the sample data.

4. Empirical analysis

4.1. Baseline regression results

4.1.1. Test results regarding the emissions reduction effect of DPV construction

Columns (1) and (2) in Table 3 present the findings concerning the impact of DPV construction on local carbon emissions. In column (1), the analysis solely includes the average impact, controlling for time, county, and city fixed effects. In column (2), we introduce a comprehensive set of variables. In both cases, the coefficients of the policy variable exhibit statistically significant negative values at the 1% level, indicating that DPV construction has significantly reduced local carbon emissions in pilot cities, with a substantial abatement effect.

Table 2
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2	15,894	2.9064	2.7698	0.0163	26.4919
GDPR	15,894	0.0995	0.1248	−0.7430	2.6170
did	15,894	0.0561	0.2300	0.0000	1.0000
ind	15,894	1.3664	1.0071	0.0182	17.2814
sav	15,894	13.4895	1.0240	8.3855	21.6914
pub	15,894	5.9462	7.4017	0.0889	135.7775
edu	15,894	0.0460	0.0141	0.0022	0.2069
fin	15,894	0.6393	0.3754	0.0003	6.0985
wel	15,894	6.7034	1.2500	1.3863	9.9422

Table 3
Baseline regression.

	CO_2		*GDPR*	
	(1)	(2)	(3)	(4)
did	−0.0681***	−0.0621***	0.0161**	0.0322***
	(0.0232)	(0.0225)	(0.0068)	(0.0070)
Controls	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Observations	15,894	15,894	15,894	15,894
R^2	0.986	0.986	0.201	0.261

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

The results from model (2) in Table 3 reveal that DPV construction reduced local carbon emissions by 6.21% on average, representing is a significant achievement toward regional energy conservation and emissions reduction goals, underscoring the policy's significant impact.

4.1.2. Test results regarding the economic growth effects of DPV construction

Columns (3) and (4) in Table 3 present the findings concerning the impact of DPV construction on the local *GDPR*. In model (3), the analysis solely includes the average impact, considering time, county, and city fixed effects. In model (4), we once again introduce a comprehensive set of variables. In both cases, DPV construction demonstrates a significant positive effect on the local *GDPR*, with statistical significance at the 1% level. This finding indicates that DPV construction plays a significant influence on driving regional economic development in pilot cities.

Furthermore, holding other variables constant, the average regional *GDPR* experienced a noteworthy 3.22% increase following DPV construction. This effect has significant economic growth implications for Chinese society, highlighting the multifaceted benefits of the policy.

4.2. Robustness test

4.2.1. Parallel trend test

The parallel trend hypothesis is a crucial assumption for appropriate DID application. In the case of this study, this implies that if the DPV construction pilot was not implemented, the carbon emissions and *GDPR* trends of the treatment and control groups within the sample should follow similar trajectories. To assess this hypothesis, this study employs the event study method, referencing Jacobson et al. (1993) and Beck et al. (2010).

The specific model for testing the parallel trend hypothesis is constructed as follows:

$$y_{i,t} = \psi_0 + \sum_{t=-5}^{5} \psi_1 D_{i,t} + \beta Z_{i,t} + \gamma_t + \tau_i + \varepsilon_{i,t} \tag{4}$$

where $D_{i,t}$ is a set of dummy variables that take a value of 1 if sample I implemented the PPAP pilot policy in year t, and 0 if sample I implemented the pilot policy in year t. The remaining variables are the same as those in Eq. (1). ψ_1 reflects the difference between the treatment and control groups' carbon emissions and *GDPR* in year t of pilot policy implementation. This study set the $D = -1$ as the base period to avoid multicollinearity.

The results of the parallel trend analysis presented in Fig. 2 demonstrate that the estimated coefficients for the periods prior to PPAP

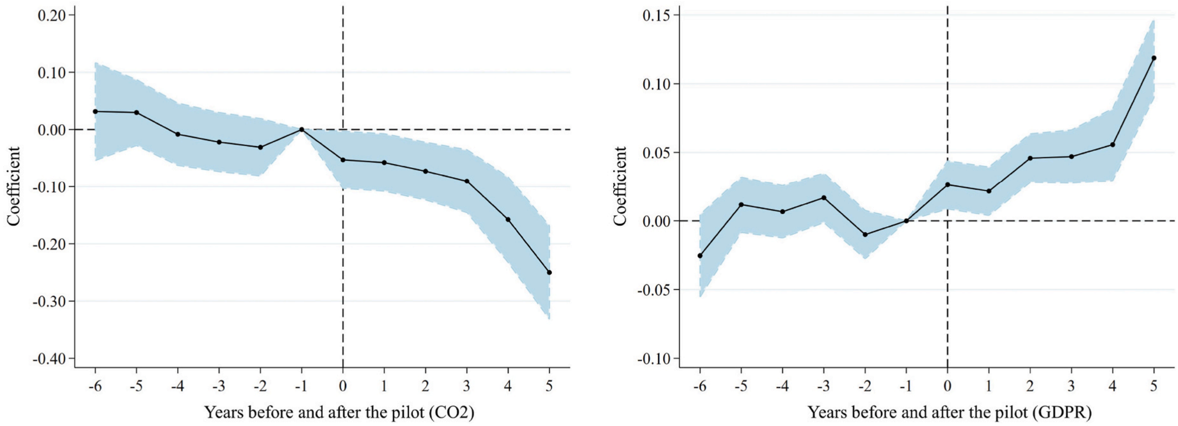

Fig. 2. Parallel trend test.

pilot policy implementation were not statistically significant. This indicates that no significant disparity is evident between the carbon emissions and *GDPR* of the treatment and control groups after accounting for potential confounding factors. This finding aligns with the prerequisites of the DID model, confirming the parallel trend assumption.

4.2.2. Placebo test

- Time-placebo test

To ensure that the policy differences observed in the treatment and control groups are not driven by a time-varying trend, this study conducts a time placebo test, referencing Beck et al. (2010) and Yu et al. (2022).

This study introduces lags to PPAP policy pilot implementation, with periods of 1, 2, and 3 years, which are denoted as *did_L*1, *did_L*2, and *did_L*3, respectively. Regressions are performed using Equation (1), and the results are presented in Table 3.

The lagged treatment of the policy point is primarily based on the assumption that the policy effect becomes more pronounced as policy implementation advances. Columns (1) to (3) in Table 4 reveal that when DPV construction is lagged by 1–3 years, regional carbon emissions continue to be significantly reduced. The absolute value of the coefficient gradually increases compared with the benchmark regression, indicating that the emissions reduction effect of DPV construction becomes more pronounced over time. This reaffirms that the policy substantially reduces regional carbon emissions.

Similarly, columns (4) to (6) in Table 4 reveal that the absolute value of the coefficient increases as the policy is lagged, indicating that the economic growth effect of DPV construction is continuously enhanced over time, providing additional confirmation of the emissions reduction and economic growth effects of DPV construction.

- Sample placebo test

To address the potential influence of unobservable omitted variables and other characteristic factors on the baseline regression results, this study adopts the methodology proposed by Liu and Lu (2015), in which an equal number of samples are randomly selected from the entire dataset, mirroring the size of the original treatment group. We then randomize the timing of policy implementation to create a new treatment group with cities and policy times assigned at random. The remaining samples are designated as a spurious control group.

This process is repeated 500 times, yielding 500 regression analyses and corresponding p-values. The kernel density distribution of the experimental regression coefficients is illustrated alongside the p-values in Fig. 3. This rigorous methodology accounts for the potential impact of unobserved variables and offers a more robust analysis of the policy's effects.

The estimation results reveal that the regression coefficients tend to cluster around zero and closely adhere to a normal distribution following randomization. Additionally, the majority of regression results yield nonsignificant p-values. Notably, when the explanatory variable is carbon emissions, the random coefficients are predominantly situated to the right of the true values found in the benchmark regression. Conversely, when the explanatory variable is *GDPR*, the random coefficients tend to be positioned to the left of the true values from the benchmark regression. This observation suggests a substantial weakening of the policy effect in terms of significance and the strength of the

Table 4
Placebo test for policy timing lag.

	CO_2			*GDPR*		
	(1)	(2)	(3)	(4)	(5)	(6)
*did_L*1	−0.0635**			0.0323***		
	(0.0250)			(0.0084)		
*did_L*2		−0.0719***			0.0408***	
		(0.0275)			(0.0105)	
*did_L*3			−0.0899***			0.0412***
			(0.0308)			(0.0148)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,894	15,894	15,894	15,894	15,894	15,894
R^2	0.986	0.986	0.986	0.261	0.262	0.261

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

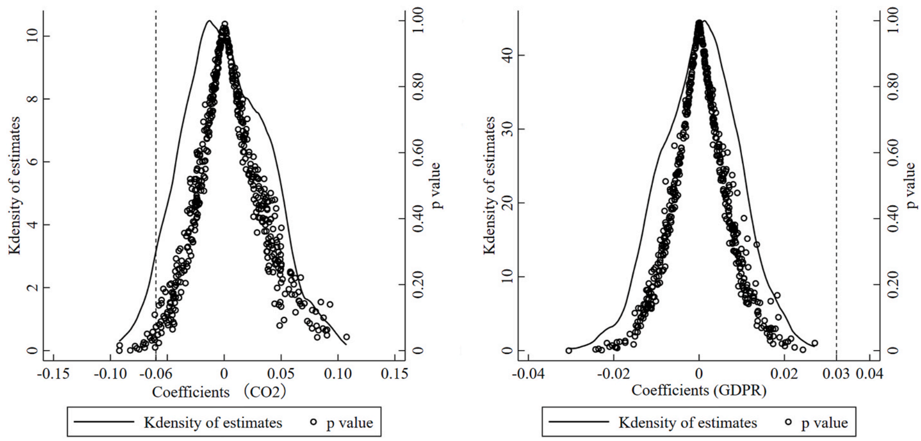

Fig. 3. Sample placebo test.

double stochastic treatment's impact. These findings diminish the likelihood that the baseline estimates in this study result from unobservable confounding factors.

4.2.3. Substituting dependent variables and changing the sample

To assess the robustness of the baseline estimation results, this study initiates robustness tests using variable substitution and sample adjustment. Existing data on carbon emissions are primarily at national and provincial levels, and more detailed data on carbon emissions are lacking. Referencing Cheng et al. (2023); Lekaki et al. (2024), this study uses EDGAR carbon emissions data (CO_2_sub) to conduct a robustness check. These data include different energy types to account for carbon emissions, encompassing carbon emissions from 214 countries and regions around the world, including China, comprising carbon emissions from energy activities, some industrial carbon emissions, some nonenergy carbon emissions, and fuel autoignition emissions. Moreover, this study uses the nighttime lighting data (*GDP_sub*) as a proxy variable for GDP per capita for robustness testing. The outcomes of these robustness tests using replacement variables are presented in columns (1) and (2) of Table 5. The results demonstrate that the emissions reduction and economic growth effects of DPV construction remain consistent, regardless of how the explanatory variables are measured. This further validates the robustness of the benchmark regression results.

Considering the pronounced resource agglomeration effects in central cities, which can exert a significant influence on the development of other regions, this study considers the unique status of municipalities and subprovincial cities within China's administrative divisions. This special status may introduce potential bias in the estimation results; therefore, this study excludes the sample of counties and districts belonging to municipalities and subprovincial cities. The results in columns (3) and (4) of Table 5 demonstrate that the findings from the benchmark regression remain robust even after accounting for the potential effects of excluding this special sample. This further confirms the stability and reliability of the estimation results.

4.2.4. Propensity score matching-DID model and replacing standard error clustering

To address potential endogeneity concerns associated with reverse causation and sample selection bias, this study employs the propensity score matching (PSM) method. In this approach, the pilot districts established during the sample period are designated as the treatment group, and 1:1 nearest-neighbor matching method is used to match them with control cities. This PSM-DID model aims to minimize endogeneity issues, providing more reliable estimations.

The results of the PSM-DID model are presented in columns (1) and (2) of Table 6. Notably, even after rematching the samples, the results remain statistically significant at the 1% level, once again validating the robustness of the baseline conclusions.

Furthermore, to account for potential correlations among counties within prefecture-level cities, this study clusters the regression standard errors at higher, prefecture-level cities, presenting the estimation results in columns (3) and (4) of Table 6. Although the significance of the emissions reduction effect of DPV construction is somewhat diminished, it remains statistically significant at the 10% level. Moreover, the economic growth effect of DPV construction continues to be significant at the 1% level. This reinforces the robustness of the benchmark regression results, even when addressing potential within-city correlations.

Table 5
Robustness tests for replacement variables and adjusted samples.

	Substitution of explanatory variables		Sample with municipalities and sub-provincial cities removed	
	(1)	(2)	(3)	(4)
	CO_2_sub	*GDP_sub*	CO_2	*GDPR*
did	−0.0226**	0.0006***	−0.0675***	0.0309***
	(0.0108)	(0.0017)	(0.0226)	(0.0070)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Observations	15,894	15,894	15,282	15,282
R^2	0.826	0.915	0.985	0.261

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

Table 6
PSM-DID model and robustness test for replacement standard error clustering.

	PSM-DID		Standard misclustering to cities	
	(1)	(2)	(3)	(4)
	CO_2	*GDPR*	CO_2	*GDPR*
did	−0.0624**	0.0330***	−0.0621*	0.0322***
	(0.0245)	(0.0072)	(0.0368)	(0.0105)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Observations	10,172	10,172	15,894	15,894
R^2	0.984	0.259	0.986	0.261

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

4.3. Heterogeneity analysis

4.3.1. Regional heterogeneity of DPV construction

The above analysis examines the average differences between the economic and environmental effects of DPV construction. Recent research has confirmed that DPV construction is closely related to regional characteristics (e.g., variability in solar resources across regions, market acceptance of solar energy use by residents, spatial variability in PV technological innovations, and other considerations), and the effects of solar energy deployment may vary across diverse regional markets (Che et al., 2022; Dokshin et al., 2024).

The availability of PV resources is a primary consideration for DPV construction, and the distribution of PV resources in China exhibits distinct regional patterns (Xu et al., 2023). According to the official standards of the National Bureau of Statistics of China, this study divides the sample into eastern, central, and western regions to investigate the regional heterogeneity characteristic of DPV construction. Table 7 presents the results of this regional analysis.

The findings from the regional heterogeneity analysis reveal two key points. First, DPV construction has a substantial and significant emissions reduction effect in the western region, while it does not exhibit a significant effect in the central and eastern regions, mirroring the findings of He et al. (2023). This suggests that the western region, with abundant PV resources, has significant potential for expanding the new PV energy industry. The construction of DPV contributes to increasing the western region's per capita GDP and significantly reduces regional carbon emissions. This aligns with the western region's vigorous pursuit of the dual carbon goal and supports the sustainable development of its economy.

The impact of DPV construction in the central and eastern regions is notably less pronounced, which may be attributed to the overall availability of PV resources, which is not as favorable in these regions compared with the western region. Data from China's Provincial Solar Energy Resources Atlas indicate that China's most abundant solar energy resources are primarily concentrated in western regions such as northern Ningxia, northern Gansu, southeastern Xinjiang, western Qinghai, and western Tibet. In contrast, the central and eastern regions have more scattered and less efficient solar energy resources for DPV power generation, which results in less significant effects in those areas.

The impact of DPV construction on the GDPR in the eastern, central, and western regions exhibits a significant driving effect, with the economic growth effect of DPV construction exhibiting a decreasing trend from the central to the eastern and western regions. These findings can be attributed to factors related to PV feed-in tariffs and regional transmission and distribution costs.

First, the economic growth effect of DPV construction is primarily attributable to increased income from integrating PV power generation into the national grid; however, the feed-in tariffs for PV power plants vary significantly among regions due to differences in resource availability. According to the Notice on Issues Related to Improving the Feed-in Tariff Mechanism for Photovoltaic Power Generation issued by the National Development and Reform Commission (Development and Reform Price [2019] No. 761), the corresponding feed-in tariffs for PPAP in resource zones I–III are set at RMB 0.65 per kWh, RMB 0.75 per kWh, and RMB 0.85 per kWh, respectively for village PPAP power stations (including joint-village power stations) and are included in the catalog of national subsidies for additional funds for renewable energy tariffs. These resource zones generally correspond to the western, central, and eastern regions. The relatively lower electricity prices in the western region primarily restrict PV revenue in that area.

Second, China's population distribution and electricity demand are predominantly concentrated in the eastern region. In comparison, the central region enjoys proximity to the power supply, providing a significant advantage for regional DPV projects to increase revenue and achieve transformation benefits. In contrast, the western region faces higher transmission and distribution costs due to geographic distance, which can limit the financial benefits of DPV construction.

4.3.2. Examining the matthew effect in poor counties

Considering that China's extensive DPV construction is primarily driven by the PPAP, it is important to note that one of the primary objectives of this project is to implement PV agricultural poverty alleviation measures by leveraging local conditions and converting underused barren slopes, mountains, and hills in impoverished areas to establish photovoltaic power plants within agricultural greenhouses or agriculture structures. The aim is to directly increase impoverished communities' income and contribute to raising the regional per capita GDP.

Previous research findings have demonstrated obvious differences in economic base, factor endowment, geographic environment, and other factors between poor and nonpoor counties, indicating important differences that must be considered when conducting economic analyses (Liu et al., 2023), making heterogeneity analysis of poor counties extremely necessary. Therefore, this study conducts an analysis of sample heterogeneity by dividing the sample into poor and nonpoor counties. Table 8 presents the results of this analysis.

The regression results presented in Table 8 demonstrate that DPV construction has a significant positive impact on the local *GDPR* and leads to reduced regional carbon emissions, regardless of whether DPV is implemented in impoverished or nonimpoverished counties.

However, notably, the emissions reduction and economic growth effects of DPV construction appear to be more pronounced in nonimpoverished areas, indicating a potential Matthew effect in which the benefits of carbon emissions reduction and economic growth disproportionately favor nonimpoverished regions (Yang and Yang, 2020). This phenomenon deviates from the original policy intent, and is a unique finding of this study that makes us rethink the link between PV

Table 7
Analysis of regional heterogeneity.

	Eastern		Central		Western	
	(1)	(2)	(3)	(4)	(5)	(6)
	CO_2	*GDPR*	CO_2	*GDPR*	CO_2	*GDPR*
did	−0.0930*	0.0449***	0.0096	0.0645***	−0.1231***	0.0223**
	(0.0497)	(0.0097)	(0.0296)	(0.0230)	(0.0323)	(0.0087)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4077	4077	5049	5049	6768	6768
R^2	0.992	0.353	0.978	0.239	0.984	0.266

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively. The eastern region includes the following provinces: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan. The central region includes the following provinces: Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan. The western region includes the following provinces: Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang.

Table 8
Heterogeneity analysis based on poor counties.

	Poorest county area		Non-poor county areas	
	(1)	(2)	(3)	(4)
	CO_2	GDPR	CO2	GDPR
did	−0.0574**	0.0253***	−0.1919***	0.2209***
	(0.0236)	(0.0074)	(0.0579)	(0.0162)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Observations	6408	6408	9486	9486
R^2	0.981	0.241	0.984	0.286

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

construction and the prevalence of poverty. There are two potential reasons for this observed disparity:

First, nonpoor counties have resource advantages and the capacity for more efficient resource integration and utilization. When DPV construction is simultaneously implemented in impoverished and non-impoverished counties, the latter can leverage existing resources to create value more swiftly. In contrast, impoverished counties may lack various types of resources and the necessary infrastructure, resulting in a slower process of resource value creation.

Second, poor counties tend to have a relatively singular industrial system and market structure. However, DPV construction involves a complex network of interrelated industries, including upstream sectors involved in mono/polysilicon production, ingot casting, bar pulling, and wafer slicing; midstream segments such as solar cell manufacturing and photovoltaic module assembly; and downstream activities related to photovoltaic system installation and services. The homogeneity of the industrial system and market structure in impoverished counties may increase the relative costs of DPV construction, diminishing the overall value generated from resource utilization.

5. Mechanisms analysis

5.1. Mechanism analysis of the emissions reduction effect of DPV construction

As China works toward the goal of carbon peak by 2030, the demand for clean and sustainable energy sources is rising, and meeting this demand requires a shift toward a multienergy approach that combines various renewable energy sources. This transition provides a unique opportunity for resource-dependent cities to transform into resource-advantaged locales. Developing a diversified energy system that includes traditional and renewable sources can integrate more low-carbon power into regional economic development while ensuring energy security.

Transforming resource-oriented cities entails two critical characteristics, namely, a shift in regional industrial structure and a significant reduction in regional energy consumption. To explore the mechanistic relationship between the transformation of resource-oriented cities and the emissions reduction effect of DPV construction, this study employs a triple difference model based on Equation (2).

First, this study uses the total tons of standard coal equivalent in fossil energy to calculate fossil fuel energy consumption based on the standard coal conversion factor provided by the Ministry of Industry and Information Technology of the People's Republic of China, where fossil energy primarily includes coal, oil, and natural gas energy.

Second, the industrial transformation of resource-based cities can take two main paths. The first involves shifting from resource-based industries to manufacturing industries, resulting in a manufacturing transformation with a close input–output correlation. The second entails a direct shift to the service industry, marking a service transformation. This study characterizes the change in regional industrial structure using the proportion of secondary industry value added to that in the tertiary industry. A higher value added in the secondary industry that is higher than that in the tertiary industry signifies a trend toward manufacturing transformation. Conversely, if the proportion decreases, it implies a shift toward service transformation.

Table 9 presents the results of this mechanism test, where CO_2 represents regional carbon emissions, and the remaining variables are consistent with the previous model. The resource cities categorization is based on the National Sustainable Development Plan for Resource Cities (2013–2020) issued by the State Council in 2013.

The results presented in Table 9 reveal significant differences between resource-based cities and other cities. Columns (1) and (2) demonstrate that DPV construction significantly reduces carbon emissions in resource-based cities, highlighting its substantial role in carbon emissions management. In comparison to nonresource-based cities, DPV construction significantly decreases fossil energy consumption levels in resource-based cities. This observation provides support for the mechanism, indicating that DPV construction contributes to emissions reduction by promoting the transformation of resource-based cities. The results in columns (5) and (6) confirm that DPV construction effectively reduces the relative proportion of value added in the secondary industry within resource-based cities, indicating progress toward a service-oriented transformation in these cities. These findings contribute to a better understanding of how DPV construction influences resource-based cities.

Moreover, this study offers a theoretical explanation for the empirical results, which adds greater value than merely analyzing the data. Firstly, resource-based cities have historically depended on high-carbon fossil fuels, such as coal. The adoption of solar photovoltaic technology as a clean energy source enhances the zero-carbon share of the city's energy supply. From a full life-cycle perspective of energy production and consumption, solar photovoltaic generates negligible carbon emissions, whereas fossil fuels produce significant carbon dioxide emissions at every stage, from mining and processing to combustion and utilization. According to energy substitution theory, an increase in the share of solar photovoltaic power in the energy mix reduces reliance on high-carbon fossil fuels, thereby decreasing carbon dioxide emissions in both the economy and society.

Secondly, from an economic cost perspective, advances in solar photovoltaic technology and economies of scale have progressively reduced the cost of solar photovoltaic power generation. According to cost-benefit analysis in energy economics, when the cost of solar photovoltaic power generation falls below or approaches that of certain fossil fuels, policymakers and consumers are more likely to choose solar photovoltaic, considering externalities like environmental costs. Consequently, price-driven market choices further accelerate the substitution of fossil fuels with solar photovoltaic, reducing fossil fuel consumption.

Finally, solar photovoltaic construction encompasses various processes, including module manufacturing, installation, maintenance, research and development, as well as related financial and consulting services. The growth of these industries encourages resource cities to transition from traditional resource-dependent sectors to emerging manufacturing and service industries. According to industrial correlation theory, the growth of the solar photovoltaic industry stimulates upstream and downstream sectors, fosters industrial clusters, increases the share of services in the industrial structure, and facilitates the transition to a service-oriented economy. Moreover, solar photovoltaic construction demands substantial technological innovation investment, attracting high-tech enterprises and innovative talent to resource-dependent cities. The concentration of innovative resources facilitates knowledge dissemination and technological spillovers, fostering emerging service industries such as technological and information services. This process accelerates the transformation of resource-dependent

Table 9
Mechanism of emission reduction effect of DPV construction.

	CO_2		Fossil energy consumption		Industrial structure	
	(1)	(2)	(3)	(4)	(5)	(6)
did × *City*	−0.1133***	−0.1018**	−0.0094***	−0.0081**	−0.2933***	−0.2520***
	(0.0435)	(0.0436)	(0.0035)	(0.0035)	(0.0441)	(0.0429)
did	−0.0036	−0.0039	0.0026	0.0016	0.1168***	0.1123***
	(0.0407)	(0.0402)	(0.0030)	(0.0030)	(0.0248)	(0.0264)
Controls	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,894	15,894	15,894	15,894	15,894	15,894
R^2	0.986	0.986	0.830	0.830	0.835	0.875

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

cities into service-oriented economies.

5.2. Mechanism analysis of the economic growth effects of DPV construction

DPV construction harnesses regional PV resources effectively, facilitating the transformation of regional resource advantages into economic gain through PV power generation and grid connection, which subsequently enhances local residents' overall wellbeing. In theory, DPV construction can convert regional resource advantages into economic benefits and foster the sustainable development of the regional economy, achieving a win–win scenario for environmental protection and economic growth.

In accordance with the classification provided by the National Meteorological Administration's Wind Energy Solar Energy Assessment Center, this study categorizes China's solar energy resource regions into four groups. The first, second, and third categories are characterized by annual hours of sunlight that exceed 2200 h and total radiation exceeding 4200 $MJ/M^2 \cdot a$, signifying ample solar energy resources in these regions, which makes them appropriate for solar energy generation. Therefore, this study designates the first, second, and third category areas as regions with abundant solar resources.

Additionally, considering that China's extensive DPV construction has primarily taken place in rural areas, this study incorporates rural per capita disposable income, rural per capita housing area, and rural residents' per capita income growth rate as explanatory variables. All other variables include those used earlier. Employing a triple difference model, the study examines the mechanisms behind the economic growth effects of DPV construction, as detailed in the findings presented in Table 10.

Table 10 reveals that the coefficients of the DID estimator *did* × *Sun* are consistently and significantly positive, indicating that DPV construction has a substantial positive impact on rural residents' overall economic growth in solar resource-rich areas. To provide more detailed insights, when compared to other regions, DPV construction increases rural per capita disposable income growth rates and income in solar resource-rich regions by an average of 3.47% and 21.98%, respectively. It also significantly expands the rural per capita housing area by nearly a factor of one. These results demonstrate that DPV construction presents promising development opportunities for rural areas with abundant solar resources that allow for the transformation of resource advantages into economic benefits and substantial welfare enhancement in these regions while also facilitating economic growth.

From a theoretical perspective, solar photovoltaic construction in rural areas with abundant solar energy resources provides residents with more convenient access to energy. On a practical level, flexible power supply ensures residents' daily lighting and appliance usage, meeting their basic needs for comfort and convenience, thereby enhancing their quality of life. For instance, adequate electricity improves nighttime lighting conditions, facilitating children's learning and family activities, thereby enhancing welfare in education and family life.

Second, solar photovoltaic is a clean energy source, and its widespread adoption mitigates air pollution from burning traditional fuels. From the perspective of welfare economics, good health is a vital aspect of residents' overall welfare. Additionally, a clean environment supports the ecological balance in rural areas, enhances residents' satisfaction with their living conditions, and ultimately improves overall welfare. Furthermore, implementing solar photovoltaic construction projects in rural areas fosters social equity. These projects provide rural residents with energy access comparable to that of urban residents, reducing the urban-rural gap in energy infrastructure.

Finally, the construction of solar photovoltaic systems lowers rural residents' spending on traditional energy sources. From a household budgeting perspective, energy expenses form a notable portion of rural household expenditures, particularly in areas with tight energy supply or reliance on external inputs. Solar photovoltaic construction

Table 10
Mechanisms for the economic growth effects of DPV construction.

	Rural disposable income per capita		Rural per capita housing area		Growth rate of per capita income of rural residents	
	(1)	(2)	(3)	(4)	(5)	(6)
did × *Sun*	0.0366***	0.0347***	0.5165***	0.4954***	0.2116**	0.2198**
	(0.0079)	(0.0077)	(0.1065)	(0.1078)	(0.0883)	(0.0897)
did	0.0145**	0.0134*	−0.3714***	−0.3771***	−0.1043	−0.0878
	(0.0072)	(0.0070)	(0.0969)	(0.0976)	(0.0693)	(0.0706)
Controls	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,894	15,894	15,894	15,894	15,894	15,894
R^2	0.970	0.971	0.919	0.919	0.872	0.872

Note: Robust standard errors clustered at the county level are estimated. Standard errors are presented in parentheses. *, ** and *** represent significance levels of 10%, 5% and 1%, respectively.

significantly reduces energy costs in such regions. Moreover, solar photovoltaic construction has fostered related industries and created employment opportunities in rural areas, providing additional income sources for residents. Additionally, the growth of the rural photovoltaic industry has stimulated supporting sectors, such as basic processing for photovoltaic equipment parts manufacturing. The expansion of the rural solar photovoltaic industry has generated new jobs and boosted local per capita disposable income.

6. Conclusions and limitations

6.1. Conclusions and implications

The development of clean energy systems based on traditional and multienergy sources is a critical step for ensuring the secure, stable, and efficient operation of China's primary energy grid. This development is also key to achieving high-quality energy consumption and meeting the nation's dual carbon goals. In this context, this study uses PPAP pilot cities to estimate the emissions reduction and economic growth effects of large-scale DPV construction in China. The study considers 1766 county-level administrative districts from 2011 to 2019 and analyzes the impacts of DPV construction from the perspective of transforming resource-oriented cities and harnessing resource advantages. The key findings of this study can be summarized as follows:

(1) DPV construction has a dual positive effect by simultaneously reducing carbon emissions and significantly enhancing regional per capita GDP growth. On average, the implementation of DPV construction leads to an approximately 6.21% reduction in local carbon emissions and a 3.22% increase in per capita GDP compared with the nonpilot control group. These findings remain robust after undergoing hypothesis testing and identification procedures.

(2) DPV construction exhibits regional heterogeneity, with a more pronounced emissions reduction effect in the western region and less impact on the central and eastern regions. Furthermore, it significantly drives per capita GDP growth in the eastern, central, and western regions, with economic growth effects that decrease in the order of central, eastern, and western areas. Notably, the effects of DPV construction indicate a Matthew effect in poor regions. This means that the emissions reduction and economic growth effects are more apparent in nonpoor areas, resulting in a unique pattern of carbon emissions reduction and economic growth.

(3) DPV construction has a crucial influence on promoting resource-oriented cities' transformation. DPV construction has significantly reduced carbon emissions in resource-based cities, emphasizing its significant role in carbon emissions management, significantly reducing fossil energy consumption in resource cities. In addition, DPV construction has effectively reduced the relative proportion of secondary sector value added in resource-based cities. These findings contribute to a better understanding of how DPV construction affects resource cities.

(4) DPV construction has provided development opportunities for solar resource-rich rural areas, allowing for the transformation of resource advantages into economic advantages, which has significantly improved the welfare of the local population while driving economic growth.

The results of this study are encouraging and provide a policy research framework for countries to assess the comprehensive impact of DPV construction. Overall, rural poor areas are still a difficult obstacle to energy transition and the historical use of traditional fossil fuels, and rural residents' use of clean energy, environmental awareness, and enthusiasm are not high. Regardless, DPV construction in the majority of rural areas still has enormous potential for development. In addition, future policies should focus on increasing support for PV construction in resource-based cities, promoting clean energy transformation and ultimately contributing to global low-carbon sustainable development.

6.2. Limitations and potential future research

This study acknowledges certain limitations and identifies avenues for future research. Firstly, the study is constrained by the limited availability of carbon emission data at the micro level. Currently, county-level carbon emission measurement remains in the exploratory phase. Numerous studies on low-carbon sustainable development require more detailed county-level carbon emission data for support. Consequently, there is significant potential to refine and expand county-level carbon emission measurement models.

Secondly, while this study examines the economic and environmental impacts of clean energy adoption, it does not address issues related to secure and stable energy supply. It is widely recognized that achieving the three objectives of energy security, environmental sustainability, and economic viability (known as the energy trilemma) can be challenging. Hence, future research should investigate the role of clean energy in ensuring energy security.

Lastly, this study focuses on the Chinese context, where the widespread adoption of renewable energy sources is anticipated to lead to a decline in energy prices, thereby diminishing the competitive advantage of traditional energy sources. Building upon this analysis, future research could explore the design of compensation mechanisms aimed at balancing the interests of traditional and renewable energy sectors.

CRediT authorship contribution statement

Yubao Wang: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Junjie Zhen:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

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Data availability

Data will be made available on request.

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