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Calculation and decomposition of indirect carbon emissions from residential consumption in China based on the input–output model

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HIGHLIGHTS

- We build the input–output model of indirect carbon emissions from residential consumption.
- We calculate the indirect emissions using the comparable price input–output tables.
- We examine the impacts on the indirect emissions using the structural decomposition method.
- The change in the consumption structure showed a weak positive effect on the emissions.
- China's population size is no longer the main reason for the growth of the emissions.

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ABSTRACT

Based on the input–output model and the comparable price input–output tables, the current paper investigates the indirect carbon emissions from residential consumption in China in 1992–2005, and examines the impacts on the emissions using the structural decomposition method. The results demonstrate that the rise of the residential consumption level played a dominant role in the growth of residential indirect emissions. The persistent decline of the carbon emission intensity of industrial sectors presented a significant negative effect on the emissions. The change in the intermediate demand of industrial sectors resulted in an overall positive effect, except in the initial years. The increase in population prompted the indirect emissions to a certain extent; however, population size is no longer the main reason for the growth of the emissions. The change in the consumption structure showed a weak positive effect, demonstrating the importance for China to control and slow down the increase in the emissions while in the process of optimizing the residential consumption structure. The results imply that the means for restructuring the economy and improving efficiency, rather than for lowering the consumption scale, should be adopted by China to achieve the targets of energy conservation and emission reduction.

1. Introduction

In the wake of the residential energy consumption outpacing that of industrial sectors in some developed countries since the 1990s, researchers came to realize that the carbon emissions from residential energy consumption, including direct and indirect emissions, might be a new growth source of carbon emissions (Weber and Adriaan, 2000; Bin and Dowlatabadi, 2005; Druckman and Jackson, 2009). At present, China is actively exploring the economic restructuring promoted by domestic demand. Thus, the impacts of residential consumption patterns on carbon emissions in China might continuously grow stronger in the future. Therefore, it is important to examine the carbon emissions based on residential consumption to help improve the decision-making process on the reduction of carbon emissions in China.

Residential carbon emissions can be categorized into two: direct emissions from household energy requirements, including cooking, hot water, heating, and so on; and indirect emissions from non-energy residential consumption goods and services, which emit carbon during, rather than after, the production process. The concept of indirect carbon emissions originated from "indirect energy requirements", defined in terms of the energy inputs used in the production of goods consumed ultimately by households (Jane Golley et al., 2008). Indirect carbon emissions cover diverse periods in the lifecycle of residential consumer goods, including raw material, manufacture, transportation, marketing, etc., and contain total emissions from the industrial

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sectors involved. Hence, understanding residential consumption patterns could be more important for recognizing future emission demand than has been recognized before.

However, calculating indirect carbon emissions from residential consumption is more complex and more uncertain. At present, the input–output analysis is the mainstream method of calculating this kind of emission, due in part to its ability to reflect the sources of the input into, and the utilization of the output from, production by various industry sectors of the economy and the inter-related and mutually dependent relations among industries (Lin and Polenske, 1995; Kok et al., 2006; Duarte et al., 2010). Furthermore, the decomposition analysis method based on the input–output model becomes an effective way to examine the impact of residential consumption on the indirect emissions (Chang and Lin, 1998; Mukhopadhyay and Chakraborty, 1999).

Much of the existing literature focuses on residential consumption-relevant carbon emissions using the input–output model. Kok et al. (2006) identified three methods that can be used to calculate the total energy requirements of households and their associated carbon emissions using input–output analysis, i.e., basic input–output energy analysis based on national accounts (IO-EA-basic), input–output energy analysis combined with household expenditure data (IO-EA-expenditure), and a hybrid method combining energy input–output analysis with process analysis (IO-EA-process). By applying all the three methods to the Netherlands and comparing the results, the authors further pointed out that using different data sources would produce different results. Papathanasopoulou (2010) used the environmentally extended input–output (EEIO) techniques to explore how Greece's household consumption changed between 1990 and 2006, as well as the environmental implications the changes had on fossil fuel demand and carbon emissions. The results showed that indirect demand accounted for an approximately 60% increase in fossil fuel demand throughout the period. Duarte et al. (2010) analyzed the relationship between household consumption patterns and carbon emissions in Spain using the Social Accounting Matrix (SAM) constructed in 1999. They found that the variations observed between CO_2 emissions associated with the consumption of final goods in households were mainly due to a scale effect in income, and consumption patterns caused a slight fall-off in emissions when income increased, which was offset by the scale effect.

To analyze and understand historical changes in economic, environmental, or other socio-economic indicators, assessing the driving forces or determinants that underlie these changes by employing a decomposition analysis is useful (Hoekstra and Bergh, 2003). With regard to analyzing energy consumption and its associated carbon emissions, the common techniques used at present are structural decomposition analysis (SDA) and index decomposition analysis (IDA). The SDA method is generally used to assess the impact factors, including the industrial sectors' requirements, international trade, etc., based on input–output tables, especially the consumption coefficient matrices. Mukhopadhyay and Chakraborty (1999) analyzed energy consumption changes that had taken place in India from the 1970s to the 1990s using the SDA; found that the energy consumption changes were the result of six different factors, including technical changes, changes in the final demand structure, and changes in energy imports. Lin and Polenske (1995) conducted a SDA analysis to explain China's energy use changes between 1981 and 1987. They found that China's energy savings during this period came primarily from changes in production technology rather than final demand shifts, and the driving force of the energy intensity decline was a range of energy efficiency improvements. Chang and Lin (1998) employed the input–output structural decomposition analysis to examine emission trends and the effects of industrial carbon emission changes in Taiwan in 1981–1991. The results indicated that the primary factor for the increase of emission was the level of domestic final demand and exports; meanwhile, the effects of decreasing industrial carbon intensity were the main reducing factor.

Some researchers have conducted meaningful studies on the residential energy requirements and their associated carbon emissions in China. Feng et al. (2009) used the IPAT model to analyze the drivers contributing to the growth of carbon emissions in 1949–2002. They found that household consumption was driven by changes in income and the increasing availability of goods and services. They also emphasized that China, which was on a fast track to modernization, needed to ensure that people's lifestyles were changing toward more sustainable ways of living. Zha et al. (2010) investigated the factors that may affect the changes in the residential carbon emissions in China from 1991 to 2004 by applying the IDA technique. They found that energy intensity and the income effects, respectively, contributed most to the decline and the increase of residential carbon emissions for both urban and rural China. Wei et al. (2007) and Feng et al. (2011) quantified the impact of the lifestyle of urban and rural residents on China's energy use and the related carbon emissions based on the CLA model. Jane et al., 2008 examined the extent of variation in total energy requirements and emissions across households with different income levels in China, drawing upon the Urban Household Income and Expenditure Survey conducted by the National Bureau of Statistics in 2005. They concluded that indirect energy from urban households comprised 32% of the national total energy demand. Niu et al. (2011) and Ye et al. (2011) designed questionnaires on household energy consumption and conducted surveys in Lanzhou, Northwest China, and Xiamen, Southeast China, respectively, and calculated residential emissions and analyzed the impact factors on the emissions.

There is a limited body of literature that investigates China's indirect carbon emissions from residential consumption based on an input–output analysis. Some reported studies, e.g., Zha et al. (2010), employed input–output tables in which data in value terms were calculated at current prices. Therefore, the results of this kind of study are difficult to compare with others due to the price fluctuations in different years.

The current paper calculates the indirect carbon emissions from residential consumption in China using input–output tables at comparable prices to eliminate the influences of the price fluctuations and to more realistically reflect the changing trends of residential emissions. On this basis, a polar decomposition model is built to analyze the impact factors, including the population size, the consumption level and structure, the emission intensity, and the intermediate demand, affecting the indirect emissions. Finally, corresponding policy proposals for China's low-carbon development project are presented in the current paper.

2. Methodology

2.1. *Calculation of indirect carbon emissions from residential consumption*

An input–output model is a quantitative economic technique that represents the interdependencies between different sectors of an economy. The model portrays economic activity as a system of interrelated goods and services and uses a matrix representation to depict inter-industry relations in an economy. By solving a set of matrix equations, an input–output model reflects the effects of changes in one industry on others or the effects of consumers, the government, and foreign suppliers on the economy. Therefore, the input–output model is highly appropriate for a study on indirect carbon emissions from residential consumption.

The input–output model for calculating indirect carbon emissions from residential consumption is given in Eq. (1):

$$CF_c = CI(I-A)^{-1}Y_c \quad (c=0,1) \tag{1}$$

where CF is the row vector for indirect carbon emissions from various species of residential consumption; c is the subscript for separating urban and rural residents; CI is the row vector for the carbon emissions per unit of gross output of each industrial sector in the input–output tables; Y is the diagonal matrix converted from the column vector of terminal residential consumption of each species of consumption goods and services in the input–output tables, and the sum of elements in Y, also called 'consumption scale', is the total consumption of all the population in terms of magnitude of value; and A is the direct consumption coefficients matrix in the input–output table $(I-A)^{-1}$ is the Leontief inverse square matrix, also called the complete demand coefficients matrix, for representing changes in the intermediate demands of each sector, i.e., the total demand of all other sectors when increasing a unit of terminal consumption in one sector. Therefore, changes in the Leontief inverse square matrix reflect the effect of changes in intermediate production on each sector's energy demands, and finally influence the indirect carbon emissions from residential consumption.

To calculate the carbon emissions per unit of gross output of each industrial sector (CI), the carbon emissions from each industrial sector must be known in advance, which can be expressed in Eq. (2)

$$CE(i) = \sum_{p=1}^{P}[k_p \times (EC_p^f(i)+EC_p^c(i))] \tag{2}$$

where CE represents the carbon emissions from the energy consumption of industrial sectors; i is the number code of the industrial sector; EC is the apparent consumption of energy; k is the carbon emission factor; f is the superscript for primary energy; c is the superscript for secondary energy; and p is the subscript for the number code of the kind of primary energy.

Then, the carbon emissions per unit of gross output of each industrial sector (CI) can be expressed as the quotient of the carbon emissions of energy consumption from a specific sector (CE) divided by the gross output of the same sector. Thus, the indirect carbon emissions from all kinds of residential consumption can be calculated using Eq. (1).

2.2. Decomposition on indirect carbon emissions from residential consumption

Structural decomposition techniques are used to break down the changes of one variable into the changes of its impact factors, and to evaluate their contributions quantitatively. As shown in Eq. (1), the impact factors on the changes in carbon emissions from residential consumption consist of the carbon emissions per unit of gross output of each industrial sector (CI), the intermediate demands of each sector $(I-A)^{-1}$, and the residential consumption of each species of consumption goods and services (Y). To look deeper into the effects of changes in population and residential consumption patterns on the emissions, we break down the residential consumption into three variables: population size, consumption level, and consumption structure, with consumption level denoting per capita consumption in terms of magnitude of value, consumption structure refering to consumption ratios of each species of residential goods or services to the total consumption. Therefore, the input–output model of indirect carbon emissions from residential consumption is expanded into the expression shown in Eq. (3)

$$CF_c = CI(I-A)^{-1}P_cYS_cYT_c \quad (c=0,1) \tag{3}$$

where P is the population size; YS is the residential consumption per capita in terms of magnitude of value; and YT is the diagonal matrix converted from the column vector of consumption structure. Consequently, the indirect carbon emissions from residential consumption are finally broken down into five impact factors, i.e., the emission intensity effect,[1] the intermediate demand effect, the population size effect, the consumption level effect, and the consumption structure effect.

Given the expression $y=\prod_{i=1}^{n}x_i$, x_i $(i=1, 2, \ldots, n)$ are independent variables. The change in y is expressed as

$$\Delta y = \prod_{i=1}^{n}x_i^T - \prod_{j=1}^{n}x_j^0 \tag{4}$$

where the superscripts 0 and T denote the base period and the calculating period, respectively. Tagging the effect of changes in x_i on Δy as $E(\Delta x_i)$, the polar decomposition (Conway, 1990) for Δy can be expressed as

$$E(\Delta x_i) = \frac{1}{2}\prod_{j=1}^{i-1}x_j^0(\Delta x_i)\prod_{k=i+1}^{n}x_k^T + \frac{1}{2}\prod_{l=1}^{i-1}x_j^T(\Delta x_i)\prod_{m=i+1}^{n}x_m^0 \tag{5}$$

The total effect is expressed as

$$\Delta y = \sum_{i=1}^{n}E(\Delta x_i) \tag{6}$$

Based on the input–output model given by Eq. (3), the polar composition of the total effect on the indirect carbon emissions is given as

$$\Delta CF_c = E(\Delta CI)+E[\Delta(I-A)^{-1}]+E(\Delta P_c)+E(\Delta YS_c)+E(\Delta YT_c) \tag{7}$$

Furthermore, based on Eq. (5), the polar compositions of changes in each impact factor on the indirect carbon emissions are expressed as follows:

The emission intensity effect:

$$E(\Delta CI) = \tfrac{1}{2}(\Delta CI)(I-A^0)^{-1}P_c^0YS_c^0YT_c^0+\tfrac{1}{2}(\Delta CI)(I-A^T)^{-1}P_c^TYS_c^TYT_c^T \tag{8}$$

The intermediate demand effect:

$$E\left[\Delta(I-A)^{-1}\right] = \tfrac{1}{2}CI^0\left[\Delta(I-A)^{-1}\right]P_c^TYS_c^TYT_c^T+\tfrac{1}{2}CI^T\left[\Delta(I-A)^{-1}\right]P_c^0YS_c^0YT_c^0 \tag{9}$$

The population size effect:

$$E(\Delta P_c) = \tfrac{1}{2}CI^0(I-A^0)^{-1}(\Delta P_c)YS_c^TYT_c^T+\tfrac{1}{2}CI^T(I-A^T)^{-1}(\Delta P_c)YS_c^0YT_c^0 \tag{10}$$

The consumption level effect:

$$E(\Delta YS_c) = \tfrac{1}{2}CI^0(I-A^0)^{-1}P_c^0(\Delta YS_c)YT_c^T+\tfrac{1}{2}CI^T(I-A^T)^{-1}P_c^T(\Delta YS_c)YT_c^0 \tag{11}$$

The consumption structure effect:

$$E(\Delta YT_c) = \tfrac{1}{2}CI^0(I-A^0)^{-1}P_c^0YS_c^0(\Delta YT_c)+\tfrac{1}{2}CI^T(I-A^T)^{-1}P_c^TYS_c^T(\Delta YT_c) \tag{12}$$

[1] In our study, we represent the emission intensity of one industrial sector by the carbon emissions per unit of gross output of this sector.

Table 1
Indirect carbon emissions from residential consumption in China (Unit: MtC).
Source: Authors' own calculation based on China's input–output table using comparable prices in 1992–2005, China energy statistical yearbook 1992–2005. All the data are adjusted to the constant prices in 2000. The same is done for all the following tables and figures.

Sector	1992	1997	2002	2005
Agriculture	87.17	104.24	67.46	53.68
Mining and quarrying	1.80	1.02	2.16	1.92
Foodstuff	40.54	58.35	34.15	44.72
Textile, sewing, leather and fur products	23.61	27.94	20.44	28.76
Manufacture of wood products and articles for cultural activities	6.09	9.57	7.28	9.41
Coking, gas, and petroleum refining	1.04	1.61	2.79	5.28
Chemical industry	26.79	24.08	21.97	32.16
Construction, building materials and non-metal mineral products	4.78	13.20	9.73	12.79
Metal products	13.35	8.52	7.75	10.04
Machinery and equipment	55.47	60.28	59.27	128.83
Production and supply of electric power, heat power, and water	2.12	5.72	11.27	15.07
Transportation, postal and telecommunication services	10.39	10.08	17.87	47.14
Wholesale and retail trades, hotels and catering services	23.94	24.17	35.75	37.88
Business services, public services, and other services	41.67	62.68	173.61	251.72
Total	338.76	411.46	471.49	679.40

3. Data, results, and analysis

3.1. Data resources and results

The original data used in our study, including the input–output tables, the energy balance tables, and the tables of final energy consumption by industrial sector, were all released by China's National Bureau of Statistics. In consideration of the elimination of the influences of price fluctuations in different years, we adopted the input–output tables at comparable prices (Liu and Peng, 2010), which contained the national input–output data from 1992, 1997, 2002, and 2005. The data in all these three kinds of tables, each containing a different number of sectors, were then aggregated into 14-sector tables.

New direct consumption coefficient matrices were calculated for the aggregated input–output tables. The measurement units for energy data were all converted into the Standard Coal Equivalent (SCE). All kinds of fossil energy were incorporated into three categories: coal, petroleum, and natural gas. The carbon emission factors for these three kinds of fossil energy were referred to the Energy Research Institute National Development and Reform Commission (2003), i.e., coal: 0.7476 kgC/kgSCE[2]; petroleum: 0.5825 kgC/kgSCE; and natural gas: 0.4435 kgC/kgSCE. All the related economic data were adjusted to the constant prices in 2000.

The calculated indirect carbon emissions from residential consumption in China are demonstrated in Table 1. The results show that there was an upward trend in the indirect emissions from 338.76 MtC[3] in 1992 to 679.40 in MtC in 2005, increasing by more than 100%. From the perspective of emission structure, the leading species of consumption goods and services contributing to indirect emissions have transformed from basic livelihood, such as the agriculture and foodstuff, to the service classes, such as the production and supply of electric power, transportation, and business services. For instance, the emission proportion of the agriculture sector had the largest share (25.7%) of the indirect emission in 1992. However, the largest contributor came to be the business services, public services, and other services sector (37%). From the perspective of industrial structure, the emission proportion of the tertiary industry increased distinctly from 22.4% to 49.6%, whereas the proportions of both the primary and the secondary industries decreased by 17.8% and 9.3%, respectively.

3.2. Decomposed results

By applying Eqs. (5)–(12), the calculated indirect carbon emissions from residential consumption are decomposed as shown in Table 2.

Based on the decomposition results, there were four impact factors exhibiting generally positive effects on the growth of indirect emissions in China in 1992–2005, i.e., the consumption level effect, the consumption structure effect, the intermediate demand effect, and the population size effect. Moreover, the consumption level effect played the dominant role, with a contribution value of 455.07 MtC. Meanwhile, the impact factor of the emission intensity presented a negative effect, with a contribution value of -341.07 MtC. Given that the sum of contribution values of the four positive effects was greater than the absolute value of that of the negative effect, the total contribution appeared to have a positive effect, with an emission growth of 341.87 MtC.

As shown in Table 3, the contribution ratios of changes in the impact factors on indirect carbon emissions fluctuated during the sample period. Moreover, the consumption level presented a persistent positive effect, with a contribution ratio increasing from 50.1% in 1992 to 134.3% in 2005; the trend of the population size effect was similar to that of the consumption level, with a contribution ratio that grew from 6.3% to 19.4%; and the emission intensity showed a persistent negative effect, with an absolute contribution ratio rising from 27.8% to 100.7%. Both the intermediate demand and the consumption structure showed analogous change trends initiated by weak negative effects, then transformed to positive effects that kept strengthening, and finally manifested positive effects with contribution ratios of 29.1% and 18.7%, respectively.

The following passages analyze the impacts of these five effects on indirect emissions based on the absolute value of their contribution ratios in descending order.

3.3. The consumption level effect

As seen in Table 2, the consumption level contributed the greatest positive effect on the growth of indirect carbon emissions from residential consumption during the sample period. Among all the 14 sectors, the three greatest contributors to the increase in emissions came from the business services, public services, and

[2] The unit kgC/kgSCE refers to kilogram carbon per kilogram standard coal equivalent.
[3] The unit MtC refers to million-ton carbon.

Table 2
Decomposition of indirect carbon emissions from residential consumption in China (unit: MtC; base period: 1992; calculating period: 2005).

Sector	Emission intensity effect	Intermediate demand effect	Population size effect	Consumption level effect	Consumption structure effect	Total effect
Agriculture	−33.10	−14.79	8.06	65.93	−59.99	−33.89
Mining and quarrying	−0.68	0.19	0.21	1.84	−1.44	0.12
Foodstuff	−29.05	−4.19	5.87	41.36	−9.86	4.12
Textile, sewing, and leather and fur products	−15.13	−3.56	3.57	25.26	−5.05	5.08
Manufacture of wood products and articles for cultural activities	−9.42	3.02	1.17	7.70	0.90	3.37
Coking, gas, and petroleum refining	0.06	0.39	0.31	2.25	1.24	4.24
Chemical industry	−22.24	9.65	3.56	28.10	−13.41	5.65
Construction, building materials and non-metal mineral products	−6.23	1.73	1.22	7.99	3.32	8.04
Metal products	−7.14	2.04	1.31	11.46	−10.90	−3.23
Machinery and equipment	−73.21	55.03	10.80	80.84	0.96	74.43
Production and supply of electric power, heat power, and water	−5.64	4.31	1.02	6.26	7.04	12.99
Transportation, postal and telecommunication services	−9.41	3.12	3.50	22.77	16.81	36.79
Wholesale and retail trades, hotels and catering services	−15.45	−10.82	4.71	30.83	4.44	13.71
Business services, public services, and other services	−114.42	52.57	20.55	122.46	129.26	210.42
Total	−341.07	98.69	65.84	455.07	63.33	341.86

Table 3
Contribution ratios of changes in impact factors on indirect carbon emissions in China (base period: 1992).

Impact factor	Contribution ratio (%)		
	1997	2002	2005
Emission intensity effect	−27.8	−77.7	−100.7
Intermediate demand effect	−5.4	0.9	29.1
Population size effect	6.3	13.5	19.4
Consumption level effect	50.1	94.0	134.3
Consumption structure effect	−1.9	8.3	18.7

other services sector, the machinery and equipment sector, and the agriculture sector, with all of their contributions totaling more than 60 MtC. In contrast, the mining and quarrying, and the coking, gas, and petroleum refining sectors showed smaller contributions.

Fig. 1 shows the residential consumption per capita for each sector in 2005 and their changing rates in 1992–2005. The residential consumption per capita rose from 1584 CNY to 4663 CNY, adjusted to the constant prices in 2000, and increased by 1.5 times during this period. The largest increasing rates were from the business services, public services, and other services sector (increased by 6.8 times), and the production and supply of electric power, heat power, and water sector (increased by 6.4 times). The indirect emissions from residential consumption per capita only doubled during the same period; therefore, the growth rate of the residential consumption per capita, in terms of magnitude of value, was much higher than that of the associated indirect emissions during this period. Hence, there must be a significant negative effect that had set off a large portion of the growth of the emissions mainly caused by increased residential consumption. As previously mentioned, this kind of negative effect came from changes in the emission intensity.

3.4. The emission intensity effect

As shown in Table 1, except for the slight positive effects of the coking, gas, and petroleum refining sector, all other species of consumption goods and services generated negative effects on indirect emissions in terms of the emission intensity during the sample period. The largest contribution came from the business services, public services, and other services sector, the machinery and equipment sector, and the agriculture sector, with their contributions to decreasing emissions all being more than 30 MtC. The mining and quarrying, and the production and supply of electric power, heat power, and water sectors, in contrast, had smaller contributions.

Fig. 2 illustrates the carbon emissions per unit of gross output of each industrial sector in 2005 and their changing rates in 1992–2005. Among all the 14 sectors, only two sectors, i.e., the coking, gas, and petroleum refining, and the wholesale and retail trades and hotels and catering services sectors, had slight increases in emission intensity, whereas the other 12 sectors had significant reductions in this indicator. The biggest declines came from the machinery and equipment (dropped 84.3%), the manufacture of wood products and articles for cultural activities (dropped 75.37%), and the chemical industry sectors (dropped 60.0%). The dramatic decrease in emission intensity directly drove the overall negative effect on indirect emissions during this period.

On the other hand, emission intensities were uneven among all sectors. The three most carbon-intense sectors in 2005, in terms of carbon emissions per unit of gross output, were the metal products (8.95 tC/kCNY), the coking, gas, and petroleum refining (6.00 tC/kCNY), and the mining and quarrying sectors (5.12 tC/kCNY); whereas the least carbon-intense sectors were the machinery and equipment (0.61 tC/kCNY), the business services, public services, and other services (0.70 tC/kCNY), and the wholesale and retail trades and hotels and catering services sectors (1.01 tC/kCNY). Thus, the difference between the highest and the lowest levels of carbon intensity was almost 14 times. Fortunately, the dominating species of consumption goods and services in 2005, in terms of the portions occupied in residential consumption, were the business services, public services, and other services, the agriculture, and the foodstuff sectors, all contributing lower carbon emissions, thus explaining from another perspective why the growth rate of residential emissions was much lower than that of residential consumption during this period.

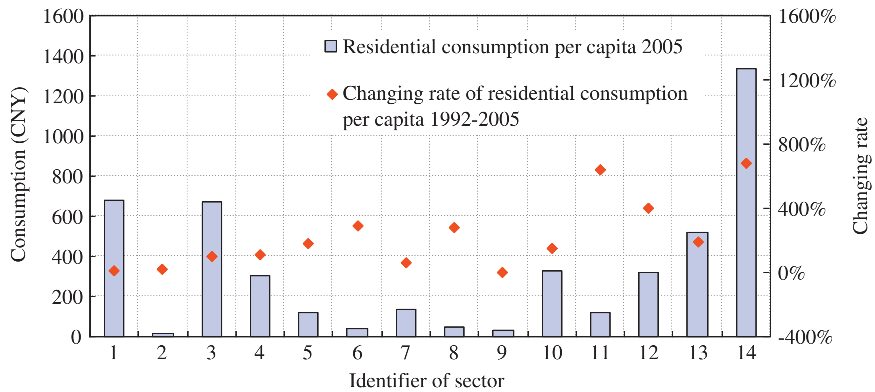

Fig. 1. Residential consumption per capita and the changing rates in China. Identifier of sector: 1. Agriculture; 2. Mining and quarrying; 3. Foodstuff; 4. Textile, sewing, leather and fur products; 5. Manufacture of wood products and articles for cultural activities; 6. Coking, gas and petroleum refining; 7. Chemical industry; 8. Construction, building materials and non-metal mineral products; 9. Metal products; 10. Machinery and equipment; 11. Production and supply of electric power, heat power and water; 12. Transportation, postal and telecommunication services; 13. Wholesale and retail trades, hotels and catering services; 14. Business services, public services and other services.

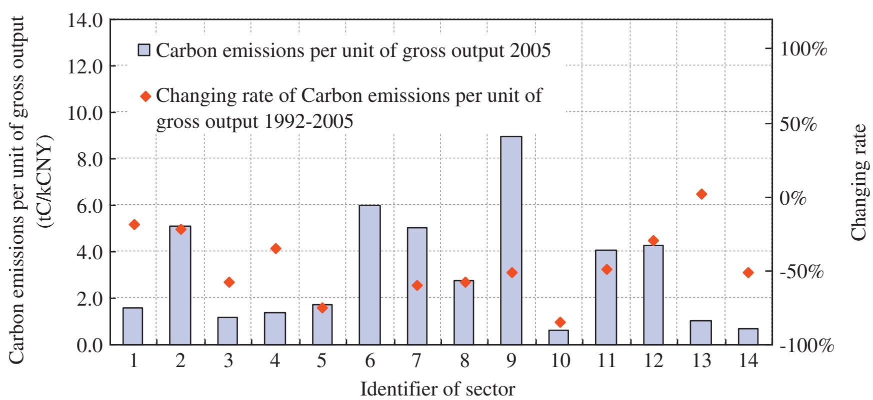

Fig. 2. Carbon emissions per unit of gross output and their changing rates in China. Identifier of sector: 1. Agriculture; 2. Mining and quarrying; 3. Foodstuff; 4. Textile, sewing, leather and fur products; 5. Manufacture of wood products and articles for cultural activities; 6. Coking, gas and petroleum refining; 7. Chemical industry; 8. Construction, building materials and non-metal mineral products; 9. Metal products; 10. Machinery and equipment; 11. Production and supply of electric power, heat power and water; 12. Transportation, postal and telecommunication services; 13. Wholesale and retail trades, hotels and catering services; 14. Business services, public services and other services.

Generally, the main influencing factors on emission intensity are energy efficiency and energy structure. The standard coal consumption rate for thermal power generation, one of the indicators of energy efficiency, has strong links to emission intensity. Based on our calculation, the standard coal consumption rates for thermal power generation in China continued to fall from 0.386 kgSCE/kWh in 1992 to 0.352 kgSCE/kWh in 2005, which means that energy efficiency continuously improved during this period. In terms of energy structure, the proportion of coal in primary energy decreased from 75.7% in 1992 to 69.5% in 2005, whereas that of non-fossil energy expanded from 4.9% to 7.1%, which means that China made some progress in energy restructure during this period. Taking both of these influencing factors into consideration, the declining trend of emission intensity in the industrial sectors became inevitable, and its significant effect on residential emissions was further explained.

3.5. The intermediate demand effect

As shown in Table 1, except for the four sectors, including the agriculture and the wholesale and retail trades and hotels and catering services sectors, all of the other 10 sectors presented positive effects on residential emissions in terms of changes on intermediate demands. The two largest contributions came from the machinery and equipment and the business services, public services, and other services sectors, with both of their contribution values reaching more than 50 MtC.

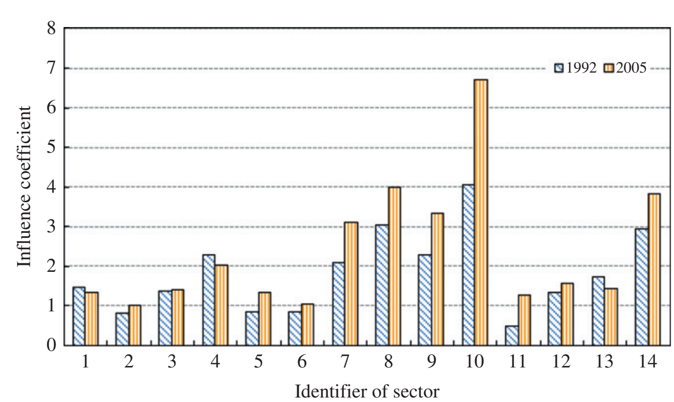

Fig. 3. Influence coefficient of each industrial sector in China. Identifier of sector: 1. Agriculture; 2. Mining and quarrying; 3. Foodstuff; 4. Textile, sewing, leather and fur products; 5. Manufacture of wood products and articles for cultural activities; 6. Coking, gas and petroleum refining; 7. Chemical industry; 8. Construction, building materials and non-metal mineral products; 9. Metal products; 10. Machinery and equipment; 11. Production and supply of electric power, heat power and water; 12. Transportation, postal and telecommunication services; 13. Wholesale and retail trades, hotels and catering services; 14. Business services, public services and other services.

Based on the input–output model shown in Eq. (3), the intermediate demands influence carbon emissions through changes in the complete demand coefficients matrix $(I-A)^{-1}$. The influence coefficient is a commonly used indicator that represents the economic links among industrial sectors, which are expressed as a row vector by summing up the column vectors of the complete consumption coefficient matrix

$$B=(I-A)^{-1}-I \tag{13}$$

The calculated influence coefficients of each sector in China in 1992–2005 are shown in Fig. 3.

As shown in Fig. 3, the influence coefficients of industrial sectors as a whole presented a fluctuating but growing trend during the sample period. Except for the three sectors, namely the wholesale and retail trades and hotels and catering services, the textile, sewing, and leather and fur products, and the agriculture sectors, all of the 11 other sectors raised their influence coefficients during this period. The machinery and equipment, and the metal products sectors increased the influence coefficients to more than 1, respectively, thus, becoming the sectors that had the largest influence coefficients in the economy.

The influence coefficient of a sector measures the impact of increasing one unit output on the demand changes of the other sectors. Generally, the higher the influence coefficient of a sector is, the larger impact this sector exerts on the others, and accordingly, the greater role this sector plays in the economy in meeting the targets of energy conservation and emission reduction. Based on the aforementioned results, in 1992–2005, sectors with significantly increased influence coefficients, such as the machinery and equipment, the construction, building materials and non-metal mineral products sectors, etc., were also the ones with the larger influence coefficients. Furthermore, the growth rates of residential consumption in these sectors were at the forefront as well. Thus, the impact of changes in the intermediate demand exhibited positive effects on residential emissions during this period.

3.6. The population size effect

Although the impact of changes in population size presented a positive effect on residential emissions, the contribution ratio was far below that of both the consumption level effect and the consumption intensity effect in 1992–2005. This finding reflects that population size is no longer the most important source of resource and environmental pressure in China.

The changing trend in China's population in 1992–2005 is shown in Fig. 4. The population continued to grow from 1.172 billion to 1.308 billion during this period, an increase of 11.6%. The growth of the population was certainly an important force driving residential consumption and its associated emissions. On the other hand, the natural growth rate of the population continued to decline from 1.16% to 0.59%, showing that the impact of changes in population size on the residential emissions might have gradually weakened. This judgment helps in investigating the future trend of residential emissions in China.

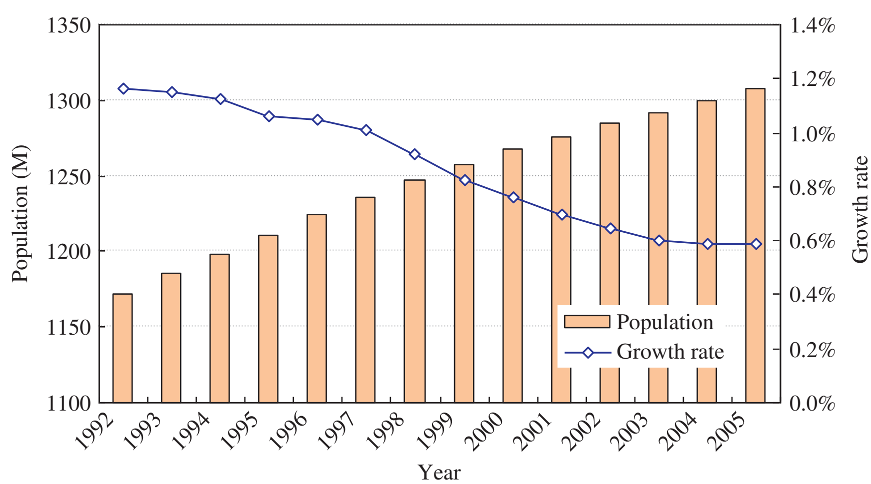

Fig. 4. China's population size and natural population growth rate.

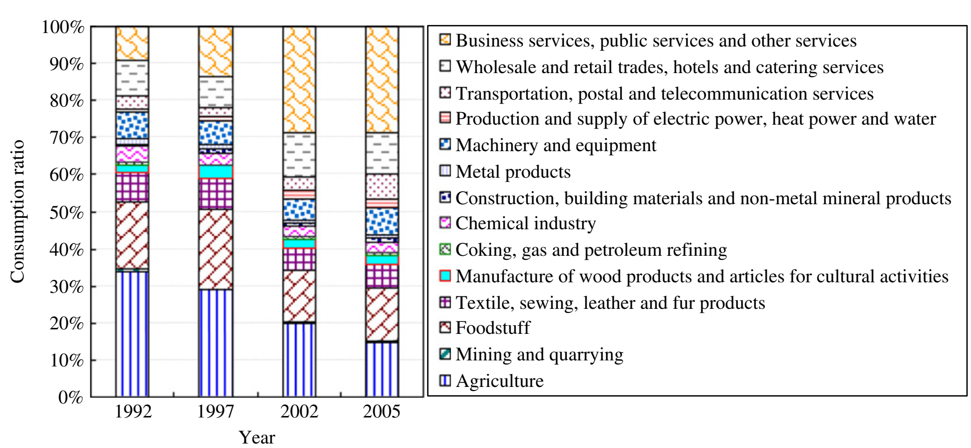

Fig. 5. Residential consumption structure in China.

3.7. The consumption structure effect

Other than the consumption level effect, changes in the consumption structure presented a fluctuant influence on residential emissions during the sample period, having made the transition from a negative to a positive effect, and the ending with a weak positive effect and with the least contribution to residential emissions compared with the other four impact factors.

As shown in Table 1, the impacts of changes in consumption structure on residential emissions were very different among the industrial sectors. Eight sectors, including the business services, public services, and other services, the transportation, postal, and telecommunication services, the production and supply of electric power, heat power, and water sectors, had positive effects on residential emissions, whereas six sectors, including the agriculture, the chemical industry, the metal products sectors, showed negative effects. Moreover, the business services, public services, and other services and the agriculture sectors, being available in both ends of the industrial chain, exhibited the dominant positive and negative effects, respectively, with both their contribution values being more than 50 MtC. The impacts of changes in the consumption structure showed a positive effect as a whole, with a contribution value of 63.33 MtC and offsetting both the positive and negative effects of all the sectors during this period.

Fig. 5 shows fluctuations in the residential consumption structure in China in 1992–2005. The main characteristic of changes in this structure can be described as ‘‘a liter of a drop’’. The proportion of the residential consumption from the agriculture sector declined from 27.2% in 1992 to 14.6% in 2005, whereas that of the business services, public services, and other services sector increased from 9.3% to 28.7%; thus, this species of consumption had the highest ratio of residential consumption in 2005. Marked by the increasing proportion of services consumption and decreasing proportion of produce consumption, as well as the enhancement of the scale of consumption, China's residential consumption pattern significantly improved during this period.

Given that the consumption structure is a relative value in terms of consumption ratio, the decline of one consequentially means the growth of another. When both the consumption scale and the intermediate demand of a species of residential consumption are constant, changes in the indirect emission from this species of consumption depend on changes in both the consumption ratio and the emission intensity of the related industrial sector. Therefore, the impact of changes in the consumption structure on the residential emissions displayed some uncertainty due to the differences between changes in emission intensity of each industrial sector. Overall, the impact transformed from a negative effect to a weak positive effect, indicating that the improvement of China's residential consumption pattern during this period had not played a necessary role in energy conservation and emission reduction.

4. Uncertainty discussion

It is undeniable that the results of indirect carbon emissions from residential consumption in our study remain uncertain. Generally, the uncertainty comes from the following aspects:

First, deriving indirect emissions by residential consumption value based on the input–output model was somewhat a roundabout method. Therefore, the results are an approximation of the residential emission partly because of the intrinsic uncertainty of the calculation model.

Second, the accuracy of this calculation partly depended on how detailed the industrial sectors had been aggregated. To establish a uniform input–output model, industrial departments were aggregated into 14 sectors from different kinds of statistics, including input–output tables, energy balance tables, and final energy consumption tables. Different species of production in one sector were assumed to have the same energy consumption efficiency and emission intensity. In this way, the smaller the granularities that the aggregated sectors had, the more accurate the calculations were.

Third, differences in energy efficiency and emission intensity between imported products and domestic products were not taken into account in our study. To simplify the calculation model, both imported products and domestic products were assumed to have the same levels of indirect energy consumption and related emissions. Thus, we might have overestimated the emissions from residential consumption due to China's emission intensity by up to 1–3 times higher than the international average level (EIA, 2009). Considering that imported products did not have a large share of China's residential consumption during this period, error from this hypothesis is acceptable when calculating emissions on a countrywide scale.

Overall, however, the methodology employed in our study is relatively reasonable for calculating indirect carbon emissions from residential consumption based on an input–output model that has limited data availability. Errors caused by the uncertainties mentioned above would not lead to a substantial misjudgment regarding the macro situation of China's residential emissions.

5. Conclusion and policy implications

Based on the input–output model and the comparable price input–output tables, the current paper investigates the indirect carbon emissions from residential consumption in China in 1992–2005, and examines the impacts on the emissions using the structural decomposition method. The results show that the rise in the residential consumption level, in terms of the absolute value of the contribution rate, played a dominant role in growth of indirect emissions, followed by emission intensity, population size, intermediate demand, and consumption structure. Furthermore, the impacts of consumption level and population size presented persistent positive effects; the impact of emission intensity exhibited a continuous negative effect; and the impacts of the intermediate demand and the consumption structure transformed from negative to positive effects and finally presented positive effects as a whole.

The impact of residential consumption on carbon emissions showed a significant positive effect, indicating that the main driving force behind indirect emissions in China was the improvement of the residential consumption level during this period. The persistent decline in the carbon emission intensity of the industrial sectors had a significant negative effect on emissions. Meanwhile, the consumption goods and services that had a larger proportion of residential consumption were mostly from the industrial sectors, which had lower emission intensity, thus, signaling the possibility of a slowdown in China's emission growth in the future. Changes in intermediate demand resulted in a positive effect as a whole, except in the initial years, wherein sectors with significantly increased influence coefficients were also the ones in which the growth rates of residential consumption were at the forefront. This situation highlighted the disadvantages the industrial structure had on the residential emissions. The impact of the increase in population size presented a positive effect, but the contribution ratio was far below that of both the consumption level effect and the consumption intensity effect, reflecting that population size was no longer the most important source of resource and environmental pressure in China.

The impact of the changes in consumption structure showed a positive effect as a whole, implying that the contribution of the improvement in the residential consumption pattern to emission reduction in China during this period was rather limited. Changes in indirect carbon emissions from residential consumption reflect changes in residential consumption patterns, including both the consumption scale and the consumption structure. The growth of consumption scale, which reflects the changes in both the consumption level and the population size, is the main driving force behind the growth of the emissions. At present, China's residential consumption level generally is able to satisfy basic needs. However, China's population will continue to grow for the short run (Peng, 2011), which means that the continuous expansion of China's consumption scale would be inevitable in the following decades. Therefore, in the context of meeting the need for the healthy development of society and the economy, the means for restructuring the economy and improving efficiency, rather than for lowering the consumption scale, should be adopted by China to achieve the targets of energy conservation and emission reduction. The present research has revealed that the impacts of the changes in emission intensity, consumption structure, and intermediate demand might be the important factors for reducing emissions; the fact that the growth rate of indirect residential emissions was much lower than that of the residential consumption scale in 1992–2005 is evidence of this.

With respect to the reduction of emission intensity, the construction, building materials and non-metal mineral products sectors showed much higher emission intensities than other sectors during the sample period; hence, their adverse impacts should not be overlooked. The coking, gas, and petroleum refining sector was the only one whose emission intensity showed a troubling rising trend during this period; therefore, both the enterprises and the government should pay more attention to this sector to control energy use and related emissions.

With regard to the readjustment of intermediate demand, both the influence coefficients and their increased values of the machinery and equipment sector were larger than those of others; thus, this sector should be the main focus of industrial restructuring.

As far as the optimization of the consumption structure is concerned, there is some uncertainty. On one hand, making a judgment on the carbon intensity of a species of residential goods or services is difficult because both the emission intensity and the intermediate demand of all sectors constantly change, and the associated indirect emissions follow accordingly. On the other hand, changes in residential consumption patterns mainly depend on the driving forces behind residential requirements, rather than specific external factors.

However, it is critical to continuously deduce the emission intensity of the whole economy. Meanwhile, advocating philosophies such as "green consumption" and "low carbon consumption" and guiding the public in developing sustainable consumption patterns from the institutional dimension are necessary.

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References

Bin, S., Dowlatabadi, H., 2005. Consumer lifestyle approach to US energy use and the related CO_2 emissions. Energy Policy 33, 197–208.
Chang, Y.F., Lin, S.J., 1998. Structural decomposition of industrial CO_2 emission in Taiwan: an input–output approach. Energy Policy 26 (1), 5–12.
Conway, J.B., 1990. A Course in Functional Analysis. Graduate Texts in Mathematics. Springer, New York.
Druckman, A., Jackson, T., 2009. The carbon footprint of UK households 1990–2004: a socio-economically disaggregated, quasi-multi-regional input–output model. Ecological Economics 68, 2066–2077.
Duarte, R., Mainar, A., Sánchez-Chóliz, J., 2010. The impact of household consumption patterns on emissions in Spain. Energy Economics 32, 176–185.
EIA, 2009. World Energy Intensity—Total Primary Energy Consumption Per Dollar of Gross Domestic 〈http://www.eia.doe.gov〉.
Energy Research Institute National Development and Reform Commission, 2003. Energy and Carbon Emissions Scenario Analysis of China's Sustainable Development. Research Report of Energy Research Institute National Development and Reform Commission.
Feng, K., Hubacek, K., Guan, D., 2009. Lifestyles, technology and CO_2 emissions in China: a regional comparative analysis. Ecological Economics 69, 145–154.
Feng, Z., Zoud, L., Y., Wei, 2011. The impact of household consumption on energy use and CO_2 emissions in China. Energy 36 (1), 656–670.
Hoekstra, R., Bergh, J., 2003. Comparing structural decomposition analysis and index. Energy Economics 25, 39–64.
Jane, G., Dominic, M., M., Xin, 2008. Chinese urban household energy requirements and CO_2 emissions. In: Ligang, S., Wing, T.W. (Eds.), China's Dilemma-economic Growth, the Environment and Climate Change. ANU E Press/Asia Pacific Press, Washington, DC.
Kok, R., Benders, R., Moll, H., 2006. Measuring the environmental load of household consumption using some methods based on input–output energy analysis: a comparison of methods and a discussion of results. Energy Policy 34 (17), 2744–2761.
Lin, X., Polenske, K.R., 1995. Input–output anatomy of China's energy use changes in the 1980s. Economic Systems Research 7 (1), 67–84.
Liu, Q., Peng, Z., 2010. China's Input–Output Tables in Comparable Prices 1992–2005. China Statistics Press, Beijing.
Mukhopadhyay, K., Chakraborty, D., 1999. India's energy consumption changes during 1973/74 to 1991/92. Economic Systems Research 11 (4), 423–438.
Niu, S., Zhang, X., Zhao, C., et al., 2011. Household energy use and emission reduction effects of energy conversion in Lanzhou city, China. Renewable Energy 36, 1431–1436.
Papathanasopoulou, E., 2010. Household consumption, associated fossil fuel demand and carbon dioxide emissions: the case of Greece between 1990 and 2006. Energy Policy 38, 4152–4162.
Peng, X., 2011. China's demographic history and future challenges. Science 333, 581–587.
Weber, C., Adriaan, P., 2000. Modelling lifestyle effects on energy demand and related emissions. Energy Policy 28, 549–566.
Wei, Y.M., Liu, L.C., Fan, Y., et al., 2007. The impact of lifestyle on energy use and CO_2 emission: an empirical analysis of China's residents. Energy Policy 35, 247–257.
Ye, H., Wang, K., Zhao, X., et al., 2011. Relationship between construction characteristics and carbon emissions from urban household operational energy usage. Energy and Buildings 43, 147–152.
Zha, D., Zhou, D., Zhou, P., 2010. Driving forces of residential CO_2 emissions in urban and rural China: an index decomposition analysis. Energy Policy 38, 3377–3383.