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Estimating long-term and short-term CO_2 rebound effects of China's urban residential sector: evidence from a dynamic econometric approach

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ABSTRACT

This study quantifies China's urban residential CO_2 rebound owing to improvements in energy efficiency. We use a dynamic econometric model (error corrected linear approximated almost ideal demand system, ECM-LA-AIDS) to examine the relationship between energy-efficiency promotion, energy consumption behaviour, and the CO_2 rebound effect. An improvement in energy efficiency lowers the energy price, resulting in unbalanced short- and long-term energy consumption behaviours. Inconsistent short- and long-term energy-efficiency policies may lead to greater rebound effects. Therefore, this study estimates the residential energy-related CO_2 (ECR-CO_2) rebound effects considering both short- and long-term consumption patterns to provide targeted policies for controlling residential ECR-CO_2. The results indicate that the short- and long-term urban residential ECR-CO_2 effects differ across regions and provinces. Additionally, the direct rebound effect contributes more to the total ECR-CO_2 rebound effect than the indirect rebound effect. Finally, at the national level, the urban residential ECR-CO_2 rebound effects exhibit a U-shaped divergence, indicating that, among the 31 Chinese provinces considered, the ECR-CO_2 rebound effect first converges and then diverges, owing to differences in the levels of technological progress.

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1. Introduction

As the world's largest developing country, China has enjoyed unprecedented economic growth and urbanisation since its 1978 economic reforms. After entering the 21^{st} century, China has quickly become the world's largest emitter of energy-related CO_2 (ECR-CO_2) (Zhang et al., 2017). In recent decades, excessive urbanisation and the rapid improvements in urban living standards have considerably increased China's urban residential ECR-CO_2 emissions. China's residential sector is the

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second-largest ECR-CO_2 emitter after the manufacturing sector, accounting for approximately 18% of the total ECR-CO_2 emissions. Meanwhile, the urban areas contribute to more than half of China's total residential ECR-CO_2. However, China's urban residential ECR-CO_2 emissions are still low compared with those of other industrialised countries, with only one-third of those in the United States and half of those in the United Kingdom (Zheng et al., 2016). Therefore, it is noteworthy that the urban residential sector will significantly influence China's increasing ECR-$CO_{2.}$

Two main factors could contribute to the potential increase in China's urban residential ECR-CO_2. First, with an increase in affluence, Chinese households are purchasing more durable consumer goods—such as for heating and cooling—or traveling to improve their quality of life (Miao et al., 2019). Second, China's urban population is expected to increase from 837 million in 2018 to 1.15 billion by the middle of the 21st century (United Nations, 2019). Given the nation's predicted potential urbanisation and the need to promote living standards, the Chinese government must implement appropriate measures to decrease urban residential ECR-CO_2 while ensuring rapid economic development.

With the increasing attention to climate change, China's government has prioritised energy-efficiency laws and policies to reduce residential ECR-CO_2. For instance, the Ministry of Housing and Construction issued its 13th Five-Year Plan for the Development of Energy-Efficient and Green Buildings, which states that energy-efficient residential buildings should account for more than 63% of the existing buildings in China's cities and towns (Ministry of Housing & Construction, 2017). Furthermore, the Beijing Municipal Government aims to increase ECR-CO_2 efficiency in new urban residential buildings by 80% (Market Supervision Administration of Beijing Municipality, 2020).

However, improving energy efficiency does not always reduce energy consumption and ECR-CO_2 emissions effectively because of the purported 'rebound effect' or the economic responses to a decrease in energy service pricing due to improved energy efficiency, which instead increases total ECR-CO_2 (Schmitz & Madlener, 2020). As early as 1865, Jevons (1866) proposed the Jevons Paradox in his book, *The Coal Question*, which is regarded as the earliest discourse on energy rebound. However, the rebound effect gained scholarly attention only after Khazzoom's (1980) study. Based on earlier work by Khazzoom (1980) and Brookes (1990), Saunders (1992) considered the rebound effect as defined by Khazzoom (1980) to propose the Khazzoom–Brookes postulate, which indicates that the actual reduction in energy consumption caused by improvements in energy efficiency will be less than that anticipated owing to the rebound effect. Furthermore, owing to the difficulty of measuring energy efficiency, researchers have substituted energy efficiency with owned energy price elasticity (Mizobuchi, 2008; Roy, 2000). Researchers generally consider their data and research needs while selecting appropriate indicators to measure the rebound effect; 'energy service' is frequently used because its data are accessible.

Binswanger (2001) further classified rebound effects as direct, indirect, or economy-wide in a multi-sector model to investigate its mechanisms. Improvements in energy service efficiency can effectively reduce the real price of energy, leading to substitution effects between the energy commodities and offsetting the actual energy savings or emission reduction more than expected (Greening et al., 2000). The substitution effect among the various energy consumption sectors constitutes a direct rebound effect. The income effect constitutes an indirect rebound effect, wherein the monetary savings are fully re-spent on energy commodities and services. Based on their magnitude, rebound effects can be classified into super conservation (less than zero), zero (equal to zero), partial (between zero and one), full (equal to one), and backfire (greater than one) rebound effects. The literature indicates that the super-conservation rebound effect is the most desirable, the backfire effect should be avoided, and the partial effect is the most common (Wen et al., 2018).

Scholars are increasingly conducting empirical studies on rebound effects. First, some studies estimate energy-rebound effects with different levels of data. For example, at the national level, Semboja (1994), Turner (2009), and Lu et al. (2017) used a computable general equilibrium model to estimate the rebound effects of Kenya, the UK, and China. At the sectoral level, Lin and Xie (2015), Baležentis et al. (2021), and Craglia and Cullen (2020) used econometric methods to analyse the rebound effects of China’s food sector, the European Union’s residential sector, and the UK’s transportation sector, respectively.

Second, although the research above confirms the existence of rebound effects, it indicates that policies for promoting energy efficiency are not very effective. Sanne (2000) emphasised that policymakers prioritising energy-efficiency improvements may threaten sustainable development goals by triggering a greater expansion of production, a greater consumption of natural resources, and, consequently, more pollutant emissions. Therefore, addressing ECR-CO_2 emissions from the perspective of energy consumption instead of the energy rebound alone may be more prudent for realising sustainable development goals (Chang et al., 2018; Vivanco et al., 2016). The impacts of one sector’s ECR-CO_2 rebound effects often spill over to other sectors (Chang et al., 2018). The greater the rebound effect, the more difficult it is to achieve emission-reduction targets by improving energy efficiency (Zhang et al., 2017). Many studies have used various approaches to prove that energy and ECR-CO_2 rebound effects are different (e.g. Li et al., 2020; Vélez-Henao et al., 2020; Wu & Zhou, 2018) in that the ECR-CO_2 rebound effect is more relevant for achieving targets for reducing greenhouse gas emissions.

Third, the input-output (IO) model and econometric methods are the mainstream methods for addressing the rebound effects from the residential sector. Freire-González (2011) proposed an IO model to estimate the direct and indirect rebound effects in households, and Wen et al. (2018) econometric and IO analyses specifically examined the direct and indirect rebound effects among urban households in China. Zha et al. (2022) utilised an environmentally extended IO model to estimate the direct and indirect carbon-rebound effects of Chinese households’ consumption. Lin and Liu (2013) used an almost ideal demand system (AIDS) model to estimate China’s urban residential electricity rebound effect from 1996 to 2010. Using the AIDS model, Chen et al. (2022) estimated the influence of a carbon tax on the residential CO_2 rebound effect in China. Li et al. (2017) incorporated a linear approximation of the AIDS (LA-AIDS) model to estimate the direct rebound effect in China’s urban households. Schmitz and Madlener (2020) refined the previous LA-AIDS model to analyse the direct and indirect household rebound effects of various types of energy consumption. The traditional static AIDS/LA-AIDS model assumes that consumption is always in equilibrium and ignores short-term adjustments to consumption behaviour (Hassan et al., 1977). In reality, consumers cannot adjust expenditures in a timely manner according to changes in income and pricing because of the persistence of consumption habits, incomplete information, adjustment costs, and inaccurate expectations (Tshikala & Fonsah, 2012).

Fourth, current studies distinguish between the short- and long-term effects from the production and consumption perspectives. From the production perspective, Sorrell et al. (2009) highlighted the importance of the production process when estimating rebound effects in the long and short term, as they correspond to fixed and variable capital stocks. Researchers have adopted various methods to estimate short- and long-term rebound effects, such as general equilibrium (Wei, 2010), computable general equilibrium (Turner, 2009), and nonlinear programming models (Li et al., 2020). From a consumption perspective, Wang et al. (2016) revealed that the short-term direct residential effects in Beijing range from 24% to 37% and are less than the long-term ones. Zhang et al. (2015) utilised a dynamic quantile regression to model the long- and short-term rebound effects in the transport sector. Zhang et al. (2015) and Wang et al. (2016) utilised energy prices as a proxy indicator for direct rebound effects without analysing the long- and short-term indirect rebound effects. These studies verify that the short- and long-term rebound effects differ on the production and consumption sides.

This paper adopts an error-corrected LA-AIDS (ECM-LA-AIDS) approach to study the direct and indirect CO_2 rebound effects in Chinese households, considering both short- and long-term energy consumption behaviours. This research is theoretically and empirically significant because it not only extends the traditional static research framework to a dynamic one to estimate residential carbon rebound effects but also offers new empirical evidence based on short- and long-term consumption patterns. In addition, it has practical significance as well since the empirical results provide an crucial foundation for the formulation of carbon emissions policies in developing countries. First, from the theoretical aspect, this study adds to the current literature on the rebound effect by constructing a research framework for considering inconsistent households' short- and long-term energy consumption behaviours due to the persistence of consumption habits. The behavioural response of consumers to the incentive of energy-efficiency improvements is a crucial factor in exploring the mechanism of the rebound effect. Ignoring the inconsistent energy consumption behaviours will lead to a biased estimation of the rebound effects. This research framework is important since the deviation of short-term consumption behaviour from long-term consumption behaviour can distort the incentives of price-based carbon mitigation policies. Second, from the empirical aspect, this study quantifies the short- and long-term residential ECR-CO_2 rebound effects. To our knowledge, few studies have distinguished the short- and long-term CO_2 rebound effects from the consumption side. This is because traditional static LA-AIDS can only estimate rebound effects based on a long-run consumption pattern. Therefore, we innovatively extend the application of the dynamic ECM-LA-AIDS model to the measurement of the rebound effect, verifying that the dynamic model can better elucidate the mechanism of the households' CO_2 rebound effect than the traditional static model. Finally, from the practical aspect, as various policy instruments have high economic and social costs, differentiating between the short- and long-term rebound effects of CO_2 and proposing policies targeted toward this differentiation can increase the implemented policies' sustainability. The empirical research framework and findings can offer new insights for other countries and industries for designing targeted short- and long-term carbon mitigation policies.

The remainder of this paper is organised as follows: Section 2 introduces theoretical research in the literature on rebound effects; Section 3 introduces the linear approximation of the almost ideal demand system (LA-AIDS) model; Section 4 presents the data and discusses the results, and Section 5 summarises and provides suggestions for future policies.

2. Methodology and data

2.1. Model for calculating the residential CO_2 rebound effect

Deaton and Muellbauer (1980) initially proposed the following LA-AIDS model:

$$w_i = a_i + \sum_j \gamma_{ij} \ln(p_i) + \beta_i \ln\left(\frac{x}{P}\right) + \varepsilon_i \tag{1}$$

where i and j represent the commodity categories; P_j represents the energy price of commodity j; x denotes the expenditures per capita; a_i, γ_{it} and β_j denote the coefficients to be estimated; and P is the price index. Following Eales and Unnevehr (1988), we chose the lagged Stone's price to represent the price index; Stone's price is defined as

$$\ln p_t = \sum_i w_i \ln(p_i) \tag{2}$$

The mainstream literature proposes imposing three restrictions on the parameters: adding-up, homogeneity, and symmetry restrictions. Formally, these restrictions are expressed as:

1. Adding up: $\sum a_i = 1$, $\sum \beta_i = 0$
2. Homogeneity: $\sum_j \gamma_{ji} = 0$
3. Symmetry: $\gamma_{ij} = \gamma_{ji}$

Based on the estimated coefficients, we further estimate the expenditure and Marshallian price elasticities for each subcategory.

$$\eta_i = 1 + \frac{\beta_i}{w_i} \tag{3}$$

$$\mu_{ij}^M = -\delta_{ij} + \frac{\gamma_{ij}}{w_i} - \frac{\beta_i}{w_i} w_j \tag{4}$$

where μ_{ij} represents the price elasticity; δ denotes the Kronecker delta, such that, if $i=j$, then $\delta_{ij} = 1$, and $\delta_{ij} = 0$ otherwise; and η_i represents the expenditure elasticity.

2.2. ECM-LA-aids

As we use panel data to estimate the rebound effect, the stationarity of all variables must be tested. Moreover, estimating the short-term rebound effect using an ECM approach requires an understanding of the data's time-series properties (Rathnayaka et al., 2019). Given that regional panel data may exhibit a potential problem with cross-sectional dependence, we apply a second-generation panel unit-root test (CIPS) to test the unit root with cross-sectional dependence (Pesaran, 2007). If all the variables are integrated in the same order, we can further test the model's co-integration. Once the variables are set to $I(1)$ and co-integrated, we follow the methodology established by Karagiannis et al. (2000) to build an adjusted ECM-LA-AIDS model and estimate the short-term consumption performance, expressed as:

$$\Delta w_{i,t} = \varphi_i \Delta w_{i,t-1} + \sum_j \gamma_{ij} \Delta \ln p_{j,t} + \beta_i \Delta \ln \left(\frac{x}{P} \right) + \lambda_i \varepsilon_{it-1} + u_t \tag{5}$$

where Δ represents the first-order difference, $\varepsilon_{it\text{-}1}$ denotes the residuals estimated from the equilibrium estimation, and $\lambda_i < 0$.

2.3. Simulating residential ECR-CO$_2$ rebound effects

As discussed previously, energy consumption behaviours change with the promotion of energy efficiency, causing a rebound effect. While estimating the cost reduction owing to energy efficiency measures is difficult, we can treat such a decrease as the real prices of energy commodities and services decrease. Therefore, following Lin et al. (2013) and Zhang et al. (2017), we propose a model that utilises the energy commodities' price reduction as a proxy for the promotion of energy efficiency. In theory, the total rebound effects can be direct or indirect because of a decrease in energy prices. This study considers both Zhang et al. (2017) approach and static data to assume that a 25% increase in a residential group's energy efficiency, with the cost of residential fuel and electricity at approximately 40%, would reduce the real prices for the residential sector by approximately 10%.

Initially, we assume a ψ reduction in real pricing in the residential sector owing to increased energy efficiency. Subsequently, the new price is expressed as:

$$P_{it}^1 = P_{it}^0 (1-\psi) \tag{6}$$

where P_{it}^0 and p_{it}^1 denote the initial and new prices, respectively.

As the change in residential price is accompanied by a change in Stone's price index, the new index can be calculated based on the new residential price. We then consider two new variables in the previously estimated equation and estimate the new proportion for each subsector, defined as w_i^1. Based on the calculation of w_i^1, we calculate the real change in household expenditure as:

$$\Delta x_i = w_i^1 \frac{x_i^1}{p_i^1} - w_i^0 \frac{x_i^0}{p_i^0} \tag{7}$$

We also calculate the total change in ECR-CO_2 emissions due to improved energy efficiency as:

$$\Delta CO = \sum_i \theta_i \Delta x_i \tag{8}$$

where ΔCO denotes the total change in ECR-CO_2 and θ_i is the emission coefficient of the ith sub-sector, calculated using Zhen et al. (2019) method. However, our work differs from previous research in that we calculate the specific ECR-CO_2 emissions coefficient for each year rather than as a unit.

According to the definition of the rebound effect, we calculate the ECR-CO_2 rebound effect as:

$$RE_c = \frac{\Delta CO}{\Delta CO_0} \times 100\% \tag{9}$$

where ΔCO_0 represents the expected decrease in ECR-CO_2.

Finally, we follow Lin et al. (2013) and Zhang et al. (2017) to calculate the indirect and direct rebound effects using the following equations:

$$RE_c^d = \frac{1}{p_j^0} \sum_i (\mu_{ij} + w_j \eta_i) x_i^0 \tag{10}$$

$$RE_c^I = -\sum_i w_j \eta_i \theta_i \frac{x_i^0}{p_j^0} \tag{11}$$

where s_j denotes the ratio of residence expenditures and x_i^0 represents the real expenditure of each subsector. Equation (10) displays the substitution or direct effect and Equation (11) illustrates the income or indirect effect.

2.4. Data sources and variables

This study utilises panel data from 31 Chinese provinces from 2001 to 2013. Owing to changes in expenditure categories before 2001 and after 2013 (Zhang et al., 2017), we select expenditure data from 2001 to 2013 to maintain statistical consistency. This study focuses only on urban rebound effects, as rural living expenditures are classified differently from those in urban environments (He et al., 2009; Lin et al., 2013). We consider the ECM-LA-AIDS model for collecting data on both urban households' expenditures per person and the price index for each subgroup as given in each province's *Statistical Yearbook* for each year in the sample period. All price indices are converted to the year 2000 price levels. Following many studies using the ECM-LA-AIDS model (Karagiannis et al., 2000; Rathnayaka et al., 2019), we adopt a one-stage model to analyse the ECR-CO_2 rebound effect. After categorising the provinces into

Table 1. Classifications of China's provinces.

Regions	Provinces
Northeast	Heilongjiang, Jilin, Liaoning
North Coast	Beijing, Tianjin, Hebei, Shandong
Central Yellow River	Shanxi, Henan, Shannxi, Inner Mongolia
East Coast	Shanghai, Zhejiang, Jiangsu
Central Yangtze River	Hunan, Hubei, Anhui, Jiangxi
South Coast	Fujian, Guangdong, Hainan
Northwest	Xinjiang, Gansu, Qinghai, Ningxia, Tibet
Southwest	Sichuan, Chongqing, Yunnan, Guizhou, Guangxi

Source: own elaboration.

eight regions, we verify the ECM's estimation effects by following Lin and Liu (2013) and classify the expenditures into four main groups: food, transport, residence, and others. The emissions coefficient is calculated based on the IO table developed by Shi et al. (2020). Unlike in previous research, we calculate the specific ECR-CO_2 emissions coefficient for each five-year period based on an IO analysis rather than a unit.

3. Results and discussion

Studies involving the LA-AIDS model cannot ignore the correlation of the error terms in the equation system, as the traditional least-squares estimates in this model are biased. Thus, we consider the three constraints of the LA-AIDS model and select the seemingly unrelated regression (SUR) method to estimate the relevant equations. This method can be used to systematically estimate a set of equations with residuals that correlate and independent variables that do not (Zellner, 1962). We then conducted a Breusch-Pagan Lagrange multiplier test to determine whether any significant correlation exists for the error terms in the equations. The SUR results can be estimated using the feasible general least-squares (FGLS) method for the long term if all variables are stationary in the same order and have a co-integrated relationship across the equations. Because the FGLS may cause a biased estimation for the short-panel data, we follow Zhang et al. (2017) method to divide the 31 Chinese provinces into eight regions, as noted in Table 1 and Figure A1. Several tests should be conducted before the ECM-LA-AIDS estimation; considering the North Coast area as an example, Tables A1–A3 display the results of the CIPS, co-integration test, and ECM-LA-AIDS, respectively. The results reveal that all the variables are $I(1)$ and co-integrated, thereby allowing us to perform an ECM estimation using the ECM-LA-AIDS model.

3.1. Short- and long-term energy consumption behaviuor

Table 2 lists the results of estimating short- and long-term own-prices and the expenditure elasticities of household expenditures as calculated using Equations (3) and (4). The estimation of the error-correction coefficient is denoted by λ, and the results of all the estimations are significant, in that consumption habits are crucial for influencing Chinese households' decisions. All regions exhibit negative values for λ, which demonstrates that, when the short-term consumption behaviour deviates from the long-term equilibrium, the deviations are automatically corrected to reach equilibrium levels. The absolute value of λ is significant and lies between 0.2 and 0.9,

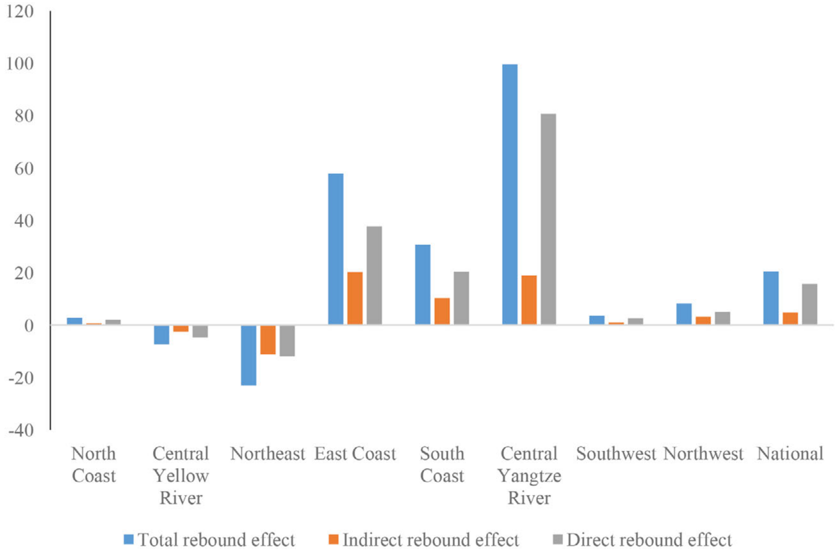

Figure 1. Short-term regional-level rebound effects.
Source: own elaboration.

Table 2. Estimated own-price elasticity and expenditure elasticity.

		Own-Price Elasticity		Expenditure Elasticity		
Region	Main Group	Long Term	Short Term	Long Term	Short Term	λ
North Coast	Residence	−1.195	−1.730	1.098	0.851	−0.575***
	Food	−0.837	−0.750	0.909	0.634	−0.347***
	Transport	−2.041	−0.048	1.369	−0.946	−0.553***
	Other	−0.642	−0.603	0.931	1.897	−0.575***
Northeast	Residence	−0.224	−0.488	1.165	2.109	−0.548***
	Food	−0.663	−0.722	0.871	1.185	−0.237**
	Transport	−1.732	−1.534	1.242	0.046	−0.430***
	Other	−0.661	−2.957	0.989	0.591	−0.350***
Central Yellow River	Residence	−2.417	−1.822	0.983	1.826	−0.568***
	Food	−0.808	−0.774	0.959	0.740	−0.364**
	Transport	−2.320	−1.234	1.203	−0.701	−0.581***
	Other	−1.547	−1.399	0.990	1.303	−0.595***
East Coast	Residence	−1.796	−2.129	1.004	1.215	−0.641***
	Food	−0.907	−0.742	0.883	0.201	−0.590***
	Transport	−1.164	−0.530	1.224	1.131	−0.675***
	Other	−0.503	−0.322	1.065	1.747	−0.683***
South Coast	Residence	−2.982	−2.986	1.175	0.535	−0.858***
	Food	−0.890	−0.775	0.924	0.730	−0.588***
	Transport	−3.244	− 1.148	1.021	0.764	−0.750***
	Other	−1.626	−0.486	1.012	1.894	−0.751***
Central Yangtze River	Residence	−4.106	−4.080	1.116	3.165	−0.665***
	Food	−0.745	−0.771	0.939	0.904	−0.391***
	Transport	−1.230	−1.996	1.234	−1.216	−0.584***
	Other	−1.214	−0.433	0.957	0.527	−0.548***
Southwest	Residence	−2.417	−2.423	1.150	1.465	−0.604***
	Food	−0.649	−0.674	0.928	0.797	−0.406***
	Transport	−0.133	−0.704	1.312	−1.145	−0.564***
	Other	−1.423	−0.438	0.933	1.575	−0.586***
Northwest	Residence	−1.764	−1.993	1.106	1.641	−0.905***
	Food	−0.672	−0.741	0.944	0.791	−0.441***
	Transport	−0.255	−0.912	1.436	0.483	−0.649***
	Other	−0.956	−0.974	0.899	1.092	−0.759***

*** Statistically significant at the 1% level; ** Statistically significant at the 5% level; * Statistically significant at the 10% level.
Source: own elaboration.

indicating that the equilibrium system will automatically correct 20% to 90% of the deviation in the subsequent period and that it will take approximately one to five years for the system to adjust itself to the equilibrium state.

Therefore, we examine our results by referring to Karagiannis et al. (2000) method. We find that each region exhibits a short-term consumption imbalance that leads to a deviation in short-term household energy consumption behaviour from the long-term equilibrium. Notably, λ in the residential sector also varies across regions, from -0.548 to -0.905. Most urban residential sectors need approximately two years to adjust to long-term equilibrium levels, whereas the sectors in the Northwest take less time. This can be explained by Hang and Shen (2004) work, which notes that the different adjustment periods in urban China result from differences in the income growth rates. Precisely, consumers constantly adjust their consumption according to income growth rates, maintaining a long-term equilibrium. Consumers will be more cautious about adjusting their short-term consumption with increasing uncertainty regarding income and expenditure. Therefore, people from most regions in China require more time to adjust their short-term consumption behaviour because of the uncertainty regarding future income and expenditures in the residential sector.

For most regions, except for the North Coast and South Coast areas, residential consumption expenditures are less elastic in the long term than in the short term, and both are greater than one. This result indicates that, in the short term, residential commodities show the features of luxury goods for most regions, which are necessities in the South Coast and North Coast areas (Pindyck & Rubinfeld, 2014). In most of these areas, residential consumption is more sensitive to short-term prices. Two possible reasons for these results are the level of economic development and increased infrastructure costs (Zhao & Xue, 2010). This is because a decrease in energy prices can stimulate consumers' purchases of new durable goods to improve their living standards in the short term; therefore, the long-term elasticities are smaller than the short-term elasticities. However, expenditures have been less elastic in the North and South Coast areas, as the ratio between residence and income is higher here, on average (21%), than in other areas (18%). Moreover, those in the residential sector tend to accumulate savings in the short term for long-term consumption. Regarding own-price elasticity, the Central Yangtze River area is more sensitive to changes in residential commodity pricing, whereas the northeast area is insensitive to such changes. This is because a central heating system is a household necessity in northeast China. According to the National Bureau of Statistics, expenditures for water, fuel, and electricity (WFE) accounted for approximately 8% of all expenditures in the northeast, much higher than the national average. Additionally, central heating contributes to a large proportion of the total WFE. Currently, the coverage of central heating in northeastern urban areas is approximately 90% (Ministry of Housing & Urban-Rural Development of the People's Republic of China, 2018).

3.2. Short- and long-term ECR-CO_2 rebound effects

As the long- and short-term consumption behaviours differ, so do the short- and long-term ECR-CO_2 rebound effects. Figures 1 and 2 illustrate the total direct and indirect ECR-CO_2 rebound effects for eight regions in the short and long term,

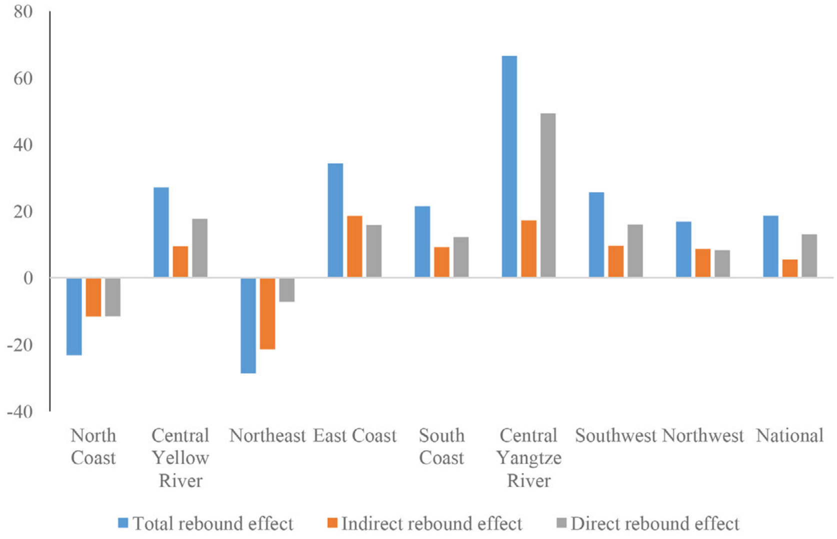

Figure 2. The long-term regional-level rebound effects.
Source: own elaboration.

and Figures 3 and 4 show those of all 31 provinces. Based on our estimation of a 30% increase in energy efficiency in the residential sector, the rebound effects at the national level are approximately 20% in both the long and short term, indicating an actual ECR-CO_2 reduction from an energy-efficiency improvement of 80%. These results differ from those in the research on residential energy rebound; for example, Wen et al. (2018) obtained a score of 74.07%, whereas Li et al. (2017) revealed a 66% national-level direct energy-rebound effect. However, our results are similar to those of Lin et al. (2013), who also studied the national-level residential ECR-CO_2 rebound effects. The energy consumption and emission coefficients indicate that the ECR-CO_2 and energy-rebound effects differ. The national-level difference between the short- and long-term rebound effects is not substantial, despite the high variation among different regions and provinces. In the long term, the ECR-CO_2 rebound effects range from −29.72% to 70.69%. As Figures 2 and 4 illustrate, in the long term, the 31 Chinese provinces experience both super-conservation and partial rebound effects. These results also differ from those of Li et al. (2017) and Wen et al. (2018), who did not discover super-conservation effects in terms of the energy-rebound effect; these authors even noted a backfiring effect in some provinces.

The super-conservation rebound effect may have occurred because of the following reasons. (a) The Northeast and North Coast regions are located in cold areas, requiring more heating than cooling. Additionally, most of these areas have adopted a centralised heating system and are insensitive to WFE pricing. (b) Technological developments can offset the increase in energy demand, resulting in a larger-than-expected reduction in the real ECR-CO_2 (Stern, 2020; c) Households in these areas are less sensitive to price changes in the residential sector than those in other areas (Table 2). Zhang et al. (2017) also found negative rebound effects from ECR-CO_2 in these areas because of the decrease in transportation prices.

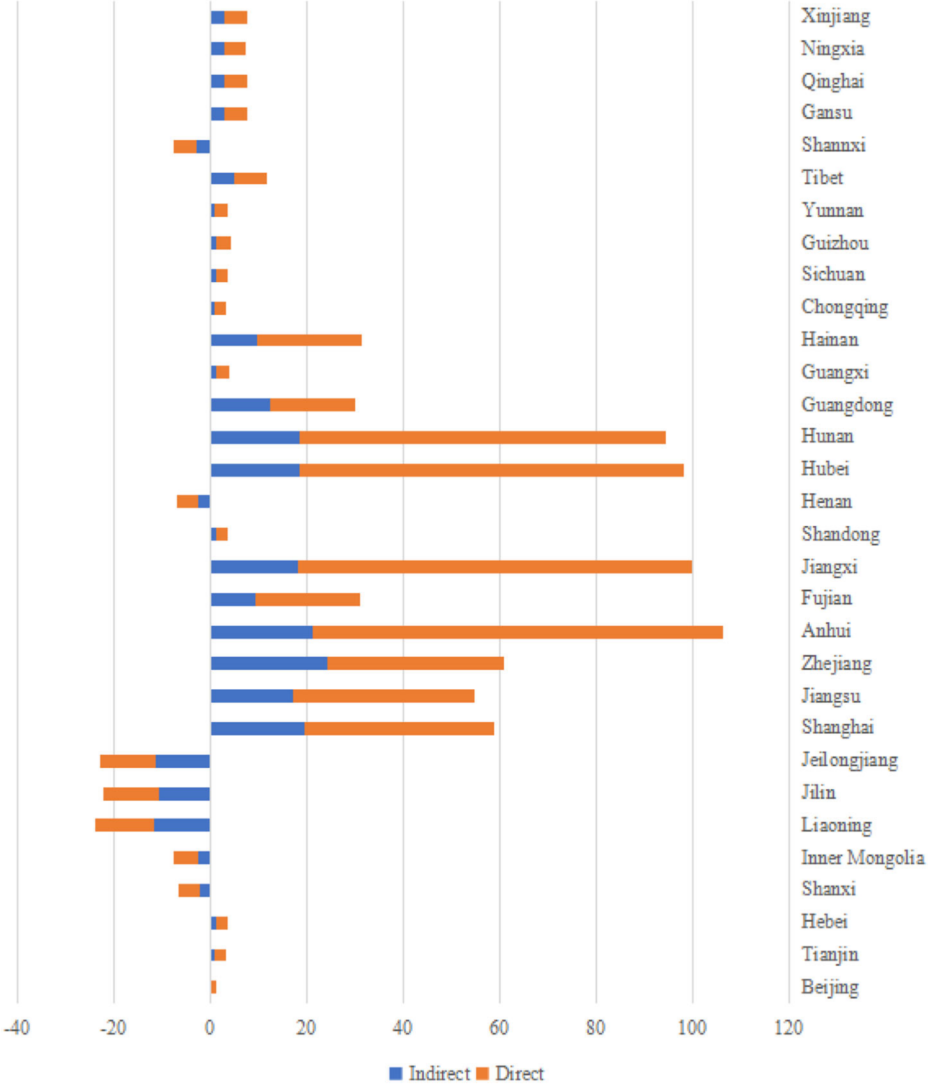

Figure 3. Short-term provincial-level rebound effects.
Source: own elaboration.

The partial rebound effects in the Central Yangtze River and the East and South Coast areas are higher than those in other areas. Specifically, both short- and long-term rebound effects are much higher in Hunan, Hubei, and Jiangxi than in the other provinces. This result can be explained in two ways. First, air conditioners are the primary cooling appliances in the Yangtze River; therefore, the households therein are more sensitive to changes in residential energy pricing. According to the National Bureau of Statistics of the People's Republic of China (2013), Yangtze River households had an average of 150 air conditioners, compared with fewer than 50 air conditioners on average in the households of northeastern China. Second, the Central Yangtze River is experiencing a high rate of economic development, resulting in increased incomes. Consequently, people tend to purchase more durable goods such

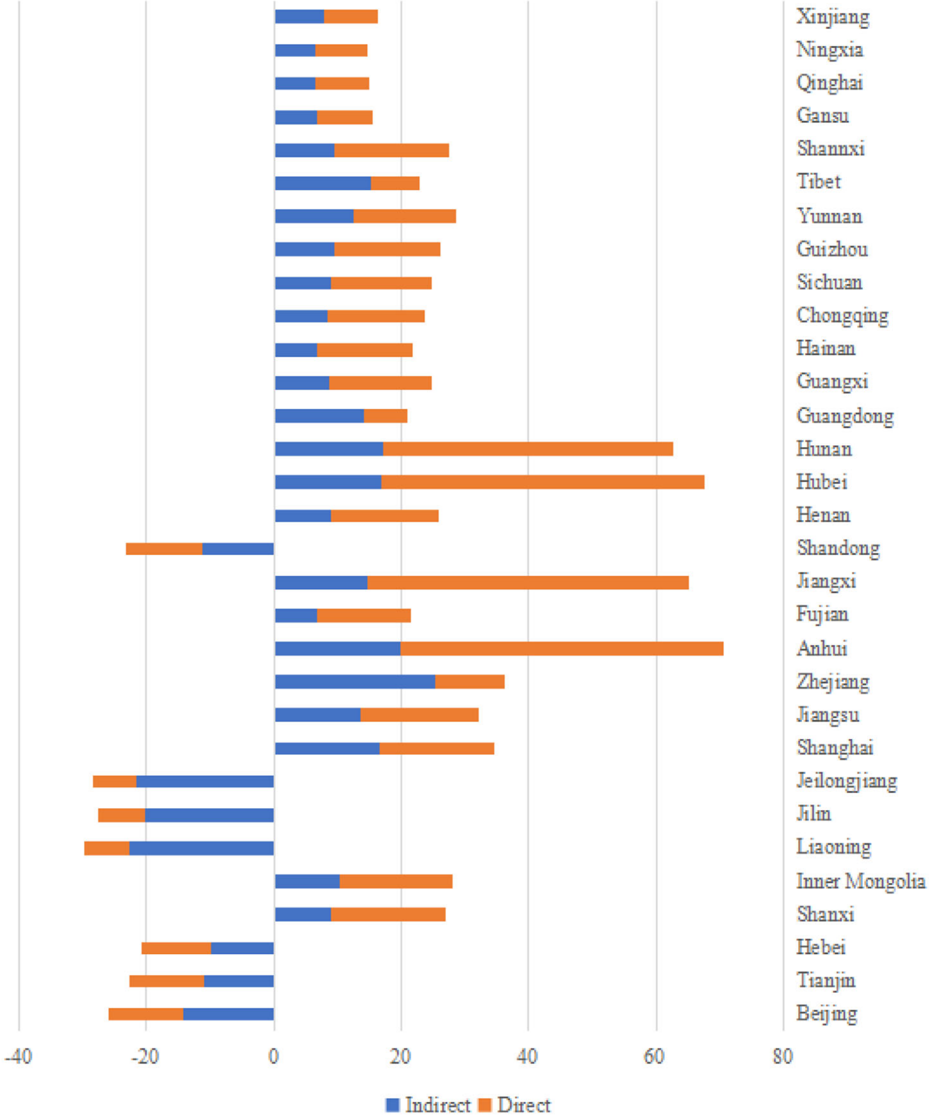

Figure 4. Long-term provincial-level rebound effects.
Source: own elaboration.

as private cars (Miao et al., 2019). This region has approximately ten fewer private cars per 100 households compared to the national average of 20 cars per 100 households. Therefore, the increasing need to improve living standards has stimulated a high rebound in areas such as the Central Yangtze River. Theoretically, a decrease in energy prices enables new consumers to use these energy services, unlike before (Sorrell et al., 2009). Herring and Roy (2007) called such consumers 'marginal consumers', who rely on reduced energy prices to purchase energy services. For example, reduced pricing enables urban residents to use air conditioners for more extended periods and set the temperatures to comfortable levels.

In terms of short-term ECR-CO_2 rebound effects, we observe a backfiring rebound effect in the Central Yangtze River, including Anhui and Jiangxi Provinces. In these areas, the improved energy efficiency did not abate ECR-CO_2 emissions. Two reasons can explain the backfiring effects in these regions. First, the Central Yangtze River is experiencing high economic development and, therefore, is sensitive to measures for promoting energy efficiency (Table 2), resulting in a higher ECR-CO_2. Second, the uncertainty in residential sector expenditures is not as high here as in more developed regions. Hence, people tend to purchase more immediate equipment in the short term, such as air conditioners and other electronic devices.

Regarding the difference between the short- and long-term rebound effects, Milgrom and Roberts (1996) argue that, according to Le Chatelier's principle, the long-term effect is more flexible than the short-term one. However, Wang et al. (2016) confirm that the short-term rebound effect is smaller than the long-term rebound effect. This study observes both results. In the Central Yangtze River and the East Coast, the short-term rebound effect is greater than that in the long term. In some other regions, such as the southwestern and northwestern regions, the long-term rebound effect is greater than the short-term rebound effect. This difference can be explained by differences in price stickiness and consumption behaviours. Figus et al. (2020) found two opposing effects: (1) in the short-term, the improved energy demand due to lower energy prices is constrained by the energy sector's temporary supply capacity, and (2) such constraints reduce because of the long-term improvement of energy supply capacity, which subsequently expands the energy demand. Turner (2009) and Allan et al. (2007) concluded that the effects of (1) are more potent than those of (2); therefore, the rebound effect in the long term is less than that in the short term. However, this discussion ignores the flexibility in consumption habits and energy prices. Amid a lack of price stickiness and persistent consumption behaviour, the short-term rebound effects will be higher than in the long-term (Figus et al., 2020). For example, Beijing and Tianjin municipalities show long-term super-conservation rebound effects with partial short-term effects. These results are similar to those of Adetutu et al. (2016), who found short-term rebound effects of approximately 90%; in the long term, these effects have sufficient adjustment time, ultimately resulting in super-conversation effects.

3.3. Direct and indirect urban residential ECR-CO_2 rebound effects

In most regions, the direct rebound effect contributes more to the total rebound effect, indicating that the substitution effect is greater than the income effect. This is because these regions are sensitive to their own price changes in the short term, which increases the direct rebound effect. Furthermore, improving energy efficiency can sharply increase the demand for residential energy commodities. In the long term, the indirect rebound effect contributes more to the total rebound effect in the Northeast, Northwest, and East Coast regions. As Table 1 indicates, the own-price elasticity of these regions decreases from the short to the long term and becomes insensitive to energy price changes in the long term. Additionally, the residential sector's ECR-CO_2 coefficient is much higher than that of the other sectors; therefore,

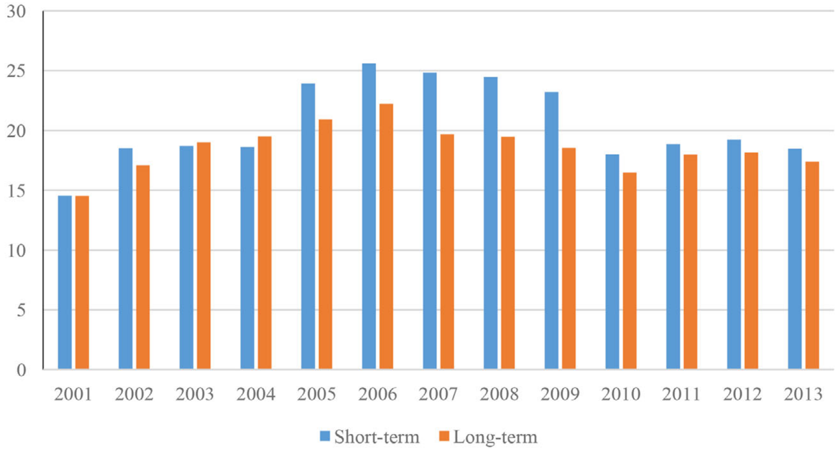

Figure 5. National-level trends of short- and long-term rebound effects.
Source: own elaboration.

the direct rebound effect has a larger magnitude with decreasing energy prices. Zhang et al. (2017) confirmed these results, whereas Wen et al. (2018) drew opposing conclusions. This is because Wen et al. (2018) calculated the direct and indirect rebound effects separately and used energy prices as a proxy for the direct rebound effect instead of calculating the direct and indirect rebound effects simultaneously, given the market's response.

3.4. Trends of the urban residential ECR-CO$_2$ rebound effects

Figure 5 displays the national-level trends of the short- and long-term ECR-CO$_2$ rebound effects. The rebound effects exhibit an inverted U-shape curve that first increases and then decreases. From 2001 to 2006, both long- and short-term rebound effects increased, and then, they decreased from 2007 to 2013. The results confirm that during China's 11th and 12th Five-Year Plans, the nation's economic development, technological progress, and carbon-emission-reduction policy offset its ECR-CO$_2$ rebound effect (Zhang et al., 2017). However, with an increase in economic development, Chinese individuals could purchase more durable goods, such as private cars, air conditioning units, and refrigerators. Consequently, both direct and indirect rebound effects increased from 2001 to 2006.

According to the National Bureau of Statistics, from 2001 to 2006, the average number of private vehicles and air conditioners increased 7.8 and 2.9 times, respectively. Since 2007, and after China hosted the Olympic Games, both the government and citizens' awareness of energy conservation and emission reduction increased. In 2007, China presented the National Program to Address Climate Change, its first comprehensive policy on this issue; established a National Leading Group to Address Climate Change; and promulgated a series of laws and regulations. These energy-conservation and emission-reduction policies reduced the total rebound effect. According to the National Bureau of Statistics, from 2007 to 2013, the government's expenditures for climate technology innovation increased from CNY 77.94 billion to 445.2

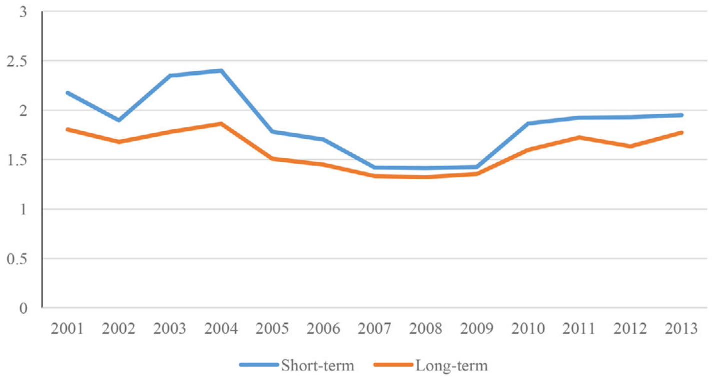

Figure 6. Convergence dynamics of national-level rebound effects.
Source: own elaboration.

billion, or approximately 5.7 times the increase seen from 2001 to 2007 (CNY 35.96 billion to 77.94 billion, respectively).

Figure 6 illustrates the regional convergence trends of short- and long-term rebound effects. Here, we use the coefficient of variation to measure the Chinese provinces' convergence levels. Both the short- and long-term rebound effects initially exhibit convergence, followed by divergence. The rebound effects from 2005 to 2009 were higher than those in other periods. Meanwhile, the gap between different provinces narrowed because durable goods such as private cars and air conditioners became increasingly popular between 2005 and 2009, as previously mentioned. However, the rebound effects diverged from 2009 to 2013, which can be explained by two possible reasons. First, the utility theory posits that the marginal utility gained from improving energy consumption decreases the substitution and income effects of ECR-CO_2 emissions, while the expected ECR-CO_2 decrease due to the improvement in energy efficiency will continue to increase. The different levels of technological development across provinces will result in divergent trends, potentially decreasing ECR-CO_2.

4. Conclusions and policy implications

This study primarily aimed to analyse the residential ECR-CO_2 rebound effects for both the short and long term from 2001 to 2013 through the ECM-LA-AIDS model, which also helped to estimate the direct, indirect, and provincial-level rebound effects. Our study showed the following results:

> First, empirical estimates confirm that persistent consumption habits lead to different short- and long-term decisions. The adjustment period from the short to long term is disparate; on average, it will take one to five years for the energy consumption system to achieve equilibrium. Collectively, expenditure elasticity reveals an increasing trend from the short to the long term, wherein consumption is more sensitive to long-term adjustment expenditures. However, sensitivity to price adjustments in the short and long term varies across regions. Therefore, considering the different levels of price stickiness and persistence of consumption habits, some provinces have larger rebound effects in the short term than in the long term, while others exhibit different trends. Second, in

> the short term, super-conservation, partial, and backfire rebound effects were detected for residential ECR-CO_2 emissions, while in the long term, no provinces exhibited the backfire effect. Finally, the national-level ECR-CO_2 rebound effects displayed an inverted U-shaped curve, indicating an upward trend followed by a downward trend. The convergence trend was also U-shaped, first decreasing and then increasing again during the same period.

Given these findings, several policy suggestions can be proposed at different levels of the Chinese government to realise the goal of decreasing ECR-CO_2 emissions in the urban residential sector:

> The first is promoting energy-market-oriented reform and enhancing the carbon mitigation incentives for urban households. This study shows that the substitution effect resulting from changes in the relative energy price is the main determinant of the rebound effect. The Chinese government's intervention in the energy market has resulted in long-term low energy prices, which distort the supply and demand in the energy market and, in turn, weaken the external cost of CO_2. Such distorted energy prices do not effectively incentivise households to engage in emission-reducing consumption. Therefore, when the government conducts policies to improve energy efficiency, it should strengthen the role of indirect market-oriented policies such as taxation to motivate households' consumption behaviours toward carbon mitigation. While implementing policies such as taxation, the government should also consider social welfare and subsidise low-income families to prevent inequality issues.

The second policy suggestion is conducting regular follow-up household consumption surveys and effectively guiding low-carbon and sustainable consumption behaviour. This study has verified the difference between long- and short-term ECR-CO_2 rebound due to inconsistent short- and long-term consumption behaviours. On the basis of a complete understanding of the consumption behaviour of energy-related appliances, the government can use administrative means such as green energy subsidies, consumer vouchers and taxes or restrictions on high-carbon-emission products, to encourage the consumption of environmentally friendly products. In formulating the above policies, for areas where the short-term consumption behaviour deviates significantly from the long-term consumption behaviour, the focus should be on improving residents' income levels and reducing the short-term income and expenditure uncertainty for purchasing green products.

The final suggestion is accelerating the restructuring of the energy-production industry and increasing the ratio of renewable energy in terminal energy usage. In addition to controlling rebound effects, radical improvement of the energy-production industry and energy consumption structure is a fundamental means for achieving China's carbon-neutrality goal. From the production side, the government should increase investment in green innovation in the thermal power industry and make full use of regional resource endowment to develop the renewable-energy industry. From the consumption side, as China's renewable energy does not have price advantages, the development of renewable energy cannot be achieved without the support of policy instruments. The government can adopt various measures such as mandatory market shares, fixed purchase tariffs, and tax incentives to encourage the development of renewable energy.

Disclosure statement

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Appendix

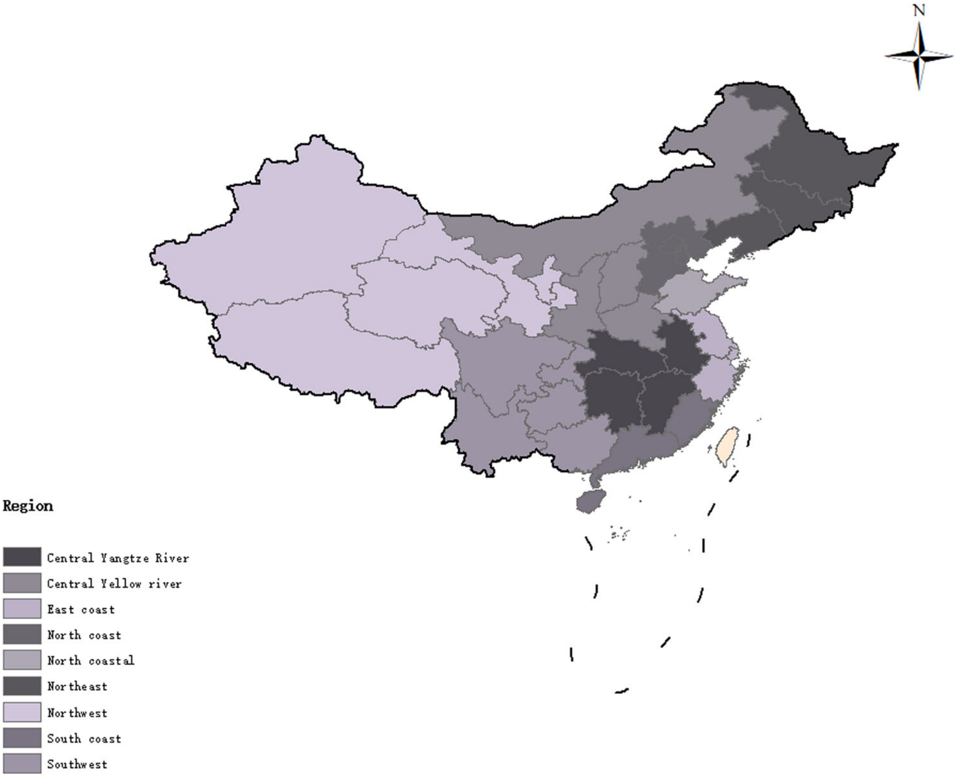

Figure A1. The distribution sample regions.

Table A1. CIPS tests(North Coast Area).[1]

	Variables	Constant	Trend
Level	Residence	−2.15	−2.72*
	Food	1.91	−2.74*
	Transportation	−1.52	−3.68***
	Expenditure	−4.00***	−2.79*
	Residence price	−1.39	−1.40
	Food price	−2.69***	−2.40
	Transportation price	−1.54	−2.05
First difference	Residence	−3.65***	−3.41***
	Food	−4.14***	−4.00***
	Transportation	−4.43***	−4.28***
	Expenditure	−3.44***	−3.03***
	Residence price	−3.23***	−3.57***
	Food price	−3.20***	−3.07***
	Transportation price	−3.02***	−2.98***

*** Statistically significant at 1% level; ** Statistically significant at 5% level; * Statistically significant at 10% level.

[1] Here we only display the results for the north coast area; the results for the other areas are available upon request.

Table A2. Co-integration test (North Coast Area).

	Modified PP	PP	ADF
Residence	2.94**	−2.76**	−2.12**
Food	2.98**	−2.72**	−2.63**
Transportation	2.51**	−3.74**	−3.19**

*** Statistically significant at 1% level; ** Statistically significant at 5% level; * Statistically significant at 10% level.

Table A3. The results of ECM-LA-AIDS (North Coast Area).

		Residence Price	Food Price	Transportation Price	Expenditure Coefficient
Long-term	Residence	−0.305	−0.060*	0.342***	0.017**
	Food		0.046*	−0.167***	−0.032***
	Transportation			−0.108	0.04***
	Breusch-Pegan	46.306***			
Short-term	Residence	−0.235**	0.089	0.432***	−0.286***
	Food		0.104	−0.196**	−0.060
	Transportation			0.020	−0.616**
	Breusch-Pegan	240.294***			

*** Statistically significant at 1% level; ** Statistically significant at 5% level; * Statistically significant at 10% level.