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Energy consumption and carbon footprint accounting of urban and rural residents in Beijing through Consumer Lifestyle Approach

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ABSTRACT

Household carbon emissions are major contributors to global emissions that is increasing recognized. In China, approximately 20 million rural populations transfer to the urban areas annually, which results in a lot of new infrastructure construction and consumer requirements. This paper quantifies the numbers and trends of urban and rural resident on energy use and carbon footprint in Beijing from 1996 to 2011 by analysis of Consumer Lifestyle Approach (CLA) and carbon footprint. It provides a better understanding of complete energy consumption and carbon emissions profile in Beijing. The results show that for the Beijing residents, when direct and indirect energy consumption and CO_2 emissions are taken into account, the total household energy consumption proportion compared to the city increases from 22.7% to 59.2%, and the total household CO_2 emissions proportion increases from 32.2% to 68.8% in the research period. In the urbanization process, total energy consumption and carbon emissions of Beijing urban residents are significantly higher than those of rural residents. However, the transformation of a rural Beijing resident into an urban Beijing resident would not create a large difference between urban and rural areas in the per-capita energy consumption and per-capita carbon footprint. Results are assessed with respect to the available scientific literature, as well as potential available technological and policy solutions. Since the implementation that different policy instruments can mitigate carbon emissions, governments are gradually combining policy measures for the same technology. The results in this paper may help promote alternative consumption strategies in household sector which could entail more reasonable resource distribution and effective reduction of both urban and rural environmental influences.

1. Introduction

The Intergovernmental Panel on Climate Change warned about GHGs emissions global dangers to people and ecosystems (IPCC, 2014). Human energy consumption radically revamped Earth's carbon cycle. Globally, household energy use takes up 22% of global energy consumption (70 EJ) annually in the mid-1990s, which is second only to industrial energy consumption (IEA, 2000). This growth is projected to continue over the next 20 years (IEA, 2010). Household energy use occupied three-quarters of total energy consumption in India (Pachauri and Spreng, 2002), 80% for the US (Shui and Dowlatabadi, 2005) and 61% for Japan (Nansai et al., 2012). In parallel, household carbon emissions (HCEs) are major contributors to global emissions (Maraseni et al., 2015; Yuan et al., 2015). For example, the proportion of household emissions to the national emissions is 20% in Australia, 40% in China (Liu et al., 2011), 74% in the UK (Baiocchi et al., 2010) and over 80% in the USA (Jones and Kammen, 2011; Shui and Dowlatabadi, 2005). Therefore, the global climate mitigation mission cannot be achieved without combating household emissions.

With the development of household living standards, the increasing energy consumption and carbon emission of households has gradually turned into one of the hot research subjects in recent years, which have been widely conducted at national (Allinson et al., 2016; Jones and Kammen, 2011; Li et al., 2015; Long et al., 2017; Markaki et al., 2017), regional (Li et al., 2016; Qu et al., 2013; Tian et al., 2016) and urban scale (Allinson et al., 2016; Gu et al., 2013; Yang et al., 2013).

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Household expenditure or income level, population, lifestyle, household size are main influencing factors in household energy consumption and carbon emissions found by these works. Moreover, indirect household energy consumption and carbon emissions are higher than direct ones, while urban ones are more than rural ones.

Urbanization is considered as one of the key influencing factors for these parameters in the case of China (Li et al., 2015). China urbanization has increased from 19.39% of total population living in urban areas in 1980 to 54.77% in 2014 (Yang et al., 2016). The urban population in China is projected to 1 billion by 2030 (Zhu et al., 2011). With the rapid economic development, the household energy consumption has reached 3617.30 Mtce in 2012 from 987.03 million tons of coal equivalent (Mtce) in 1990 (Sun et al., 2014). The National Bureau of Statistics in China reported an increase of average urban living area per capita from 24.5 m^2 in 2002 to 32.9 m^2 in 2014. Meanwhile, the number of private cars increased more than 23.5 times. In addition, a series of obvious changes are happening in people, living standards, employment patterns, consumer behavior and similar sociological indicators. Therefore, it is urgent to address the overall problem to develop appropriate sectoral energy policies.

China, being a socially diverse country, has still a typical binary economy, although the urban–rural gap is becoming gradually smaller (Wei et al., 2007). Rural households still use the straw, wood, coal and other traditional and locally polluting energy carriers, even if gradually substituted by electricity and natural gas. In parallel, modern energy carriers represented by electricity, natural gas and LPG are dominant in urban areas (Fan et al., 2013; Zhao et al., 2011). This is why the assessment should be conducted both for households of urban and rural residents.

In China, annually about 20 million rural populations transfer to the urban areas, which results in extensive new infrastructure and housing requirements (Feng and Hubacek, 2016). This migration, obviously, implies a huge effect on both energy use and carbon emissions. In particular, two main implication exist with respect to this phenomenon: direct energy requirement for electricity, oil and natural gas will grow, due to the consuming behavioral change in rural areas (e.g.: lighting, cooking, showering and heating); due to the increased income level in urban and rural areas, the indirect energy use embodied in the production of all commodities consumed by households will increase (e.g.: furniture, food, clothes, services, etc.) Two income-related drivers should be considered in this framework (Wei et al., 2007; Hubacek et al., 2009): enhanced living level of rural residents will entail greater demand and increases for durable consumer goods (e.g.: refrigerators, cars, computers and other fast moving consumer goods); the increased income will change the living consumption structure for urban residents. Consequently, the transformation of urban -rural lifestyles and consumption structure could exert an important impact on future energy use and carbon emissions.

As a premise to the research on energy use and carbon emissions, the term “household carbon emission” should be defined and the present state-of-the art should be assessed. Household carbon emissions are defined as “the emissions emitted by individuals or their families so as to satisfy the requirements of their existence and development in the particular socio-economic situation, including both direct and indirect emissions” (Qu et al., 2013). More in detail, direct emissions refer to emission from energy consumption, such as electricity, heating, gas and other liquids, for consumer goods in a household. Indirect emissions refer to the emissions embodied in the production of all other consumer goods for households, for instance the emissions from the manufacture process of clothes, food, furniture, services, etc. (Liu et al., 2011).

Data analyses can be approached through different quantification methodologies, including Input-Output Analysis (IOA), life Cycle Assessment (LCA), Emission Coefficient Method (ECM) and Consumer Lifestyle Approach (CLA) (Zhang et al., 2015). IOA was often applied to account the embodied carbon emissions from main materials and services consumed by households (Brizga et al., 2017; Long et al., 2017; Meng et al., 2017a). This fraction is relevant, amounting at 45–55% of total, depending on consumer activities (Feng et al., 2011). ECM was employed to assess direct household carbon emissions (Fan et al., 2013). Finally, CLA is an integrated approach, combining ECM and IOA, to account the full household carbon emission including direct and indirect emissions (Shui and Dowlatabadi, 2005; Liu et al., 2011).

An integrated evaluation framework is constructed by CLA. It definitely considers the interconnected factors that affect household lifestyle including individual determinants, external environmental variables, residential features, consumption option and consequences (Zhang et al., 2015; Zhang and Wang, 2017). In this study, Beijing is selected as the case, being the China’s epitome, which best integrates the enhancement of urban and rural household lifestyle with the rapid urbanization trend in China. In particular, CLA is used to assess the household energy use and carbon emissions so as to provide a better understanding of complete energy use and carbon emissions profile in Beijing. This evaluation can facilitate decision-makers to set rational carbon reduction policies of household sector.

The paper explores the following science questions: (1) What is the situation of household energy use and carbon emissions in Beijing for the years period 1996–2011? (2) How do we study the urban and rural residents’ lifestyle change impacts on energy consumption and carbon emissions? (3) What are the most energy/carbon-intensive consumption behaviors? To address those topics, the paper is structured as follows. Section 2 describes data sources, the methods used to account direct and indirect household energy use and carbon emissions. Section 3 presents the current situation of household energy consumption and carbon emissions in Beijing from 1996 to 2011, analyzing the changing trends for the direct and indirect energy consumption and carbon emissions induced by rural and urban households, discussing the results and policy implications. Section 4 draws conclusions.

2. Methods and data

2.1. CLA methods

Underlying the analysis of carbon footprint and CLA model framework, the study takes into account all CO_2 emissions which derive from direct energy usage and indirect embodied energy used in the production of goods and services to satisfy Beijing resident demand. Direct household energy consumption refers to the energy directly consumed by residents to meet their daily energy consumption demands, resulting in direct carbon emissions. Indirect household energy consumption is defined here as the energy use associated with producing goods and providing services for residents in a household, limitedly to when these goods and services are purchased by residents, resulting in indirect carbon emissions.

Carbon emissions associated with direct household energy consumption include those from fossil fuels (coal, oil, and natural gas) consumed for household lighting, cooking, heating, electrical appliances, as well as private transportation. Large amounts of fossil fuels are consumed during electricity and heat production. Therefore, heat and electricity consumed by residents are included in direct household energy consumption. In addition, fuels, such as gasoline and diesel oil, are consumed, when residents travel by cars and motorcycles. Thus, these related emissions are classified under direct household energy use.

Carbon emissions associated with indirect household energy consumption are produced by energy used in the production, processing, transportation, and use of non-energy goods and services, which residents consume due to basic necessities. For convenience of calculation and comparison, only energy consumption and carbon emissions from upstream processes are considered (e.g.: production, processing, manufacturing, and transportation of non-energy goods and services). Instead, energy consumption and carbon emissions from downstream use and disposal processes are excluded.

Fig. 1 summarizes the classification of household energy

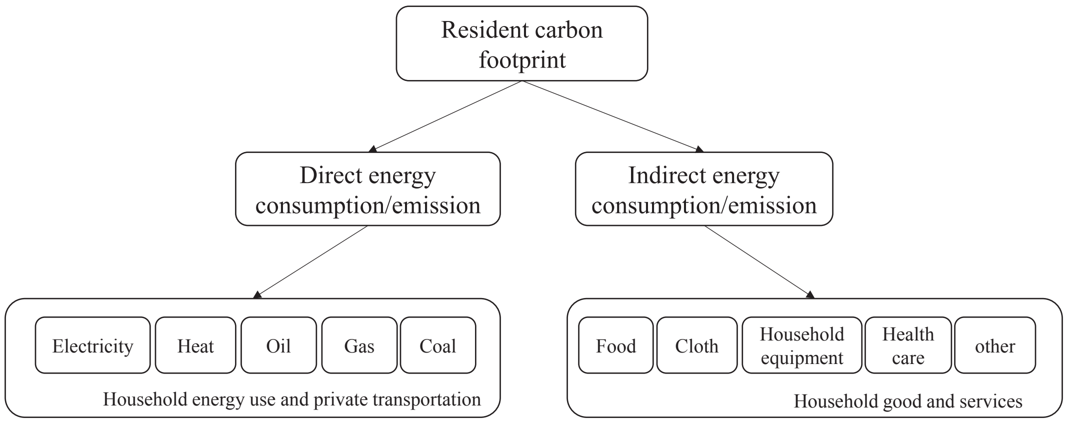

Fig. 1. Boundary map of resident carbon footprint.

consumption in combination with carbon emission sources.

Household energy consumption, defined by Eq. (1), is composed of two parts: direct household energy consumption and indirect household energy consumption:

$$E = E_{dir} + E_{emb} \tag{1}$$

where E represents household energy consumption, E_{dir} represents direct household energy consumption, and E_{emb} represents indirect household energy consumption.

In the same way, household carbon emissions (Eq. (2)) consist of direct household carbon emissions and indirect household carbon emissions:

$$C = C_{dir} + C_{emb} \tag{2}$$

where C represents household carbon emissions, C_{dir} represents direct household carbon emissions, and C_{emb} represents indirect household carbon emissions.

2.2. Data of direct household energy consumption and carbon emissions in Beijing

Data of various types of physical energy directly used by urban and rural residents are taken from energy balance table in the Beijing Statistical Yearbooks of the years' period 1996–2011. Expenditure data specific to each consumption category, as well as population data, are also obtained from the above statistical source. Current-price expenditures between 1995 and 2011 were converted into expenditures at the reference price of year 1990. This is done to allow a time comparison for energy consumption and carbon emission intensities.

Energy used directly in urban households in Beijing includes coal, natural gas, liquefied petroleum gas, coal gas, gasoline, diesel oil, electricity, and heat. Coal gas exited in the energy market in year 2006. Compared to urban households, rural households consume less types of energy: mainly coal, gasoline, and electricity. Emissions from electricity and heat, viewed from both production and consumption perspectives, are usually categorized as implicit carbon emissions. However, in household-related studies, they are often regarded as direct sources of emissions (Dong and Geng, 2012). The carbon emissions from direct household energy consumption (Eq. (3)) are calculated by the equation below:

$$C_{dir} = \sum_{i=1}^{n} F_i \times E_i \tag{3}$$

where F_i represents the physical consumption of i energy sources and E_i represents the carbon emissions of i energy sources. Based on China's national and provincial greenhouse gas inventories, the local emissions factors for Beijing were obtained by considering the fuel heat value and oxidation rate for fuel sources in Beijing, as shown in Table 1.

2.3. Data of indirect household energy consumption and carbon emissions in Beijing

Indirect energy consumption refers to the energy use associated with producing goods or providing services for residents when these goods or services are purchased by residents. At present, three methods, namely mixed energy analysis, household metabolism, and consumer lifestyle analysis, are used to assess indirect household energy consumption and indirect carbon emissions. These methods focus on the calculation and assessment of indirect energy consumption, and are all based on the input–output model (Zhu et al., 2011).

This study used the input–output model to perform carbon footprint calculations. Principally formulated by Leontief in the 1930s, input–output analysis requires a checkerboard pattern input–output table and the establishment of a corresponding linear algebraic equation system, in order to describe the product flows through the economy. The input–output model can quantitatively reflect the interdependence among various economic sectors and facilitate the study of household energy consumption and carbon emissions. The basic expression of the input–output model is as follows:

$$E = F(I - A)^{-1}Y \tag{4}$$

where E is the indirect household energy consumption or carbon emissions; F is the energy intensity or carbon emission intensity of each industry in the $n \times n$ input–output table; A is the direct consumption coefficient in the input–output table; $(I - A)2^{-1}$ is a Leontief inverse matrix, which represents the complete input of all industries required for the unit output of each industry; Y is the final demand.

Indirect energy consumption is associated to the indirect impacts on energy consumption and carbon dioxide emissions. These include food, household appliances and services, clothing, medical services, housing, education and cultural and recreational services on energy consumption and carbon dioxide emissions. A method, previously used to assess the indirect energy consumptions, is applied, due to the fact that the available categories within the Beijing Statistical Yearbook are different from the ones applied here (Wei et al., 2007; Feng et al., 2011). Specifically, eight sectors related to household expenditures were chosen. Then, similar sectors in the statistical yearbook were incorporated into household expenditure categories. Finally, the indirect energy consumption and carbon emissions generated in each of the categories were separately calculated. The categories of the sectors are listed in Table 2.

Main data of indirect energy consumption and carbon emissions came from Beijing's input–output tables for the relevant years. Since the input–output tables were developed, based on the prices of corresponding years, the price fluctuation factor was considered. Using the price of 1990 as the benchmark, the producer price index method was used to obtain the revised input–output tables for 1997, 2002, and

Table 1
Direct emission factors of residential energy consumption.

	Coal (t/t)	Gasoline (t/t)	Diesel (t/t)	Liquefied petroleum gas (LPG) (t/t)	Natural gas (t/km^3)	Heat (t/GJ)	Electricity (t/MWh)
Direct emission factors	1.82	3.03	3.23	3.13	2.43	0.118	1.02

2007. Industry categories varied between the input–output and the final energy consumption table. Thus, a comparative analysis between the energy balance sheet and the industrial subsector final energy consumption table is performed. All sectors were merged into 34 groups, which could be compared in parallel. The input–output direct consumption coefficient matrix was recalculated for the 34 sectors. Then, the complete consumption coefficient matrix was calculated. Finally, the household consumption was multiplied by the complete consumption coefficient matrix to obtain the indirect household energy consumption and carbon emissions for all the 17 years. The calculation of the indirect carbon footprint excluded household fuel from the housing-associated expenditures and excluded transportation fuel from the transport and communications expenditures. This choice depends on the fact that household energy consumption (e.g.: electricity, heat, natural gas, and vehicle oil) was already calculated in the direct carbon footprint.

3. Results and discussion

3.1. Direct household energy consumption and carbon emissions in urban and rural areas in Beijing

3.1.1. Background information on direct household energy consumption and carbon emissions in Beijing

Direct carbon emissions caused by energy consumption in urban and rural areas of Beijing are represented in Fig. 2. In the last two decades, direct household energy consumption in Beijing has grown continuously. From 1995 to 2011, it increased by 1.9 times, from 4,385,000 tons of standard coal to 12,559,000 tons of standard coal, with an average annual growth rate of 7.0%. Direct household energy consumption per capita also rose by 77.4%, from 350.8 kg of coal to 622.2 kg of coal, with an average annual growth rate of 3.8%. During this period, growth rates of direct energy consumption both for all households and per capita had similar trends. In parallel, the growth rate of direct energy consumption per capita was lower than the total direct energy consumption.

The period from 2000 to 2007 witnessed the highest growth rates of the total and per-capita direct household energy consumption, with the annual growth rates exceeding 10.3% and 6.4%, respectively. This was closely related to the strong economic growth in Beijing in the meantime. Household energy consumption was driven by the rapid growth of the economy and living standards, the acceleration of urbanization, the improvement of housing conditions and the increase of purchases of high-end consumer goods such as private cars. After 2007, the growth rates of both total and per-capita direct household energy consumption dropped. It was attributed to the shortage in transport of coal, electricity, and oil in 2005. In parallel, also the demand for lower consumption of energy resources and higher utilization efficiency grew. Energy-saving emission reduction targets and tasks were deployed in the outline of Beijing's 11th Five-year Plan. Another reason for such a drop was the 2008 Summer Olympic Games. In fact, in this occasion, household consumption patterns were driven toward energy-saving and lower carbon emissions under the guidance of the concept of green Olympics.

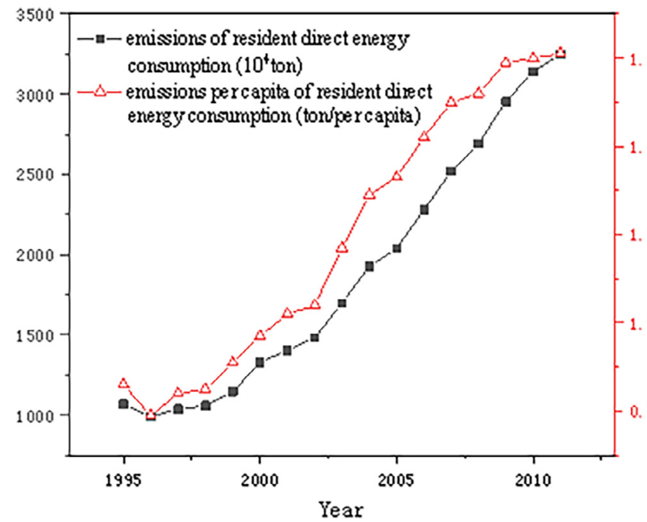

Fig. 2. CO_2 emission of direct resident energy consumption and energy consumption per capita in Beijing.

The growth of household carbon emissions was even more apparent. From 1995 to 2011, the total carbon emissions arising from direct household energy consumption of Beijing increased by 2 times, from 10,705,000 tons of carbon to 32,498,000 tons of carbon, with an average annual growth rate of 7.3%. The carbon emissions arising from direct household energy consumption per capita rose by 87.2%, from 0.86 tons to 1.61 tons, with an average annual growth rate of 4.1%. The growth trends of total and per-capita direct household carbon emissions were similar to those of total and per-capita direct household energy consumption, respectively. The growth rate of per-capita carbon emissions was lower than that of total carbon emissions.

From 1995 to 2011, the household energy consumption structure of

Table 2
Classification of residential consumption and industrial sectors.

No.	Residential consumption	Industrial sectors
1	Food	Food processing industry, food manufacturing and tobacco processing industry, beverage manufacturing industry
2	Clothes	Textile industry, leather & fur manufacturing industry
3	Living	Power, thermal production and supply industry, non-metallic ore and other mining industry, metal mining industry, construction industry
4	Household facilities and services	Wood processing and furniture manufacturing industry, electrical machinery and equipment manufacturing industry
5	Education cultural entertainment service	Paper printing and culture and education goods manufacturing industry, scientific research, technical services and geological survey, education, public administration and social organization
6	Medical care	Chemical industry
7	Transportation & communication	Transportation equipment manufacturing industry, transportation and warehousing and postal services industry
8	Other commodities and services	Wholesale and retail industry, accommodation and catering industry

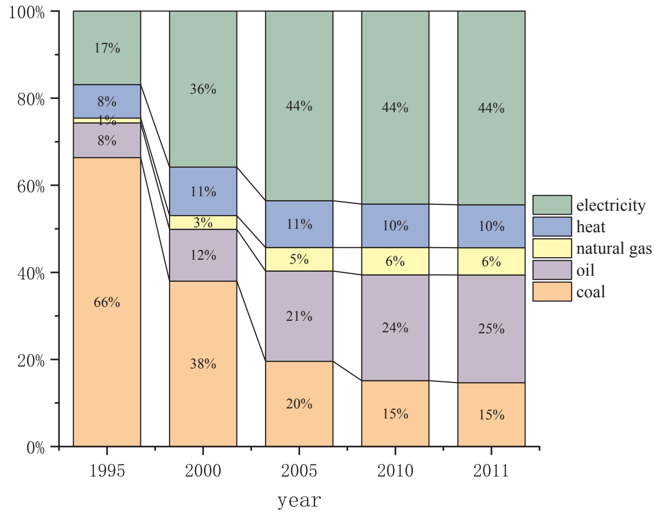

Fig. 3. The proportion of CO_2 emission of direct household energy consumption.

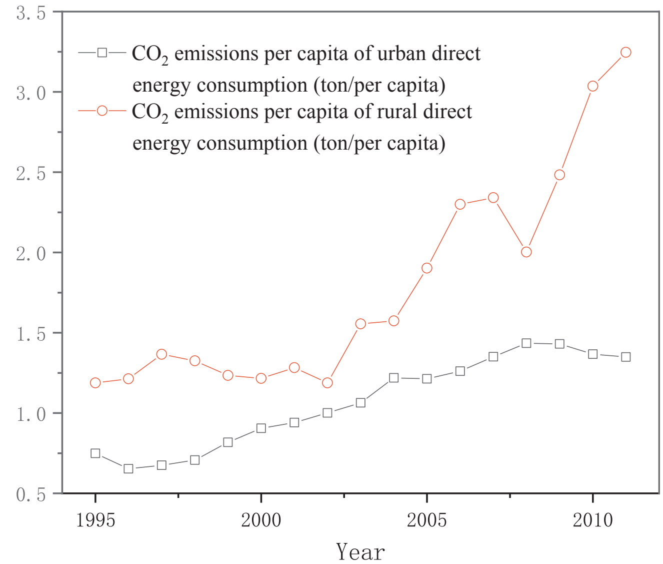

Fig. 4. Historical changes in CO_2 emission per capita of urban and rural residents.

Beijing was gradually optimized. The proportion of coal consumption dropped from 69.6% to 15.9%, while that of electricity consumption rose from 12.4% to 34.8%. Clean energy, such as electricity and natural gas played a key role in eliminating the coal-dominated consumption from the 1990s. In addition, due to the improvement of the household consumption levels, household owned cars and oil consumption continuously increased.

Comparing energy consumption with carbon emissions, per-capita direct household energy consumption in Beijing increased by 77.4% from 1995 to 2011, while per capita carbon emissions increased only by 6.0% in the same period. While urban population increased, the continuous improvement of the household energy consumption structure and the development of renewables use partially offset the growth rate of carbon emissions, leading to small growth in per-capita carbon emissions. The urban per capita coal consumption decline, from 243.9 kgce in 1995 to 98.9 kgce in 2011, in parallel with the increase in electricity consumption per capita, which grew from 43.4 kgce in 1995 to 215.1 kgce in 2011, confirms the validity of this statement.

The structure of household carbon emissions, represented in Fig. 3, changed together with the household energy consumption structure. Carbon emissions from coal combustion accounted for approximately 66.4% of the total emissions in 1995 and dropped to only 14.7% in 2011. Oil and electricity consumption have become the main sources of household carbon emissions. In 2011, carbon emissions from these two sources amounted to 69.2% of the total emissions, i.e. 44% higher than in 1995 (25.2%).

The proportion of direct household energy consumption with respect to the city's total energy consumption showed an upward trend in the period from 1995 to 2011, with the lowest proportion at 10.7% (1996) and the highest at 18.0% (2011). The proportion of direct household carbon emissions with respect to the city's total carbon emissions also showed an upward trend, with the lowest proportion at 15.5% (2002) and the highest at 20.5% (2011). This fact demonstrates that Beijing's urban household energy consumption and carbon emissions are important factors in the growth of the city's total energy consumption and carbon emissions.

These results are contrary to the findings of a Chinese urban household study previously conducted by Ge and Fang (2011). China is still a developing country. At the national level, the increase in direct household energy consumption and carbon emissions were much lower than that of industrial energy consumption and carbon emissions. Therefore, the proportion of national household energy consumption within the national total energy consumption continued to decline, along with the proportion of national household carbon emissions in the national total carbon emissions. However, according to statistics derived from 2011 from the Beijing Municipal Bureau of Statistics, Beijing's GDP per capita ranked first in China, while its residential income level was close to that of most developed countries. This fact shows that households had an increasingly higher demand for energy and produced increasingly higher carbon emissions in big cities, such as Beijing.

3.1.2. Comparison of direct household energy consumption and carbon emissions between urban and rural areas

Significant differences in direct household energy consumption and carbon emissions were found between urban and rural areas of Beijing. The entire household energy consumption and carbon emissions in urban areas were higher than those in rural areas, whereas the per-capita indicators of urban areas were much lower than those of rural areas (see Fig. 4). From 1995 to 2011, the total urban direct household energy consumption rose from 2,927,000 tons of standard coal to 9,297,000 tons of standard coal, with an increase of 2.2 times. The corresponding direct carbon emissions rose from 7,084,000 tons to 23,478,000 tons, having a growth of 2.3 times. The total rural direct household energy consumption rose from 1,458,000 tons to 3,262,000 tons of standard coal, increasing of 1.2 times. The corresponding carbon emissions rose from 3,620,000 tons to 9,021,000 tons, recording an increase of 1.5 times. In 1995, the total direct household energy consumption and carbon emissions in urban areas were, respectively, 1.6 times and 2 times higher than those in rural areas. In 2011, the two urban indicators were 2.8 times and 2.6 times higher than the two rural indicators, respectively. These results showed that the urban household energy consumption and carbon emissions were increasing, and their gaps with rural indicators were widening.

The household energy consumption and carbon emissions per capita in rural areas were greater than in urban areas. Between 1995 and 2011, the urban household energy consumption and carbon emissions per capita increased steadily, while the two indicators in rural areas showed a more dramatic change. The urban household energy consumption and carbon emissions per capita increased moderately, and showed a downward trend after 2008. Rural household energy consumption and carbon emissions per capita, instead, increased significantly, especially from 2002 to 2011. Prior to the 2008 Summer Olympics, the consumption of heavily polluting coal was suppressed, and the rural household energy consumption and emissions per capita declined. After the Olympics, the improvement of living standards led to a rapid rebound of rural energy consumption and emissions per capita. In the future, if rural residents will not adopt energy-saving measures, the gap between rural and urban energy consumption and carbon emissions will further widen.

The difference in household carbon emissions per capita between urban and rural areas can be explained by the different energy consumption structures. Urban areas saw a significant decrease in the proportion of household coal consumption. In fact, this proportion dropped rapidly from 1995 to 2003. Since 2004, the share of coal in the urban household energy consumption structure has been very low. The proportion of household coal consumption remained below 8% after 2004. On the contrary, the proportions of urban household electricity and oil consumption showed an upward trend. Electricity consumption rose rapidly from 13.4% in 1995 to 36.3% in 2002, remaining, since then, at about 30%. The proportion of urban household oil consumption showed a moderate increase, from 15.8% to 22.4% from 1995 to 2001. After that period, the proportion grew remarkably, raising to approximately 40% in 2011. The increase of urban household oil consumption was attributed directly to the growth of households' ownership of mobility devices, such as private cars. Coal and electricity consumption were closely related to housing-associated energy use. The variation in the urban household energy consumption structure showed that, with the improvement of living standards, the focus of urban household energy use changed from housing-associated energy consumption to mobility-associated energy consumption.

In the rural household energy consumption structure, coal and electricity accounted for the most important two parts, while the proportions of natural gas and heat were very low. Before 2004, electricity and coal accounted for more than 99% of household energy consumed in rural areas. Since 2005, the proportions of oil and natural gas have increased gradually, but remained low. This shows that the rural energy infrastructure is relatively weak and inappropriate for oil and natural gas, which is an important cause of the high carbon emissions per capita in rural areas.

The energy consumption and carbon emissions per capita of urban and rural areas varied greatly. From 1995 to 2011, urban areas showed a decline in per-capita household coal consumption and a significant increase in per-capita household electricity and oil consumption. Rural areas showed a growth in the per-capita household consumption of both coal and electricity. Moreover, coal and electricity saw the most significant changes both rural and urban areas.

From the per-capita energy consumption perspective, coal energy was the most important both in urban and in rural areas along the 1990s, when rural coal consumption was higher. In 1995, the per-capita coal consumption of rural residents was 429 kgce, 2.33 times higher than that of urban residents in the same year. In 2011, the per-capita coal consumption of rural residents rose to 540 kgce, 18.62 times higher than that of urban residents in the same year. The gap between urban and rural coal consumptions continually widened.

In recent years, urban areas are making efforts in adjusting the energy consumption structure and in creating coal-free areas. Because projects to shift from coal to electricity or gas were implemented, most urban residents, except certain cottage areas, no longer burn coal. Residents of Beijing's rural areas were highly dependent on coal. Coal was used, mainly, for heating in winter and for daily cooking. Therefore, the per-capita coal consumption of rural residents was much higher than that of urban residents. At present, the proportion of rural household coal consumption with respect to the total energy consumption is approximately 45% or greater. Due to the economic conditions, living habits and convenience factor, it will be difficult to change the high coal consumption of rural residents in a short period of time.

Urban residents witnessed the fastest growth in consumption of natural gas. In fact, per-capita natural gas consumption of urban residents increased by 7.9 times, from 8 kgce in 1995 to 71 kgce in 2011. While the consumption of cleaner energy, such as natural gas and electricity, increased, there was a decline in urban residents' demand for coal. Although rural areas saw a continuous increase in the per-capita consumption of natural gas, the growth rate was significantly lower than in urban areas, due to the lack of energy supply infrastructures in rural areas.

The electricity consumption per capita of urban residents was lower than that of rural residents in each period. The ratio, between rural and urban residents, of per-capita electricity consumption was 1.17 in 1995, rising to 3.22 in 2011. In particular, rural residents' per capita electricity consumption increased faster. This trend paralleled the increase of rural residents' income level, which led to a rapid growth in the use of electrical appliances and consumption of electricity. However, energy saving and emissions reduction should be still drastically reduced in rural households.

Per-capita oil consumption of urban and rural residents grew very quickly. Especially in urban areas, oil still constitutes the highest proportion of energy consumption per capita, exceeding the consumption of natural gas. Beijing's economy has developed rapidly. In fact, its per-capita GDP ranks second in China, following Shanghai. The car ownership rate of urban residents continues to grow, increasing the consumption of gasoline and diesel oil. Thus, the next step for energy-saving efforts should focus on reducing the transportation-associated energy consumption and household electricity consumption of urban residents. In parallel, coal consumption and electricity consumption of rural residents should be lowered.

The difference in household energy consumption per capita between urban and rural areas also determines the carbon emission differences. The per-capita carbon emissions caused by coal burning in urban areas dropped significantly from an annual average of 0.42 tons to 0.07 tons: a fivefold decrease. However, the per-capita carbon emissions caused by coal burning in rural areas showed an increasing trend, from 1.02 tons to 1.29 tons.

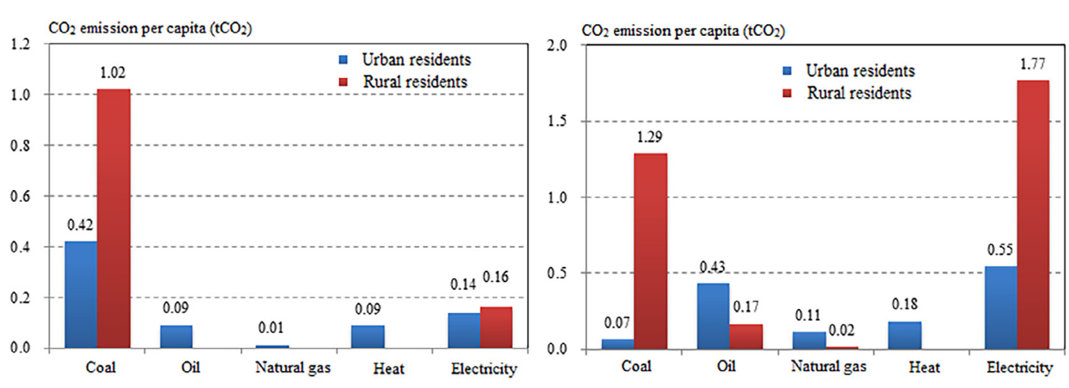

Fig. 5. Comparison of CO_2 emission per capita between urban and rural residents: (a) year 1995; (b) year 2011.

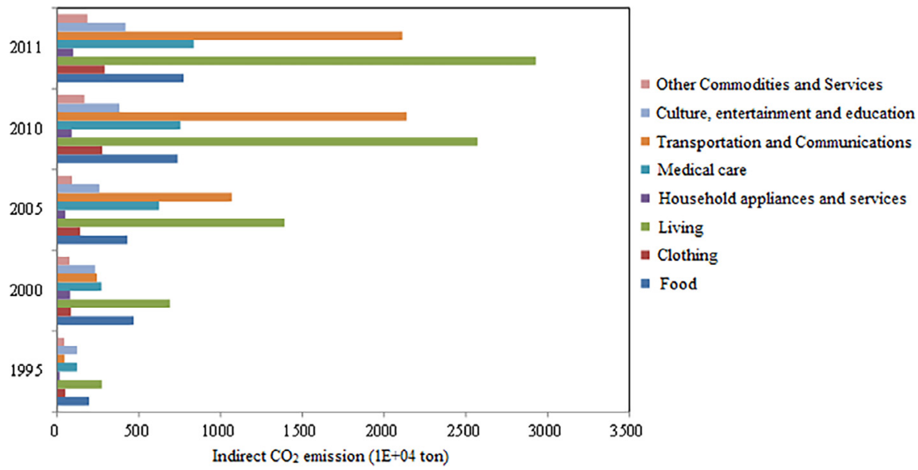

Fig. 6. Carbon emissions caused by indirect household energy consumption in Beijing.

The per-capita electricity emissions of rural residents increased more than those of urban residents (Fig. 5). Electricity has become the highest contributor to emissions both for urban and rural residents. In 1995, the per-capita electricity emissions of rural and urban residents were 0.16 tons per capita and 0.14 tons per capita. In 2011, the per-capita electricity emissions of rural residents rose to 1.77 tons per capita (10 times higher than those in 1995), while they grew to 0.55 tons per capita for urban residents.

Electricity, as the most important 'commercial' form of energy, reflects the urban–rural differences and the historical changes of household energy consumption. Beijing is one of the regions with the highest degree of modernization in China. Moreover, Beijing witnessed the widening of the urban–rural income gap together with rapid economic development and urbanization. Consequently, Beijing is experiencing a transition from fair low-income to unfair low- and high-income (Chen and Li, 2009).

With the improvement of living standards, urban and rural residents own significantly more household appliances. Before year 2000, the prevalence of traditional household appliances, such as refrigerators, washing machines, color televisions, and water heaters, were slightly lower in rural areas than in urban areas. After year 2000, instead, the urban–rural gap in household appliances, except for computers and air conditioners, rapidly declined. It shows that, although Beijing saw an increase in the urban–rural income gap, the higher income of urban residents did not make much difference in the divide of household appliances ownership. The markets for traditional household appliances, such as refrigerators and televisions, now tend to be saturated. However, air conditioners and computers have a large potential to grow in both urban and rural areas. In the future, in absence of any action, there will still be room for carbon emissions associated with household energy consumption to increase.

3.2. Indirect household energy consumption and carbon emissions in urban and rural areas

3.2.1. Basic information about indirect household energy consumption and carbon emissions

In the last two decades, the indirect household energy consumption in Beijing has grown rapidly. In fact, from 1995 to 2011, the total indirect household energy consumption in Beijing increased by 6.9 times, from 3,639,000 tons of standard coal to 28,869,000 tons of standard coal, with an average annual growth rate of 14.4%. Indirect household energy consumption per capita rose 3.9 times, from 291 kg to 1430 kg, with an average annual growth rate of 11.1%. With the economic growth, indirect household energy consumption saw a significant increase. The different increase rate between the total indirect household energy consumption, which was higher, and the indirect household energy consumption per capita, was linked with the change in composition and structure of urban and rural populations. Consequently, also consumptions changed. However, further analyses will be necessary to better describe these modifications.

The growth rate of indirect carbon emissions was slightly higher than that of indirect household energy consumption. From 1995 to 2011, the total carbon emissions in Beijing increased by 7.8 times, going from 8,698,000 tons to 76,418,000 tons, with an average annual growth rate of 15.2%. In parallel, carbon emissions per capita rose by 4.4 times, from 0.7 tons to 3.8 tons, with an average annual growth rate of 11.8%.

Indirect energy consumption shifted from basic consumption of household goods (e.g., food and clothing) to service products (e.g., transport, housing, and information). In the indirect energy consumption structure, transport and communications accounted for the highest proportion from 1995 to 2011 (21.6%). In detail, the average proportion of housing accounted for 21.4%, followed by food, health care and medical services, education, cultural services, and recreational services. Household appliances and services has the lowest ranking place with respect to the total indirect energy consumption (about 2.1%). Residents' expenditures varied among the eight sectors, displaying also a different energy intensity per sector. Therefore, each sectorial indirect energy consumption proportion varied significantly. In particular, the housing-associated energy intensity was much higher than the other ones. However, the highest increase in expenditure was for transportation and communications.

The differences in sectorial indirect household energy consumptions led to the differences in indirect carbon emissions (Fig. 6). In particular, there was a decline in indirect carbon emissions from food, education, cultural and recreational services, clothing, and health care and medical services. However, an increase was recorded for housing, transportation, and communications. Unlike for the indirect energy consumption, housing had the largest indirect carbon emissions, constituting an average proportion of 31.6% of the emissions structure in the period from 1995 to 2011.

The transportation and communications sectors produced the second largest amount of indirect carbon emissions, constituting an average proportion of 17.8% during that period. The third largest indirect carbon emissions were produced by health care and medical services, education, and cultural and recreational services. From 1995 to 1999, housing-derived indirect carbon emissions were still less than 4,000,000 tons. In 2000, instead, they exceeded 6,500,000 tons, and they have grown rapidly since then. Emissions rose to 13,910,000 tons in 2005 and 29,270,000 tons in 2011.

Housing-associated indirect consumptions involve electricity and heat production, supply industries, non-metallic mineral and other mineral mining industries, metal mining industry, and construction industry sectors. Electricity and heat production, as well as supply industries, have a higher intensity of energy consumption. In recent years, urban and rural residents in Beijing saw a significant rise in electricity and heat requirements, increasing the indirect carbon emissions of the housing-associated industries.

Transportation and communications sectors also grew significantly since year 2000. Indirect carbon emissions of transportation and communications increased by about 3 times, from 5,070,000 tons in 2000 to 21,110,000 tons in 2011. Transportation is used as example here. With the economic development and improvement of living standards in Beijing, residents are less likely to opt between public transportation and bicycle, while the preference is given to public transportation and cars. In 2005, the urban car park was 71% higher than in 2000, rising by 94.2% to approximately 5,000,000 cars in 2011. In addition, the dramatic increases in urban population and area led to fundamental changes in the urban land use and spatial layout. The transportation demand is continuing to increase due to expansion of the urban area. In 2005, the total number of trips in the city reached 29,200,000 trips/day, which was 26.9% higher than in 2000. All of these factors stimulated the growth of consumption associated with the transportation and communications sector.

3.2.2. Comparison of indirect household energy consumption and carbon emissions in urban and rural areas

The total indirect household energy consumption and carbon emissions in urban areas are much higher than those in rural areas in Beijing due to the differences in population numbers. With respect to direct consumptions and emissions, indirect household energy consumption and carbon emissions per capita in urban areas are higher than those in rural areas. From 1995 to 2011, the total urban indirect household energy consumption increased by 8.4 times from 2,752,000 tons of standard coal to 25,783,000 tons of standard coal. The corresponding indirect carbon emissions increased by 9.2 times, from 6,578,000 tons to 67,079,000 tons.

The total rural indirect household energy consumption increased by 1.2 times, from 887,000 tons to 3,086,000 tons (Fig. 7). The corresponding carbon emissions increased by 2.5 times, from 3,620,000 tons to 9,021,000 tons. In 1995, the total indirect household energy consumption and carbon emissions in urban areas were 3.1 times higher than those in rural areas. In 2011, the two urban indicators were 8.4 times and 7.2 times higher than the two rural indicators. This shows that the gap between urban and rural indirect household energy consumption and carbon emissions is widening. Beijing's urbanization acceleration, movement of rural residents toward urban areas, which lead to a higher urban population, are among the causes of the observed records. In fact, the ratio of urban residents to rural residents in Beijing was 3.1:1 in 1995, and rose to 6.3:1 in 2011. A higher population base is inevitably leading to greater energy consumption and carbon emissions. Another reason for widening of the gap is that the per-capita indirect energy consumption and carbon emissions of urban residents are higher than those of rural residents.

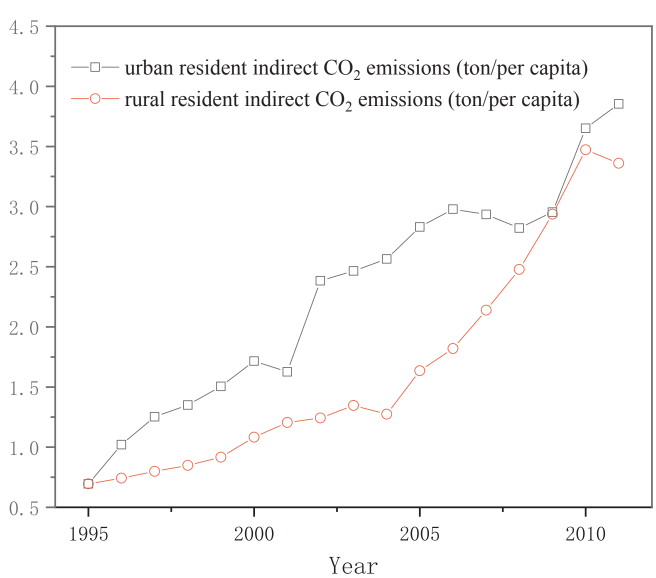

Fig. 7. Historical changes on indirect CO_2 emission per capita of urban and rural residents.

Contrary to the direct indicators per capita, per-capita indirect energy consumption and carbon emissions of urban residents are higher than those of rural residents. The per-capita indirect energy consumption and carbon emissions in urban areas showed a gradual upward trend over time. The changes were relatively steady in the periods 1995–2000 and 2002–2007, with an average growth rate of 11.8% and 9.6% in per-capita indirect energy consumption and carbon emissions, respectively. However, the periods 2001–2002 and 2009–2010 saw significant increases in the growth rate, with the rates of 32.4% and 35.1%, respectively.

The changes in the per-capita indirect energy consumption and carbon emissions of rural residents can be divided into two periods. The first period is from 1995 to 2004, when the growth rates were low at 5.3% and 7.1%, respectively. The second period is from 2004 to 2011, when the growth rates were higher at 13.6% and 15.2%, respectively. According to the comparison between urban and rural per-capita indirect energy consumption and carbon emissions, the sheer difference between urban and rural development common in other regions of China is not apparent in Beijing. The potential energy consumption and emissions of rural residents in Beijing are gradually catching up with those of urban residents.

3.3. Total household energy consumption and carbon emissions in urban and rural areas

3.3.1. Basic information on total household energy consumption and carbon emissions

The total energy consumption and carbon emissions are equal to the sum of direct and indirect energy consumption and carbon emissions. The trends the total energy consumption and carbon emissions of Beijing residents, both for rural and urban areas, is shown in Fig. 8.

From 1995 to 2011, the total household energy consumption of Beijing residents rose by 4.2 times, from 8,024,000 tons of standard coal to 41,428,000 tons of standard coal, with an average annual increase of 11.0%. The corresponding total carbon emissions rose by 4.6 times, from 19,403,000 tons to 108,916,000 tons, with an average annual increase of 11.6%. The total energy consumption and carbon emissions per capita increased moderately. The total energy consumption per capita increased by 1.55 times, from 0.64 tons of standard coal in 1995 to 2.05 tons of standard coal in 2011. The corresponding carbon emissions per capita increased by 2.5 times, from 1.55 tons to 5.4 tons.

Direct energy consumption and carbon emissions were smaller than indirect consumption and emissions. The gap between those direct and indirect indexes grew over time. In 1995, the direct household energy consumption was slightly higher than indirect household energy consumption in urban areas.

In 2000, indirect energy consumption was 1.74 times higher than direct energy consumption. The Fig. 8 rose to 2.30 in 2011. The ratio of direct to indirect emissions of urban residents was approximately the same as that of direct to indirect energy consumption. Indirect emissions were 1.61 times higher than direct emissions in 2000. The difference increased for year 2011, when indirect emissions were 2.35 times higher than direct ones. Since the 1990s, the income level and consumption patterns of urban residents in Beijing have undergone

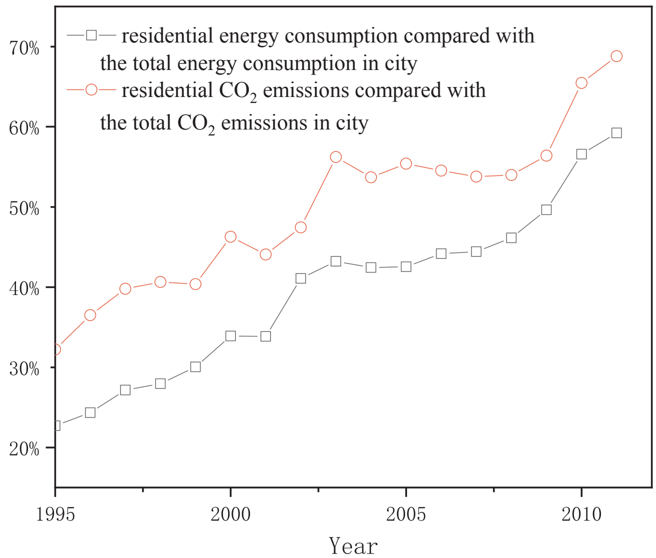

Fig. 8. The total energy consumption and carbon emissions of urban and rural residents in Beijing compared with the total energy consumption and carbon emissions in the city.

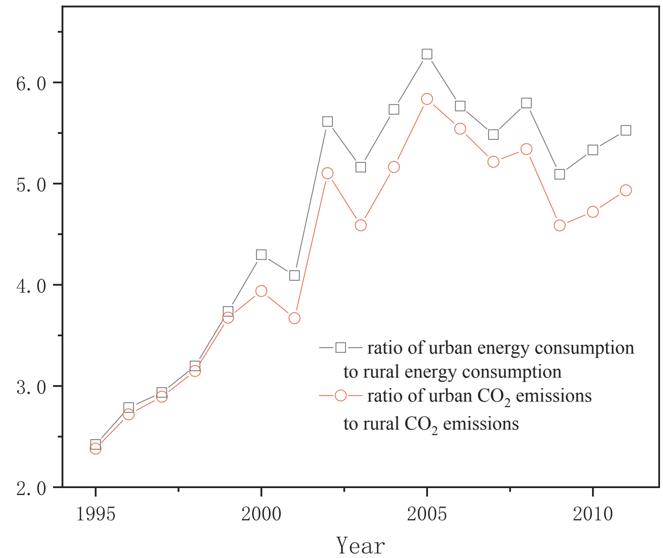

Fig. 9. The total household energy consumption and carbon emissions of urban residents compared with rural residents in Beijing.

significant changes. The number of products and services consumed by residents increased and the consumption structure has become more complicated. This is why energy consumption activities and carbon emissions of Beijing urban residents are mainly attributed to indirect consumption. Therefore, exploring indirect energy consumption and carbon emissions is key to understanding the trends of total energy consumption and carbon emissions.

In the last two decades, the per-capita total household energy consumption of Beijing residents has risen by 3.9 times, from 641 kgce to 2105 kgce, with an average annual increase of 7.7%. The growth rate of the total household energy consumption was greater than that of the total energy consumption per capita, and the gap has widened further in the past two years. The growth rate of the total carbon emissions was also slightly higher than that of the per-capita carbon emissions. From 1995 to 2011, the total carbon emissions arising from the total (direct and indirect) household energy consumption of Beijing increased by 7.8 times, from 8,024,000 tons to 41,428,000 tons, with an average annual growth rate of 15.2%.

The total energy consumption and carbon emissions of urban and rural residents in Beijing were compared with other obtained data. There was a significant increase in the total household carbon emissions compared with the city's total carbon emissions. The proportion of the residents' total energy consumption with respect to the city's total energy consumption from 1995 to 2011 showed an upward trend, increasing from 22.7% (year 1995) to 59.2% (year 2011). There was also a large increase of the proportion of the total household carbon emissions with respect to the city's carbon emissions, rising from 32.2% (year 1995) to 68.8% (year 2011). It means that in 2011, carbon emissions generated by direct and indirect energy consumption of urban residents accounted for more than two-thirds of the city's carbon emissions. This proportion is very close to that of urban residents in developed countries found by other similar studies (Shui and Dowlatabadi, 2005).

3.3.2. Comparison of total household energy consumption and carbon emissions in urban and rural areas

The total household energy consumption and emissions in urban and rural areas of Beijing are summarized (Fig. 9). In the period from 1995 to 2011, the total energy consumption and carbon emissions of urban residents showed an upward trend. The total energy consumption of urban residents rose by 5.2 times, from 5,679,000 tons of standard coal (year 1995) to 35,080,000 tons of standard coal (year 2011), with an average annual increase of 12.3%. The total carbon emissions of urban residents rose by 5.6 times, from 13,663,000 tons (year 1995) to 90,556,000 tons (year 2011), with an average annual increase of 12.8%. The total energy consumption and carbon emissions of rural residents showed an upward trend, but the increase was smaller than that of urban residents. The total energy consumption of rural residents rose by 1.7 times, from 2,345,000 tons of standard coal in 1995 to 6,348,000 tons of standard coal in 2011, with an average annual increase of 6.7%. The total carbon emissions of rural residents rose by 2.2 times, from 5,740,000 tons in 1995 to 18,360,000 tons in 2011, with an average annual increase of 7.9%.

The total household energy consumption and carbon emissions of urban residents were higher than those of rural residents. The ratio of urban indicators to rural indicators continued to rise from 2.42:1 (year 1995) to 6.3:1 (year 2005) and, then, dropped to 5.5:1. The widening gap between urban and rural populations, rise in the income level of urban residents and consequent diversification of their consumption of goods and services, impacted on the difference in the total energy consumption between urban and rural residents. The same trend applied to the total household carbon emissions.

The total energy consumption and carbon emissions per capita of urban and rural residents also grew. Overall, the energy consumption and carbon emissions per capita of urban residents rose steadily, with an average annual growth rates of 8.14% and 8.63%. The energy consumption and carbon emissions per capita of rural residents showed a rapid increase, especially after 2001, with average annual growth rates of 9.62% and 10.50%. In the period 1995–1999, the total energy consumption and carbon emissions per capita of urban residents were lower than those of rural residents. The same was true for the period of 2000–2008. Since 2008, the energy consumption and carbon emissions per capita of rural residents increased rapidly, becoming higher than those of urban residents.

These changes were caused by multiple factors. Urban and rural residents in Beijing have relatively high income levels. Engel coefficient (refers to the proportion of income that goes into food) dropped to below 0.4 since 2000. Both urban and rural residents have entered the affluent stage defined by the general evaluation criteria. Higher income levels make the difference in the living expenditure of Beijing's urban and rural residents less significant, which in turn reduces the difference between their direct and indirect carbon emissions. Additionally, infrastructure in rural areas, such as heating facilities and garbage disposal facilities, are less developed than in urban areas. Although there are far more urban residents than rural residents, undeveloped infrastructure in rural areas leads to higher per-capita energy consumption and carbon emissions of rural residents.

The comparison between urban direct and indirect energy consumptions, as well as between urban direct and indirect emissions, show that indirect energy consumption and indirect emissions dominated the urban household energy and carbon emission structures. From 1995 to 2011, the ratio of indirect energy consumption to direct energy consumption of urban residents rose from about 1:1 to 2.8:1. Direct energy consumption increased by 1.18 times while indirect energy consumption increased by 7.37 times. In 2011, indirect energy consumption accounted for almost three-quarters of the total energy consumption. This was similar to the corresponding direct and indirect carbon emissions of urban residents. The ratio of indirect emissions to direct emissions of urban residents rose from 1:1 in 1995 to 2.9:1 in 2011. During this time, the direct emissions of urban residents increased by 1.31 times while indirect emissions of urban residents increased by 8.2 times.

Opposite trends were observed for the ratio between rural direct and indirect energy consumption and between rural direct and indirect emissions. In particular, direct energy consumption and emissions were higher than indirect consumption and emissions. The ratio of indirect energy consumption to direct energy consumption of rural residents was 0.61:1 in 1995 and 0.95:1 in 2011. The growth rate of indirect energy consumption increased, but the amount of indirect energy consumption was still less than the amount of direct energy consumption. During this time, the direct energy consumption of rural residents increased by 24%, whereas the rural indirect energy consumption increased by 1.48 times. This trend also applies to the ratio of direct carbon emissions to indirect carbon emissions of rural residents.

The direct and indirect energy consumption structures of urban and rural households reflect the difference in living standards between urban and rural residents. It can be seen from the dynamics of energy consumption that resident's consumption behavior has gradually shifted from survival-oriented consumption to development-oriented consumption. Without considering other factors, the transformation of a rural Beijing resident into an urban Beijing resident would not create a large difference between urban and rural areas in the per-capita energy consumption and per-capita carbon footprint. Since 2008, the transformation of rural residents into urban residents led to more efficient energy use and a reduction in carbon emissions. In 2011, the per-capita energy consumption of rural residents was 269 kgce higher than that of urban residents, and the per-capita carbon emissions of rural residents were 1.404 tons higher than those of urban residents. The proportion of indirect energy consumption of urban residents was higher than that of rural residents. In 2011, urban indirect household energy consumption accounted for 73.5% of the total household energy consumption, while rural indirect household energy consumption accounted for only 48.6% of total household energy consumption. The expenditures of rural and urban residents varied among various industrial sectors, and the energy intensity varied within each sector. Therefore, the proportion of indirect energy consumption varied significantly with each industry.

3.4. Discussion

In the previous subsections, this paper described the trends of direct and indirect urban and rural energy consumption and carbon emissions for Beijing area. The first comment is made with respect to coal consumption, which still occupies a large fraction as energy source in Beijing, particularly in its rural sub-areas, as well as in other areas in China (Xu et al., 2015). It is known, in fact, that life expectancy is reduced in areas where a higher amount of coal is burnt for household consumption (Wang and Luo, 2018). It is important to remark that rural particulate matter and sulfur dioxide emissions derived from raw coal were found higher than urban ones in a previous case study in China (Zhi et al., 2017). However, the combination of low costs and supply security still create an inertia in the transition toward cleaner energy sources (Kerimray et al., 2017).

The adoption of efficient household appliances would for sure improve energy savings, as discussed in a previous research applied to Xianmen city as well as for other case studies (Xing et al., 2015; Guo et al., 2018). It was esteemed that stove improvements, in particular, would reduce the existing emissions up to 82% (Winijkul and Bond, 2016). As parallel to this case study, also in Europe ICT-related household energy consumption is increasing, despite the increase of energy efficiency measures (Werner, 2015). Another case of interest is the use of room air conditioners, whose daily use, in case of more efficient technologies, impacted negatively on residential energy demand in China (Liu et al., 2016; Wu et al., 2017). The existence of such a rebound effect, confirmed by another study, which esteems a level of impact up to 66%, suggest the need of complementing efficiency policies with a reform of pricing in energy sector (Li et al., 2017). It is also important to remark here the potential role of urban agriculture in supporting the overall energy sustainability of urban systems (Viglia et al., 2013; Pereira et al., 2013; Zucaro et al., 2013; Ghisellini and Casazza, 2016)

With respect to household in China, it is proved that the majority of carbon emissions derived from indirect fraction of energy consumption (Zhang et al., 2017a). In parallel, socio-economic structure changes play a major role in the observed energy and emission trends, as confirmed by other works (Tian et al., 2017; Wei et al., 2017). In China, an indirect energy consumption sector connected to household which was influenced by the rebound effect is car transport (Zhang et al., 2017b). However, more generally, the search of optimal solutions for energy-efficient and low carbon private and public transportations will continue to be crucial (Zacharias and Zhang, 2015; Meng et al., 2017a,b; Yang et al., 2017).

The integrated adoption of adequate environmental and socio-economic measures, focused on technology efficiency, pricing reforms and specific sectorial improvements require also a developed system of results monitoring, able to capture the dynamics of energy consumption as well as emissions variability. This is why the integration of smart meters and GIS tools is suggested for energy consumption behavioral dynamics control (Murtagh et al., 2014; Naus et al., 2014; Rosas-Flores et al., 2016; Stankovic et al., 2016; Silva et al., 2017). In parallel, atmospheric emissions can be monitored integrating the use of remote and proximal sensing (Gargiulo et al., 2013; Lega and Persechino, 2014; Errico et al., 2014), as well as smart sensors networks integrated into appropriate air quality nowcasting systems (Casazza, 2015).

4. Conclusions

This paper presents the trends of household energy consumption and carbon emissions in Beijing from 1996 to 2011, analyzing their variability with respect to direct and indirect energy use and carbon emissions induced by rural and urban households. We estimate that for the Beijing residents, when direct and indirect energy consumption and CO_2 emissions are taken into account, the total household energy consumption proportion compared to the city increases from 22.7% to 59.2%, and the total household CO_2 emissions proportion increases from 32.2% to 68.8% in the research period. In the urbanization process, total energy consumption and carbon emissions of Beijing urban residents are significantly higher than those of rural residents. However, the transformation of a rural Beijing resident into an urban Beijing resident would not create a large difference between urban and rural areas in the per-capita energy consumption and per-capita carbon footprint. It is clear that urban and rural households vary considerably in their responsibility to direct and indirect footprint. Results are assessed with respect to the available scientific literature, as well as potential available technological and policy solutions. Since the realization that different types of policy instruments can reduce GHG emissions, governments are increasingly combining policy measures for the same technology. The obtained results may help foster alternative household consumption strategies which could result in more equitable resource allocation and effective mitigation of both urban and rural environmental influences.

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