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# The impact of urban–rural integration on carbon emissions of rural household energy consumption: evidence from China

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**Abstract**

The symbiotic relationship between urban–rural integration and carbon emission reduction constitutes the fundamental objectives and impetus in China's economic metamorphosis. The intricate interplay between urban–rural integration and carbon emission reduction represents the critical factor for the consummate achievements of China's environmental overhaul in the forthcoming future. The current concentration of research on urban–rural integration (URI) is primarily centered on urban and agricultural production regions, while the effect of URI on carbon emissions of rural household energy consumption (CRE) being largely disregarded. Furthermore, the diversity in the effects of URI on CRE at different stages has not been considered, which could pose challenges in achieving China's environmental sustainability objectives. To supplement the above content, this study analyzes CRE using data from 30 provinces spanning the years 2005 to 2020. By employing ordinary least squares and mediated effects analysis, we empirically examine the influence of URI on CRE. The findings indicate the following: In general, URI can significantly reduce CRE. Integration of human, land, and capital is essential factors suppressing emissions, and the suppression effect of 'human integration' is the strongest. The impact of URI on CRE operates through various channels, including energy consumption intensity, per capita consumption, and energy consumption structure. There exists an "inverted N" curve relationship between URI and CRE. As integration increases, carbon emissions initially decrease, then increase, and finally decrease again. Therefore, it is imperative for various regions to vigorously promote URI and effectively leverage its positive role in energy conservation and emission reduction, providing important insights for synergistically advancing urban–rural integration and energy conservation and emission reduction.

**Keywords** Urban–rural integration · Energy conservation · Carbon emission reduction · Rural household carbon emissions · "Inverted N" curve · Mediated effects

Extended author information available on the last page of the article

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## 1 Introduction

In order to promote the development of an ecological civilization and implement the concept of harmonious coexistence with nature, China is transitioning its economic development model from one focused solely on rapid growth to a comprehensive, coordinated, and sustainable approach. This new model emphasizes structural adjustment and environmental efficiency. Within this context, urban–rural integration and emissions reduction are key themes in China's green transformation and development (Li & Liu, 2020; Shao et al., 2019). Urban–rural integration (URI) aims to improve the efficiency of spatial resource allocation, address distortions in economic structure, enhance industrial efficiency, stimulate domestic demand, and improve labor productivity, ultimately fostering efficient and high-quality development (Gao & Kong, 2019). Simultaneously, China, as the world's largest carbon emitter (Fu et al., 2021), recognizes the significance of energy conservation and emission reduction. In 2013, the residential energy consumption in China amounted to 455.31 million tons of standard coal, accounting for 11% of the total energy consumption. The residential sector is positioned as the second most significant energy-consuming sector, after the industrial sector (Wei & Shen, 2019). Approximately 40% of China's populace dwell in rural areas (Ma et al., 2022), thereby rendering their output and domestic energy utilization a pivotal component of the administration's agenda for energy preservation and mitigation of carbon emissions (Niu et al., 2019). According to statistics, the per capita carbon emissions of rural household energy consumption in China have increased from 0.170t in 1995 to 0.507t in 2010, reflecting a growth of 196.9% (Ma et al., 2022). Additionally, the aggregate energy usage within the rural regions of China witnessed a surge from 0.30 billion tons in the year 1979 to 2.37 billion tons as of 2018, which symbolizes an amplification of 7.9 times (Zhang et al., 2022). Looking ahead, given the implementation of strategies aimed at stimulating rural revitalization and fostering integration amidst urban and rural localities, rural energy demand is expected to rise substantially, posing a potential challenge to emission reduction efforts in China.

Simultaneously, URI is a significant driver of China's economic transformation and development, and it is closely linked to efforts to reduce carbon emissions. The relationship between the two cannot be overlooked. Between 1978 and 2017, the urbanization rate in China witnessed a prominent surge, augmenting from a mere 17.92–58.50% (Yao et al., 2023). The Chinese regime, besides focusing on fundamental aspects such as rural populace migration, land coordination, and economic integration, has emphasized environmental protection in the process of China's novel urbanization and rural–urban interaction. On one hand, URI serves as a tool for allocating resources more effectively, improving resource utilization efficiency, promoting technological progress. These factors contribute positively to energy conservation and emission reduction. On the other hand, the process of integration may lead to increased emissions as a result of adjustments in resource inputs and the release of domestic demand potential. This can potentially hinder China's low-carbon objectives.

As China progresses through its current stage of socio-economic development (North, 1992), it becomes crucial to explore the direction and mechanisms through which URI influences carbon emissions of rural household energy consumption (CRE). These questions hold significant importance in understanding the impact of integration on emission reduction and identifying strategies to align URI with China's low-carbon goals.

China's ongoing enhancement of institutional and policy systems, coupled with its extensive implementation of URI, has emerged as prominent subjects of academic investigation. Viewed through the lens of functional attributes, URI yields distinct economic, social, and ecological impacts on regional development. Economically, URI optimizes the economic interdependencies between urban and rural regions, consolidates urban–rural connectivity, amends the disadvantaged status of rural advancement, and enhances the exploitation of rural resourcefulness. This unleashes the multiplier effect of integration and fosters high-quality development (Gao & Kong, 2019; Jiang & Zhou, 2018). From a social perspective, URI encompasses the fair and just distribution of resources and components to rural regions, effectively closing the disparity in public utility development between urban and rural locales. It invigorates social development, facilitates the equitable sharing of growth benefits among urban and rural residents, and promotes social harmony. Ecologically, URI has the capacity to promote the dissemination of green technologies and features into rural zones, establish a green closed-loop supply chain (Abbasi et al., 2023). Furthermore, it encourages modernization of the agricultural practices and rural regions, while also optimizing rural energy consumption in order to effectively mitigate carbon emissions (Ren & Zhou, 2021; Xie et al., 2022).

Global warming and the energy crisis have prompted international scholars to focus on the energy and emission implications of URI. Research has examined its environmental impacts at the national (Liddle & Lung, 2010), regional (Zhang et al., 2017), and household scales (Li et al., 2015). Additionally, studies have explored the relationships between infrastructure investment, household income (Huang, 2014; Zhou et al., 2022b), energy resource endowment (Zhang et al., 2022), and rural $CO_2$ emissions. While some suggest that these factors contribute to increased emissions from energy consumption, other scholars have presented findings based on the energy ladder and fuel stacking theories. They have demonstrated that as income rises, rural households display a greater inclination toward modern fuels rather than biomass, resulting in a reduction in household emissions (Zhou et al., 2022b).

Research on the effects of URI is abundant, but there is still room for further improvement. On the one hand, most existing research focuses on the urban context and assesses its carbon emissions effects in rural production areas, ignoring its impact on carbon emissions of rural household energy consumption (CRE). On the other hand, most studies do not consider the heterogeneous effects of URI on CRE at different stages. To supplement the research, this paper comprehensively discusses the impacts and underlying mechanisms of the URI on CRE. The relevant findings not only contribute valuable insights to previous studies, but also provide theoretical support for optimizing the development model and policy design of urban–rural integration in China.

In sum, this study makes several notable contributions. Firstly, it methodically assesses the impact of URI (urban–rural integration) on CRE (carbon emissions of rural household energy consumption), hence broadening the ambit of ecological evaluation within the framework of URI. Secondly, by considering the dual urban–rural system in China, along with factors such as rural household energy consumption intensity, per capita consumption, and energy consumption structure, it provides an extensive comprehension of the mechanisms which underlie the influence of URI on CRE. Thirdly, it investigates the nonlinear correlation between URI and CRE, offering fresh insights into this connection within the Chinese context. Finally, this study utilizes sturdy methodologies such as 2SLS and system GMM estimation to alleviate prospective endogeneity concerns, therefore producing strong empirical proof for the researched relationship.

The following is structure of thesis. Section 2 provides the literature review and hypotheses. Section 3 is the models, variables, data, and summary statistics. Section 4 describes the empirical results and discussion. Section 5 shows the conclusion and the prospect of research. Section 6 provides the policy and managerial implications.

## 2 Literature review and hypotheses

### 2.1 The impact of URI on CRE

URI seeks to enhance collaboration and exchange between the relatively less developed agricultural sector and the more advanced non-agricultural sector. This process aims to achieve a proper flow and optimal combination of production factors such as human resources, land, and capital, ultimately reducing the income gap and promoting regional convergence (Huang, 2014). The theoretical understanding of URI is enriched by various perspectives, including social development history, regional coordination, and economic integration (Cao et al., 2021). The relationship amidst urban and rural forms a complex dynamic system. In line with the work of Liu et al. (2019), this paper refines URI into three dimensions: 'human integration,' 'land integration,' and 'capital integration.' It examines the individual impacts of each dimension on CRE.

Firstly, 'human integration' primarily involves the efficient movement of labor amidst urban and rural localities. This process enables rural areas to accumulate human capital, improve income and consumption levels, and raise environmental awareness among residents (Du, 2020). On one hand, 'human integration' can enhance rural self-development capabilities, increase residents' income, and stimulate consumption, consequently leading to higher carbon emissions. On the other hand, through the reduction of the rural population, the concept of 'human integration' enhances the interaction between urban and rural sectors, thus easing the transmission of modern ideas on low-carbon consumption from metropolitan to non-urban regions. This results in a shift toward a greener energy consumption structure, which promotes energy conservation and emission reduction in rural households.

Secondly, 'land integration' is an essential component of the dynamics amidst urban and rural localities, entailing the synchronization and redistribution of production factors across these regions. Its primary aim is to optimize resource allocation and foster mutual development (Zhou et al., 2022a).This integration offers several advantages. Firstly, it ensures effective coordination and reallocation of production factors, leading to improved resource allocation and mutually beneficial outcomes (Li & Xu, 2018). It enables the efficient use of land resources, supporting sustainable development in both urban and rural regions. Additionally, 'land integration' promotes agglomeration by reducing spatial distances amidst urban and rural localities. This enables efficient allocation of land resources, resulting in economies of scale and positive externalities such as the diffusion of innovative technologies and knowledge. Consequently, it helps reduce carbon intensity within rural households (Shao et al., 2019).

Thirdly, 'capital integration' involves the integration of construction investments amidst urban and rural localities. The objective is to attain an equitable distribution of urban and

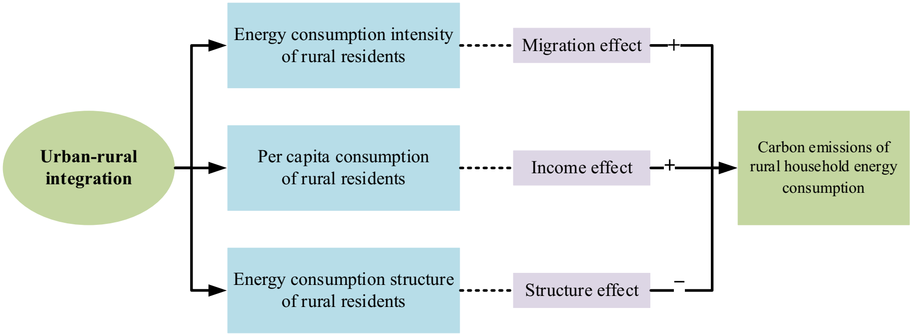


**Fig. 1** The influence mechanisms of URI on CRE

rural industries, safeguard the welfare and entitlements of agriculturists, and catalyze technological advancement (Zhou, 2018). 'Capital integration' yields both positive and negative effects. On one hand, investment in rural fixed assets and the optimization of industry structures can drive rural economic development and increase rural incomes (Zhou et al., 2022b). This can have implications for energy consumption and carbon emissions as economic growth may lead to increased energy usage. On the other hand, improvements in healthcare and social security in rural areas can unleash the consumption potential of rural residents, thereby potentially increasing energy consumption and carbon emissions (Tang & Guo, 2022). However, 'capital integration' also promotes investment in rural environmental management and technological advancements, which can help mitigate carbon emissions stemming from energy consumption. Taken together, the analysis demonstrates that rural–urban integration has diverse effects on CRE. In light of these findings, the following hypothesis is proposed:

**Hypothesis 1** The direction of impact of URI on CRE is uncertain.

## 2.2 The influence mechanisms of URI on CRE

Through utilization of the carbon emissions accounting method, the impact of URI on CRE can be comprehended through three distinct perspectives: energy consumption intensity, per capita energy consumption, and energy consumption structure (Fig. 1). Firstly, URI is expected to increase rural household energy consumption intensity, resulting in higher carbon emissions. The process of integration involves changes in production and lifestyles, which can lead to an increase in energy demand and consumption intensity in rural areas (Han et al., 2022). Moreover, inadequate public transport infrastructure amidst urban and rural localities may further contribute to increased energy demand and consumption intensity, subsequently raising carbon emissions (Zhou et al., 2022b). These changes in household energy consumption patterns are referred to as the migration effect (Salim & Shafiei, 2014). Secondly, URI is anticipated to raise rural household energy consumption and carbon emissions. Integration facilitates the exchange of knowledge and technology between rural and urban areas, leading to advancements in agricultural technology and improved knowledge among farmers. This, in turn, tends to increase agricultural and non-agricultural income for rural households, consequently driving up domestic energy consumption and resulting carbon emissions (Han et al., 2022). Changes in rural household energy consumption influenced by URI are known as the income effect (Wang et al., 2016). Lastly, URI is expected to bolster the development of a diversified and cleaner energy consumption structure among rural residents, ultimately reducing the carbon emissions. The energy ladder hypothesis suggests that as income increases, there is a shift in energy consumption patterns from traditional and unclean sources like firewood to modern, efficient, and cleaner alternatives such as natural gas and electricity (Ma et al., 2019). Therefore, URI may facilitate the adoption of cleaner energy sources and contribute to a reduction in CRE. These changes are collectively referred to as the structural effects of URI (Wang et al., 2020a). Based on the above understanding, the following hypothesis is proposed:

**Hypothesis 2** URI will have a mixed effect on CRE. It is expected to promote carbon emissions by increasing energy consumption intensity and per capita consumption, while also exerting a mitigating influence by improving the energy consumption structure.

### 2.3 The nonlinear effect of URI on CRE

Due to the significant differences in energy supply and household energy demand at different stages of URI, its impact on CRE may depend on the stage. Meanwhile, due to concerns regarding environmental issues, many scholars currently prioritize the relationship between urbanization and carbon emissions utilizing evidence from various countries (Wang & Zheng, 2021). The prevailing viewpoint suggests 'inverted U-shaped' relationship between urbanization and carbon emissions (Martinez-Zarzoso & Maruotti, 2011), which supports the Environmental Kuznets Curve theory, although contrasting perspectives do exist(Effiong, 2018; Liu et al., 2015). Drawing inspiration from current research and theory, this paper seeks to demonstrate a distinct 'inverted N-shaped' relationship between URI and CRE. It aims to address the lack of attention given to this area in academia.

This paper draws on Jiang et al. (2018), dividing the history of URI into initial, growth, and mature stages. We explore the intrinsic relationship between URI and CRE by stage.

Firstly, in the initial stage, a negative correlation exists between URI and CRE. During this phase, URI leverages the economic agglomeration effect, shares basic infrastructure with rural areas, and improves rural energy efficiency to reduce CRE (Scott, 2012). On one hand, economic agglomeration has the potential to mitigate spatial distance, reduce commuting costs for rural residents, and ultimately curtail their carbon footprint. Additionally, research indicates that URI is more likely to generate environmental "economies of scale," such as the scale economy resulting from the provision of sanitation facilities (Martinez-Zarzoso & Maruotti, 2011). Because the reduction is greater than the rise in carbon emission intensity brought on by the development of rural economic, URI has a mitigating effect on CRE.

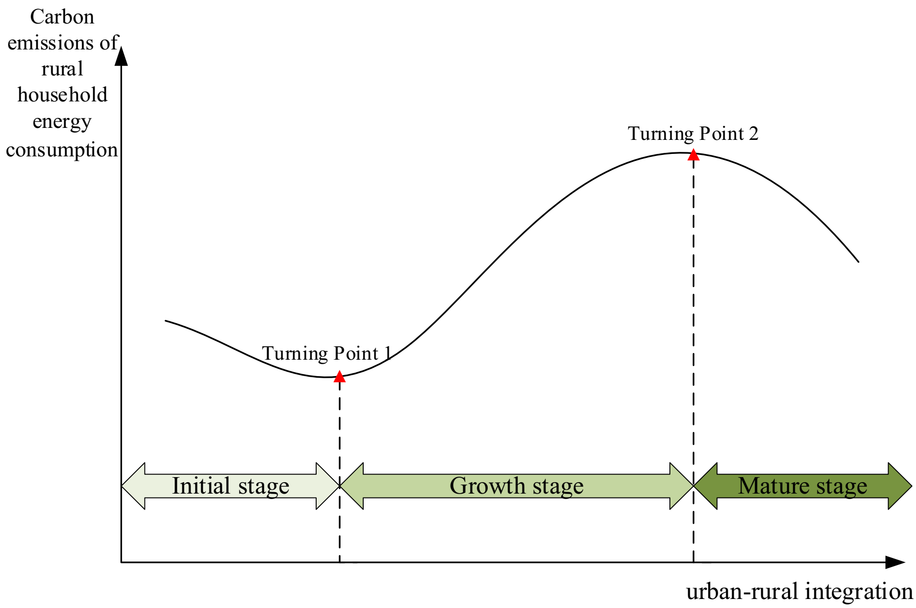


**Fig. 2** “Inverted N” relationship between URI and CRE

Furthermore, throughout the developmental phase, URI has a beneficial influence on the CRE. At this stage, as China’s household registration system undergoes significant reforms and urbanization develops further, the polarized dichotomy between urban and rural has been significantly weakened. The flow of factors amidst urban and rural localities has continuously increased, bringing vitality to rural development (Kong & Zhou, 2020). This is primarily reflected in the expansion of channels for increasing farmers’ income, the improvement of rural infrastructure, and the increase in agricultural production efficiency (Deng et al., 2022; Yao et al., 2023), all of which may have the potential to result in a rise in CRE. At the same time, with economic and technological progress, energy supply capacity and reasonable energy prices in rural areas increased rural household energy demand.

Finally, in the mature stage, a negative correlation exists between URI and CRE. At this stage, more attention is paid to the development of urban–rural relations in the direction of green and low-carbon. In this process, URI greatly reduced the exchange costs between the agricultural and non-agricultural sectors, which is conducive to integrated regional environmental management, thus strengthening environmental regulation in rural areas (Lai et al., 2022). On the one hand, stronger environmental laws and supervision encouraged rural residents to choose clean energy or products with low energy consumption. On the other hand, URI reduces the transaction and promotion costs of environmental protection technologies through market integration, generating knowledge and technology spillovers. The promotion and use of energy conservation and emissions reduction technologies improve the energy efficiency of the rural sector and reduce household carbon emissions (Xiao et al., 2022). Thus, an “Inverted N” relationship may exist between URI and CRE (Fig. 2). Accordingly, this paper proposes the following hypothesis.

**Hypothesis 3** Ceteris paribus, an "inverted N" relationship exists between URI and CRE, i.e., the latter will show a downward, then upward, then downward trend as integration progresses.

## 3 Study design

### 3.1 Model setting

(1) Baseline regression for testing the effect of URI on CRE. The following model to be tested is constructed in this paper.

$$\mathrm{CRE}_{it} = \alpha_0 + \alpha_1 X_{it} + \alpha_2 \mathrm{CON}_{it} + \vartheta_t + \theta_i + \varepsilon_{it} \tag{1}$$

In Eq. (1), $i$ represents the province, $t$ represents the year, $\mathrm{CRE}_{it}$ represents the level of CRE in province $i$ in year $t$; the key variables $X_{it}$ represents the level of URI of province $i$ in year $t$ and its sub-indicators, i.e., human integration (*human*), land integration (*land*), and capital integration (*capital*); to control the influence of the time-varying factor characteristics of each province on CRE, a series of control variables $\mathrm{CON}_{it}$ are selected in this paper. $\vartheta_t$ is the year-fixed effect, $\theta_i$ represents province-fixed effects, and $\epsilon_{it}$ is the random error term.

$$M_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 \mathrm{CON}_{it} + \vartheta_t + \theta_i + \varepsilon_{it} \tag{2}$$

$$\mathrm{CRE}_{it} = \gamma_0 + \gamma_1 X_{it} + \eta M_{\tau it} + \gamma_2 \mathrm{CON}_{it} + \vartheta_t + \theta_i + \varepsilon_{it} \tag{3}$$

(2) Mechanism test model for testing the mediating effect of three aspects, namely energy consumption intensity of rural residents, per capita consumption level of rural residents, and energy consumption structure of rural residents, in the mechanism of the impact of URI on CRE. This paper mainly draws on the widely adopted stepwise method as the test method for the mediating effect and constructs the following mediating effect model based on Eq. (1).

In Eqs. (2)–(3), the $M_{it}$ denotes the mediating variables of URI affecting CRE, mainly including energy consumption intensity of rural residents (*ei*), per capita consumption level of rural residents (*pc*), and energy consumption structure of rural residents (*es*). The key variable of this part $X_{it}$ is the level of URI of province $i$ in year $t$. The rest of the variables have the same meaning as in Eq. (1).

(3) Nonlinear relationship test model is used to test the nonlinear effect of URI on the CRE. The following model to be tested is constructed in this paper.

$$\mathrm{CRE}_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 X_{it}^2 + \beta_3 X_{it}^3 + \delta \mathrm{CON}_{it} + \vartheta_t + \gamma_i + \varepsilon_{it} \tag{4}$$

The critical variable in Eq. (4) $X_{it}$ is the level of URI of province $i$ in year $t$. $X_{it}^2$ and $X_{it}^3$ are its quadratic and cubic terms. The rest of the variables have the same meaning as in Eq. (1).

### 3.2 Variables

(1) The explanatory variable, carbon emissions of rural household energy consumption (*CRE*), is quantified by the ratio of total carbon emissions resulting from energy consumption in rural households to the permanent rural population. To measure CRE, the study considers the energy consumption of 15 primary energy sources within each province. The measurement method relies on the reference formula designated by the national greenhouse gas emission inventory as outlined by the IPCC.[1] Following the approach outlined by Jiang (2015), the study employs the following formula to directly estimate emissions based on the physical quantity of energy consumed.

$$C = \sum_i C_i = \sum_i \mathrm{EQ}_i \times \mathrm{NCV}_i \times \mathrm{CEF}_i \tag{5}$$

To estimate carbon emissions ($C$), the following variables are considered: $\mathrm{EQ}_i$ representing the consumption of energy source $i$, (measured in kg or $m^3$); $\mathrm{NCV}_i$ indicating the net heating value coefficient of energy source $i$; and $\mathrm{CEF}_i$ representing the carbon emission coefficient per unit of energy source $i$. This study utilizes data from the China Energy Statistical Yearbook's energy balance sheet to calculate carbon emissions for 15 energy categories. These classifications encompass unprocessed coal, refined coal, miscellaneous purified coal, solid fossil fuel, carbonized fuel, byproduct gas of carbonization, unprocessed petroleum, petrol, aviation fuel, gas oil, heavy fuel oil, compressed hydrocarbon gas, vaporized petroleum gas, gaseous fossil fuel, electrical power, and thermal energy. For electricity consumption, carbon emissions are determined by multiplying household electricity consumption by the baseline carbon emission factor specific to each regional power grid in the given calendar year. To estimate carbon emissions from heat consumption, it is first converted into a standard coal equivalent, and then, the resulting carbon emissions are measured using the appropriate carbon emission factor.

(2) Core explanatory variable. The core explanatory variable is urban–rural integration (URI). URI involves the integration of human, land, and capital factors (Liu and Long 2022).[2] Building upon previous research (Liu & Lu, 2019), this paper develops three primary indicators: 'human integration,' 'land integration,' and 'capital integration.' These primary indicators are further expanded into 13 secondary indicators and 23 tertiary indicators (Table 1) to comprehensively measure URI in China from 2005 to 2020. To determine the weights of the indicators at all levels and measure human, land, and capital integration, as well as overall URI, the entropy method of objective assignment is employed. This study not only incorporates the overall integration level into the measurement model but also includes the decomposed indicators, namely human, land, and capital integration. The research explores the impact of URI and its dimensions on CRE.

[1] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 1.1 Introductions.

[2] Liu Shouying, Rural revitalization and urban–rural integration - two keywords in the urban-rural China stage, http://www.aisixiang.com/data/106548.html, 2017-10-23.

**Table 1** Index system of urban–rural integration (URI)

| Sub-item | Basic indicators | | Indicator meaning and attributes | |
|---|---|---|---|---|
| Human integration | Total urban–rural economy | GDP per capita | Total GDP/total population | Positive |
| | | Share of non-farm output | Secondary and tertiary sector GDP/primary sector GDP | Positive |
| | Income of urban–rural residents | Per capita income ratio of urban and rural residents | Per capita disposable income of urban residents/per capita net income of rural residents | Negative |
| | | Wage income ratio of urban and rural residents | Per capita wage income of urban residents/per capita wage income of rural residents | Negative |
| | | Property income ratio of urban and rural residents | Per capita property income of urban residents/per capita property income of rural residents | Negative |
| | Urban–rural residents' consumption | Per capita consumption ratio of urban and rural households | Urban household per capita consumption/rural household per capita consumption | Negative |
| | | Urban–rural Engel coefficient ratio | Urban Engel Coefficient/rural Engel coefficient | Positive |
| | | The ratio of cultural, educational, and recreational expenditure of urban and rural households | Urban households' expenditure on culture, education, and entertainment/rural households' expenditure on culture, education, and entertainment | Negative |
| | | Energy consumption structure | The proportion of coal energy consumption | Positive |
| Land integration | Living space clustering | Level of Urbanization | Number of urban population/total population | Positive |
| | Urban–rural circulation | Private car ownership ratio | The private car ownership/total population | Positive |
| | | Traffic network density | Total road and rail mileage in operation/total area of the region | Positive |
| | | Post and telecommunications business per capita | Total postal and telecommunications services/total population | Positive |
| | Urban–rural land allocation | Urban-to-rural population density ratio | Rural population density/urban population density | Positive |
| | | Urban–rural land use ratio | Rural residential area/urban built-up area | Positive |
| | | Arable land area ratio | An arable land area/total area | Positive |

**Table 1** (continued)

| Sub-item | Basic indicators | | Indicator meaning and attributes | |
|---|---|---|---|---|
| Capital integration | Financial investment | The ratio of urban and rural fixed asset investment in the whole society | Investment in fixed assets per rural resident/investment in fixed assets per urban resident | Positive |
| | Technological advances | Agricultural mechanization level | Total power of agricultural machinery/total cultivated area of arable land | Positive |
| | Industry structure | Binary comparison factor | (output value of primary industry/employees in the primary industry)/(output value of secondary and tertiary industries/employees in secondary and tertiary industries) | Positive |
| | Environmental governance | Environmental pollution control investment ratio | Investment in environmental pollution control/total output | Positive |
| | Urban–rural medical coverage | The ratio of urban and rural per capita medical security expenditure | Urban per capita health care expenditure/rural per capita health care expenditure | Negative |
| | Urban and rural social security | Urban and rural residents' primary pension insurance expenditure ratio | Expenditure on basic pension insurance for urban and rural residents/general budget expenditure of local finance | Positive |
| | | The number of urban and rural residents covered by unemployment insurance | Number of urban and rural residents with unemployment insurance/total number of insured (power) | Positive |

(3) *Control variables* Referring to the literature (Cao et al., 2021; Zhang et al., 2022), this study includes the following control variables: (1) Rural household fixed asset investment (*Invest*), deflated using the fixed asset investment price index for the base period of 2005. *Invest* can reflect the input of production and living elements of rural household. High fixed asset investment may improve the advancement of household equipment and facilitate the transition toward a cleaner energy consumption structure, ultimately enhancing the efficiency of energy utilization and indirectly affecting the total carbon emissions of rural household (Hu, 2012; Wang & Dong, 2023). (2) Population (*pop*), expressed as the number of the rural residents, which is used to reflect the scale of rural population development. A larger rural population may significantly enhance CRE through means such as increasing population density and energy utilization density (Liu et al., 2021). (3) Old age dependency ratio (*old*), expressed as the dependency ratio of the elderly population in the population sample survey data,[3] used to test whether rural aging will have an external effect on carbon emissions. The aging of China's rural areas is becoming increasingly severe. Furthermore, the massive outflow of rural labor has resulted in a lack of mobility among the elderly population, which may lead to an increase or decrease in their energy consumption and impact the CRE (Zhang et al., 2022). (4) Energy consumption per capita (*consume*), expressed as total energy consumption in standard coal equivalent/year-end population, used to reflect the level of household energy consumption, which directly affects carbon emissions. (5) Infrastructure construction (*gov*), measured as the ratio of government public finance expenditure to GDP, an important measure for local governments to promote regional economic growth which may increase direct energy consumption by rural residents. On one hand, infrastructure development facilitates market expansion, promoting regional economic growth through direct and indirect spillover effects, increasing demand for primary energy sources, and hence influencing CRE. On the other hand, infrastructure development can provide favorable conditions for knowledge and technology spillovers, harnessing the effects of technological innovation and its interconnected economic growth effects, in turn promoting CRE (Xie et al., 2017).

(4) *Mediating variables*. Based on the previous theoretical analysis, the following mediating variables are used. (1) Energy consumption intensity of rural residents (*ei*), based on Cao et al. (2021) (2) Per capita consumption of rural residents (*pc*), expressed using constant prices 2005. (3) Energy consumption structure of rural residents (*es*), drawing on relevant research (Sun & Chen, 2022), measured as the ratio of standard coal equivalent consumed by electricity to that consumed by the other types of energy.

### 3.3 Data source

This paper uses rural household energy consumption data at the provincial level. The data are provided in the China Energy Statistics Yearbooks. These balance sheets offer detailed information on the consumption of each energy type by provinces, as well as their urban and rural residents, spanning multiple years. Notably, the sample excludes Hong Kong, Macao, Taiwan, and Tibet due to limited data availability in these regions. The panel data used in the analysis cover the period from 2005 to 2020, resulting in a sample size of 480

[3] The rural old-age dependency ratio is the proportion of the rural population aged 65 and above to those aged 15–64 [see Luo and Xie (2013)]. The data are sample data from the 1% Population Sample Survey in 2005 and 2015, and the 1‰ Population Change Survey in other years. For details of the specific sampling ratios, see the China Statistical Yearbooks in the references.

observations for the 30 Chinese provinces. It should be mentioned that while the earliest available energy balance sheet is from 2003, there are missing values for other variables in the years 2003 and 2004.

The various sources and processing methods for the other variables are as follows:

*Heat and Electricity Sources* (1) The standard coal coefficients for different heat and electricity sources are primarily derived from the General Rules for Comprehensive Energy Calculation (GB/T 2589-2020). In cases where data for the net calorific value of other washed coals are unavailable, they are substituted with the corresponding data for washed coal. The net calorific value data for coal briquettes are replaced with the net calorific value data of brown coal briquettes from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (2) *Carbon Emission Coefficients* The carbon emission coefficients per unit calorific value are mainly sourced from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. For coal-based energy sources, the carbon emission coefficients use the coefficient for brown coal briquettes. The carbon emission coefficients per unit calorific value of thermal power are obtained from Jiang (2015). (3) *Carbon Emission Coefficients of Regional Grids* The carbon emission coefficients for each regional grid are primarily sourced from the China Regional Grid Carbon Dioxide Baseline Emission Factors for previous years. (4) *Control Variables* The control variables are obtained from various sources, including the China Statistical Yearbooks, China Statistical Abstracts, and statistical yearbooks of each province from previous years. Detailed definitions of each variable and their descriptive statistics can be found in Table 2.

# 4 Empirical results and discussion

## 4.1 Empirical results on the influence of URI on CRE

### 4.1.1 Baseline regression results

Table 3 shows the results of the regression model based on Eq. (1). Columns (1) and (2) analyze the overall effect of URI on CRE. The coefficient of URI is significantly negative at the 1% level, implying that URI significantly suppresses carbon emissions. The reasonable explanation in this paper as follows. As seen from the current status of economic and social development in China, although URI has achieved some success, in most periods, China's regions are still in the primary stage (Xie & Wu, 2023). Therefore, overall, URI will mainly be achieved by leveraging economic agglomeration effects, sharing infrastructure with rural residents, reducing commuting time, generating environmental scale benefits, and thus restraining the rural household carbon emissions.

To further investigate the specific factors affecting this result, columns (3)–(7) further analyze the effects of human, land, and 'capital integration'. All three coefficients are significantly negative at the 1% level.

**First**, 'human integration' has the most substantial inhibitory effect, column (3) and column (7) indicate that as 'human integration' increases by 1%, the CRE decrease by 1.495–1.217%. This implies that at the current stage, URI encourages the rural migrant population to go out for non-agricultural employment, improving awareness of low-carbon environmental protection and energy consumption structure (e.g., the use of clean energy such as coal-to-gas), which significantly reduces the use of energy and carbon emissions by rural residents. Ma et al. (2019) and Rahut et al. (2017) also support this conclusion.

**Table 2** Definitions and descriptive statistics of each variable

| Variable category | Symbols | Meaning | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|---|
| Explained variables | CRE | Per capita carbon emissions of rural household energy consumption (tons) | 0.730 | 0.437 | 0.114 | 3.552 |
| Explanatory variables | URI | Urban–rural integration | 0.102 | 0.076 | 0.041 | 0.511 |
| | human | Human integration | 0.144 | 0.123 | 0.025 | 0.941 |
| | land | Land integration | 0.091 | 0.098 | 0.069 | 0.698 |
| | capital | Capital integration | 0.101 | 0.101 | 0.018 | 0.705 |
| Intermediate variables | ei | Energy consumption intensity of rural residents (t/yuan) | 0.017 | 0.009 | 0.004 | 0.072 |
| | pc | Per capita consumption level of rural residents (yuan), taking the logarithm | 3.897 | 3.642 | 3.220 | 4.351 |
| | es | Energy consumption structure of rural residents (%) | 30.697 | 18.330 | 2.188 | 85.306 |
| Control variables | invest | Investment in fixed assets of rural households (billion) | 6.738 | 1.314 | 2.944 | 9.718 |
| | pop | Number of rural population (million), taking logarithms | 7.326 | 0.913 | 5.328 | 8.780 |
| | old | Rural elderly dependency ratio (%) | 13.766 | 3.251 | 7.400 | 24.900 |
| | consume | Per capita energy consumption (tons of standard coal) | 3.409 | 1.740 | 0.993 | 11.466 |
| | gov | Infrastructure construction (%) | 0.026 | 0.012 | 0.010 | 0.087 |

**Table 3** Baseline regression

| Variables | Explained variable: carbon emissions of rural household energy consumption (CRE) | | | | | | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| URI | − 2.338*** | − 1.614*** | | | | | |
| | (− 10.83) | (− 8.90) | | | | | |
| Human | | | − 1.495*** | | | − 1.848*** | − 1.217*** |
| | | | (− 7.50) | | | (− 12.13) | (− 6.13) |
| Land | | | | − 0.839*** | | − 0.608*** | − 0.636*** |
| | | | | (− 6.77) | | (− 4.87) | (− 5.21) |
| Capital | | | | | − 0.481*** | − 0.474*** | − 0.421*** |
| | | | | | (− 2.89) | (− 3.00) | (− 2.76) |
| Invest | | − 0.121*** | − 0.121*** | − 0.120*** | − 0.114** | | − 0.120*** |
| | | (− 4.26) | (− 4.22) | (− 4.16) | (− 3.77) | | (− 4.37) |
| Pop | | 0.882*** | 0.399*** | 1.009*** | 1.05$^{3}$*** | | 0.454*** |
| | | (7.63) | (2.75) | (8.76) | (8.79) | | (3.24) |
| Old | | − 0.011** | − 0.002 | − 0.009* | − 0.012** | | − 0.006 |
| | | (− 2.07) | (− 0.44) | (− 1.74) | (− 2.19) | | (− 1.08) |
| Consume | | 0.060*** | 0.042** | 0.062*** | 0.068*** | | 0.044*** |
| | | (4.82) | (3.31) | (4.93) | (5.24) | | (3.55) |
| Gov | | 6.619*** | 5.646*** | 6.752*** | 6.229*** | | 6.188*** |
| | | (3.40) | (2.83) | (3.37) | (2.90) | | (3.27) |
| Constant | 0.964*** | 7.901*** | 4.371*** | 8.669*** | 8.987*** | 1.095*** | 4.865*** |
| | (41.89) | (9.33) | (4.17) | (10.25) | (10.18) | (42.57) | (4.80) |
| City fixed effect | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effect | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 480 | 480 | 480 | 480 | 480 | 480 | 480 |
| Adj. $R^2$ | 0.8706 | 0.9027 | 0.9017 | 0.8995 | 0.8909 | 0.8974 | 0.9089 |

*, **, ***Denote 10%, 5%, and 1% significance levels, respectively, and *t*-values in parentheses are the same below

Although 'human integration' can increase income, unleash consumption potential, and increase CRE, the population movement and changes in consumption concepts resulting from urban–rural interaction have a stronger inhibitory impact on CRE. Therefore, it is imperative for the Chinese government to accentuate the significance of "human integration" and achieve substantial outcomes with minimal effort.

**Second**, 'land integration' has the second-highest inhibitory effect, column (4) and column (7) indicate that as 'land integration' increases by 1%, the CRE decrease by 0.636–0.839%. This implies that the formation of a well-structured, well-positioned, orderly urban–rural spatial layout and circulation environment helps generate positive externalities from economic agglomeration, promote technological progress, enhance the efficiency of energy consumption, and reduce CRE. This finding also verifies Shao et al. (2019). Simultaneously, the scale effect of economic agglomeration generated by 'land integration' has a greater inhibitory effect on CRE than the promoting effect of carbon emissions brought by the improvement of rural circulation environment, ultimately showing a restraining effect on CRE caused by 'land integration'.

**Finally**, 'capital integration' has the weakest inhibitory effect, column (5) and column (7) indicate that as 'capital integration' increases by 1%, the CRE decrease by 0.421–0.481%. This finding is likely related to China's long-standing urban–rural dual economic structure. For example, the long-term urban–rural dichotomy and the agricultural policy orientation of "taking more and giving less" have led to a considerable capital gap in agricultural and rural development (Jiang & Zhou, 2018). As a result, investment in rural environmental management, green technological innovation, infrastructure construction, and public service protection lag behind urban areas (Gao, 2020). The resulting low carbon awareness of rural residents, backwardness of energy technology (coal-to-gas), underdevelopment of rural public transportation, and uneven protection of farmers' rights and interests do not help reduce CRE. Therefore, advanced forms of URI such as investment in urban–rural environmental management, financial investment support, and equalization of public services are the future keys to high-quality economic growth. These results show that URI and integration of people, land, and capital inhibit, not promote CRE—i.e., the direction of influence in Hypothesis 1 is negative.

From the control variables, the coefficient of fixed asset investment is significantly negative, indicating that more inputs help reduce CRE. The coefficients of rural population, per capita energy consumption, and infrastructure construction, however, are significantly positive. With the continuous improvement of economic development and infrastructure construction in rural areas, quality of life can be improved, and the driving effect of population size and energy consumption level on carbon emissions continues to increase.

#### 4.1.2 Discussion of endogeneity

To account for the dynamic nature of changes in CRE, a panel regression with lagged terms of the explanatory variables is employed, considering the influence of both current and past factors. This approach helps addresses the endogeneity issue arising from omitted variables. Year- and province-level fixed effects are included to control for unobserved heterogeneity. However, there is a potential concern regarding reverse causality between URI and CRE. In a general panel data model regression, the lagged effects of the explanatory variables might be correlated with random disturbances, leading to endogeneity. To mitigate this issue and obtain unbiased results, the System Generalized Method of Moments (System GMM) technique proposed by Arellano et al. (1995) is utilized. System GMM allows for the estimation of the dynamic relationship between CRE and the explanatory variables. This approach helps account for potential endogeneity concerns and yields more reliable results.

For comparison and to assess the robustness of the findings, the results of the 2SLS model are also presented in Table 4. In the 2SLS model, the lagged term of the explanatory variables (lag_CRE) serves as an instrumental variable to address the endogeneity problem in the model.

The statistical tests conducted in Table 4 provide valuable insights into the reliability and validity of the estimation results. The F-statistics in columns (1)–(4) demonstrate that there is no weak identification problem, as they are all significantly larger than the critical value of 10. The Kleibergen–Paap rk LM statistics, with corresponding *P* values below 0.05, pass the under-identification test. Analyzing the autocorrelation, the AR (1) term in columns (5)–(8) of Table 4 is significant, indicating the presence of first-order autocorrelation. However, the AR (2) term is not significant, suggesting that the model does not exhibit second-order autocorrelation. This implies that the System GMM method employed in this study is appropriate for addressing the autocorrelation issue.

Furthermore, the Sargan over-identification test results indicate that the null hypothesis of the instrumental variables' validity cannot be rejected at the 10% significance level. This suggests that the instrumental variables used in the estimation are reasonable and do not suffer from over-identification problems.

Considering all these statistical tests, it can be concluded that the coefficients of URI and its sub-indicators (*human*, *land*, and *capital*) remain significantly negative. While the absolute values of the coefficients may vary to some extent compared to the baseline results, their sign and significance level remain consistent. This further reinforces the finding that URI continues to significantly suppress CRE even after accounting for endogeneity concerns. Thus, Hypothesis 1 is confirmed by considering these robustness tests.

#### 4.1.3 Robustness tests

To enhance the credibility of the previous findings, several robustness tests were conducted and the results are presented in Table 5. These tests aim to validate the robustness of the main findings by examining alternative specifications and addressing potential concerns. (1) In the first robustness test, the dependent variable measure was switched to per capita domestic energy consumption of residents in each province, following the approach used by Cao et al. (2021). Despite this change, all coefficients remained significant, supporting the conclusion that URI has an inhibitory effect on CRE. (2) The second robustness test involved lagging the core explanatory variable by one period, as suggested by Liu et al. (2018). This approach helps mitigate potential endogeneity issues arising from reverse causality. (3) Tailoring. To address the influence of outliers, the third robustness test tailored all variables to the 1% and 99% percentiles. (4) Additional variables. Omission of variables is a frequent problem in research, and adding as many control variables as possible can increase the accuracy of the model to a greater extent. Therefore, the two variables (regional economic structure, energy price index) are added and simultaneously included in the regression model for estimation. The regional economic structure (*structure*) is represented by (value added of secondary industry + value added of tertiary industry)/value added of primary industry; the energy price index (*price*) is obtained from China Wind database. (5) Adjust the sample period. Considering that 2009 is an important turning point in China's nationwide rural fuel transformation, the sample period is adjusted to 2009–2020. The results of this test, presented in Table 5, show that all coefficients passed the significance test. This finding provides further support for the inhibitory effect of URI on CRE and confirms the robustness of the previous conclusions.

### 4.2 Empirical results on the influence mechanisms of URI on CRE

The above analysis has confirmed that rural–urban integration significantly suppresses CRE. How is this suppression achieved? What is the intrinsic mechanism of action? This paper uses the mediating effect model of Eqs. (1)–(3) to test three mechanisms: energy consumption intensity (*ei*), per capita consumption level (*pc*), and energy consumption structure (*es*).

**Table 4** Endogeneity regression results

| Variables | 2SLS | | | | System GMM | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| lag_CRE | −0.062*** | −0.078*** | −0.087** | −0.036* | 0.626*** | 0.643*** | 0.641*** | 0.688*** |
| | (−2.99) | (−4.71) | (−2.38) | (−1.76) | (5.51) | (5.47) | (5.63) | (6.15) |
| Integration | −9.064*** | | | | −0.828*** | | | |
| | (−4.30) | | | | (−4.15) | | | |
| Human | | −9.288*** | | | | −0.680*** | | |
| | | (−4.70) | | | | (−6.24) | | |
| Land | | | −6.974*** | | | | −0.452*** | |
| | | | (−2.60) | | | | (−3.87) | |
| Capital | | | | -3.120* | | | | −0.228*** |
| | | | | (−1.94) | | | | (−2.71) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| City fixed effect | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effect | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| *N* | 480 | 480 | 480 | 480 | 420 | 420 | 420 | 420 |
| *F*-statistic | 15.06 | 15.00 | 10.68 | 10.85 | | | | |
| LM statistic | 8.87*** | 16.82*** | 6.707*** | 4.324** | | | | |
| Sargan test | | | | | 0.460 | 0.366 | 0.506 | 0.457 |
| AR (1) | | | | | 0.049 | 0.047 | 0.051 | 0.054 |
| AR (2) | | | | | 0.211 | 0.193 | 0.214 | 0.213 |

*, **, ***Denote 10%, 5%, and 1% significance levels, respectively, and t/z values are in parentheses

**Table 5** Robustness test results

| Variables | Replacement of dependent variable measures | Core explanatory variables are lagged by one period | Tailoring | Supplementary variables | Adjusting the sample period |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| Integration | −0.223* | | −1.760*** | −1.547*** | −1.711*** |
| | (−1.77) | | (−8.90) | (−9.42) | (−7.61) |
| lag_ integration | | −2.442*** | | | |
| | | (−9.99) | | | |
| Constant | 0.855*** | 2.395*** | 2.314*** | 2.476*** | 2.013*** |
| | (5.20) | (8.16) | (9.58) | (7.42) | (8.43) |
| Control variables | Yes | Yes | Yes | Yes | Yes |
| City fixed effect | Yes | Yes | Yes | Yes | Yes |
| Time fixed effect | Yes | Yes | Yes | Yes | Yes |
| $N$ | 480 | 450 | 480 | 480 | 360 |
| Adj. $R^2$ | 0.910 | 0.887 | 0.903 | 0.876 | 0.927 |

Considering the potential endogeneity between URI and these mediating variables, the lagged term of the explanatory variable (lag_CRE) is again used as an instrumental variable, following the previous approach. The results are shown in Table 6. The mediating effects of the three mediating variables are significant, confirming Hypothesis 2. Among them, es has a partial mediating effect, while ei and pc have masking effects.

Specifically, columns (2), (4), and (6) of Table 6 show the respective results of URI on the three mediating variables. URI has a significant positive effect on the mediating variables (i.e., $\beta_1 > 0$ ), meaning that it significantly increases rural household energy consumption intensity and per capita consumption, and optimizes the energy consumption structure. Columns (3), (5), and (7) show the results of URI and the three mediating variables, respectively. The estimated coefficients of ei and pc are both significantly positive (i.e., $\eta > 0$), and the coefficients of es is significantly negative (i.e., $\eta < 0$), which confirms the migration effect, income effect, and structural effect as per the previous theoretical analysis. In other words, URI promotes CRE by increasing energy consumption intensity and per capita consumption and suppresses it by improving the energy consumption structure. However, it is worth emphasizing that in columns (3), (5), and (7), the regression coefficients of URI are significantly negative (i.e., $\gamma_1 < 0$), and the product of the estimated coefficients of ei $\beta_1\eta > 0$, the product of the estimated coefficients of pc $\beta_1\eta > 0$, and the product of the estimated coefficients of es $\beta_1\eta < 0$. That is to say, the estimated coefficient product $\beta_1\eta > 0$ of energy consumption intensity and per capita consumption are opposite to the sign of $\gamma_1$, indicating that the two have a masking effect. The sign of the estimated coefficient product $\beta_1\eta$ of energy consumption structure is consistent with that of $\gamma_1$, indicating that energy consumption structure has a partial mediating effect.

Therefore, in exploring the impact of URI on CRE, it is crucial to consider not only their direct effects but also the influence of the increased energy consumption intensity and level, and the transformation of consumption structure brought about by URI. In policy-making, the government should emphasize the promotion and dissemination of environmental knowledge among rural residents, enhance their awareness of energy conservation and environmental

**Table 6** Mediating effect tests

| Variables | CRE | ei | CRE | pc | CRE | es | CRE |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| URI | −9.064*** | 0.2425*** | −9.069*** | 0.303*** | -9.740*** | 1.700*** | −8.409*** |
| | (−4.30) | (2.99) | (−2.62) | (4.79) | (-3.41) | (3.37) | (−3.16) |
| ei | | | 3.258*** | | | | |
| | | | (2.77) | | | | |
| pc | | | | | 0.395** | | |
| | | | | | (2.01) | | |
| es | | | | | | | −0.774*** |
| | | | | | | | (−7.21) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| City fixed effect | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effect | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| *N* | 480 | 480 | 480 | 480 | 480 | 480 | 480 |
| Adj. $R^2$ | 0.9025 | 0.7437 | 0.9427 | 0.9896 | 0.9040 | 0.9083 | 0.9128 |
| Results of the first stage estimation | | | | | | | |
| lag_CRE | −0.062*** (−2.99) | −0.062*** (−2.99) | −0.047** (−2.42) | −0.062*** (−2.99) | −0.062*** (−3.02) | −0.062*** (−2.99) | −0.056*** (−2.88) |
| *F*-statistic | 15.06 | 29.93 | 38.57 | 49.73 | 67.80 | 24.96 | 36.92 |
| LM statistic | 8.87*** | 10.05*** | 11.35*** | 10.05*** | 10.24*** | 10.05*** | 9.34*** |
| Intermediary effect as a percentage | | Masking effect: −8.72% | | Masking effect: −1.32% | | Partial mediating effect: 14.52% | |

protection, guide them in adopting a low-carbon lifestyle, promote the cleanness of rural residents' energy consumption structure, and reduce their carbon emissions in daily life.

Drawing on Jiang's (2022) reflections and suggestions on mediating effects in causal inference, this paper uses the Sobel test and bootstrap method to assess the robustness of the above three impact paths. The results are shown in Table 7. It is worth emphasizing that some differences exist between the results of the Sobel and bootstrap tests and the stepwise regression method. Still, the results all indicate that the mediating effects of energy consumption intensity (*ei*), per capita consumption (*pc*), and energy consumption structure (*es*) are significant (*p* values less than 0.05), once again verifying Hypothesis 2.

### 4.3 Empirical results on the nonlinear effect of URI on CRE

To examine Hypothesis 3, which proposes a nonlinear relationship between URI and CRE, Eq. (4) is utilized. The results are presented in Table 8. Columns (1) to (6) of Table 8 incorporate the quadratic and cubic terms of URI in a sequential manner. Columns (1), (3), and (5) do not include control variables, while (2), (4), and (6) do. Comparing the estimated coefficients of the critical variables in columns (5) and (6) with those in columns (1) to (4), it is observed that the directions of action and significance levels of the coefficients undergo varying degrees of change. This finding confirms the presence of a significant nonlinear relationship between URI and CRE. By considering the nonlinear nature of this relationship, it becomes possible to account for the heterogeneity of effects at different stages of integration. Ignoring this non-linearity could potentially lead to the oversight of important variations in the impact of URI on carbon emissions across different integration stages.

The results obtained from columns (5) and (6) indicate that the coefficients of the primary, secondary, and tertiary terms of URI are all significant and negative at different levels of significance. This finding supports the existence of an "inverted N" relationship between URI and CRE,[4] thus confirming Hypothesis 3. In column (6), the first inflection point of URI is identified as 0.1097, while the second inflection point is determined to be 0.2754.

Below is an explanation of the three stages of the nonlinear relationship between URI and CRE:

Firstly, when the level of URI is below the first inflection point, further URI leads to a suppression of carbon emissions. In this initial stage of URI, the large rural population base constrains the growth of per capita arable land and income for rural residents who are left behind. The utilization of clean energy incurs high costs, and the conservative consumption habits of rural residents are resistant to immediate change. Additionally, there are significant consumption constraints among Chinese farmers (Wang et al., 2020b). As a result, the increase in consumption demand is limited, leading to a minor impact of integration on carbon emissions.

Secondly, when URI surpasses the first inflection point but remains below the second inflection point, further URI significantly contributes to carbon emissions. This is the growth stage of URI, characterized by substantial improvements in income and living

[4] The inflection point values are obtained by solving the regression equation by setting the first-order partial derivatives to zero. The values are calculated by direct estimation of the parameters, retaining four digits.

**Table 7** Sobel and bootstrap tests

| Sobel test | | Estimated coefficient | Standard error | Z-value | P>\|Z\| | Intermediary effect as a percentage |
|---|---|---|---|---|---|---|
| ei | Indirect | 0.3950 | 0.0706 | 3.4878 | 0.0005 | Masking effect: −66.41% |
| | Direct | −0.5948 | 0.1969 | 3.0210 | 0.0025 | |
| pc | Indirect | 0.3831 | 0.0940 | 4.0749 | 0.0000 | Masking effect: −47.49% |
| | Direct | −0.8067 | 0.2536 | 3.1808 | 0.0015 | |
| es | Indirect | −0.3176 | 0.0855 | 3.7160 | 0.0002 | Some agents: 36.41% |
| | Direct | −0.8722 | 0.2568 | 3.3964 | 0.0007 | |
| Bootstrap inspection | | Estimated coefficient | Standard error | P>\|Z\| | 95% confidence interval | Intermediary effect as a percentage |
| ei | Indirect | 0.4083 | 0.1067 | 0.000 | (0.3011,0.9154) | Masking effect: −68.10% |
| | Direct | −0.5996 | 0.3074 | 0.049 | (−0.0030, −1.2021) | |
| pc | Indirect | 0.4401 | 0.1143 | 0.000 | (0.2162, 0.6640) | Masking effect: −57.33% |
| | Direct | −0.7677 | 0.3244 | 0.018 | (−0.1319, −1.4035) | |
| es | Indirect | −0.3213 | 0.0847 | 0.000 | (−0.1552, −0.4874) | Some agents: 36.24% |
| | Direct | −0.8865 | 0.3699 | 0.017 | (−0.1616, −1.6114) | |

Bootstrap sample size is 1000

**Table 8** Nonlinear effects of URI on CRE

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| URI | − 2.338*** | − 1.760*** | 2.590*** | 1.469** | − 1.798*** | − 2.123*** |
| | (− 10.83) | (− 8.90) | (3.67) | (2.23) | (− 8.72) | (− 8.99) |
| Secondary term of Integration | | | − 6.853*** | − 4.655*** | 15.566* | 13.531* |
| | | | (− 7.29) | (− 5.12) | (1.78) | (2.11) |
| Three terms of Integration | | | | | − 29.023** | − 23.424** |
| | | | | | (-2.59) | (-2.23) |
| Constant | 0.964*** | 2.314*** | 0.577*** | 1.963*** | 0.785*** | 2.038*** |
| | (41.89) | (9.58) | (10.03) | (8.03) | (7.95) | (8.30) |
| Control variables | No | Yes | No | Yes | No | Yes |
| City fixed effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Time fixed effect | Yes | Yes | Yes | Yes | Yes | Yes |
| *N* | 480 | 480 | 480 | 480 | 480 | 480 |
| Adj. $R^2$ | 0.8706 | 0.9025 | 0.8845 | 0.9079 | 0.8860 | 0.9087 |

standards for rural residents. With active government efforts to integrate the labor market, rural residents migrate in large numbers to cities and towns, leading to a significant increase in per capita arable land for those who are left behind (Cao et al., 2021). This increase in per capita farming income occurs at a faster rate. Moreover, according to the theory of migrant remittances emphasized in new migration economics, migration of household members not only boosts their own income but also enhances the socio-economic status of their families in the local community (Hong, 2007). Consequently, rural residents increase their per capita consumption and energy consumption demand, thereby promoting carbon emissions.

Lastly, when URI exceeds the second inflection point, which represents a higher degree of integration and a mature stage, carbon emissions are once again suppressed. At this stage, China's urbanization rate exceeds 80%, indicating a stable level of integration, and rural living standards reach a high level. However, weak ecological awareness among rural residents has led to environmental problems in rural areas, particularly in the context of the national emphasis on green development (Li, 2019). Consequently, the government has strengthened rural environmental governance and construction during the transition period of the "new normal." This has significantly improved rural residents' awareness and demand for clean energy consumption, resulting in a reduction in household emissions.

To further corroborate the inverted "N" shaped nonlinear correlation between URI and CRE, this paper employs a random forest model to assess the robustness of their relationship. For a random forest model with the dependent variable being a continuous variable, the mean square error is used as the optimization criterion, with regression trees as the fundamental learning algorithm. Random forest regression was utilized in Python to investigate the rural–urban integration. The output revealed that the training dataset had an *R*-squared value of 0.91, while the testing dataset had an *R*-squared value of 0.79. Both datasets had *R*-squared values that exceeded 0.6, indicating that the model results are reliable. Based on this, further investigation will be conducted to examine the relative importance of URI and the classic factors that affect rural residents' carbon emissions, using a split variable's residual sum of squares descent degree to measure variable importance.

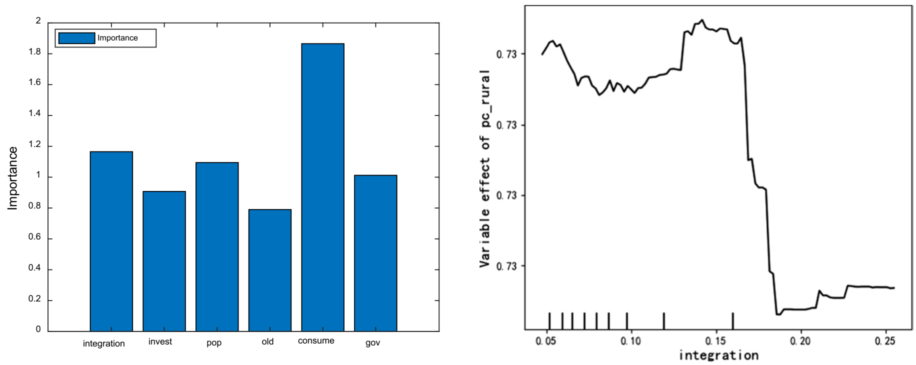


**Fig. 3** Ranking of variable importance (left) and biased dependency graph of urban–rural integration (right)

According to Fig. 3(the left), compared to the classic factors, the importance of URI in affecting CRE ranks second, following only per capita energy consumption. This demonstrates the significance of URI in influencing CRE. Figure 3(the right) illustrates the partial dependence relationship between CRE and URI. The curve depicts the partial dependence function, with the internal scale of the abscissa representing the 1/10, 2/10, …, 9/10 quantiles of URI. The partial dependence plot further verifies the unmistakable inversed N nonlinear relationship between URI and CRE, thus providing further validation of Hypothesis 3.

According to Fig. 4, among the provinces, only Shanghai had already exceeded the second inflection point in 2005. Beijing, Tianjin, Hebei, Anhui, and Hainan were in the second stage of the "inverted N" curve, while the other 24 provinces were in the first stage. With the adoption of the policy guideline for Coordinating Economic and Social Development between Urban and Rural Areas in 2007, the disparity between urban and rural regions started to diminish gradually ( & Zhou, 2018). By 2020, Shanghai, Beijing, and Tianjin had all surpassed the second inflection point. The remaining 27 provinces were situated between the first and second inflection points, indicating that China is poised to confront enduring pressure in mitigating carbon emissions, as it further integrates most provinces.[5]

## 5 Conclusion and prospect

Under the concurrent tactics of novel urbanization and agrarian resurgence, the interrelations amidst urban and rural areas in China have embarked on a fresh phase of unified advancement. It is crucial to conduct a systematic investigation into the impact of URI on CRE and understand its underlying mechanisms to foster the development of a beautiful

[5] Further, the difference between the urban–rural integration level of each province in 2020 and the second inflection point value of 0.2761 is used to obtain urban–rural integration gaps. −0.1 and −0.15 are used as cut-off points to subdivide provinces lagging in urban–rural integration development into slightly (−0.1–0), moderately (−0.15 to −0.1), and severely lagging provinces (−0.15 or more). Beijing, Tianjin, and Shanghai are advanced in urban–rural integration; Anhui is a slightly lagging province; Heilongjiang, Jiangsu, Zhejiang, and Hainan are moderately lagging provinces; and Xinjiang, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, and Ningxia are the heavily lagging provinces.

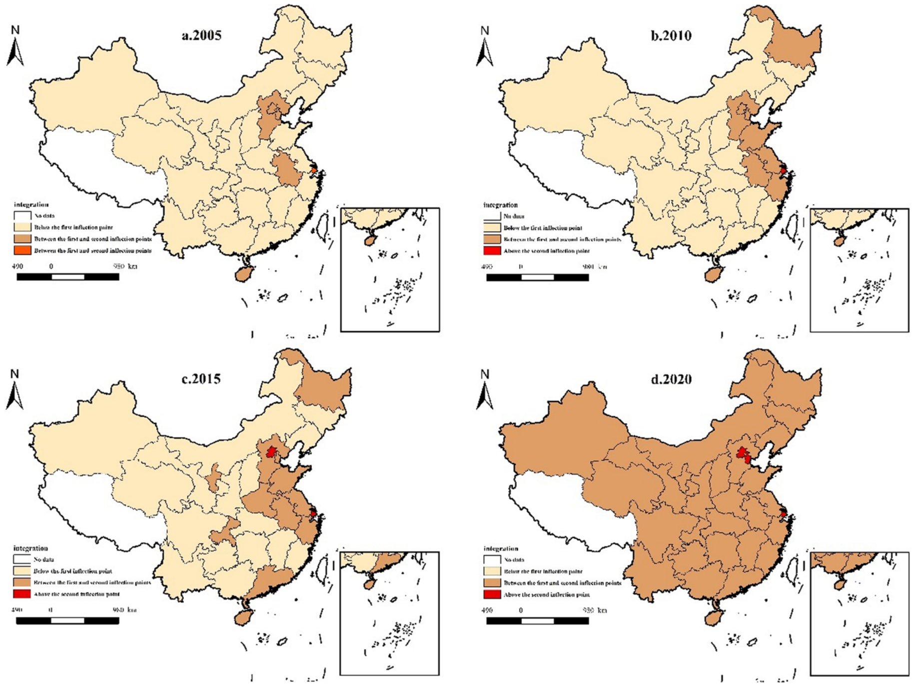


**Fig. 4** Stages of URI and CRE by province in 2005, 2010, 2015 and 2020

countryside. This study examines the empirical effects of integration using ordinary least squares and stepwise regressions based on measurements of CRE in 30 provinces from 2005 to 2020. The analysis yields the following key findings:

(1) Overall, URI leads to a reduction in CRE. Human, land, and capital integration are vital factors that contribute to the suppression of carbon emissions, with 'human integration' exerting the strongest effect.
(2) The examination of mechanisms reveals that URI promotes CRE by increasing energy consumption intensity and per capita consumption. Conversely, integration suppresses emissions by improving the energy consumption structure.
(3) A nonlinear analysis uncovers an "inverted N" relationship between URI and CRE. Specifically, as integration increases, emissions initially decline, then rise, and subsequently decrease again.

Realizing China's green transformation and development is currently a hot topic in academic research. This paper, combining theoretical analysis with empirical research, focuses on the integrated development of urban and rural areas and explores the impact on rural residents' carbon emissions. Many valuable conclusions have been drawn, but there are still some shortcomings. On one hand, the connotation of URI is continuously enriching and sublimating. This paper constructs an indicator system from three dimensions: "human," "land," and "capital," but the measurement methods still need improvement. Subsequent studies could consider refining the above three dimensions and constructing a multidimensional system for URI based on 'human integration,' 'land integration,' 'capital integration,' industrial integration, ecological environment integration, scientific and educational integration, and other main elements. This will enable the deep exploration of the impact of URI on the carbon emissions of rural household energy consumption.

On the other hand, from a realistic perspective, the URI has primarily been carried out at the county level, with limited research on a provincial level. However, considering data availability, this paper utilizes provincial panel data, with the possibility of further research at the county level if data become accessible. Considering the concerns, further exploration of a multidimensional development system for URI from a county-level perspective is necessary to investigate the spatial characteristics and formation mechanisms of URI at various scales nationwide. This will be the direction of future research.

## 6 Policy and managerial implications

Drawing on the research findings and in combination with the current state of energy consumption in rural China, this paper presents the following policy recommendations.

First, local governments should proactively establish and enhance institutional mechanisms for urban–rural integration, aiming to expedite the transition to a mature stage of integration. Lagging provinces should prioritize integration efforts based on their unique local development context. Specifically, they should focus on promoting 'human integration' by fostering economic growth, narrowing the urban–rural income gap, and unlocking the consumption potential of rural residents. These measures will contribute to reaching the peak of rural household carbon emissions at the earliest opportunity.

Secondly, rural governments should endeavor to improve the energy structure by implementing effective strategies to raise awareness about energy conservation and environmental protection among residents. Guiding rural communities toward a low-carbon lifestyle is crucial. This can be achieved by phasing out coal usage in favor of electricity and implementing subsidies and other policies that encourage the adoption of clean energy sources. Additionally, conducting public awareness campaigns and educational activities to promote the concepts of energy conservation and low-carbon living will further enhance carbon consciousness among rural residents. These initiatives will help mitigate household carbon emissions to the maximum extent possible while simultaneously advancing the goals of urban–rural integration and emission reduction.

Third, the government should pay attention to the complexity and specificity in urban–rural integration development. In addition to promoting the transformation and upgrading of rural energy use, it should also encourage the establishment of coordinated and linked-up cooperation between urban and rural development in environmental policies and regional functions. In addition, during the initial stage of urban–rural integration, developing countries and regions should consider the unique impact of the output-restraining effect and the environmental resilience's system. Employing the "latecomer advantage," and concurrently facilitating urban–rural integration development, they should preserve equilibrium between the urban–rural integration's collection benefits and the output expansion's discharge benefits, while preventing irreversible environmental deterioration arising from excessive urbanization pollution.

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**Data availability** The data that support the findings of this study are openly available in China Energy Statistical Yearbook, National Bureau of Statistics at http://www.stats.gov.cn/tjsj/tjcbw/201303/t20130318_451533.html.

## Declarations

**Conflict of 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.

## References

Abbasi, S., Daneshmand-Mehr, M., & Ghane Kanafi, A. (2023). Green closed-loop supply chain network design during the coronavirus (COVID-19) pandemic: A case study in the Iranian automotive industry. *Environmental Modeling & Assessment, 28*(1), 69–103.

Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. *Journal of Econometrics, 68*(1), 29–51.

Cao, X., Gao, Y., & Liu, Z. (2021). The impact of urbanization of rural residents on carbon emissions from household energy consumptior. *Chinese Rural Economy, 10*(10), 64–83. (in Chinese).

Deng, X., Wang, G., Song, W., Chen, M., Liu, Y., Sun, Z., Dong, J., Yue, T., & Shi, W. (2022). An analytical framework on utilizing natural resources and promoting urban–rural development for increasing farmers' income through industrial development in rural China. *Frontiers in Environmental Science, 10*(01), 865883.

Du, Q. (2020). The movement of the rural population in integrated urban–rural development. *Macroeconomic Management, 04*, 64–70. (in Chinese).

Effiong, E. L. (2018). On the urbanization-pollution nexus in Africa: A semiparametric analysis. *Quality & Quantity, 52*(1), 445–456.

Fu, Y., He, C., & Luo, L. (2021). Does the low-carbon city policy make a difference? Empirical evidence of the pilot scheme in China with DEA and PSM-DID. *Ecological Indicators, 122*(1), 107238.

Gao, B., & Kong, L. (2019). An analysis on the economic growth effect of the integration of urban and rural development in China. *Journal of Agrotechnical Economics, 8*(08), 4–16. (in Chinese).

Gao, G. (2020). A new idea of development from dual segmentation to urban rural integration: A study on the high quality development of China's rural economy. *Modern Economic Research, 01*, 108–116. (in Chinese).

Han, J., Yang, Q., & Zhang, L. (2022). What are the priorities for improving the cleanliness of energy consumption in rural China? Urbanisation advancement or agriculture development? *Energy for Sustainable Development, 70*, 106–114.

Hong, X. (2007). Family migration from rural to urban China and its causal factors: The case of Beijing. *Chinese Journal of Population Science, 06*, 42–50. (in Chinese).

Hu, Y. (2012). Energy conservation assessment of fixed-asset investment projects: An attempt to improve energy efficiency in China. *Energy Policy, 43*, 327–334.

Huang, X. (2014). Lncome gap, deepening of human capital in the rural areas and the integration of city and the countryside. *Economist, 01*, 84–91. (in Chinese).

Jiang, J. (2015). China's urban residential carbon intensity decomposition and energy policy rethink. *The Journal of Quantitative & Technical Economics, 32*(06), 90–104. (in Chinese).

Jiang, T. (2022). Mediating effects and moderating effects in causal inference. *China Industrial Economics, 05*, 100–120. (in Chinese).

Jiang, Y., & Zhou, Y. (2018). Urban and rural integration development in the past 40 years of reform and opening up: Retrospect and summary. *Journal of Guizhou University of Finance and Economics, 05*(05), 1–10. (in Chinese).

Kong, X., & Zhou, Z. (2020). The course, basic experience and deepening path of rural factor marketization reform in China. *Reform, 7*(07), 27–38. (in Chinese).

Lai, A., Wang, Q., & Cui, L. (2022). Can market segmentation lead to green paradox? Evidence from China. *Energy, 254*, 124390.

Li, A. (2019). The progress, problems and path of China's integrated urban–rural development. *Macroeconomic Management, 2*(02), 35–42. (in Chinese).

Li, L., & Liu, B. (2020). Prospect for major issues of China's regional economic development during the 14th five-year plan period. *Journal of Management World, 36*(05), 36–51. in Chinese.

Li, L., & Xu, D. (2018). A study on the impact of gap between urban and rural circulation on the consumption of rural residents–taking Beijing as the example. *China Business and Market, 32*(02), 28–36. in Chinese.

Li, Y., Zhao, R., Liu, T., Zhao, J. (2015). Does urbanization lead to more direct and indirect household carbon dioxide emissions? Evidence from China during 1996–2012. *Journal of Cleaner Production, 102*, 103–114.

Liddle, B., & Lung, S. (2010). Age-structure, urbanization, and climate change in developed countries: Revisiting STIRPAT for disaggregated population and consumption-related environmental impacts. *Population and Environment, 31*(5), 317–343.

Liu, J. H., Li, M. X., & Ding, Y. T. (2021). Econometric analysis of the impact of the urban population size on carbon dioxide ($CO_2$) emissions in China. *Environment Development and Sustainability, 23*(12), 18186–18203.

Liu, M., & Lu, F. (2019). Study on the influence of factor mismatch on urban–rural integration development: Evidence from Chinese provincial panel data. *Journal of Agrotechnical Economics, 2*(02), 33–46. in Chinese.

Liu, X., Liu, Y., & Wang, J. (2018). Leverage, growth and recession. *Social Sciences in China, 6*(06), 50. (in Chinese).

Liu, S., & Long, T. (2022). The Theory of Urban-rural Integration: Stages, Characteristics and Enlightenment. *Economic Perspectives,*(03),21–34.(in Chinese).

Liu, Y., Zhou, Y., & Wu, W. (2015). Assessing the impact of population, income and technology on energy consumption and industrial pollutant emissions in China. *Applied Energy, 155*, 904–917.

Luo G, Xie W. (2013). Population dependency ratio and household consumption in China: Based on life cycle theory [J]. *Population and Economics,.05*, 3–9. (in Chinese)

Ma, W., Zhou, X., & Renwick, A. (2019). Impact of off-farm income on household energy expenditures in China: Implications for rural energy transition. *Energy Policy, 127*(APR), 248–258.

Ma, X. W., Wang, M., Lan, J. K., Li, C., Zou, L. (2022). Influencing factors and paths of direct carbon emissions from the energy consumption of rural residents in central China determined using a questionnaire survey. *Advances in Climate Change Research, 13*(5), 759–767.

Martinez-Zarzoso, I., & Maruotti, A. (2011). The impact of urbanization on $CO_2$ emissions: Evidence from developing countries. *Ecological Economics, 70*(7), 1344–1353.

Niu, S., Li, Z., Qiu, X., Dai, R., Wang, X., Qiang, W., & Hong, Z. (2019). Measurement of effective energy consumption in China's rural household sector and policy implication. *Energy Policy, 128*, 553–564.

North, D. C. (1992). Institutions. *The Journal of Economic Perspectives, 36*(1), 3–6.

Rahut, D. B., Mottaleb, K. A., & Ali, A. (2017). Household energy consumption and its determinants in Timor-Leste. *Asian Development Review, 34*(1), 167–197.

Ren, H., & Zhou, W. (2021). Local low-carbon society scenarios of urban–rural linkage. *East Asian Low-Carbon Community, 10*, 137–150.

Salim, R. A., & Shafiei, S. (2014). Urbanization and renewable and non-renewable energy consumption in OECD countries: An empirical analysis. *Economic Modelling, 38*, 581–591.

Scott, A. J. (2012). Triumph of the city: How our greatest invention makes us richer, smarter, greener, healthier, and happier. *Economic Geography, 88*(1), 97–100.

Shao, S., Zhang, K., & Dou, J. (2019). Effects of economic agglomeration on energy saving and emission reduction: Theory and empirical evidence from China. *Journal of Management World, 35*(01), 36. (in Chinese).

Sun, H., & Chen, F. (2022). The impact of green finance on China's regional energy consumption structure based on system GMM. *Resources Policy, 76*, 102588.

Tang, B., & Guo, J. (2022). How to expand rural domestic demand: From the perspective of rural household consumption. *Issues in Agricultural Economy, 03*, 73–87. (in Chinese).

Wang, Q., Lin, J., Zhou, K., Fan, J., Kwan, MP. (2020). Does urbanization lead to less residential energy consumption? A comparative study of 136 countries. *Energy, 202*, 117765.

Wang, X., & Dong, F. (2023). The dynamic relationships among growth in the logistics industry, energy consumption, and carbon emission: Recent evidence from China. *Journal of Petroleum Exploration and Production Technology, 13*(1), 487–502.

Wang, X., Wen, T., & Han, L. (2020). The evolvement of habit formation and farmers' consumption behavior: An empirical verification since China's reform and opening-up. *Chinese Rural Economy, 1*(01), 17–35. in Chinese.

Wang, Y., Chen, L., & Kubota, J. (2016). The relationship between urbanization, energy use and carbon emissions: Evidence from a panel of Association of Southeast Asian Nations (ASEAN) countries. *Journal of Cleaner Production, 112*, 1368–1374.

Wang, Y., & Zheng, Y. (2021). Spatial effects of carbon emission intensity and regional development in China. *Environmental Science and Pollution Research, 28*(11), 14131–14143.
Wei, C., & Shen, Z. (2019). Determinants of residential energy consumption: A urban–rural comparison. *Economic Theory and Business Management, 12*, 4–16. (in Chinese).
Xiao, R., Tan, G., Huang, B., Li, J., Luo, Y. (2022). Pathways to sustainable development: Regional integration and carbon emissions in China. *Energy Reports, 8*, 5137–5145.
Xie, H., & Wu, X. (2023). Impact and its mechanism of urban–rural integration on the efficiency of agricultural carbon emissions in China. *Resources Science, 45*(01), 48–61. (in Chinese).
Xie, R., Fang, J. Y., & Liu, C. J. (2017). The effects of transportation infrastructure on urban carbon emissions. *Applied Energy, 196*, 199–207.
Xie, R., Yu, D., Zhang, X., Yang, Z., Yang, J. (2022). Analysis of regional carbon emission decoupling coupling in China based on ArcGIS analysis-empirical evidence from urban–rural integration in Fujian Province. *Frontiers in Energy Research, 10*, 910565.
Yao, Y., Shen, Y., & Liu, K. (2023). Investigation of resource utilization in urbanization development: An analysis based on the current situation of carbon emissions in China. *Resources Policy, 82*, 103442.
Zhang, H., Li, S., & Peng, M. (2022). Regional imbalance of carbon emissions from China's rural energy consumption and dynamic identification of driving factors. *Chinese Rural Economy, 445*(01), 112–134. (in Chinese).
Zhang, N., Yu, K., & Chen, Z. (2017). How does urbanization affect carbon dioxide emissions? A cross-country panel data analysis. *Energy Policy, 107*, 678–687.
Zhou, J., Duan, K., Du, Y., Zou, W. (2022). How does land allocation promote urban–rural multi-dimensional integration? An efficient market and effective government. *China Land Science, 36*(03), 32. (in Chinese).
Zhou, L. (2018). Capital in the era of urban and rural China went to the countryside. *People's Tribune, 28*, 70–72. (in Chinese).
Zhou, Q., Liu, Y., & Qu, S. (2022). Emission effects of China's rural revitalization: The nexus of infrastructure investment, household income, and direct residential $CO_2$ emissions. *Renewable and Sustainable Energy Reviews, 167*, 112829.



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