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Synergistic effects of regional environmental governance on alleviating energy poverty and promoting household decarbonization

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ABSTRACT

Alleviating energy poverty and lowering carbon emissions are two crucial goals that can help achieve sustainable regional development. However, to make this a reality, it is vital to understand the relationship between environmental governance and these goals, especially at the household level. This study utilizes microdata from the 2012–2020 China Family Panel Studies (CFPS) to construct models. We examine the synergies between reducing household energy poverty and emissions mitigation under regional policies, aiming to solve the long-standing energy poverty problem and reduce carbon emissions. Our findings emphasize that China's environmental governance exhibits significant synergies by concurrently addressing household energy security and promoting carbon reductions through integrated policy approaches. The efficacy and synergy depend critically on optimizing energy consumption structure, decreasing carbon intensity, and enabling technological advancement. These insights highlight the importance of top-level government design in balancing energy security and emissions reductions. Recommendations include establishing a robust governance framework to coordinate energy and climate goals while integrating climate and ecological governance regulations. The income-differentiated analysis provides valuable guidance for policymakers seeking to alleviate energy poverty and strengthen decarbonization, underscoring the importance of targeted interventions for disadvantaged households.

1. Introduction

China's energy system is heavily dependent on fossil fuels, leading to high carbon emissions. To combat this, China has set ambitious targets of achieving carbon neutrality by 2060 and aiming to peak carbon emissions by 2030. However, despite such efforts, energy consumption remains high, which poses a significant challenge to carbon reduction initiatives. The issue of energy security is also a primary concern for China, as it directly impacts national stability, sustainable growth, and social harmony. Since 1992, China has been consuming more energy than it produces, leading to a growing supply-demand imbalance.

Energy poverty negatively impacts physical, mental, and social well-being, hindering sustainable socioeconomic development. Numerous policy directives underscore the need to address relative poverty, enhance energy allocation efficiency, curb pollutant emissions, and advance green development (Henderson and Millimet, 2007; Fylan et al., 2016; Du et al., 2022; Luan et al., 2023). Addressing energy poverty includes optimizing consumption structures, reducing carbon intensity, and fostering technological progress. However, the challenge remains multifaceted. Concurrently, addressing climate change necessitates accelerated green and low-carbon governance, urging society to embrace eco-friendly consumption and encouraging the adoption of low-carbon lifestyles (Tiwari et al., 2023).

Energy poverty adversely affects economic growth, environmental resources, and societal welfare, making it a formidable impediment to inclusive green progress. Energy security entails ensuring the accessibility and usability of energy resources, and carbon neutrality offers a pathway to address China's energy security concerns. Against the backdrop of robustly safeguarding national energy security, supporting carbon peak and carbon neutrality targets, and bolstering high-quality socioeconomic development, balancing energy security and carbon reduction has become a pivotal focus for China's government. In this new era, comprehensively identifying the existing energy poverty landscape among Chinese households and delineating strategies for its amelioration holds profound theoretical and empirical significance.

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Nomenclature

CFPS	China Family Panel Studies
EC	Households' per capita annual energy expenditure
P	Energy prices
X_i	Represents the control variables, where the control variables include the individual's age, gender, urban status, job status, marital status, health status, and education level, as well as the household's household size, annual net household income per capita, annual household expenditure per capita, modern fuel, housing size, home ownership, and plumbing facilities
Y_k	The income percentile
P_p	Province-fixed effects
T_t	Year-fixed effects
ε	Random error term
ε_t	Year-fixed effects
ε_i	Province fixed effect
ε_{it}	The unexplained random error in the model
GDP	Gross domestic product
CNY	China Yuan
kg	kilogram
CO_2	Total household carbon emissions
CI_i	The carbon emission intensity of type *i* consumption
Y_i	The total expenditure for type *i* consumption
Gk_i	The carbon emissions of *k* industrial sectors corresponding to type *i* consumption activities
GEEP	Government expenditure on environmental protection
FE	Fiscal expenditure
lnD	The logarithm of the coupling coordination index
RREGP	Local fiscal environmental protection expenditure
IC	High school low-income
CE	Low-carbon emissions in high and middle schools
DL	Degree of coupling
U_1	Subsystem standardized value of carbon emission reduction
U_2	Subsystem standardized values for energy poverty alleviation
C	Coupling degree
T	Coordinated development degree
D	Coupling coordination index
CCD	The coupling coordination degree
Lsdv	Least squares dummy variable
2SLS	Two-Stage least squares
LIML	Limited information maximum likelihood method
AT	Average annual temperature
EP	Energy poverty
REGP	Regional environmental governance
EI	Energy intensity
ES	Energy consumption structure
TPL	Technological progress
FDL	The level of financial development
lnPGDP	Per capita GDP
P	Energy prices

Household energy consumption has persistently ranked high, surpassing even industrial consumption, representing a critical driver of China's carbon emissions surge.

In the context of dual constraints—the imperative to achieve both carbon peak and carbon neutrality—focusing on the household sector is instrumental in effectively realizing emission reduction goals. Despite the efforts to promote "ecological civilization" and the implementation of environmental inspections in China, the country still faces challenges in its energy sector. These include single energy structure, low efficiency, limited capacity, prevalent energy poverty, and high carbon emissions. However, there are ongoing efforts to address these issues and create a more sustainable energy system in China. Navigating the path to alleviate energy poverty and achieve timely carbon reduction is a pressing issue demanding immediate resolution, i.e., solving the long-standing energy poverty problem and focusing on reducing carbon emissions. Regional environmental governance—aligning with environmental protection and resource conservation objectives—emerges as a catalyst for optimizing energy consumption structures, enhancing energy efficiency, and propelling technological advancements. Such governance is pivotal in breaking the energy impasse, promoting carbon reduction, and advancing inclusive green development.

China's environmental governance demonstrates significant synergies by concurrently addressing household energy security and promoting carbon reductions through integrated policy approaches. The efficacy and synergy depend critically on optimizing energy consumption structure, decreasing carbon intensity, and enabling technological advancement (Mahony, 2013). Top-level government design is essential in balancing energy security and emissions reductions, and a robust governance framework should be established to coordinate energy and climate goals while integrating climate and ecological governance regulations. Income-differentiated analysis can provide valuable guidance for policymakers seeking to alleviate energy poverty and strengthen decarbonization, underscoring the importance of targeted interventions for disadvantaged households. Limited by data and measurement methods, regional environmental-specific investment governance aspects have not been explicitly presented. Moreover, database limitations and other reasons have limited the exploration of the governance effects of different regions. The bulk coal governance policy has been implemented in northern China during the heating season to accelerate the energy transition and environmental governance in rural areas of China. From the perspective of the implementation effect of the policy, the policy intervention effectively improved the environmental quality (Wu et al., 2020). However, the rising gas prices caused by the gas shortage have made households less able to afford the cost of high-quality energy, representing a considerable challenge for policymakers. Energy poverty and climate change are two major problems that restrict the sustainable development of humankind. On the one hand, in 2014, the United Nations proposed that the goal of sustainable development for humanity is to eliminate all forms of poverty. During the Executive meeting of The State Council on January 20, 2020, it was emphasized that a long-term mechanism must be established to address poverty and maintain the achievements of poverty alleviation. This approach requires the government to pay more attention to relative poverty and new types of poverty to eliminate absolute (income) poverty.

As a new type of energy poverty, energy poverty is mainly manifested in the nonpayment and unavailability of energy consumption fees. On the other hand, at the 75th session of the United Nations General Assembly, China said that carbon dioxide emissions would peak before 2030 and achieve carbon neutrality before 2060. The Climate Change and Poverty report jointly released by Greenpeace and Oxfam in 2009 indicated that poverty would increase if countries do not implement effective measures to mitigate climate change. Governments and academia tend to focus on methods to establish a relationship between improving energy poverty and mitigating climate change to achieve dual economic goals. Therefore, regional environmental governance has drawn further attention to the comprehensive management of energy poverty and carbon emission reduction.

The extant literature shows that mitigating energy poverty and promoting carbon reduction has garnered substantial attention, constituting focal points of research for scholars both domestically and internationally. Nevertheless, there remains significant scope for further exploration in this domain. Compared to extant scholarship, this study's contributions are articulated as follows. First, we leverage microdata from the CFPS and employ a synergistic and coupled coordination model to investigate the impact of China's regional environmental governance enhancement from 2012 to 2020 on the synergistic governance of energy poverty and household carbon emissions. Second, we explore demographic groups pivotal to synergistic outcomes through the lens of income differentiation and pinpoint the focal points of future governance efforts, delineating pathways for enhancing the combined efficacy of energy poverty alleviation and household carbon reduction. These contributions offer invaluable insights and guidance for constructing a balanced mechanism that safeguards energy security and propels carbon reduction efforts.

The structure of this study is arranged as follows. Section 2 comprises the literature review and theoretical hypotheses, and Section 3 presents the research design. Section 4 includes the empirical results and analysis, while Section 5 offers the conclusion and policy recommendations.

2. Literature review and theoretical hypothesis

2.1. Literature review

Energy poverty and climate change are closely correlated. Policies to mitigate climate change or promote renewable energy and energy transition will exacerbate energy poverty (Bouzarovski et al., 2012). However, an effective synergy mechanism should be established between improving energy poverty and climate change mitigation (Ürge-Vorsatz and Tirado Herrero, 2012), and measures to protect energy-poor groups should be included in the action against climate change (Dobbins et al., 2019). Related studies have found that reducing carbon emissions can improve energy poverty at the same time. Regarding indirect carbon emission reduction policies, the carbon tax policy actively promoted by the government can reduce carbon emissions and achieve the goal of reducing energy poverty (Winkler et al., 2015; Hyder, 2008). Some scholars proposed that the government levy an oil tax to establish an "energy poverty alleviation" fund to reduce energy poverty and carbon emissions (Sagar, 2005). Regarding direct carbon emission reduction policies, the transition of households to a carbon-free environment can improve energy poverty (Papadopoulou et al., 2019). In recent years, the problem of individual carbon emissions and energy poverty in various countries has become increasingly prominent. In terms of personal carbon emissions, personal carbon emissions at the consumer end are an essential reason for the increase in carbon emissions (Meng et al., 2023). Residents fall into energy poverty due to their inability to obtain sufficient energy (He and Reiner, 2016). The carbon emissions generated by household energy consumption (whether in China or other countries) account for a large proportion of the total carbon emissions (Bin and Dowlatabadi, 2005). Furthermore, energy poverty is very prominent (Zhang et al., 2019; Jiang et al., 2020; Khandker et al., 2012; Barnes et al., 2011). The critical importance of addressing energy poverty and promoting household carbon reduction has garnered significant attention from governments and scholars alike, becoming a focal point of research and policy discussion on both national and international levels. This section reviews and analyzes the literature on energy poverty, household carbon emissions, and regional environmental governance, highlighting their interconnectedness and potential synergistic effects. We also consider relevant control variables that influence the dynamics of these relationships.

(1) Energy Poverty

Energy poverty is characterized by the lack of access to affordable and adequate energy services and has far-reaching implications for social equity and economic development. Scholars have recognized the intricate relationship between energy poverty and socioeconomic well-being, with disparities in energy consumption exacerbating inequalities and hindering poverty reduction efforts (Tang and Liao, 2014; Robinson et al., 2018). The unreasonable structure of household energy consumption directly affects the welfare of residents. Using inferior energy will aggravate economic poverty (Spreng and Pachauri, 2003). For example, poor people often spend significant time collecting straw and fuel wood to obtain the most basic energy needs, which takes away time that poor households could use for labor production and reduces the time and energy that children could use for education. The dual limitation of physical capital accumulation and human capital accumulation restricts the improvement of the income level of poor households, leading to a cycle of energy and economic poverty (Liddell and Morris, 2010; Betto et al., 2020). Various measurement methods have been proposed to effectively address energy poverty, including the "10% indicator" method, the "low-income high costs" indicator, the "minimum energy performance index," and the "basic needs" approach (Papada and Kaliampakos, 2018; Grey et al., 2017). This study applies the "basic energy needs" approach (Barnes et al., 2011; Grey et al., 2017) to measure energy poverty, focusing on ensuring access to a minimum level of energy consumption necessary for basic living standards (He and Reiner, 2016).

$$EC = \delta_0 + \delta_1 P + \sum_{i=1}^{n} \gamma_i X_i + \sum_{k=2}^{10} \eta_k Y_k + P_p + T_t + \varepsilon, \tag{1}$$

where EC represents households' per capita annual energy expenditure; P denotes energy prices; P_p represents province-fixed effects; T_t represents year-fixed effects; X_i includes the individual's age, gender, urban status, job status, marital status, health status, and education level, as well as the household's household size, annual net household income per capita, annual household expenditure per capita, modern fuel, housing size, home ownership, and plumbing facilities. Additionally, in the macro factors, the annual average temperature and gross domestic product (GDP) per capita, Y_k represents the income percentile. Energy poverty is measured based on the core concept that household energy usage cannot meet basic needs. The fundamental idea behind this method is that the primary energy consumption level is insensitive to changes in income and does not vary with fluctuations in household income. A threshold is set when energy consumption responds to changes in revenue. This threshold corresponds to the level of energy consumption expenditure at which household energy consumption begins to respond to income changes, defined as the energy poverty line. When household energy consumption levels fall below this threshold, energy poverty exists. The specific criteria for determination are shown in Equation (2):

$$EP = \begin{cases} 1 \text{ if } EC \le z, \\ 0 \text{ if } EC \ge z. \end{cases} \tag{2}$$

(2) Household Carbon Emissions

Households are pivotal as energy consumers and carbon emitters. As urbanization accelerates and living standards improve, the carbon emissions associated with household activities become increasingly significant (Liu et al., 2011; Jiang and Hardee, 2011). Thus, addressing household carbon emissions is crucial for achieving carbon reduction targets. Unreasonable household energy consumption structure also seriously threatens the environment, climate, and residents' health (Bruce et al., 2015; Zhang et al., 2013). Household carbon emissions can be assessed from various perspectives, including input-output analysis, household size, and consumption patterns. This study combines carbon emission coefficients with input-output analysis (Vringer and Blok, 1995; Wang et al., 2016; Ding et al., 2017; Wang and Zhang, 2021) to comprehensively measure household carbon emissions, considering both direct and indirect emissions associated with different consumption categories.

Household carbon emissions were obtained by summing the product of each type of household consumption and its corresponding carbon intensity. We then classified the kinds of household consumption into food, clothing, household equipment, health insurance, housing, education and recreation, and miscellaneous goods and services. Table 1 presents the correspondence between the various types of consumption activities and the relevant industrial sectors. The carbon intensity corresponding to each consumption activity is expressed using the average carbon intensity of the relevant industrial sector. Specific carbon emission factors for each industry are shown in Table 2.

The specific calculation formula is as follows:

$$CO_2 = \sum_{i=1}^{7} CI_i \times Y_i = \sum_{i=1}^{7} \frac{\Sigma_k}{\Sigma_k} \frac{G_{k_i}}{G_{ki}} \times Y_i, \tag{3}$$

where CO_2 represents total household carbon emissions; CI_i denotes the carbon emission intensity of type i consumption; Y_i indicates the total expenditure for type i consumption; G_{ki} means the carbon emissions of k industrial sectors corresponding to type i consumption activities.

(3) Regional Environmental Governance

Regional environmental governance is crucial in mitigating energy poverty and promoting carbon reduction. The effectiveness of regional environmental governance lies in its ability to enhance technological upgrades, optimize energy structures, and stimulate green innovation (Smulders et al., 2012). Government interventions, such as carbon emissions trading, environmental subsidies, and market-driven incentives, facilitate the adoption of cleaner technologies and enhance the availability of clean energy sources (Wang et al., 2022; Yuan et al., 2017; De Santis et al., 2021). Additionally, regulatory instruments like emission rights, environmental taxes, and subsidies guide enterprises toward more sustainable practices, reducing carbon intensity and promoting carbon reduction (Gray and Shimshack, 2011; Yuan et al., 2021). Implementing regional environmental governance measures provides a conducive environment for reducing carbon emissions, supporting economic growth, and alleviating energy poverty.

(4) Control Variables

Table 1
Main consumption expenditure of residents and related industrial sectors.

Consumption type	Related industrial sectors
Food industry	Agricultural and sideline food processing industry, food manufacturing industry, beverage manufacturing industry, tobacco
Clothing industry	Textile industry, textile clothing, shoes, hat manufacturing, leather, fur, feathers (velvet), and its products industry
Residential industry	Construction, production, and supply of electricity and heat; gas production and supply; production and supply of water
Household goods and services	Wood processing and wood, bamboo, rattan, palm, grass products, industry furniture manufacturing, electrical machinery and equipment manufacturing, metal products industry, plastic products industry
Transportation communication	Transportation equipment manufacturing, communication equipment, computer and other electronic equipment manufacturing, transportation, storage, and postal services
Education, culture and entertainment	Paper making and paper products industry, cultural and educational sports goods manufacturing industry, printing industry and recording media replication, instruments, and cultural, office machinery manufacturing industry
Health care	Pharmaceutical industry
Other supplies and services	Wholesale, retail and accommodation, catering, crafts and other manufacturing

Table 2
Carbon dioxide emission coefficient of household consumption (kg/CNY).

Consumption type	Coefficient
Food industry	0.068
Clothing industry	0.065
Residential industry	1.001
Household goods and services	0.032
Transportation communication	0.134
Education, culture, and entertainment	0.166
Health care	0.050
Other supplies and services	0.058

Several control variables significantly shape the relationships between energy poverty, household carbon emissions, and regional environmental governance. Energy intensity (EI), technological progress (TPL), and energy consumption structure (ES) are critical factors influencing energy poverty and carbon reduction pathways. The level of financial development (FDL) and per capita GDP (lnPGDP) reflect regional economic conditions, while energy prices (P) and average annual temperature (AT) represent macro environmental factors. We include these variables as controls in our empirical analysis to analyze their interactions.

In summary, regional environmental governance can be a powerful catalyst for synergistically addressing energy poverty and promoting household carbon reduction. Regional environmental governance can enhance technological upgrades, optimize ESs, and foster green innovation, making it crucial in achieving sustainable development goals and ensuring a more equitable and environmentally responsible future.

2.2. *Theoretical hypothesis*

Under the influence of ideologies such as "ecological civilization" and measures like environmental inspections, discernible shifts have occurred in China's energy consumption and usage patterns. However, persistent challenges such as singular energy structures, low energy efficiency, inadequate energy capacity, pronounced energy poverty, and elevated carbon emissions remain prominent issues in the country. Thus, it is crucial to determine how we can simultaneously alleviate energy poverty and achieve timely carbon reduction.

According to the energy ladder hypothesis, if the quality of energy consumption is lower, the carbon emissions generated are higher, and the heat is lower. As shown in Fig. 1, the energy consumption ladder of residents is roughly divided into three stages. Traditional biomass energy is an important energy source for many residents in their daily lives. However, its low utilization efficiency and lack of heat can prevent residents from falling into energy poverty. With the optimization of energy consumption quality and the improvement of regional environmental governance level, the energy ladder has risen, and the heat and

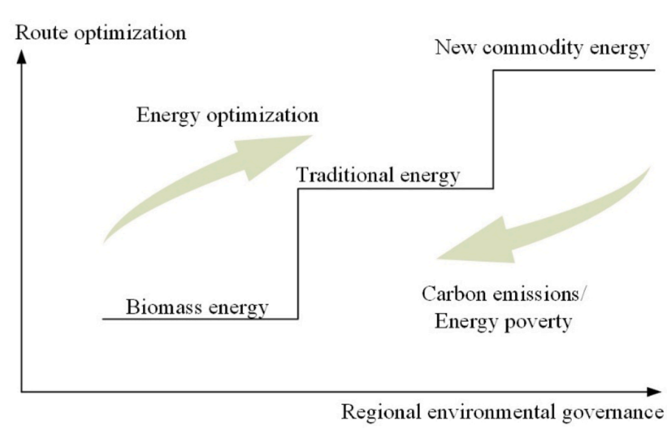

Fig. 1. Environmental governance and pathway optimization map.

carbon emissions generated by energy have been improved to a certain extent. Therefore, to improve energy poverty, it is necessary to optimize the quality of energy consumption and enhance the level of regional environmental governance to promote the upgrading of energy consumption. Regional environmental governance—the proportion of government environmental protection expenditure to total fiscal outlay—is determined by local economic development levels, budgetary spending, and environmental needs (Smulders et al., 2012). Governments can leverage fiscal subsidies and encourage private sector involvement to address energy poverty and promote carbon reduction to support innovative, high-cost, and long-recovery-cycle green technologies (Leontief, 1974; Dinh Thanh and Canh, 2019). Measures like photovoltaic poverty alleviation, gas poverty alleviation, and rural grid upgrades can enhance energy accessibility (Wang et al., 2022). Additionally, energy subsidies under regional environmental governance policies can incentivize the development of low-carbon industrial practices, providing households and enterprises with affordable clean energy options and enhancing their accessibility and usability. A study on the carbon efficiency of various economic regions employing three-stage data envelopment analysis (DEA) and a three-stage DEA--Malmquist index found a significant negative correlation between government environmental governance and total energy consumption (Chen et al., 2016; Zhou et al., 2019, 2023). Government interventions in the environmental sphere can effectively reduce carbon emissions, contributing to the objectives of household carbon reduction and energy poverty alleviation. As a substantial component of government fiscal expenditure, environmental protection spending bears policy characteristics. Environmental protection spending emphasizes pollution control, energy conservation, and comprehensive resource utilization, aligning with pathways crucial for promoting household carbon reduction and alleviating energy poverty. Furthermore, the coordinated governance of promoting household carbon reduction and alleviating energy poverty could amplify results. Building upon the aforementioned theoretical premises, we present the following hypothesis.

Hypothesis 1. Regional environmental governance significantly enhances the synergistic efficacy of alleviating household energy poverty and promoting household carbon reduction.

As mentioned, the unreasonable structure of household energy consumption directly affects the welfare of residents. Unreasonable household ES also seriously threatens the environment, climate, and residents' health (Bruce et al., 2015; Zhang et al., 2013). Local governments employ carbon emissions permits, environmental taxes, subsidies, and energy use rights to mitigate energy poverty and promote household carbon reduction. These strategies optimize energy consumption structures, enhance energy efficiency, and innovate toward green development. This efficiency culminates in technological upgrades, energy structure optimization, and industrial restructuring, reducing household carbon emissions (Grey et al., 2017; Zhang et al., 2017). These measures simultaneously improve energy efficiency and accessibility, stimulating green innovation, elevating output levels, and ultimately alleviating energy poverty. The "forcing reduction" theory posits that local governments reduce local demand for high-carbon resources through technological upgrades, energy structure optimization, and industrial restructuring, thereby compelling emission reduction and lowering carbon intensity. Moreover, these efforts to enhance energy structure and carbon intensity simultaneously improve energy accessibility and usability, helping to alleviate energy poverty. From the perspective of technological advancement, an analysis of regional environmental governance indicates that it can optimize EI and consumption structures, thereby decreasing carbon emissions (Yuan et al., 2017). Local governments should explore new modes and approaches to environmental governance to adapt to evolving environmental challenges while optimizing energy structures, developing low-carbon technologies, and expanding the scope and utilization of clean and renewable energy sources. Fig. 2 details the optimized path of energy

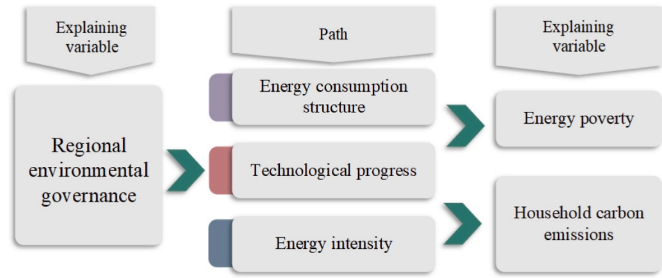

Fig. 2. Theoretical analysis diagram.

poverty and household carbon emissions. Drawing from these theoretical underpinnings, we present the following hypothesis.

Hypothesis 2. The effectiveness and synergy of alleviating energy poverty and promoting household carbon reduction can be achieved through optimizing energy consumption structures, reducing carbon intensity, and facilitating technological advancements.

This study synthesizes existing literature, utilizes empirical data from the CFPS, and applies robust analytical methodologies to test the proposed hypotheses empirically. The findings can shed light on the intricate interplay between regional environmental governance, household energy poverty, and carbon reduction, ultimately contributing to a deeper understanding of the mechanisms underpinning sustainable regional development.

3. Research design

3.1. Data description

This study utilized microdata from the China Family Panel Studies (CFPS) conducted by the China Social Science Survey Center at Peking University between 2012 and 2020. The CFPS comprises four types of questionnaires (community, household, adult, and child) covering multiple provinces and exhibiting strong national representativeness, thus providing an accurate reflection of the overall national situation. Meticulous data matching was conducted to establish a one-to-one correspondence between household sample data, household energy data, and household carbon emission data, resulting in a final selected sample size of 33,345 households. The data pertinent to this study primarily encompass household energy poverty, household carbon emissions, and regional environmental governance. Table 3 shows the descriptive statistical results.

Data from the CFPS were used to calculate household energy poverty and carbon emissions. Energy price data and other related variables were obtained from the National Research Center for China Economic Research Network. Data on regional environmental governance, specifically government environmental protection expenditures and fiscal expenditures, were acquired from various provincial-level "Statistical Yearbooks" and the CEIC China Economic Database. Annual average temperature, ES, and EI were computed from the "China Energy Statistical Yearbook." Finally, technological progress and per capita GDP were extracted from the China Economic Information Network (CEInet) or computed based on CEInet data.

3.2. Calculation results of energy relative poverty

Table 4 presents the specific energy expenditure levels across income percentiles, indicating that the relationship between energy consumption expenditure and income percentile remains relatively consistent across various energy price indices. Notably, a significant change begins from the fourth income percentile, indicating that the energy consumption expenditure at this threshold constitutes the fundamental level

Table 3
Interpretation of variables and descriptive statistics.

Variable	Description	Observation	Mean	Std.Dev	Minimum	Maximum
REGP	Regional environmental governance	33,345	0.0283	0.0084	0.0132	0.0567
The lagged term of *REGP*	The first lagged term of regional environmental governance	33,345	0.0295	0.0089	0.0132	0.0681
GEEP	Government expenditure on environmental protection	33,345	146.2535	96.5790	21.2300	567.4100
FE	Fiscal expenditure	33,345	5132.4840	2900.6697	864.3600	17430.7891
EI	Energy intensity	33,345	1.1023	0.5047	0.4370	3.0237
TPL	Technological progress	33,345	1.3487	0.8927	0.3331	10.3902
ES	Energy consumption structure	33,345	2.9397	0.8783	1.5651	9.3382
FDL	The financial inclusion index	33,345	226.5361	88.4551	75.8700	431.9300
lnPGDP	Per capita GDP	33,345	9.2275	0.4358	8.5984	10.7525
P	Energy prices	33,345	100.0432	6.0616	88.2000	112.00
CO_2	Household carbon emissions	33,345	0.1090	0.2616	0.0000	11.1843
AT	Average annual temperature	33,345	12.3981	4.8641	1.6634	22.6289
lnD	The logarithm of the coupling coordination index	33,345	−0.6514	0.5696	−2.2673	−0.0052
RREGP	Local fiscal environmental protection expenditure	33,345	0.0167	0.0103	0.0038	0.0567
IC	High school low-income	33,345	1.8864	0.8287	1.0000	3.0000
CE	Low-carbon emissions in high and middle schools	33,345	1.9000	0.8307	1.0000	3.0000
DL	Degree of coupling	33,345	0.4395	0.4963	0.0000	1.0000

Table 4
Estimates of household energy demand.

Variable	Total fuel (1)	Petroleum and products (2)	Coal and products (3)
Fuel price index	7.7514** (3.060)	4.2921 (3.648)	2.3030** (1.171)
2nd	26.1945 (18.150)	26.0777 (18.153)	25.8475 (18.148)
3rd	9.9330 (18.395)	10.3406 (18.396)	10.1921 (18.393)
4th (Energy poverty line)	79.1061*** (18.446)	78.9567*** (18.448)	79.1357*** (18.446)
5th	68.0878*** (18.998)	68.4337*** (19.001)	67.6668*** (19.000)
6th	123.4455*** (19.179)	123.8301*** (19.180)	123.5184*** (19.179)
7th	115.7703*** (19.246)	115.6548*** (19.249)	115.1766*** (19.245)
8th	130.7279*** (20.260)	130.6048*** (20.263)	130.0939*** (20.260)
9th	235.8574*** (20.877)	235.7124*** (20.879)	235.3764*** (20.877)
10th	332.2879*** (22.910)	331.9690*** (22.911)	332.0120*** (22.912)
Cons	2202.7883*** (387.787)	2564.5248*** (423.427)	2722.6767*** (271.850)
Control	YES	YES	YES
N	33,345	33,345	33,345
Province	YES	YES	YES
Year	YES	YES	YES
R^2	0.0845	0.0789	0.0846

Note: * = Significant at 10%; ** = Significant at 5%; *** = Significant at 1%. Values in parentheses are standard errors.

of energy necessity (i.e., the energy consumption poverty line). We used information from Tables 4 and 5 to determine the energy poverty line, which is 620.6. Households with energy consumption below this threshold are classified as experiencing relative energy poverty.

3.3. Model design

(1) Synergistic Trend Model

The synergistic trend model investigates the synergistic effects between household energy poverty and carbon emissions. This model is designed to construct the relationships between regional environmental governance's alleviation of energy poverty and its promotion of household carbon reduction. The interaction of these two effects is examined and discussed within the framework of the synergistic trend. The specific formulations for modeling these interactions are outlined below.

$$CO_2 = \alpha_0 + \alpha_1 REGP + \alpha_2 EI + \alpha_3 ES + \alpha_4 TPL + \alpha_5 FDL + \alpha_6 lnPGDP + \alpha_7 P + \alpha_8 AT + \varepsilon_i + \varepsilon_t + \varepsilon_{it}, \tag{4}$$

$$EP = \alpha_0 + \alpha_1 REGP + \alpha_2 EI + \alpha_3 ES + \alpha_4 TPL + \alpha_5 FDL + \alpha_6 lnPGDP + \alpha_7 P + \alpha_8 AT + \varepsilon_i + \varepsilon_t + \varepsilon_{it}, \tag{5}$$

where i and t denote province and year, respectively; *EP* and CO_2 represent energy poverty and household carbon emissions; *REGP* stands for regional environmental governance; *EI* represents energy intensity; *ES* signifies energy consumption structure; *TPL* denotes technological progress measured by the ratio of patent applications to GDP; *FDL* represents the level of financial development indicated by the financial inclusion index; lnPGDP represents per capita GDP; *P* denotes energy prices; *AT* signifies annual average temperature; ε_i and ε_t represent province and year-fixed effects, respectively; ε_{it} represents the unexplained random error.

(2) Coupling Coordination Model

We investigate the dynamic coupling relationship to explore the synergistic enhancement effects between EP and household carbon emissions in China (Wang, 2022). The study of coupling effects employs various modeling methods, including double exponential models, coupling degree models, gray relational degree models, and coupling coordination models. Among these, the coupling coordination model captures the collaborative development trends of different subsystems and the overall effects among systems. Therefore, we employ a binary system coupling degree approach to calculate the coordination of pollution reduction and carbon reduction in urban areas. The coupling coordination formula is as follows:

Table 5
Energy consumption expenditure per capita by income decile (CNY/year).

Quantile	1	2	3	4	5	6	7	8	9	10
Line of consumption	498.7	520.5	520.5	620.6	617.9	745.1	805	903.3	1112.3	1367.8

$$C = \sqrt{[1 - (U_2 - U_1)] \times \frac{U_1}{U_2}}, \tag{6}$$

$$T = \sum_{i=1}^{n} \beta_i \times \mu_i, \sum_{i=1}^{n} \alpha_i = 1, \tag{7}$$

$$D = \sqrt{C \times T}, \tag{8}$$

where U_1 and U_2 represent the standardized values of the subsystems for reducing carbon emissions and alleviating EP, respectively, which are defined using the annual carbon dioxide emissions (in metric tons per year) and the standardized indicator for EP; C, T and D represent coupling degree, coordinated development degree, and coupling coordination index, respectively; α_i represents the weight of the ith subsystem. When the value of D is higher, it suggests that the subsystems are less disparate and more coordinated, indicating a stronger synergy between promoting household carbon reduction and alleviating household EP. On the other hand, a smaller D value indicates a weaker synergy. To explore the influence of regional environmental governance and other socioeconomic factors on the synergistic effect, an extended STIRPAT model has been constructed as follows:

$$lnD = \alpha_0 + \alpha_1 REGP + \alpha_2 EI + \alpha_3 ES + \alpha_4 TPL + \alpha_5 FDL + \alpha_6 lnPGDP + \alpha_7 P + \alpha_8 AT + \varepsilon_i + \varepsilon_t + \varepsilon_{it}, \tag{9}$$

where D represents the coupling coordination index for alleviating EP and promoting household carbon reduction; i and t denote provinces and years, respectively; lnD indicates the logarithm of the coupling coordination index for alleviating EP and promoting household carbon reduction; $REGP$ stands for regional environmental governance; EI is energy intensity; ES is energy consumption structure; TPL is technological progress level; FDL is financial development level; lnPGDP is per capita GDP; P is energy price; AT is annual average temperature; ε_i and ε_t represent province and year-fixed effects, respectively; ε_{it} is the random error term not accounted.

4. Results analysis

4.1. Synergistic trend analysis

Table 6 presents eight columns representing regression results with different control variables. A Hausman test was conducted before regression, and the resulting P-values were all less than 0.05, indicating that the random effects are rejected and the fixed-effects model is valid. Therefore, the fixed-effects model was employed for estimation. The overall significance of parameter estimates was relatively high, specifically for the EP in columns (1)–(4). The estimated coefficients were −1.9946, −1.9625, −1.9683, and −1.9689, all significant and negative at the 1% level. These results imply that improving regional environmental governance can significantly alleviate EP. For the CO_2 (household carbon emissions) in columns (1)–(4), the estimated coefficients were −1.6311, −1.5377, −1.6184, and −1.6226, all significant at the 1% level and negative. These results indicate that enhancing regional environmental governance can significantly promote household carbon reduction.

Based on the regression results, the following conclusions can be drawn. Regional environmental governance not only mitigates household EP but also plays a promoting role in household carbon reduction. The estimated coefficients suggest that regional environmental governance exhibits almost equal synergistic effectiveness in both aspects. In other words, improving regional environmental governance can achieve comprehensive and coordinated control of household EP and carbon emissions. With the nationwide implementation of the incremental tiered pricing policy in China, the implementation of the tiered pricing policy has a positive role in energy conservation, income redistribution, and reducing cross-subsidies. It provides relatively clean and efficient modern energy for energy-poor residents while promoting carbon emission reduction (Van Der Kroon et al., 2013).

Table 6
Synergistic trend analysis.

Variable	*EP*		CO_2	
	EP (1)	*EP* (2)	CO_2 (1)	CO_2 (2)
REGP	−1.9946***	−1.9625***	−1.6311***	−1.5377***
	(0.6412)	(0.6485)	(0.2828)	(0.2879)
FDL	−0.0004	−0.0004	0.0014***	0.0013***
	(0.0004)	(0.0005)	(0.0003)	(0.0003)
lnPGDP	0.3393***	0.3438***	0.0003	0.0132
	(0.0450)	(0.0470)	(0.0223)	(0.0246)
P	−0.0036*	−0.0035	0.0004	0.0007
	(0.0021)	(0.0021)	(0.0011)	(0.0011)
AT	−0.0146**	−0.0146**	0.0060	0.0061
	(0.0057)	(0.0057)	(0.0042)	(0.0042)
EI		0.0116		0.0340**
		(0.0354)		(0.0162)
TPL				
ES				
Cons	−1.8885***	−1.9426***	−0.2866	−0.4445
	(0.4539)	(0.4819)	(0.2511)	(0.2837)
N	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES
Year	YES	YES	YES	YES
R^2	0.1255	0.1255	0.0293	0.0294
Variable	*EP*		CO_2	
	EP (3)	*EP* (4)	CO_2 (3)	CO_2 (4)
REGP	−1.9683***	−1.9689***	−1.6184***	−1.6226***
	(0.6519)	(0.6520)	(0.2947)	(0.2946)
FDL	−0.0004	−0.0005	0.0012***	0.0010***
	(0.0005)	(0.0005)	(0.0003)	(0.0004)
lnPGDP	0.3427***	0.3468***	−0.0016	0.0257
	(0.0485)	(0.0542)	(0.0257)	(0.0281)
P	−0.0035	−0.0035*	0.0007	0.0006
	(0.0021)	(0.0021)	(0.0011)	(0.0011)
AT	−0.0146**	−0.0145**	0.0051	0.0058
	(0.0057)	(0.0058)	(0.0043)	(0.0042)
EI	0.0111	0.0117	0.0268	0.0304*
	(0.0359)	(0.0361)	(0.0165)	(0.0165)
TPL	0.0008	0.0007	0.0108**	0.0104**
	(0.0083)	(0.0083)	(0.0051)	(0.0051)
ES		−0.0011		−0.0073***
		(0.0037)		(0.0023)
Cons	−1.9310***	−1.9592***	−0.2816	−0.4679
	(0.4993)	(0.5270)	(0.2946)	(0.3008)
N	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES
Year	YES	YES	YES	YES
R^2	0.1255	0.1255	0.0295	0.0297

4.2. Further analysis of synergistic effects

The coupling coordination degree (CCD) model was introduced for the next-stage analysis to delve deeper into the synergistic enhancement effect of regional environmental governance on alleviating household EP and promoting household carbon reduction. Table 7 shows the estimation results, in which the four columns respectively describe the regression results of regional environmental governance on the CCD under different control variables.

Specifically, the estimated coefficients for columns (1)–(4) were 2.3492, 2.3092, 2.3181, and 2.3189, respectively, all significant and positive at the 1% level. The coefficients in columns (1)–(4) related to REGP indicate a significant promoting effect of regional environmental governance on the synergistic effect. These estimated coefficients portray the impact of policies represented by regional environmental governance on the synergistic effect of alleviating EP and promoting household carbon reduction. With the improvement of regional environmental governance (Cheng et al., 2017), household EP and

Table 7
Further analysis of synergistic effects.

Variable	*lnD*			
	lnD (1)	*lnD* (2)	*lnD* (3)	*lnD* (4)
REGP	2.3492***	2.3092***	2.3181***	2.3189***
	(0.7359)	(0.7444)	(0.7482)	(0.7483)
FDL	0.0004	0.0005	0.0005	0.0005
	(0.0005)	(0.0005)	(0.0005)	(0.0006)
lnPGDP	−0.3900***	−0.3955***	−0.3939***	−0.3992***
	(0.0517)	(0.0539)	(0.0556)	(0.0622)
P	0.0041*	0.0040	0.0040	0.0040
	(0.0024)	(0.0024)	(0.0024)	(0.0024)
AT	0.0164**	0.0163**	0.0164**	0.0163**
	(0.0065)	(0.0065)	(0.0066)	(0.0066)
EI		−0.0145	−0.0137	−0.0144
		(0.0406)	(0.0412)	(0.0414)
TPL			−0.0012	−0.0011
			(0.0095)	(0.0095)
ES				0.0014
				(0.0043)
Cons	2.1803***	2.2478***	2.2300***	2.2659***
	(0.5209)	(0.5529)	(0.5729)	(0.6047)
N	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES
Year	YES	YES	YES	YES
R^2	0.1254	0.1254	0.1254	0.1254

household carbon emissions have improved somewhat. Furthermore, the coupling coordination between the two has also been enhanced, making the two promote each other, improve each other, and develop in a coordinated manner.

In light of the above observations, regional environmental governance substantially enhances coupling coordination, which signifies that regional environmental governance demonstrates a favorable synergy between alleviating EP and reducing household carbon emissions. Regional environmental governance holds the potential for effective, comprehensive management of both aspects.

4.3. Synergistic analysis across different income backgrounds

In general, high-quality energy is more expensive, which exacerbates the difficulty of energy transition. With the rapid development of China's social economy and sticky energy prices, examining the impact of income changes is imperative. An income-based perspective was adopted for the subsequent analysis to gain deeper insights into the governance impact of regional environmental management on various demographic groups and identify focal points for future governance efforts. Household net income was divided into low-income, middle-income, and high-income, based on ratios of 40%, 30%, and 30%, respectively. Table 8 shows the regression results of CCD, EP, and household carbon emissions under low, middle, and high income, respectively. The results from Table 8 reveal that regional environmental governance significantly impacts the low-income group.

Specifically, the estimated coefficients of REGP for coupling coordination under different income groups are 4.7358, 1.4299, and 1.2086, respectively. Notably, the coefficient for the low-income group is positively significant at the 1% level. In contrast, the results for middle and high-income groups are insignificant, displaying a decreasing coefficient trend, suggesting that the influence of REGP on coupling coordination diminishes as income levels rise. According to the energy hierarchy hypothesis, as income increases, residents will constantly change their type of energy consumption (Van Der Kroon et al., 2013). Because of their limited income, low-income households do not have much energy available for consumption. Thus, consumption fluctuates with price, government policies, and other influencing factors (He and Reiner, 2016; Zhang et al., 2019; Zhou et al., 2023; Meng et al., 2023). Promoting regional environmental governance, the government advocates or encourages relatively low prices and high-quality clean energy. Thus, low-income households choose clean energy with low emissions. This approach can alleviate EP and improve carbon emissions, so the impact of REGP on coupling coordination decreases with the increase in income level.

For household carbon emissions across different income groups, the estimated coefficients of REGP are −1.8015, −1.2388, and −1.7763,

Table 8
Synergistic analysis across different income backgrounds.

Variable	*lnD*		
Income brackets	Low-income (*lnD*)	Middle-income (*lnD*)	High income (*lnD*)
REGP	4.7358*** (1.1652)	1.4299 (1.3781)	1.2086 (1.3885)
EI	−0.0211 (0.0619)	−0.0948 (0.0809)	−0.1532* (0.0837)
TPL	−0.0358** (0.0150)	0.0035 (0.0181)	−0.0001 (0.0167)
ES	0.0013 (0.0068)	0.0242*** (0.0073)	−0.0010 (0.0086)
FDL	0.0009 (0.0011)	0.0025** (0.0012)	0.0007 (0.0008)
lnPGDP	−0.2229** (0.1085)	−0.6643*** (0.1151)	−0.3068*** (0.0983)
P	0.0044 (0.0036)	0.0014 (0.0044)	0.0030 (0.0044)
AT	0.0116 (0.0084)	0.0203 (0.0130)	0.0022 (0.0161)
Cons	0.3720 (1.0417)	4.4709*** (1.1037)	2.0944** (1.0010)
N	13,559	10,015	9771
Province	YES	YES	YES
Year	YES	YES	YES
R^2	0.0767	0.1060	0.1224

Variable	*CO_2*			*EP*		
Income brackets	Low-income (CO_2)	Middle-income (CO_2)	High income (CO_2)	Low-income (*EP*)	Middle-income (*EP*)	High income (*EP*)
REGP	−1.8015*** (0.3674)	−1.2388*** (0.4572)	−1.7763*** (0.6702)	−4.0653*** (1.0150)	−1.2167 (1.2007)	−1.0030 (1.2097)
EI	−0.0655*** (0.0222)	−0.0397 (0.0312)	0.0760** (0.0372)	0.0199 (0.0539)	0.0828 (0.0705)	0.1315* (0.0729)
TPL	0.0056 (0.0057)	0.0087 (0.0076)	0.0118 (0.0126)	0.0311** (0.0130)	−0.0032 (0.0158)	−0.0003 (0.0145)
ES	−0.0014 (0.0037)	−0.0136*** (0.0034)	−0.0002 (0.0050)	−0.0011 (0.0059)	−0.0208*** (0.0064)	0.0008 (0.0075)
FDL	0.0005 (0.0004)	0.0003 (0.0006)	0.0012** (0.0006)	−0.0008 (0.0010)	−0.0022** (0.0010)	−0.0007 (0.0007)
lnPGDP	−0.0019 (0.0309)	0.0273 (0.0452)	−0.0220 (0.0563)	0.1942** (0.0945)	0.5771*** (0.1003)	0.2677*** (0.0856)
P	−0.0023* (0.0013)	−0.0026 (0.0021)	0.0058** (0.0025)	−0.0037 (0.0031)	−0.0012 (0.0038)	−0.0028 (0.0039)
AT	0.0030 (0.0051)	0.0084 (0.0091)	−0.0085 (0.0097)	−0.0105 (0.0073)	−0.0179 (0.0114)	−0.0018 (0.0140)
Cons	0.3267 (0.2949)	0.0565 (0.5629)	−0.4678 (0.6205)	−0.3394 (0.9074)	−3.8842*** (0.9621)	−1.8082** (0.8717)
N	13,559	10,015	9771	13,559	10,015	9771
Province	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
R^2	0.0151	0.0277	0.0287	0.0764	0.1057	0.1223

which are significantly negative at the 1% level. The absolute value of the coefficient for the middle-income group is comparatively lower, indicating that regional environmental governance has a notable carbon reduction effect across all households, particularly for low and high-income groups. Because low-income households have relatively low incomes, they are more susceptible to the impact of policy effects. Due to the high income of high-income households, carbon emissions consumption is relatively higher, and the marginal effect of government restrictions or low-carbon policies is more pronounced than in other households. The primary consumption necessities of middle-income households are relatively stable and difficult to change due to their relatively limited income. Thus, the effect of regional environmental governance on moderate carbon emissions is not apparent.

Regarding household EP among different income groups, the estimated coefficients of REGP are −4.0653, −1.2167, and −1.0030, with the low-income group showing a significant negative impact at the 1% level. The results for middle and high-income groups are insignificant, and the absolute values of the coefficients exhibit a decreasing trend, which implies that the influence of REGP on household EP decreases as income levels rise, with regional environmental governance having a more pronounced effect on the low-income demographic. Low-income families can easily escape poverty due to their relatively low household income and government support.

Collectively, the findings from Table 8 underscore the relatively pronounced synergistic governance effect of regional environmental management on the low-income group while demonstrating a less pronounced impact on middle and high-income groups. Therefore, future governance efforts can focus on improving conditions for the middle-income and high-income populations.

Figs. 3–5 show a positive correlation between the high coordination rate and income. Moreover, the proportion of high coordination rates has steadily increased each year, indicating a gradual improvement in synergistic effects over time. Upon comparison, EP incidence is notably high for the low-income group, exceeding 60%. Similarly, the poverty incidence for the middle-income group remains substantial, while the higher-income group experiences relatively lower poverty rates. Overall, EP across different income brackets has been somewhat alleviated, suggesting a certain level of facilitation through regional environmental management. However, the issue of EP remains severe for the middle and low-income groups. Therefore, the subsequent focus of governance efforts should address EP among these income segments.

Furthermore, the higher-income group exhibits higher carbon emission rates, progressively rising annually. The middle and low-income groups also experience a certain degree of carbon emission rate increase. Therefore, the forthcoming governance efforts should target carbon emissions from higher-income households.

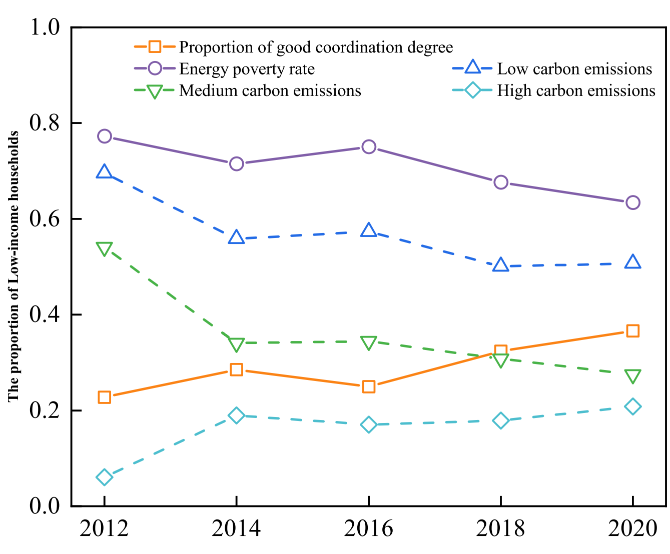

Fig. 3. Low-income households.

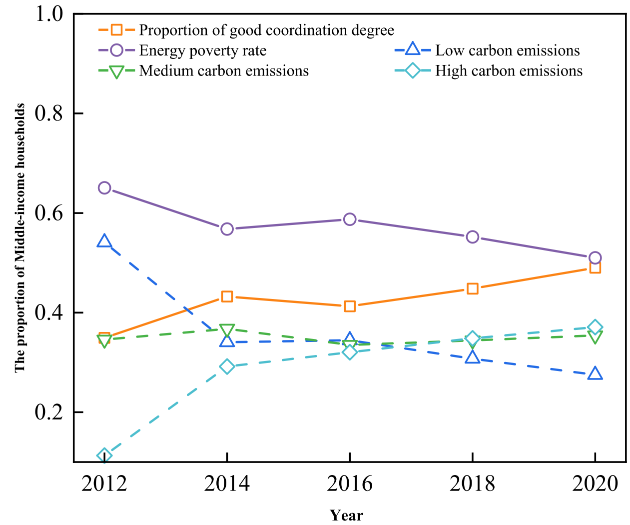

Fig. 4. Middle-income households.

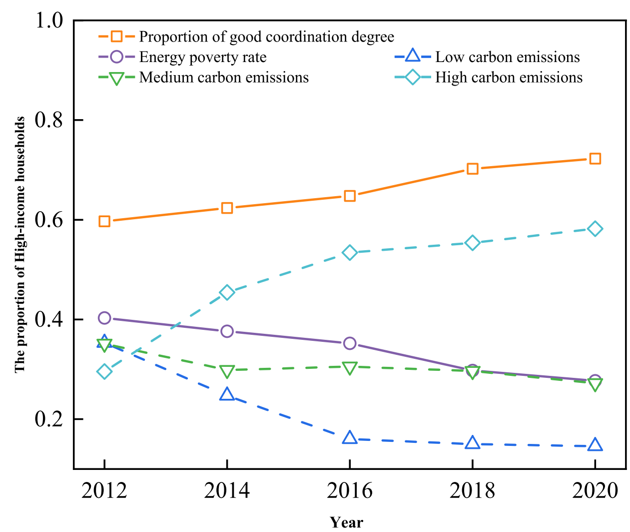

Fig. 5. High-income households.

In summary, the EP situation is less pronounced among higher-income groups, with relatively better synergistic effects. Their main challenge lies in higher carbon emissions, which significantly impact a household's carbon footprint but have a relatively minor impact on EP. In contrast, the EP issue is more prominent for middle and low-income groups, with weaker synergistic effects. Regional environmental management shows a more evident impact on these groups' EP and a lesser impact on their carbon emissions. Thus, the next steps in regional environmental governance should concentrate on alleviating EP for middle and low-income households while enhancing the efficiency and level of synergy. Simultaneously, sustained attention and governance are required for carbon emissions from higher-income households.

4.4. Path analysis

Fig. 6 illustrates three paths of synergistic enhancement, where the effectiveness primarily hinges on ES, EI, and technological progress.

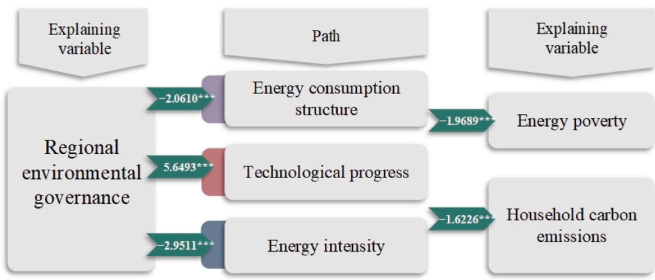

Fig. 6. Three paths to synergy.

Consequently, three paths of synergistic enhancement emerge:

Path 1: Regional environmental management optimizes ES to alleviate EP and promote household carbon reduction, achieving a synergistic effect.

Path 2: Regional environmental management reduces EI to alleviate EP and encourage household carbon reduction, achieving a synergistic effect.

Path 3: Regional environmental management fosters technological advancement to alleviate EP and encourage household carbon reduction, achieving a synergistic effect.

The subsequent assessment of these three paths focuses on whether regional environmental management can optimize ES, lower EI, and foster technological progress. Suppose regional environmental management significantly optimizes ES, reduces EI, and promotes technological advancement. In that case, the current regional environmental management achieves synergistic enhancement through these three paths.

Next, we examine the three paths to determine whether regional environmental management can effectively optimize ES, reduce EI, and promote technological progress. The optimization of ES, reduction in EI, and promotion of technological advancement by regional environmental management indicate that the decrease in household carbon emissions and the alleviation of household EP occur through these three pathways of synergistic enhancement.

Table 9 shows the regression results of ES, scientific and technological progress, and EI under different control variables. In columns (1) and (2) of "ES," Path 1 is examined. The estimated coefficients of "REGP" are negative and significant at the 1% level, suggesting that regional environmental management significantly promotes optimizing ES. It notably reduces the utilization of fossil fuels, particularly coal resources, achieving synergistic effects through optimizing ES to alleviate household EP and reduce household carbon emissions.

Path 3 is analyzed by testing "TPL." The estimated coefficient of "REGP" is 5.6493, significant at the 1% level, indicating that regional environmental management significantly fosters synergistic enhancement by boosting technological progress.

Path 2 is investigated by examining "EI." The estimated coefficients of "REGP" are −2.7500 and −2.9511, both significantly significant at the 1% level. This result demonstrates that "REGP" also substantially promotes the optimization of EI to achieve synergistic enhancement.

These three paths reveal that regional environmental management optimizes ES, reduces EI, and fosters technological progress. It underscores the achievement of synergistic enhancement in reducing household carbon emissions and alleviating household EP.

In summary, regional environmental management's synergistic nature and effectiveness are primarily achieved through optimizing ES, reducing carbon emission intensity, and subsequent technological advancement. With economic development and the progression of regional environmental management, a certain degree of optimization has occurred in ES and carbon emission intensity, accompanied by advancements in science and technology. As a result, both EP and carbon reduction have witnessed improvement.

4.5. *Robustness and endogeneity analysis*

To ensure the robustness of regional environmental governance synergy results, we approach the verification from three perspectives: endogeneity, regional environmental governance indicators' robustness, and the estimation method's robustness. Endogeneity could arise due to a reverse causal relationship between regional environmental governance and household carbon emissions or EP (i.e., more robust regional environmental governance in response to higher household carbon emissions or EP rates). An instrumental variable approach is adopted to address this concern. The first lagged term of regional environmental governance is selected as the instrumental variable, and limited information maximum likelihood (LIML) and two-stage least square (2SLS) regressions are conducted. The instrumental variable passed the test, and the estimation results indicate that the baseline model does not exhibit severe endogeneity.

We mitigate the influence of other fiscal and economic factors by using local fiscal environmental protection expenditure as an explanatory variable to examine the robustness of regional environmental governance indicators. Tables 10–12 present the estimation results with regional environmental governance replaced by local fiscal environmental protection expenditure, showing that the magnitude of the REGP coefficient is similar to that of the baseline model in Tables 6 and 7 Additionally, using Lsdv for estimation reveals consistency with the baseline model in Tables 6 and 7 These results demonstrate that the constructed indicators in this study possess a certain degree of validity, and the estimation results of the baseline model exhibit strong local robustness. These findings collectively verify the robustness of the estimation results and indicate relatively minor endogeneity.

5. Conclusion and policy implications

This study utilizes household microdata from the CFPS from 2012 to 2020 to examine the synergistic effect of regional environmental governance on alleviating household EP and promoting household

Table 9
Examine the path of synergies.

Variable	ES	ES	TPL	EI	EI
	ES (1)	ES (2)	TPL	EI (1)	EI (2)
REGP	−2.2582*** (0.5192)	−2.0610*** (0.5126)	5.6493*** (0.3946)	−2.7500*** (0.1014)	−2.9511*** (0.1036)
FDL	−0.0275*** (0.0010)	−0.0271*** (0.0009)	0.0105*** (0.0002)	0.0038*** (0.0001)	0.0034*** (0.0001)
GDP	3.5065*** (0.1646)	3.5456*** (0.1673)	1.1223*** (0.0306)	−0.3813*** (0.0094)	−0.4213*** (0.0095)
P	−0.0162*** (0.0028)	−0.0164*** (0.0028)	−0.0068*** (0.0018)	−0.0076*** (0.0003)	−0.0074*** (0.0003)
AT	0.0931*** (0.0054)	0.0962*** (0.0054)	0.0909*** (0.0046)	−0.0036*** (0.0007)	−0.0068*** (0.0008)
TPL		−0.0349*** (0.0055)			0.0356*** (0.0014)
Cons	−22.6546*** (1.1461)	−23.0734*** (1.1751)	−11.9993*** (0.3127)	4.6451*** (0.0885)	5.0723*** (0.0894)
N	33,345	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
R^2	0.6361	0.6362	0.8804	0.9801	0.9805

Table 10
Coupling coordination.

Variable	RREGP	Lsdv	2SLS (first stage)	2SLS (second stage)	LIML
REGP	2.2836*** (0.7544)	2.3189*** (0.7483)	0.4454*** (104.4090)	6.2475*** (4.1350)	6.2475*** (1.4786)
Cons	2.3058*** (0.6068)	2.2659*** (0.6047)	−0.1278*** (−29.2447)	3.3173*** (4.8673)	3.3173*** (0.6851)
N	33,345	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Control	YES	YES	YES	YES	YES
R^2	0.1254	0.1254	0.8397	0.1246	0.1246
F value			10901.2		

Table 11
Household carbon reduction.

Variable	RREGP	Lsdv	2SLS (first stage)	2SLS (second stage)	LIML
REGP	−1.7197*** (0.3861)	−1.6226*** (0.2946)	0.4454*** (104.4090)	−2.1382*** (−2.9272)	−2.1382*** (0.6338)
Cons	−0.5057 (0.3074)	−0.4679 (0.3008)	−0.1278*** (−29.2447)	−0.4954 (−1.5033)	−0.4954 (0.3280)
N	33,345	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Control	YES	YES	YES	YES	YES
R^2	0.0298	0.0297	0.8397	0.0297	0.0297
F value			10901.2		

Table 12
Energy poverty.

Variable	RREGP	Lsdv	2SLS (first stage)	2SLS (second stage)	LIML
REGP	−1.9271*** (0.6572)	−1.9689*** (0.6520)	0.4454*** (104.4090)	−5.3759*** (−4.0838)	−5.3759*** (1.2886)
Cons	−1.9920*** (0.5288)	−1.9592*** (0.5270)	−0.1278*** (−29.2447)	−2.8745*** (−4.8408)	−2.8745*** (0.5971)
N	33,345	33,345	33,345	33,345	33,345
Province	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Control	YES	YES	YES	YES	YES
R^2	0.1255	0.1255	0.8397	0.1248	0.1248
F value			10901.2		

carbon reduction. We consider income disparities, investigating the groups targeted by the synergy and highlighting those that require focused attention for future policy interventions. Furthermore, we have drawn from the extant literature to outline and empirically examine three pathways to achieve synergy between EP alleviation and carbon reduction. The results lead us to the following key conclusions.

(1) China's regional environmental governance efforts exhibit a substantial synergistic effect, effectively addressing household EP and carbon reduction. This environmental policy achieves comprehensive management of these two critical challenges. Moreover, the synergistic effectiveness varies among income groups, with lower-income households experiencing more pronounced effects.
(2) Regional environmental governance's effectiveness and synergy primarily stem from optimizing energy consumption patterns, reducing carbon emission intensity, and advancements in scientific and technological progress. This conclusion is reinforced through robustness checks from the perspectives of endogeneity, the robustness of regional environmental governance indicators, and estimation methods.

Drawing on these findings, we present the following policy recommendations to help achieve the goals of carbon peak, carbon neutrality, and supporting high-quality economic and social development.

(1) Establishing Institutional Support: The government must devise a multitier development strategy for energy security and carbon reduction, fostering a balanced and systematic approach. This approach should prioritize resource allocation and ensure the orderly progression of energy security and carbon reduction efforts. Regional environmental governance has a substantial synergistic effect. Therefore, a governance framework focused on balancing energy security and carbon reduction should be expedited and perfected. Alongside the continuous refinement of climate change laws and regulations, efforts should be intensified to integrate climate governance with ecological environmental protection regulations.
(2) Tailored Interventions for Income Groups: Policy initiatives should be tailored to address the specific needs of income groups, focusing on enhancing energy security for lower-income households and bolstering the efficiency and effectiveness of synergy. A specialized institution dedicated to strengthening energy security and promoting household carbon reduction is recommended. This institution would offer timely and effective decision-making support for these vital goals.
(3) Continued Structural Optimization: Future governance strategies should prioritize improving energy consumption patterns and reducing GDP EI. These goals can be achieved by eliminating high-energy and high-emission sources, such as outdated boilers and vehicles, particularly in less developed regions and among higher-income individuals. A robust emphasis on technological innovation within low-carbon and environmentally friendly industries is also crucial.
(4) Strengthening Technological Innovation: Technological breakthroughs remain pivotal for achieving energy security and low-carbon emissions. Thus, China should intensify efforts to cultivate talent within relevant fields while offering policy incentives,

such as improved energy access for lower-income individuals and emission constraints for higher-income groups. Notably, provisions targeting lower-income households' energy access and emission limitations for higher-income individuals are paramount. Furthermore, transforming scientific and technological achievements into practical applications should be expedited, facilitating seamless integration between technological advancements and business enterprises.

This study underscores the profound synergistic potential of regional environmental governance in addressing EP and promoting household carbon reduction. The policy recommendations outlined above can help policymakers to effectively harness this potential and drive the nation closer to its carbon reduction objectives while ensuring equitable access to energy resources across diverse income groups.

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Consent

All authors have approved the manuscript.

Data transparency

All data support published claims.

CRediT authorship contribution statement

Baogui Xin: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Tengda Zhang:** Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Ernesto D.R. Santibanez-Gonzalez:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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