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Multi-Perspective Analysis of Household Carbon Dioxide Emissions from Direct Energy Consumption by the Methods of Logarithmic Mean Divisia Index and σ Convergence in Central China

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Abstract: Currently, household carbon dioxide (CO₂) emissions (HCEs) as one of the leading sources of greenhouse gas (GHG) have drawn notable scholarly concern. Thus, here, taking six provinces in the period of 2000–2017 of Central China as a case, we analyzed the characteristics and the driving factors of HCEs from direct energy consumption and three perspectives: Central China as a whole, urban-rural differences, and inter-provincial comparison. The drivers of direct HCEs were analyzed by the Logarithmic Mean Divisia Index (LMDI). The σ convergence was adopted for analyzing the trend of inter-provincial differences on the HCEs. The key findings are as follows. First, all the direct HCEs from three perspectives had an obvious growth trend. The total direct HCEs grew from 9596.20×10^4 tonnes in 2000 to $30,318.35 \times 10^4$ tonnes in 2017, with an increase of 2.16 times. Electricity and coal use were the primary sources. The urban and rural increases of direct HCEs were up 2.57 times and 1.77 times, respectively. The urban-rural gap of direct HCEs narrowed first and then widened. The direct HCEs in the six provinces varied significantly, but the gap was narrowing. Second, as a whole the per capita consumption expenditure and energy demand were the main drivers to the increment of HCEs, with cumulative contribution rates of 118.19% and 59.90%. The energy price effect was mainly responsible for the mitigation of HCEs. Third, the similar drivers' trend can also be seen from the perspective of inter-provincial comparison. However, from the perspective of urban and rural difference, the population urban-rural structure effect played a reverse influence on both urban and rural areas. Thus, raising the energy prices appropriately, upgrading the residents' consumption to a sustainable pattern, controlling the growth of population size reasonably, and optimizing the household energy structure might effectively mitigate the growth of HCEs in Central China.

Keywords: multi-perspective; household carbon dioxide (CO₂) emissions (HCEs); Logarithmic Mean Divisia Index (LMDI); σ convergence; driving factors; urban-rural differences; inter-provincial comparison

1. Introduction

Alleviating climate change is one of the key objectives to realize sustainable development. Human activity was found to have an important effect on global warming by the Intergovernmental Panel on Climate Change (IPCC) [1]. Therefore, reducing the emissions of man-made greenhouse gas (GHG) is one of the fundamental steps to address global climate change [2]. Moreover, the low-carbon economy has gradually become an important target worldwide [3,4]. China has been by far the biggest energy user and carbon

dioxide (CO₂) emitter. In 2018, China's CO₂ emissions accounted for 27.8% of total CO₂ worldwide [5,6]. Therefore, a series of targets and policies were formulated by China to mitigate emissions under huge pressure. Recently, it has aimed to reach CO₂ summits around 2030, to strive to reach the peak as early as possible and realize carbon neutrality by 2060. Currently, some policies put in place by China are largely focused on the industrial production sector. For example, a review of studies has shown that the pulp and paper industry is one of the largest energy consumers and GHGs and pollutant emitters among manufacturing industries. Many measures for reducing emissions from this industry were proposed [4,7]. Nevertheless, the energy consumption from the household sector has also developed into one of the key drivers of increasing CO₂ emissions as the economic level rises [8–10]. In previous studies, household CO₂ emissions (HCEs) were reported to account for more than 80% of the total in the United States (US) [11], more than 70% in the United Kingdom (UK) and India [12,13], and more than 50% in Korea [14]. For China, the HCEs represented approximately 40% [15] and increased yearly, with an annual growth rate of 8.7% [16]. With the rapid economic growth and improved living standards, the household energy consumption will remain to grow in China. The household sector will likely become one of the major contributors to future GHG emissions. Therefore, reducing the HCEs has become more and more necessary and urgent for achieving carbon mitigation targets.

The HCEs consist of both direct and indirect components [17]. Direct HCEs are associated with the direct consumption of energy products for household power, cooking, heating, and personal travel in daily life [18,19]. Indirect HCEs are induced by the energy use of non-energy products consumed by residents in clothing, food, housing, and transportation for all life-cycle links [20]. Diverse models have been put forward to calculate the HCEs in different countries and regions, to understand the status and drivers of these important sources of CO₂ [11,21–24]. These methods can be classified into four major types [25,26]: emission coefficient method (ECM), consumer lifestyle approach (CLA), life-cycle assessment (LCA), and input-output analysis (IOA). ECM is widely adopted to measure the direct HCEs [27,28], while CLA [11,29,30], IOA [8,31,32], and LCA [33] are mostly used to calculate the indirect HCEs. In the existing literatures on energy consumption from the household sector of China, scholars have analyzed the HCEs in terms of their urban-rural or regional differences. From the perspective of urban-rural differences, numerous researchers have illustrated that the energy uses of urban households were more diversified compared to rural [34], and the corresponding HCEs were also higher than rural [35,36]. Direct HCEs and indirect HCEs dominated rural and urban regions, respectively [19,37]. In addition, the dominant consumption patterns in urban and rural were also different. Wei et al. found that housing made the greatest contribution to CO₂ in urban areas, while food contributed most in rural [29]. Furthermore, Zhou et al. [38], Ding et al. [39], Shi et al. [40], Feng et al. [34], Zhang et al. [41], and Li et al. [42] compared the regional differences of household energy use and CO₂ emissions based on the national or specific regional perspective in China. The variations mainly relied on economic level, weather conditions, number of households, and energy intensity of each region. Moreover, Zheng et al. investigated the household carbon footprint of 74 major cities in China and found that colder cities in January tended to produce higher HCEs [43].

The decomposition analysis and the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model were usually used for analyzing the drivers of HCEs. The decomposition methods used are Index Decomposition Analysis (IDA) and Structure Decomposition Analysis (SDA). The SDA model can examine the indirect effects of variables on other sectors through input-output data [44]. Li et al. used the SDA model to analyze the changes of indirect HCEs in China during 2000–2014 [31]. Since the SDA requires input-output data, which are normally published every five years in China, it is unsuitable for further studies. Generally, compared with SDA, Logarithmic Mean Divisia Index (LMDI) as one of the IDA methods is a better option to decompose and compare the effects of various driving forces in energy use and CO₂ emissions on time-

series analysis. Using the LMDI model, Zha et al. [45], Shi et al. [40], and Zhou et al. [38] decomposed Chinese HCEs into carbon emissions coefficient, energy structure, energy intensity, income, population and so on. Yin et al. [46], Yang et al. [27], and Wang et al. [35] used a similar method to explore the influencing factors of HCEs in Beijing, Jiangxi, and Guangdong, respectively. Moreover, more and more scholars have used the STIRPAT model to analyze the impact factors of HCEs in recent years, such as Jin et al. [30], Wang et al. [47], Zhu et al. [48], Miao et al. [49], and Wang et al. [50]. The STIRPAT model is more extensible, and more socioeconomic factors can be incorporated. Therefore, the results from the model analysis are also more comprehensive [47].

In summary, the above empirical studies on HCEs are mainly conducted at the national level and single region or province of China as the case. The research perspectives focus mostly on a single analysis of urban-rural difference or regional comparison (Table 1). Few studies have been undertaken to integrate the HCEs from multiple perspectives for a particular region, particularly in underdeveloped or developing regions in China. Thus, in this paper, we take Central China as a study object. Figure 1 shows the location of six provinces in Central China. Central China is the second echelon of China's economic development, accounting for about 10.7% of the national land, and carrying approximately 26.51% of the country's population. Statistically, its GDP reached CNY 17.94 trillion in 2017. It plays a significant role in the geographical division of labor in China. Since the implementation of the "Central China Rising Strategy" in 2004, it has become an essential economic growth pole in China. However, meanwhile it can be easily seen that Central China has the enormous potential of increasing CO₂ emissions from household consumption. Therefore, it is crucial to study the HCEs in this region. So, we first demonstrated the characteristics and drivers of the HCEs from direct energy consumption and three perspectives: Central China as a whole, urban-rural differences, and inter-provincial comparison. The trend of inter-provincial differences on the HCEs was also analyzed. Finally, some specific countermeasures of emission reduction are proposed for this region's development based on the empirical results. The remainder of the paper is arranged as follows. The detailed methodology and data are in Section 2. The analysis and discussion of the empirical results are presented in Section 3. Section 4 concludes the results and proposes some reasonable countermeasures.

Table 1. The summary of relevant studies on energy consumption and CO₂ emissions in the household sector.

Reviewed Paper	Location and Period	Subject	Scale	Urban-Rural Differences	Regional Differences
Li et al. [19]	China 1996–2012	HCEs	Nationwide	✓	
Wei et al. [29]	China 1999–2002	Residents' energy use and CO ₂ emissions	Nationwide	✓	
Zha et al. [45]	China 1991–2004	Residential CO ₂ emissions	Nationwide	✓	
Liu et al. [15]	China 1992–2007	HCEs	Nationwide	✓	
Feng et al. [33]	China and its four regions 2002–2007	Household energy use and HCEs	Nationwide and Regional	✓	✓
Shi et al. [40]	China and its 30 provinces 2000–2015	HCEs	Nationwide and Provincial		✓
Zhou et al. [38]	China and its 30 provinces 2007–2012	Household living energy use and CO ₂ emissions	Nationwide and Provincial		✓
Zheng et al. [43]	74 major cities in China 2006	HCEs	City		✓
Li et al. [42]	Northwest China 2011–2012	HCEs	Regional		✓
Ding et al. [39]	30 provinces in China 1997–2013	Household energy consumption	Provincial	✓	✓
Wang et al. [35]	Guangdong 1995–2012	HCEs	Provincial	✓	
Jin et al. [30]	Beijing 1993–2012	HCEs	City	✓	
This paper	Central China 2000–2017	HCEs	Regional and provincial	✓	✓

Figure 1. Location of six provinces in Central China.

2. Materials and Methods

2.1. Emission Coefficient Method

According to the IPCC [28], the direct HCEs were calculated by the consumption amounts of fuel and the corresponding carbon emission coefficients. The equation is:

$$C = \sum_i \sum_j C_{ij} = \sum_i \sum_j E_{ij} \cdot f_j \quad (1)$$

where C is the amount of direct HCEs (10^4 tonnes), i is the type of residents, i.e., urban residents and rural residents, j denotes the fuel type, E_{ij} denotes the consumption of energy by resident i , and f_j the carbon emission coefficient of j fuel type.

2.2. LMDI Model

In this paper, we used the LMDI model to explore the driving factors influencing the direct HCEs of Central China. This method can eliminate the residual term in the basic model and handle zero values in data [51,52]. While the basic principle of the LMDI model is the same, the formulas vary with the factors studied. The detailed formula can be expressed as the following extended identity:

$$\begin{aligned} C &= \sum_i \sum_j C_{ij} = \sum_i \sum_j \frac{C_{ij}}{E_{ij}} \cdot \frac{E_{ij}}{E_i} \cdot \frac{E_i}{Y_{ie}} \cdot \frac{Y_{ie}}{Y_i} \cdot \frac{Y_i}{P_i} \cdot \frac{P_i}{P} \cdot P \\ &= \sum_i \sum_j F_{ij} \cdot ES_{ij} \cdot EP_i \cdot ED_i \cdot PC_i \cdot PS_i \cdot P \end{aligned} \quad (2)$$

where the variables are defined in Table 2.

Based on the above formula, we take C_0 and C_t as the direct HCEs in the baseline period and target period. Thus, the change of total direct HCEs (C_{TOT}) can be written as:

$$\Delta C_{TOT} = C_T - C_0 = \Delta C_{F_{ij}} + \Delta C_{ES_{ij}} + \Delta C_{EP_i} + \Delta C_{ED_i} + \Delta C_{PC_i} + \Delta C_{PS_i} + \Delta C_P \quad (3)$$

Table 2. Definition of variables.

Variable	Definition
C	Total direct HCEs
C_{ij}	Direct HCEs of energy j by resident i
E_{ij}	Energy consumption of energy j by resident i
E_i	Energy consumption of resident i
Y_{ie}	Energy consumption expenditure of resident i
Y_i	Consumption expenditure of resident i
P_i	Population of resident i
P	Total population of Central China
F_{ij}	Carbon emission coefficient of energy j by resident i
ES_{ij}	Share of energy j in energy consumption by resident i
EP_i	Energy consumption per unit of residential expenditure for resident i
ED_i	Share of residential expenditure to consumption expenditure of resident i
PC_i	Per capita consumption expenditure of resident i
PS_i	Share of resident i

Notably, the CO₂ emission coefficients of various fuels are all considered constant when calculating the direct HCEs, which have no contribution to changes in CO₂ emissions. Thus, based on the additive LMDI method, we finally analyzed the following six effects: the energy structure effect (ΔC_{ES}), energy price effect (ΔC_{EP}), energy demand effect (ΔC_{ED}), per capita consumption expenditure effect (ΔC_{PC}), population urban-rural structure effect (ΔC_{PS}), and population size effect (ΔC_P).

Each sub-effect can be expressed as:

$$\Delta C_{ES_{ij}} = \sum_i \sum_j \frac{C_{ij,T} - C_{ij,0}}{\ln C_{ij,T} - \ln C_{ij,0}} \cdot \ln \frac{ES_{ij,T}}{ES_{ij,0}} \quad (4)$$

$$\Delta C_{EP_i} = \sum_i \sum_j \frac{C_{ij,T} - C_{ij,0}}{\ln C_{ij,T} - \ln C_{ij,0}} \cdot \ln \frac{EP_{i,T}}{EP_{i,0}} \quad (5)$$

$$\Delta C_{ED_i} = \sum_i \sum_j \frac{C_{ij,T} - C_{ij,0}}{\ln C_{ij,T} - \ln C_{ij,0}} \cdot \ln \frac{ED_{i,T}}{ED_{i,0}} \quad (6)$$

$$\Delta C_{PC_i} = \sum_i \sum_j \frac{C_{ij,T} - C_{ij,0}}{\ln C_{ij,T} - \ln C_{ij,0}} \cdot \ln \frac{PC_{i,T}}{PC_{i,0}} \quad (7)$$

$$\Delta C_{PS_i} = \sum_i \sum_j \frac{C_{ij,T} - C_{ij,0}}{\ln C_{ij,T} - \ln C_{ij,0}} \cdot \ln \frac{PS_{i,T}}{PS_{i,0}} \quad (8)$$

$$\Delta C_P = \sum_i \sum_j \frac{C_{ij,T} - C_{ij,0}}{\ln C_{ij,T} - \ln C_{ij,0}} \cdot \ln \frac{P_T}{P_0} \quad (9)$$

2.3. Classical Convergence Regression Method— σ Convergence

The trend of inter-provincial differences in direct HCEs across the six provinces can be determined using the classical convergence regression method. The σ convergence is mainly tested by the coefficient of variation, which is expressed as:

$$CV_t = \frac{\sqrt{\frac{1}{n-1} \sum_{k=1}^n \left(C_{k,t} - \frac{1}{n} \sum_{k=1}^n C_{k,t} \right)^2}}{\frac{1}{n} \sum_{k=1}^n C_{k,t}} \quad (10)$$

where CV_t denotes the coefficient of variation in year t and $C_{k,t}$ denotes the direct HCEs of the k province in year t . If CV_t keeps decreasing, it means that there is σ convergence in

the direct HCEs in the six provinces, and the difference of direct HCEs in each province is gradually decreasing.

2.4. Description of the Data

The data on household energy consumption for urban and rural areas in the six provinces are found in the China Energy Statistical Yearbook (2001–2018) [53]. The energy sources involved in measuring the direct HCEs are raw coal, washed coal, other washed coal, briquettes, coke, coke oven gas, blast furnace gas, converter gas, other gas, gasoline, kerosene, diesel, fuel oil, lubricants, petroleum asphalt, liquefied petroleum gas (LPG), refinery dry gas, other petroleum products, natural gas, liquefied natural gas (LNG), electricity, heat, and other types. It should be noted that heat and electricity are the secondary energy sources with no direct use of fuel, while a large amount of fuel is consumed in the production process. Thus, in this paper, electricity and heat are also considered. The emission coefficients for different types of primary energy can be calculated using the method recommended by the IPCC (2006), as listed in Table A1. Given the complexity of calculating emission factors from electricity and heat, we used the statistical data on average CO₂ emissions per unit of electricity supply in the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (for Trial Implementation) [54]. The emission factors for electricity are shown in Table A2. The emission coefficient of heat adopted 0.11 t-CO₂/GJ according to the reference of Jia et al. [55]. Relevant data of influencing factors such as consumption expenditure and population size in the six provinces are from Statistical Yearbooks (2001–2018) [56–61]. All the economic data are comparable in that they are converted into 2000 standard prices. The CO₂ emission coefficient for standard coal is 2.4567 [54]. The conversion factor of standard coal for various energy types is from the China Energy Statistical Yearbook (Table A1).

3. Results

3.1. Characteristics of the Amount and Structure of Direct HCEs in Central China

3.1.1. Overall Analysis

Figure 2a shows the trend of direct HCEs in Central China from 2000 to 2017. The direct HCEs kept increasing (except slightly decreasing in 2004 and 2013) by approximately 215.94% from 9596.20×10^4 tonnes to $30,318.35 \times 10^4$ tonnes during 2000–2017, with an annual growth of 7.00%. It accounted for about 28.72%, 24.19%, and 24.51% of national direct HCEs in 2000, 2006, and 2012, respectively (Table 3). The per capita direct HCEs rose from 0.27 tonnes to 0.77 tonnes, with an average annual increase amount and rate of 0.03 tonnes and 6.32%, respectively. All energy types were divided into five categories, and the electricity and coal consumption dominated the direct HCEs. For example, the cumulative share of CO₂ emissions from the electricity during 2000–2017, accounted for 46.55% of total HCEs in Central China (Figure 2b).

Table 3. Comparison of direct HCEs in Central China and the whole of China.

Carbon Emissions (10 ⁴ t)	2000	2006	2012
Total direct HCEs in Central China	10,485.40	14,248.12	23,701.63
Total direct HCEs in China	36,513.00	58,894.00	96,694.00
Share (%)	28.72%	24.19%	24.51%
Urban direct HCEs in Central China	4679.08	7083.59	12,632.23
Urban direct HCEs in China	20,931.00	34,841.00	56,614.00
Share (%)	22.35%	20.33%	22.31%
Rural direct HCEs in Central China	4917.12	7164.53	11,069.40
Rural direct HCEs in China	15,581.00	24,053.00	40,080.00
Share (%)	31.56%	29.79%	27.62%

Figure 2. Trends in the amount and structure of direct HCEs (a) and the cumulative share of CO₂ emissions from five energy types during 2000–2017 (b) in Central China.

The structure for direct HCEs has varied significantly in the 2000–2017 years (Figure 2a). The coal-related emissions dropped remarkably from 6423.21×10^4 tonnes to 4875.82×10^4 tonnes, and their share decreased at an average annual rate of -1.61% from 66.93% in 2000 to 16.08% in 2017. This trend can be explained by three reasons. Firstly, the utilization rate of coal was improved due to the revolution of coal engineering by technological progress. Secondly, coal-to-gas conversion has been implemented in several locations by China's policy against dry fog. Residential heating has been converted to a centralized type in recent years. Thirdly, the global financial crisis caused a rapid rise in coal prices. On the contrary, the CO₂ emissions generated by four other energy use were all up. Significantly, the CO₂ emissions of oil grew fastest, followed by electricity. Their average annual growth rates were 16.44% and 11.82% , respectively. In 2017, the shares of CO₂ emissions from oil and electricity were up to 26.25% and 55.53% . Meanwhile, the CO₂ emissions induced by oil have surpassed those from coal, making it the second-largest energy type. Oil, like diesel, was mainly used for transportation. Since people's demand for transportation has escalated with household income, the number of people purchasing motorcycles and family cars increased. Statistically, the average number of motorcycles and family cars per 100 households owned by residents of Central China was 43.35 and 23.08 in 2017, respectively, which were about 2.75 times and 128.00 times that of 2000 (Table 4). In addition, the growth in household appliances (especially those that consume large amounts of electricity, such as air conditioners) has increased the CO₂ emissions from electricity. The average number of air conditioners per 100 households owned by residents of Central China increased by 616.48% from 13.29 units in 2000 to 95.22 units in 2017. The share of CO₂ emissions caused by natural gas has increased over the past few years, while its overall proportion was relatively low at just 4.85% in 2017. People would prefer cleaner and more convenient natural gas in their energy choices with economic growth and improved living standards. However, the economy of the study region is slightly lower than that of Eastern China, resulting in relatively low use of natural gas. The CO₂ emissions of heat also presented an increased tendency (212.64×10^4 tonnes in 2000 and 2157.89×10^4 tonnes in 2017), the share of which increased from 2.22% in 2000 to 7.12% in 2017. In general, the energy use structure has been progressively improved and decarbonized, and the share of clean energy and low-carbon energy use has risen. However, given that heat and electricity

are produced with coal as the raw material, the energy structure has not been completely altered.

Table 4. Ownership of major durable consumer goods per 100 households at year end in Central China.

Item	2000	2005	2010	2015	2017
Family car	0.18	1.37	3.48	16.48	23.08
Motorcycle	15.74	29.97	39.12	46.25	43.35
Washing machine	54.98	55.95	75.70	83.53	89.25
Refrigerator	43.44	46.80	70.46	88.32	94.32
Color TV set	73.73	104.90	118.66	118.57	121.07
Air conditioner	13.29	37.74	58.20	79.23	95.22
Shower heater	42.68	31.64	38.95	67.33	75.78
Mobile telephone	14.19	62.35	151.61	222.80	238.32
Computer	7.05	16.94	32.26	49.53	51.23

3.1.2. Urban-Rural Differences

It can be seen that the direct HCEs of both urban and rural households have risen continuously (Figure 3). More CO₂ emissions were caused by urban household in most years. The urban and rural direct HCEs significantly increased by 2.57 times (from 4679.08×10^4 tonnes to $16,698.56 \times 10^4$ tonnes) and 1.77 times (from 4917.12×10^4 tonnes to $13,619.79 \times 10^4$ tonnes), respectively. The corresponding annual average growth rates were 7.77% and 6.18%. They accounted for approximately 20% and 30% of national urban and rural direct HCEs, respectively (Table 3). For the entire study period, the growth amount and rate in urban areas were apparently higher than that of rural. This can be divided into two stages. From 2000 to 2006, rural direct HCEs were higher than those in urban areas. The average annual growth rate of direct HCEs in rural areas was 6.48%, which was lower than that of 7.16% in urban. The urban-rural ratio of direct HCEs increased to 0.99 from 0.95, gradually approaching 1. Thus, the gap between direct HCEs for urban and rural regions was gradually narrowing. After 2006, the direct HCEs in urban areas began to be higher than those of rural areas, and the urban-rural ratio rose from 0.99 to 1.23, with the gap gradually widening again. The result was consistent with previous studies, such as Zhang et al. [62]. This could be caused by the rapid urbanization. The commercial energy use has increased due to urban population growth, while rural areas are still dominated by non-commercial energy after 2006 [29].

Figure 3. Trends in direct HCEs from urban and rural areas and the urban-rural ratio in Central China.

There were also many significant differences in the structure of direct HCEs between urban and rural regions. The rural direct HCEs caused by coal consumption were considerably higher than those of urban (Figure 4b), whereas the other four types of energy use were opposite (Figure 4a). A typical dichotomy existed between urban and rural areas in China [29]. The urban-rural differences in the direct HCEs structure were likely caused by substantial variability in income level, energy supply, and energy use habits of urban and rural residents. At present, centralized heating and gas supply have not been taken yet in most rural areas of Central China. The residents mainly use coal for heating and cooking, resulting in heavy coal use. The economic conditions, quality of life, and the ownership of vehicles and household appliances (washing machines, refrigerators, and air conditioners) in urban areas were higher than in rural areas (Table 5), which resulted in greater consumption of oil and electricity in urban areas than in rural. As shown in Table 5, the average number of family cars owned by urban households (per 100 households) was as high as 31.50, while the number was only 14.40 in rural areas in 2017. Natural gas was mainly used for heating and cooking, and indoor heating was centralized for urban dwellers. Urban energy was supplied centrally, which had a specific intensive and scale effect compared to rural areas.

Figure 4. Trends in the structure of direct HCEs in urban (a) and rural (b) areas in Central China.

Table 5. Urban and rural ownership of major durable consumer goods per 100 households at year end in Central China.

Item (Unit)	2000		2010		2017	
	Urban	Rural	Urban	Rural	Urban	Rural
Family car	0.35	-	6.96	-	31.50	14.40
Motorcycle	16.13	15.36	22.00	56.24	24.47	62.98
Washing machine	88.83	21.14	96.95	54.45	98.53	79.40
Refrigerator	79.76	7.13	94.80	46.13	99.43	89.05
Color TV set	108.56	38.90	130.74	106.59	122.80	119.40
Air conditioner	26.37	0.22	100.93	15.46	135.25	54.62
Shower heater	42.68	-	77.90	-	91.88	59.28
Mobile telephone	14.19	-	167.82	135.40	236.35	240.17
Computer	7.05	-	57.66	6.86	75.48	26.32

3.1.3. Inter-Provincial Comparison

In terms of inter-provincial comparison, there was an evident disparity in direct HCEs among the six provinces. Henan Province is the most populous province contributing the largest HCEs during 2000–2017. It contributed a 24.71% to the total HCEs of Central China, followed by Shanxi (18.52%), Hubei (17.12%), Hunan (15.98%), Anhui (15.11%), and Jiangxi (8.56%). Remarkably, the direct HCEs from the six provinces all displayed a fluctuating upward trend during 2000–2017 (Figure 5a). The lowest level of direct HCEs was in Jiangxi, while the overall tendency was on the rise, with an increase of 288.61% and an average annual growth rate of 8.31%. On the contrary, the direct HCEs of Henan Province were always the highest during the same period, whereas the growth amount and rate were both lower than that of Jiangxi, with an increase of about 175.42% and an average annual growth rate of 6.14%.

Figure 5. Trend of the direct HCEs (a) and the coefficient of variation of direct HCEs in six provinces (b).

The HCEs of the remaining four provinces (Hunan, Anhui, Shanxi, and Hubei) were at a medium level during 2000–2017, which can be roughly analyzed in two stages (2000–2005 and 2005–2017). From 2000 to 2005, Hunan Province had the lowest direct HCEs, while it had a speedy growth trend with a growth rate much higher than the other three provinces. The average annual growth rate was 14.9% and the total increase amount was about 100.3%. The average annual growth rate of Anhui (Shanxi) was 8.64% (3.87%), with the total increase amounts of about 51.32% (20.9%). Hubei's HCEs had the lowest average annual growth rate of only 1.98%. During 2005–2017, Hunan Province had the highest growth rate of direct HCEs among the four provinces, with an average annual growth rate of 7.9%. Beginning in 2015, the direct HCEs of Hunan reached the highest level among the four provinces gradually and significantly, reaching 5489.00×10^4 tonnes in 2017. Over this period, there was no significant disparity in the growth rate of direct HCEs for the four provinces. The average annual growth rates of other three provinces (Shanxi, Hubei, and Anhui) were 6.88%, 7.77%, and 6.77%, respectively. Their direct HCEs in 2017 were 5145.26×10^4 tonnes, 4932.79×10^4 tonnes, and 4797.57×10^4 tonnes.

To understand whether the difference of direct HCEs among the six provinces is narrowing or widening, we adopted the σ convergence test in neoclassical theory to describe it. The coefficient of variation of direct HCEs was used to test. If the coefficient of variation shows a downward trend, there is convergence, indicating that the difference of direct HCEs in the six provinces is progressively decreasing. Based on Equation (10), the coefficient of variation of direct HCEs in the six provinces was calculated. The result

indicated that the coefficient of variation exhibited an interval increase and decrease from 2000–2017 (Figure 5b). From 2000 to 2003, the coefficient of variation of direct HCEs presented a linearly decreasing trend. The σ convergence was obvious over this period. The difference in direct HCEs was steadily declining among the provinces. From 2003 to 2012, the trend in the coefficient of variation was fluctuating upwards, indicating that there was no σ convergence in this period. From 2012 to 2017, it declined first and rebounded somewhat in 2017, which is a dispersion stage. The disparity in direct HCEs increased among the provinces. Overall, the coefficient of variation of direct HCEs decreased from 0.35 in 2000 to 0.25 in 2017, indicating that there was σ convergence of direct HCEs in the six provinces. It can also be easily seen that the direct HCEs gap was decreasing in the six provinces from an overall perspective.

The cumulative shares of CO₂ emissions from five energy types in each province were calculated (Figure 6). Then, the emission structure of each province was compared and analyzed. First, Shanxi Province took the largest share of CO₂ from coal use at 45.14% in comparison with other provinces, followed by Henan (34.59%), Hubei (34.59%), Hunan (31.92%), and Anhui (27.71%). The share of CO₂ emissions from coal use in Jiangxi was the lowest, at 26.86%. The coal resources of Shanxi Province were the richest compared to the other five provinces, with more production and usage, so the share of coal consumption and CO₂ emissions was the highest. The largest share of CO₂ emissions induced by oil was in Hubei, and the smallest share was in Shanxi, with 16.17% and 3.24%, respectively. The share of CO₂ emissions caused by natural gas was relatively small in all six provinces, ranging from 1.72% to 4.21%. The share of Anhui was the highest and Hunan Province was the lowest. The CO₂ emissions generated by electricity consumption represented a large proportion, with Jiangxi, Hunan, and Anhui all exceeding 50%, while Shanxi represented the least, at only 34.38%. The share of CO₂ emissions from heat use in Shanxi was high, at 14.49%. Thus, it can be seen that Shanxi Province had a poor low-carbon energy structure.

Figure 6. The share of CO₂ emissions from five types of energy consumption by provinces in Central China.

3.2. Decomposition Analysis of Direct HCEs in Central China

3.2.1. Overall Analysis

The complete decomposition results are presented in Figure 7 and Table 3. The cumulative contribution of each driver was calculated from 2000 to 2017 for the ease of analysis (Figure 8a). During the whole study, the change of total direct HCEs was $20,722.15 \times 10^4$ tonnes. Generally, the energy structure effect, energy demand effect, per capita consumption expenditure effect, population urban-rural structure effect, and popu-

lation size effect positively affected the growth of direct HCEs. On the contrary, the energy price effect showed a negative impact, which decreased the direct HCEs. Next, the contribution of each driving factor at four different stages (2000–2005, 2005–2010, 2010–2015, and 2015–2017) is drawn out in Figure 8b.

Figure 7. Changes in the contribution values of the driving factors of direct HCEs in Central China from 2000 to 2017.

Figure 8. The cumulative contribution rate of each decomposition factor of direct HCEs in Central China during the period 2000–2017 (a) and at four stages (2000–2005, 2005–2010, 2010–2015, and 2015–2017) (b).

Energy Price Effect

The energy price effect was mainly responsible for mitigating direct HCEs in Central China (Figures 7 and 8a), which was consistent with the previous studies of Yang et al. and Wang et al. [27,35]. However, it was also contrary to the results of a few studies, such as Zhao et al. [63]. The change of energy price decreased $21,228.36 \times 10^4$ tonnes CO₂ from 2000 to 2017, with a contribution rate of -102.44% . Specifically, for each of the four stages, the contribution values (rates) were 382.90×10^4 tonnes (1.85%), -5958.82×10^4 tonnes (-28.76%), $-13,064.61 \times 10^4$ tonnes (-63.05%), and -2587.84×10^4 tonnes (-12.49%),

respectively (Table 3 and Figure 8b). The corresponding average annual contribution rates in the four stages were 0.37%, −5.75%, −12.61%, and −6.24%, respectively (Table 6). This mitigation effect may be caused by the increase in the average energy prices during the study period. The Chinese government has launched price deregulation in the energy sector, which has led to an overall increase in energy prices. From 2000 to 2017, the average energy prices in Central China increased to 1.02×10^4 CNY/tonne of standard coal equivalent (tce) from 0.48×10^4 CNY/tce, with an average annual growth rate of 4.55% (Figure 9a). The average annual growth rates of energy prices in the four phases were 4.07%, 0.82%, 5.65%, and 2.26%, respectively. Obviously, the energy price effect had the strongest impact on the decrease of direct HCEs in 2010–2015.

Table 6. The average annual contribution rate of various effects at different stages in Central China.

Effects	Average Annual Contribution Rate (%)			
	2000–2005	2005–2010	2010–2015	2015–2017
Energy structure	0.58	0.90	−0.39	1.48
Energy price	0.37	−5.75	−12.61	−6.24
Energy demand	−1.42	2.95	9.18	3.19
Per capita consumption expenditure	3.63	5.92	10.55	8.87
Population urban-rural structure	0.37	0.46	0.04	1.09
Population size	0.31	0.76	0.51	0.74

Figure 9. Variation trend of various influencing factors of direct HCEs in Central China. (a) Energy price; (b) Per capita consumption expenditure; (c) Per capita residence expenditure and energy demand; (d) Population size and urbanization rate.

Per Capita Consumption Expenditure Effect and Energy Demand Effect

The per capita consumption expenditure may, to some extent, reflect the living standard of a region. It represents the residential energy consumption level with the energy demand together. The per capita consumption expenditure effect played the most important role in promoting the growth of direct HCEs (Figures 7 and 8a). It contributed a total

of $24,490.81 \times 10^4$ tonnes CO₂ over the study period and accounted for 118.19% of total change of direct HCEs. Meanwhile, the energy demand was another major contributor for the increment of direct HCEs. It contributed $12,413.03 \times 10^4$ tonnes CO₂ and the contribution rate was 59.90%. Concretely, in the four stages, the corresponding contribution values (rates) were 3757.91×10^4 tonnes (18.13%), 6130.93×10^4 tonnes (29.59%), $10,926.11 \times 10^4$ tonnes (52.73%), and 3675.86×10^4 tonnes (17.74%) for the per capita consumption expenditure effect, and -1472.68×10^4 tonnes (-7.11%), 3051.96×10^4 tonnes (14.73%), 9511.01×10^4 tonnes (45.90%), and 1322.74×10^4 tonnes (6.38%) for the energy demand effect (Figure 8b and Table 3). The average annual contribution rates of the per capita consumption expenditure effect (energy demand effect) in the four stages were 3.63% (-1.42%), 5.92% (2.95%), 10.55% (9.18%), and 8.87% (3.19%), respectively (Table 6). It can be seen that the driving effect of per capita consumption expenditure and energy demand on the total direct HCEs was increasing. However, their driving role declined in 2015–2017. The continued increase in residence expenditure has promoted the continued growth of HCEs directly. During 2000–2017, the per capita residence expenditure in Central China rose from CNY 290.11 to CNY 2064.30, an increase of 611.57%, with an average annual growth rate of 12.24% (Figure 9c). The average annual growth rates were 5.32%, 9.77%, 18.42%, and 10.76%, respectively in the four stages. The overall increase in household consumption level was also an essential reason for the rapid growth of direct HCEs in this region. Throughout the study period, the per capita consumption expenditure was up from CNY 2309.46 to CNY 10,087.93, an increase of 336.81%, with an average annual growth rate of 9.06% (Figure 9b). The average yearly growth rates in the four phases were 8.62%, 6.96%, 7.28%, and 3.65%, respectively. Therefore, people had the capacity to purchase more energy-intensive appliances and transportation tools, resulting in greater energy use. The number of air conditioners, refrigerators, and family cars owned per 100 households at the 2017 year-end were 95.22, 94.32, and 23.08, compared to 13.29, 43.44, and 0.18 in 2000, with an increase of 616.48%, 117.13%, and 12,722.22%. Hence, it is vital to reduce the direct HCEs by limiting the growth of transportation tools and high energy-consuming appliances and improving energy use efficiency.

Population Size Effect and Population Urban-Rural Structure Effect

The population size effect and population urban-rural structure effect had less impact in promoting the direct HCEs in Central China during 2000–2017. The effects of population and population urban-rural structure, respectively, caused an increase of 1948.67×10^4 tonnes and 1354.44×10^4 tonnes with contribution rates of 9.4% and 6.54%. In the four stages, the contribution values (rates) for the population effect were 318.37×10^4 tonnes (1.54%), 790.83×10^4 tonnes (3.82%), 532.04×10^4 tonnes (2.57%), and 307.43×10^4 tonnes (1.48%), respectively. The contribution values (rates) of population urban-rural structure effect were 387.37×10^4 tonnes (1.87%), 473.62×10^4 tonnes (2.29%), 43.05×10^4 tonnes (0.21%), and 450.41×10^4 tonnes (2.17%), respectively (Figure 8b and Table 3). The average annual contribution rates of the population effect (population urban-rural structure effect) in the four stages were 0.31% (0.37%), 0.76% (0.46%), 0.51% (0.04%), and 0.74% (1.09%), respectively (Table 6). The population growth of Central China played a certain role in promoting the increase of direct HCEs. The total population in Central China increased by 11.49% from $35,370.39 \times 10^4$ persons in 2000 to $39,434.67 \times 10^4$ persons in 2017, increasing energy demands and related emissions directly (Figure 9d). The average annual population growth rates in the four stages were 0.57%, 0.93%, 0.46%, and 0.56%, respectively.

There are two reasons why the population urban-rural structure showed a positive effect. One was that the per capita direct HCEs in urban areas were all higher than those in rural; the other was that the proportion of urban population continued to rise, and the urbanization rate kept increasing, owing to the continuous urbanization process. The urban population ratio rose by 63.80% from 28.22% in 2000 to 46.23% in 2017, with an average

annual growth rate of 2.95% (Figure 9d). The average annual growth rates were 3.73%, 3.31%, 1.41%, and 3.97% for each of the four stages, respectively.

Energy Structure Effect

The energy structure effect played a minor role in increasing the direct HCEs, which contributed 1743.56×10^4 tonnes CO₂ over this 17-year period and the contribution rate was 8.41%. Specifically, the contribution values (rates) at each of the four stages were 603.48×10^4 tonnes (2.91%), 935.23×10^4 tonnes (4.51%), -409.25×10^4 tonnes (−1.97%), and 614.10×10^4 tonnes (2.96%), respectively (Figure 8b and Table 3). The corresponding average annual contribution rates of the energy structure effect were 0.58%, 0.90%, −0.39%, and 1.48%, respectively (Table 6). It should be particularly noted that the growth of direct HCEs was inhibited during 2010–2015. The reason could be that the energy structure was being optimized in Central China at this period, which reduced CO₂ emissions. As mentioned above, it was clear that CO₂ emissions from coal use were gradually falling, while emissions from oil, natural gas, heat, and electricity were rising. China is constrained by coal-based resource endowments and the production of electricity and heat are also based on coal as the primary raw material. Consequently, coal is used in great quantities. Therefore, the government should strengthen the encouragement and support for developing non-fossil fuel energy sources such as wind energy, nuclear power, biomass, solar energy, and other clean energy. Natural gas is also a relatively low-carbon emitting energy of fossil fuels. At the same time, the consumption share of natural gas has been low due to the relatively underdeveloped economic conditions in Central China. Therefore, the natural gas industry should be strongly supported in this region, especially in rural areas, so that natural gas can be widely used. It is also an issue worthy of attention in the decarbonization of household consumption.

3.2.2. Urban-Rural Differences

The decomposition results of direct HCEs from urban and rural areas during 2000–2017 are presented in Tables 4 and 5. The same drivers affected urban and rural areas differently. As a whole, the energy structure effect, energy demand effect, per capita consumption expenditure effect, and population effect all contributed to the growth of direct HCEs in both urban and rural areas during 2000–2017 (Figure 10). The effects' contribution of the energy structures and per capita consumption expenditure contributed more to rural compared with urban areas. In 2017, these drivers increased direct HCEs by 72.07% and 54.53% in rural and urban areas. Conversely, the effects of energy demand and population in urban areas were greater than that in rural, which increased by 45.42% and 23.88% of total CO₂ emissions. The energy price effect was negative for urban and rural direct HCEs, with cumulative contribution rates of −61.70% and −40.74%, respectively.

The differences in drivers between urban and rural areas can be explained by different change rates of various influencing factors. For example, the difference in the magnitude of the energy price effect can be explained by the variation in the average energy prices for urban and rural areas. The energy prices rose from 0.44×10^4 CNY/tce and 0.52×10^4 CNY/tce in 2000 to 1.11×10^4 CNY/tce and 0.93×10^4 CNY/tce in 2017 for urban and rural regions, respectively. In terms of the growth rate, compared to 2000, it was 153.95% for urban areas and 78.69% for rural (Figure 11a). The change rates of per capita consumption expenditure for urban and rural areas were 228.31% and 344.13%, respectively (Figure 11b). The growth rate of urban energy demand was higher than that of rural areas during the study period, as depicted in Figure 11c. The energy demand of urban and rural areas rose from 11.59% and 13.54% to 19.39% and 22.26%, with the growth rates of 67.29% and 64.44%, respectively (Figure 11c). The population urban-rural structure effect promoted the growth of direct HCEs in urban areas, whereas the opposite was true for rural. The contribution rates for urban and rural areas were 34.05% and −31.46%, respectively. By 2017, the ratio of urban and rural population increased by 63.8% and −25.1% than that in 2000 (Figure 11d).

Figure 10. The cumulative contribution of decomposition factors of direct HCEs between urban and rural areas in Central China.

Figure 11. The variation trend of various influencing factors of direct HCEs in urban and rural areas in Central China. (a) Energy price; (b) Per capita consumption expenditure; (c) Energy demand; (d) Population share.

In short, the two drivers with the greatest degree of influence on direct HCEs in rural areas were the effects of per capita consumption expenditure and energy demand, cumulatively contributing 85.14% of total HCEs. The population urban-rural structure effect and energy price effect reduced 53.96% of total direct HCEs. In urban areas, the two factors that contributed most to direct HCEs were also the per capita consumption expenditure and energy demand, contributing about 92.95% of direct HCEs. The change of energy price in urban areas mitigated the direct HCEs by 61.70%.

3.2.3. Inter-Provincial Comparison

The cumulative contributions of various drivers to the HCEs for each province are exhibited in Figure 12, and the inter-provincial differences are noticeable.

Figure 12. The cumulative contribution of different decomposition factors by province in Central China.

The energy price effect mitigated the growth of direct HCEs in all six provinces from 2000–2017. The absolute value of cumulative contribution of Henan Province was the largest (25.70%), followed by Shanxi (24.21%). The variation of energy prices in Hunan mitigated the smallest direct HCEs (8.11%). This could be explained by the prominent gap of the change rate in average energy prices among provinces. The energy prices of Hunan, Anhui, Jiangxi, Hubei, Henan, and Shanxi increased by 21.86%, 117.46%, 125.17%, 155.55%, 197.57%, and 272.10%, respectively (Figure 13a). The more energy prices rise, the stronger the contribution to carbon reduction will be. Therefore, Hunan Province had the largest flexibility to increase energy prices, while the opposite was true for Henan Province. It indicated that Hunan has a greater potential to reduce the direct HCEs by raising energy prices relative to Henan.

The per capita consumption expenditure effect boosted the growth of direct HCEs in all provinces. The largest contribution to direct HCEs was found in Henan, with a contribution rate of 29.44%. Conversely, the change of the per capita consumption expenditure in Jiangxi contributed the least direct HCEs (9.72%). Shanxi, Hubei, Anhui, and Hunan, whose contribution rates were 21.26%, 19.75%, 19.55%, and 18.46%, respectively. From 2000–2017, the per capita consumption expenditure in Shanxi Province and Jiangxi Province increased by 390.89% and 361.05%, while Hunan Province increased by only 251.65% (Figure 13b). It can be seen that the difference in the per capita consumption expenditure effect was mainly caused by the change of the per capita consumption expenditure for each province.

Figure 13. Variation of various influencing factors of direct HCEs in six provinces from 2000–2017. (a) Energy price; (b) Per capita consumption expenditure; (c) Population size; (d) Urban population share; (e) Energy demand.

The population effect likewise contributed the most strongly to direct HCEs in Henan Province, followed by Shanxi, with cumulative contribution rates of 2.88% and 2.12%, respectively. The pulling effect on direct HCEs was more remarkable than in the other four provinces (Hunan, Jiangxi, Hubei, and Anhui). The population effect made the smallest contribution to Jiangxi, by only 0.76%. From 2000 to 2017, the population of Henan, Shanxi and Jiangxi provinces was increasing year by year. The largest growth rate of population was 14.39% in Henan, and the growth rates of population of Shanxi, Anhui, Hunan, Hubei, and Jiangxi were 14.00%, 12.44%, 11.18%, 4.53%, and 11.41%, respectively (Figure 13c), indicating that the gap of population growth was responsible for the difference of the population effect in the six provinces.

The energy structure effect was only negative in Anhui Province, with a cumulative contribution rate of -1.15% during 2000–2017. This can be explained by the change of energy structure in Anhui reduced the direct HCEs overall. Conversely, the energy structure effect in Shanxi contributed the highest direct HCEs (3.94%), indicating that the shift in Shanxi's energy structure was most unfavorable to the reduction of direct HCEs. Therefore, it is more imperative for Shanxi to adjust the energy structure effectively by reducing the use of fossil energy such as coal and oil and accelerating the development of non-fossil energy sources such as wind energy and nuclear power.

The population urban-rural structure effect only showed a negative effect on direct HCEs in Hunan Province. The contribution rate of the population urban-rural structure effect varied significantly between provinces from 2000–2017. The aggregate contribution of the population urban-rural structure effect in Anhui Province was the highest at 2.64% , followed by Henan Province (2.39%), and Hunan Province had the lowest cumulative contribution of -1.15% . It can be derived that the change of population urban-rural structure in Hunan Province was generally beneficial to mitigating the direct HCEs. In the survey period, the share of urban population in Henan province increased from 23.20% to 50.16% , with an increase of 116.23% , while the proportion of urban population in Hunan province increased from 29.75% to 33.54% , with a growth rate of only 12.73% (Figure 13d). Thus, it can be seen that the inter-provincial differences in the contribution of population urban-rural structure effect were mainly caused by the different change rates of the urban population share in each province.

The energy demand effect showed the strongest impact on the direct HCEs growth in Shanxi Province (11.51%), and the smallest impact on the increment of direct HCEs in Jiangxi Province (6.97%). The effect of energy demand in Hubei, Henan, Hunan, and Anhui contributed 10.74% , 10.52% , 10.36% , and 9.81% to total change of direct HCEs, respectively (Figure 12). Energy demand in Shanxi Province increased from 10.01% in 2000 to 18.39% in 2017, with a growth rate of 83.65% . The change rates of energy demand in Hubei, Henan, Hunan, Anhui, and Jiangxi were 49.89% , 33.04% , 60.71% , 86.15% , and 72.39% , respectively (Figure 13e). This difference was mainly due to the different extent of variation in the share of residential energy consumption between provinces.

4. Conclusions and Suggestions

4.1. Main Conclusions

Taking Central China in the 2000–2017 years as an example, we analyzed the characteristics and driving factors of the direct HCEs from three perspectives. The urban-rural differences and inter-provincial comparison were highlighted. The conclusions are set out below.

From 2000 to 2017, total direct HCEs increased at an average annual growth of 7.00% from 9596.20×10^4 tonnes to $30,318.35 \times 10^4$ tonnes. Electricity and coal consumption were the primary sources. The direct HCEs in both urban and rural rose continuously. The growth amount and rate of urban direct HCEs were all higher than those from rural areas. The urban-rural gap of direct HCEs narrowed during 2000–2006 and then widened after 2006. There were also significant differences in the structure of direct HCEs between urban and rural areas. The share of CO_2 emissions generated by coal consumption in rural areas was higher than that in urban, whereas CO_2 emissions from oil, natural gas, heat, and electricity use were the opposite. From the perspective of inter-provincial comparison, the direct HCEs in the six provinces were all on the rise, while the growth rate and amount differed significantly. Among these, Henan, Shanxi, Hubei, Hunan, Anhui, and Jiangxi occupied 24.71% , 18.52% , 17.12% , 15.98% , 15.11% , and 8.56% , respectively, in the order of cumulative value. The difference in the amount of direct HCEs among provinces was decreasing.

Overall, the effects' contribution of energy structure, energy price, energy demand, per capita consumption expenditure, population urban-rural structure and population were 8.41% , -102.44% , 59.90% , 118.19% , 6.54% , and 9.40% , respectively. The results indicated

that the growth in per capita consumption expenditure was the most prominent driver behind the increase of direct HCEs in Central China, followed by energy demand. The effects of population size, energy structure and population urban-rural structure had less impact on the growth of direct HCEs. However, energy price presented the most obvious mitigation effect. From the perspective of urban-rural differences, the effects of per capita consumption expenditure and energy structure had a greater impact on direct HCEs in rural areas than in urban among the contributing factors, whereas the energy demand effect and the population size effect were the opposite. The energy price effect was the greater disincentive on urban areas than on rural. The effect of population urban-rural structure promoted the growth of direct HCEs in urban areas, whereas the opposite was true for rural. There were also some variabilities in the extent to which the same driving factor affected different provinces.

4.2. Discussion

It would be meaningful to compare the results of this paper with previous studies. First of all, the direct HCEs had an obvious growth trend in Central China, with an average annual growth of 7.00%. On the other hand, the direct HCEs of China increased by $51,883 \times 10^4$ tonnes during 1996–2012 [19], and the direct HCEs in China grew at an average annual rate of 7% from 2000–2015 [40]. Therefore, it can be seen that the growth rate of total direct HCEs in Central China is similar to that of the whole of China. Additionally, coal and electricity consumption were the main sources of HCEs. The cumulative share of CO₂ emissions from electricity and coal during 2000–2017 accounted for 46.55% and 34.99% of the total HCEs in Central China. Nationally, the total share of CO₂ emissions from coal and electricity ranged from 45.7% to 61.4% [45]. Moreover, the direct HCEs and growth rate in urban areas were higher than those in rural areas, and the urban-rural differences were significant, which was in line with Li et al. [19] and Feng et al. [33]. From a single year, the direct HCEs in Central China were $26,535.65 \times 10^4$ tonnes in 2015, accounting for approximately 22.85% of the national direct HCEs ($11,6120 \times 10^4$ tonnes) [40].

The LMDI decomposition analysis was then applied to investigate the factors that might affect the changes of the direct HCEs. The decomposition results in Central China were similar to those of Zha et al. in the whole of China [45]. They both indicated that the energy price (energy intensity) and per capita consumption expenditure (income) effects contributed most to the decline and the increase of CO₂ emissions, respectively. Other factors had less impact on the growth of CO₂ emissions. However, our decomposition results differed from those in Guangdong Province [35]. The first promoting factor to HCEs in Guangdong were population size (1996–2004) and energy use level (2005–2016). The carbon emission coefficient was the main inhibiting factor. This fact could be explained by the differences in the level of economic development and resource endowments between regions.

In addition, there are some limitations in this paper. Only six driving factors affecting the direct HCEs in Central China were explored, specifically energy structure, per capita consumption expenditure, energy price, energy demand, population urban-rural structure, and population size. However, direct HCEs may be influenced by the number of households [48], temperature, Engel coefficient [30], demographic structure [48], and other socioeconomic factors. Thus, in our future work, these factors to the direct HCEs should be given greater attention.

4.3. Suggestions

Based on these results, some particular countermeasures and suggestions for sustainable household energy consumption of Central China are put forward and listed as follows.

First, the energy prices should be adjusted appropriately. The energy price effect was the biggest factor in mitigating the direct HCEs. It indicated that the deregulation of energy prices in the above text was an effective scientific way to realize energy conservation

and emission reduction. The corresponding energy prices need to be further adjusted by government appropriately, especially the price of energy with a high emission coefficient. The six provinces should develop different policies for adjusting energy prices based on respective development characteristics, particularly those provinces that are greatly affected by fluctuations in energy price, such as Hunan Province, which needs to raise energy prices appropriately.

Additionally, the residents' consumption should be upgraded to a green and sustainable pattern. The effect of per capita consumption expenditure had the most impact on the growth of direct HCEs in Central China. With the development of economy and the improvement of residents' living standard, the government should advocate the shift of residents' consumption patterns to green and sustainable, and reasonably control the growth rate of transportation and energy-intensive devices. Some measures can be implemented. For example, the charging model of residential energy consumption needs to be adjusted, the energy-saving standards for household appliances need to be popularized, and the energy-saving behavior patterns need to be promoted and publicized with the aid of the media.

Next, population size and low-carbon urbanization should be reasonably controlled. The growth of direct HCEs in Central China has been less influenced by population size and population urban-rural structure. However, the net population continues to rise due to the large population base and the liberalization of the three-child policy in this region. Consequently, the government should control population growth within a reasonable range. This is particularly true for provinces with a large population, such as Henan Province. In addition, the urban pattern should be scientifically designed in the process of urbanization, and the development of low-carbon infrastructure should be encouraged. Meanwhile, raising people's awareness of energy conservation is an important goal in the cultivation of urbanized humanities. The urbanization can be developed along the new direction of intensive, green and low-carbon.

Lastly, the household energy structure should be optimized and the development and use of clean energy should be accelerated. Greater efforts should be made to optimize the household energy structure by reducing the use of coal and developing the use of natural gas, especially in rural areas, and encouraging the use of renewable energy. From the perspective of the emission structure of each province, the modification of Anhui's energy structure was most conducive to the reduction of CO₂ emissions. Shanxi Province needs to cut the use of fossil energy such as coal and oil, and accelerate the development of non-fossil fuel energy such as wind and nuclear, in comparison to other the five provinces.

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Appendix A

Table A1. Carbon emission coefficients and standard coal coefficients for each energy type.

Energy Type	Emission Coefficient (t-CO ₂ /t)	Standard Coal Coefficient (Kg ce/kg)
Raw coal	1.977	0.7143
Cleaned coal	2.488	0.9000
Other washed coal	0.795	0.2857
Briquettes	1.717	0.6000
Coke	3.019	0.9714
Coke oven gas	7.421 ¹	0.5714 ²
Blast furnace gas	3.019 ¹	0.1286 ²
Converter gas	3.524 ¹	0.2714 ²
Other gas	2.319 ¹	0.1786 ²
Gasoline	3.185	1.4714
Kerosene	3.153	1.4714
Fuel oil	3.126	1.4286
Diesel oil	3.185	1.4571
Lubricants	2.948	1.4143
Bitumen asphalt	—	1.3100
Liquefied petroleum gas (LPG)	2.983	1.7143
Refinery gas	2.850	1.5714
Other petroleum products	2.948	1.2000
Natural gas	21.840 ¹	1.3300 ²
Liquefied natural gas (LNG)	2.836	1.7572

¹ The unit is t-CO₂/10⁴ m³, ² the unit is Kg ce/m³.

Table A2. Average CO₂ emission factor per unit of power supply in six central provinces.

Province	Shanxi	Henan	Anhui	Hubei	Hunan	Jiangxi
Emission coefficient	1.246	0.801	0.928	0.801	0.801	0.801

Note: The unit is kg/kw·h.

Table 3. Decomposition results of direct HCEs in Central China (10⁴ tonnes).

Periods	ΔC_{ES}	ΔC_{EP}	ΔC_{ED}	ΔC_{PC}	ΔC_{PS}	ΔC_P	ΔC_{TOT}
2000–2001	202.20	−921.04	299.34	513.11	86.35	60.16	240.12
2001–2002	85.23	−142.38	−258.34	826.14	79.40	59.04	649.08
2002–2003	137.37	622.70	−570.99	470.91	81.67	59.06	800.73
2003–2004	241.47	−220.50	−678.76	707.93	102.12	−213.81	−61.56
2004–2005	−62.79	1044.13	−263.93	1239.81	37.83	353.92	2348.98
2005–2006	398.85	−2087.24	738.53	1441.12	111.31	72.00	674.56
2006–2007	84.63	−1442.48	514.79	1363.59	76.03	83.08	679.63
2007–2008	0.94	−421.79	918.81	734.18	76.64	86.05	1394.83
2008–2009	285.09	−2175.40	1749.22	1475.69	63.05	91.75	1489.40
2009–2010	165.72	168.09	−869.38	1116.36	146.59	457.95	1185.32
2010–2011	−22.13	1197.31	−1149.62	2108.72	116.51	117.77	2368.55
2011–2012	54.67	−876.57	860.86	2115.31	75.67	105.83	2335.77
2012–2013	−106.05	−3292.00	1581.21	1818.44	57.90	73.38	132.87
2013–2014	−351.91	−10,702.11	8549.70	3095.71	42.55	110.96	744.90
2014–2015	16.18	608.76	−331.13	1787.93	−249.58	124.09	1956.25
2015–2016	793.38	−2316.14	893.60	1982.69	200.02	202.59	1756.15
2016–2017	−179.28	−271.70	429.13	1693.17	250.39	104.84	2026.55
2000–2017	1743.56	−21,228.36	12,413.03	24,490.81	1354.44	1948.67	20,722.15
2000–2005	603.48	382.90	−1472.68	3757.91	387.37	318.37	3977.36
2005–2010	935.23	−5958.82	3051.96	6130.93	473.62	790.83	5423.75
2010–2015	−409.25	−13,064.61	9511.01	10,926.11	43.05	532.04	7538.34
2015–2017	614.10	−2587.84	1322.74	3675.86	450.41	307.43	3782.70

Table 4. Decomposition results of direct HCEs of urban areas in Central China (10^4 tonnes).

Periods	ΔC_{ES}	ΔC_{EP}	ΔC_{ED}	ΔC_{PC}	ΔC_{PS}	ΔC_P	ΔC_{TOT}
2000–2001	48.92	−884.94	87.95	262.40	123.45	28.93	−333.28
2001–2002	141.23	225.20	−478.95	481.18	203.33	27.99	599.99
2002–2003	130.84	−267.89	−30.27	308.34	167.64	28.14	336.80
2003–2004	49.52	100.53	−394.98	271.66	318.20	−108.96	235.98
2004–2005	−148.32	715.31	−76.85	534.35	73.40	192.97	1290.86
2005–2006	201.34	−784.87	−78.79	645.89	254.15	36.44	274.16
2006–2007	6.97	−200.89	−248.05	713.16	219.61	42.51	533.31
2007–2008	−137.76	253.95	174.39	223.95	239.16	44.09	797.77
2008–2009	153.52	−1019.54	626.42	883.02	217.87	46.60	907.89
2009–2010	−130.81	104.27	−128.33	637.04	361.30	227.70	1071.17
2010–2011	−41.60	924.27	−1170.68	889.20	383.71	64.16	1049.05
2011–2012	−24.71	−272.24	198.24	864.27	368.42	55.47	1189.45
2012–2013	78.01	−2292.42	1487.86	795.20	288.59	40.45	397.69
2013–2014	−249.94	−8300.18	7864.60	679.59	274.03	60.25	328.35
2014–2015	37.81	989.25	−370.34	838.92	−662.77	67.34	900.20
2015–2016	401.02	−1862.68	634.05	955.90	562.38	106.04	796.71
2016–2017	−82.85	−212.76	297.08	882.92	699.99	58.99	1643.38
2000–2017	433.18	−12,785.62	8393.35	10,866.99	4092.47	1019.10	12,019.48
2000–2005	222.19	−111.78	−893.09	1857.93	886.02	169.07	2130.35
2005–2010	93.26	−1647.08	345.64	3103.05	1292.10	397.34	3584.30
2010–2015	−200.44	−8951.32	8009.68	4067.18	651.98	287.66	3864.74
2015–2017	318.17	−2075.44	931.13	1838.82	1262.37	165.03	2440.09

Table 5. Decomposition results of direct HCEs of rural areas in Central China (10^4 tonnes).

Periods	ΔC_{ES}	ΔC_{EP}	ΔC_{ED}	ΔC_{PC}	ΔC_{PS}	ΔC_P	ΔC_{TOT}
2000–2001	153.27	−36.10	211.39	250.71	−37.10	31.24	573.40
2001–2002	−56.00	−367.59	220.61	344.96	−123.93	31.05	49.09
2002–2003	6.53	890.59	−540.72	162.57	−85.96	30.93	463.93
2003–2004	191.95	−321.04	−283.78	436.27	−216.08	−104.86	−297.54
2004–2005	85.54	328.82	−187.07	705.46	−35.58	160.95	1058.12
2005–2006	197.51	−1302.37	817.32	795.23	−142.85	35.56	400.40
2006–2007	77.66	−1241.58	762.84	650.43	−143.58	40.57	146.33
2007–2008	138.70	−675.74	744.42	510.24	−162.52	41.96	597.07
2008–2009	131.57	−1155.86	1122.80	592.67	−154.82	45.15	581.51
2009–2010	296.53	63.82	−741.05	479.31	−214.71	230.25	114.14
2010–2011	19.47	273.05	21.06	1219.52	−267.20	53.61	1319.51
2011–2012	79.38	−604.33	662.62	1251.04	−292.75	50.36	1146.32
2012–2013	−184.06	−999.58	93.34	1023.25	−230.69	32.93	−264.82
2013–2014	−101.97	−2401.93	685.10	2416.12	−231.48	50.71	416.55
2014–2015	−21.62	−380.49	39.21	949.00	413.19	56.76	1056.05
2015–2016	392.36	−453.46	259.56	1026.79	−362.36	96.55	959.44
2016–2017	−96.44	−58.94	132.05	810.25	−449.60	45.85	383.17
2000–2017	1310.37	−8442.75	4019.67	13,623.82	−2738.03	929.57	8702.67
2000–2005	381.29	494.68	−579.59	1899.98	−498.65	149.31	1847.01
2005–2010	841.97	−4311.74	2706.33	3027.88	−818.48	393.49	1839.45
2010–2015	−208.81	−4113.29	1501.33	6858.93	−608.93	244.37	3673.61
2015–2017	295.92	−512.40	391.61	1837.04	−811.96	142.40	1342.61

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