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Working Paper 16
http://ceep.bit.edu.cn/english/publications/wp/index.htm

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March 2011

This paper can be cited as: *Fan J-L, Liao H, Liang Q-M, Tatano H, Liu C-F, Wei Y-M. 2011. Residential carbon emission evolutions in urban–rural divided China: An end-use and behavior analysis. CEEP-BIT Working Paper.*

This study is supported by the National Natural Science Foundation of China under Grant Nos. 71001007, and 71020107026, National Basic Research Program of China under the Grant No. 2012CB955704, the CAS Strategic Priority Research Program Grant No. XDA05150600, EU-FP7 under the Grant Nos. 226282 and SRFDP under the Grant No. 20091101110044. The views expressed herein are those of the authors and do not necessarily reflect the views of the Center for Energy and Environmental Policy Research.

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Residential carbon emission evolutions in urban–rural divided China: An end-use and behavior analysis

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Abstract:

The residential sector is the second largest consumer in China with great room for energy consumption growth, as well as the related carbon emissions. Thus, how to reduce the growth rate of carbon emissions is crucial for realizing the target of energy conservation and emission mitigation in the residential sector. Based on a bottom-up framework with survey data and official statistics, this paper examines the changes of aggregate residential carbon intensity, and analyzes its driving factors from an end-use perspective over the period of 1996-2008. The Adaptive Weighting Divisia with rolling base year index specification is applied to identify the quantitative effects of driving components and their further decomposing results of end-use activities. Results show that, the residential aggregate carbon intensity has grown rapidly since 2002 in both urban and rural China. The changes in primary fuel mix for electricity and heat generation have an overall negative but insignificant effect on the residential aggregate carbon intensity, while the effect of final energy structure is positive with a rising tendency. The significant impact of changes in energy intensity shift from negative to positive over time, and contribute more to a decline than to an increase. The driving force arising from the residential end-use mode has the highest contribution to the increase of aggregate carbon intensity. Finally, some policy implications are proposed to effectively slow down the accelerated rate of the residential aggregate carbon intensity. Guiding households towards energy-saving behaviors is recommended as a wise and first policy choice.

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Key words: Residential carbon intensity; End-use activity; Divisia index decomposition

1. Introduction

The residential sector is currently the second-largest energy consumer in China, just following the industrial sector [1]. Due to the improvement of living standards, the energy consumption and related carbon emissions in the residential sector have greatly increased. In particular after the year 2000, noticeable trends with annual increase rates of 8.4% and 8.7% for energy consumption and carbon emissions were presented in the residential sector respectively (see Fig. 1). Reducing the fast rising rate of residential carbon emissions can contribute a lot to realizing the emission reduction target in China. This paper selects a new perspective of end-use to analyze the driving factors of residential carbon emission intensity[1] in urban and rural China for the period 1996-2008, in which the results refer to the end-use activities. It fills the research gaps for China and the conclusions on end-use can more effectively guide the direction of energy conservation in this sector.

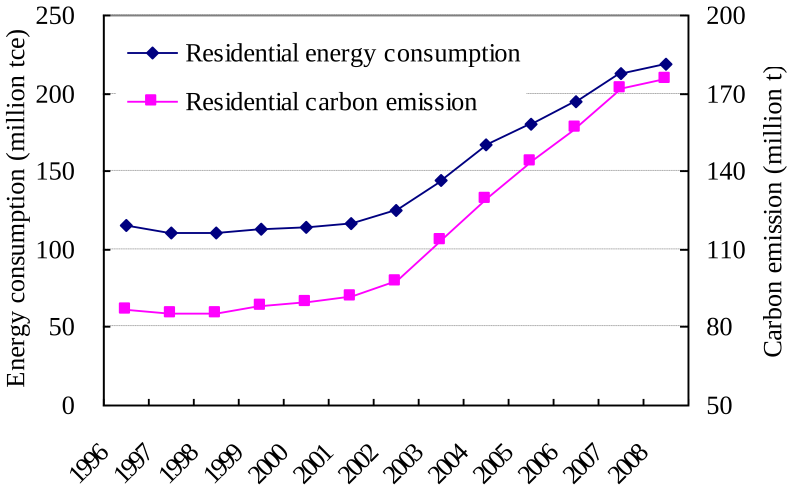

Fig. 1 Residential energy consumption and carbon emissions from 1996 to 2008

Note: tce is the abbreviation of tone coal equivalent.

Most previous studies about energy consumption or carbon emissions have focused on two aspects. First, some studies perform macroscopic analysis [2-13], in which the related macro impact factors include income, price, population, lifestyle, information feedback and so on. Second, other studies focus on energy efficiency analysis from the view of technical parameters of end-use appliances or electricity generation [14-18]. These studies focus either on macro factors using aggregate data or on some special end-use activities. However, few

[1] The residential carbon emission intensity here refers to residential carbon emission per capita, which will be interpreted in section 2.

studies consider all the behaviors through an end-use analysis, especially for developing countries.

The few end-use analysis literature on residential sector has mainly been carried out by the Lawrence Berkeley National Laboratory towards OECD countries. For example, Schipper *et al*. [19] decompose carbon emissions in residential sector for the period 1973 to 1991 for 10 OECD countries. Using a fixed base-year Laspeyres index decomposition, the authors attribute changes in aggregate emissions to five factors, i.e. changes in population, changes in primary mix for the generation of electricity, changes in the final fuel mix, changes in energy intensity and changes in structure. For another example, Greening *et al*. further analyze the development of carbon intensity of the residential sector in 10 OECD countries using the same data but varied specification of five terms and the indexing method [20]. Up to now, however, there is no literature studying residential carbon emissions from an end-use viewpoint for China. This is due to the difficulties in obtaining good time-series data on each end-use activity.

To overcome the data limitation, this study conducts surveys through the distribution of questionnaires and review of the literature to collect detail data. It is necessary and valuable to examine residential carbon intensity from the end-use perspective. On the one hand, residential energy consumption exhibits marked variability among countries [20], resulting from the differences in income, climate and the structure of energy supply. Thus existing results on OECD countries may not be valid for the situation of China. On the other hand, compared to the traditional analysis in the same research topic (see [21]), the end-use or said bottom-up analysis in the present paper is more effective and important [22]. Therefore, this paper is innovatively conducted from the end-use point of view to analyze Chinese residential carbon emissions; meanwhile, it offers more effective policy recommendations for China.

From the end-use perspective, this work decomposes the changes in residential aggregate carbon intensity from 1996-2008 into four aspects for China, i.e. changes in primary fuel mix for the generation of electricity and heat, changes in final energy mix for all residential end uses, changes in energy intensity of residential end uses and changes in end-use activity structure. And further decomposition on the key factors is also included to identify more detailed causes. In this paper, five end-use activities, two behavioral agents, seven measures of activities and nine categories of fuels are included. Based on synthesis of statistics and investigation data, it applies the Adaptive Weighting Divisia index method with rolling base year to capture the driving factors.

This paper is organized as follows. Section 2 presents the theoretical framework of carbon emissions of the residential sector, while Section 3 describes the decomposition method and the time series data source used in the paper. The results from the decomposition model are then discussed in section 4, and the final Section summarizes the main findings and conclusions.

2. The Theoretical Framework of Carbon Emissions of the Residential Sector

Decomposing aggregate carbon intensity in the residential sector from a perspective of end-use behavior is much more complex than that in other sectors [20]. For instance, the residential sector does not create product value, so carbon intensity in the residential sector cannot use the traditional measurement, i.e. carbon emissions per value added. Referring to the definition of carbon intensity for the residential sector in Greening *et al*. [22], this paper uses the measurement carbon emissions per capita to identify the carbon intensity in residential sector, known as "residential carbon intensity". To better understand the special character of decomposing residential carbon intensity, this section introduces the theoretical framework of residential carbon emissions through the following four aspects.

2.1 End-use Activities and Behavioral Agents

Unlike studies in other countries [19, 20, 23], private transportation in China is classified as one of energy-consumers in residential sector. Therefore, the utilization of residential energy consumption in China can be classified into five major end uses namely, heating and cooling, cooking and water heating, lighting, main household appliances and private transportation respectively. They are illustrated in the middle main block of Figure 2, constituting the main body of the theoretical framework.

Based on the feature of dual economic structure in China, there is considerable distinction between urban and rural areas, which can be directly reflected in different energy-use modes and comfort requirements. For example, the main energy source used in urban areas are natural gas and electricity, while most rural residents are still using many traditional biomass fuels such as stalks and firewood in daily life. Therefore, urban and rural residents should be considered respectively when studying the residential carbon intensity, seeing the behavioral agents from the top block of Fig 3.

2.2 Quantitative Measurement of End-use Activities

To decompose residential carbon intensity from an end-use perspective, we should firstly discuss how to quantitatively measure each activity, indicating the end-use modes in the decomposition process. As illustrated in the left block of Fig 3, floor area can be regarded as measurement of lighting [20] and cooking and water heating can be represented by the square root of household occupancy [24]. Also, space heating can be measured by floor area, of which, however, houses heated by central heating systems are counted at twice the weight of those heated by room stoves [25-27]. Given that central heating systems only exist in urban areas in China, the summation of the floor area and central heating area is then regarded as a measurement for urban space heating and cooling while floor area is for rural areas. With respect to the private transportation, we consider the possession of private vehicles and motorcycles respectively as measures for urban and rural residents, owing to the fact that the share of private-owned cars in rural households is still very low.

Major household appliance use, is usually measured by the simple summation of the owned appliances in previous studies [19, 20]. But because equipment differs widely in capacity and usage time, electricity consumption in practice for each equipment will not be equivalent, which means that taking simple summation of appliances as a proxy is inaccurate. To overcome the problem, a questionnaire survey method is adopted to identify the annual average utilized time that is then multiplied by the average power to yield the amount of average energy consumption of each device[2]. Furthermore, we calculate the equivalent summation of the main household appliances taking the amount of average energy consumption of each device as weight. The Eq. (1)-(2) exhibit the present process and four appliances are involved.

$$I_{tot} = \sum_{i=1}^{4} w_i I_i \tag{1}$$

$$w_i = P_i T_i \Big/ \sum_i P_i T_i \tag{2}$$

Where I_{tot} is the equivalent summation of main household appliances, w_i represents the weight of the appliance i, i.e. refrigerator, washing-machine, television and home computer, P_i denotes the average power of the appliance i mainly based on market selling survey, T_i means the average operating time of equipment i based on the questionnaire survey.

[2] Fifty-five questionnaires are released of which the recovery rate is 100% and the valid ones account for 92.7%. Among the respondents, the proportions of rural, town and urban household are 33.3%, 23.5% and 43.1% respectively including all eight main regions of China. Household occupy ranges from one to eight and have almost balanced distribution of income level.

2.3 Distribution of Fuels on End-use Activities

To get detailed end-use decomposition results, an important and difficult step is to identify which and how much energy would be consumed by each end-use activity. According to the classification of the Chinese National Bureau of Statistics, thirteen commercial fuels are consumed by residential sector, including raw coal, other washed coal, briquettes, coke, coke oven gas, other gas, gasoline, kerosene, diesel oil, liquefied petroleum gas (LPG), natural gas, heat and electricity. To simplify the division of end-use structure of energy consumption, we consolidate raw coal, other washed coal, briquettes and coke into one category called coal, and consolidate coke oven gas and other gas into one category called gas. Therefore, nine types of fuel are considered in this study. Then, we will explain how these fuels are distributed into the five end-use activities, and as showed in the right block of Figure 2.

First, lighting mainly depends on electricity, because most appliances for lighting, such as incandescent bulbs, fluorescent lamp and LED, are all based on electricity. Besides, there are still some poor households in underdeveloped areas of China employing only kerosene lamp for lighting. Thus, electricity and kerosene are the two types of fuel consumed for lighting (see Fig 2).

Second, residential activities named heating and cooling include space heating and cooling. In China the main fuels used are coal, electricity and heat. On the one hand, space heating not only uses coal-fired equipment such as household coal-stoves, low-capacity boilers and cauldrons, but also include electric apparatus such as electric heats and air conditioners. Moreover, heat is also one kind of energy in Chinese Energy Balance. It is used for central heating in urban China, so it should be also regarded as one fuel for space heating. Additionally, some households take natural gas as fuel for space heating in recent years, but it costs so much that penetration rate is still very low. Therefore in this study it is ignored. On the other hand, for space cooling, electricity consumed by air conditioners in summer is considered here.

Third, the activity of cooking and water heating refers to households' daily-life behaviors of boiling water and cooking dinner, which utilize stoves burning coal, gas, LPG or natural gas and electric cookers such as induction cookers and microwave ovens. As a result, five types of energy are used for cooking and water heating, i.e. coal, gas, LPG, natural gas and electricity.

Then, the activities of household appliances consume energy by the major household appliances such as refrigerators, washing machines and TVs, etc.. These appliances only use electricity for operation, so electricity is the only energy for the activities of household appliances. Finally, opposed to public transportation, private transportation is assumed to be an activity of residential sector in China. Therefore, gasoline and diesel oil used by residential sector constitute the energy source for private transportation. The distributed results of energy on five end-use activities are shown in the right block of Fig. 2.

From the above analysis, it can be seen that coal and electricity are utilized in more than one end-use activity. The problem is then how to ration the two fuels among the different activities. To cope with this problem, detailed survey data in previous studies [28-33] are investigated and applied in this paper. Because all of the survey data in previous studies is regional or local level only focusing on one particular area in China [28-33], we have to adjust them to the national level. The adjustment in this paper involves two aspects. On the one hand, we adjust the economic development between the certain area and nation. First we gain the time-series equivalent income level in the certain area through adjusting the original survey data by consumer price index. Then the time-series equivalent income level is compared with the according time-series national income level and finally we choose the closest set in the certain year as the national level. On the other hand, the energy consumption for space heating and cooling is adjusted by degree days (including heating degree days and cooling degree day, HDD and CDD). Based on the HDD and CDD rate between national level and the inquired areas, the national equivalent amount of fuel consumption is calculated. The method for calculating HDD and CDD can be found in the literature [34]. In addition, time-series energy use in unknown years is estimated based on the same average growth rate.

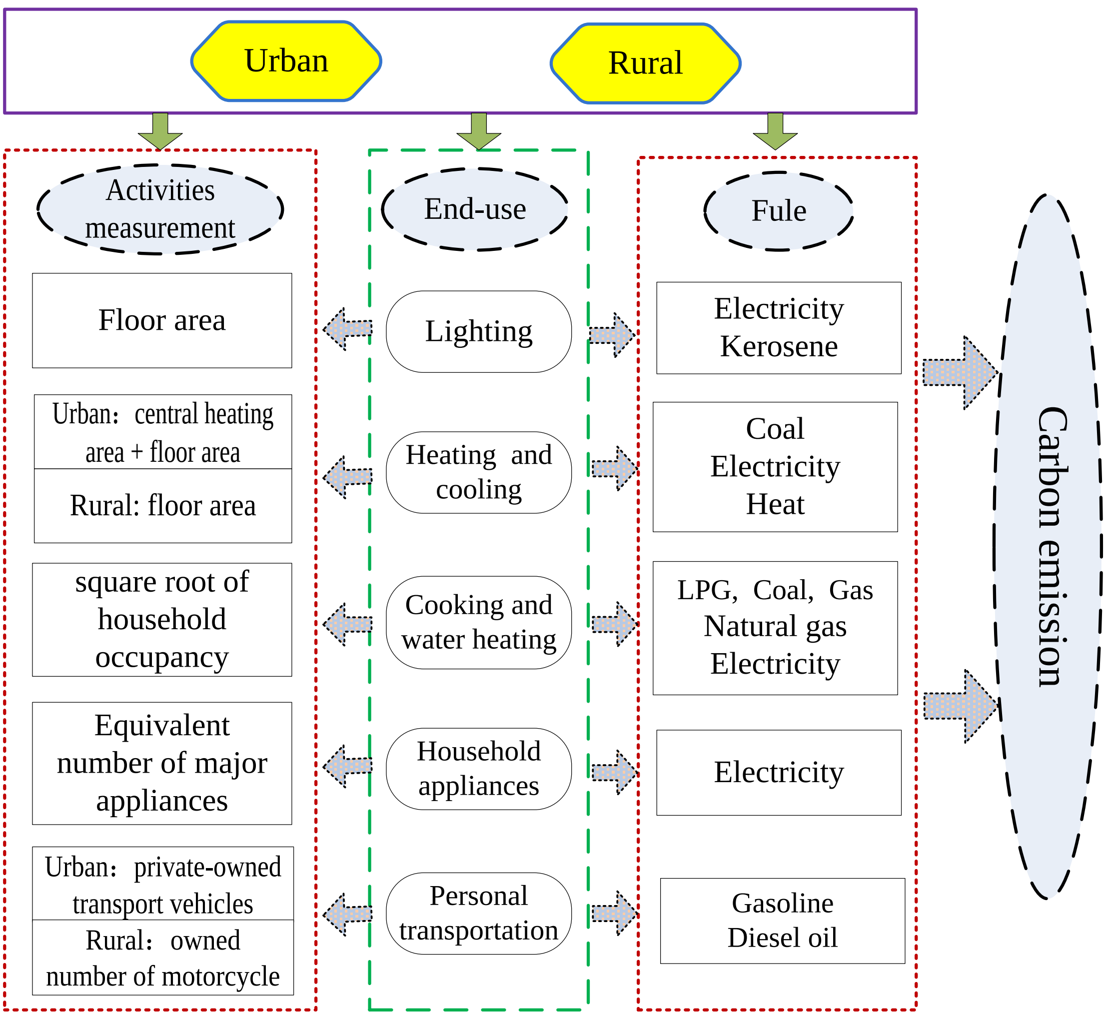

Fig. 2 Residential energy consumption and carbon emission framework

2.4 Carbon Emission of Residential Sector

After getting the detailed energy consumption of each activity from section 2.3, we can calculate the carbon emissions in the residential sector (i.e. the index of residential carbon intensity). Because of the fact that residential energy consumption comes from direct combustion rather than raw materials or non-energy uses, as well as the assumption that all the fuel inputs for electricity and heat production are used for combustion, the formula of carbon emission calculation from IPCC [35] is simplified as follows:

$$C_{emi} \equiv \sum_i (E_i * CC_i * COF_i) \tag{3}$$

Where C_{emi} means total carbon emission, E_i denotes fuel i consumption by standard quantity, CC_i means carbon coefficient of fuel i, including secondary energy sources electricity and heat , COF_i is oxidation rate of fuel i.

When decomposing the residential carbon intensity, we assume that the carbon emission coefficients of primary energy are constant for the researched period. Therefore, the effect of carbon emission coefficients on residential carbon intensity is restricted to the changes of carbon emission coefficient of electricity generation and heat generation. This consideration not only captures the change in fuel mix used in the production of electricity and heat, but also contains technological improvements in generation. Annual average emission coefficient for electricity generation or heat generation is determined by Equation (4).

$$(C/E)_{ave} \equiv \sum_{j} \left[E_j * (C_j / E_j) \right] / P_{tot} \tag{4}$$

Where $(C/E)_{ave}$ is the average carbon emission coefficient for electricity production or heat production, E_j denotes the amount of primary fuel j consumed by electricity generation or heat generation, C_j / E_j equals to the carbon emissions per unit of consumed fuel j, i.e. the emission coefficient of primary fuel j, and P_{tot} represents total final electricity actually produced including thermal power, hydropower and nuclear power or total heating supply

3. Method and Data Source

3.1 Divisia Parameter Decomposition Method

The index decomposition methods in energy analysis can be divided into two categories, "period-wise" specifications and "time series" methods. Most commonly used methods are "period-wise" specifications of either the Laspeyres or the simple average Divisia[36]. One of the most used simple average Divisia index methods is the so-called Logarithmic Mean Weight Division Index (LMDI) proposed by Ang *et al.* [37]. It is known to perform better than Laspeyres index [38]. LMDI has become the current mainstream decomposition method due to none unexplained error and easy to use even if it has its own limitation in handling data with negative values [37, 39, 40]. However, "period-wise" specifications can cause problems such as information loss and less reliable results [41].

The other index decomposition methods are called "time series" specifications with either a rolling base year or an annually changing weighting scheme. Compared to "period-wise" methods, these methods capture more information about changes in the underlying effects over time or how energy consumption has evolved over time and thus provide more reliable results[41]. The adaptive weighting Divisia (AWD) adopted in this paper is included in the "time series" methods. Parameters in AWD are determined by both the considered year and the benchmark year, which avoids the ‘arbitrary’ estimation of parameters [41]. Many decomposition method comparisons have shown that AWD are more competitive than other decomposition methods because they provide more robust estimates and smallest residual term with the least variation [36, 41-43].

Also, AWD decomposition has been successfully applied in previous papers. Greening *et al.* [44], Greening *et al.* [22] and Greening [45] analyzed the changes in carbon intensity of manufacturing, residential and that of personal transportation sectors respectively in 10 OECD countries using AWD decomposition. Fan *et al.* [46] quantified the driving forces behind China's primary energy-related carbon intensity and measured the material production sectors' final energy-related carbon intensity.

But current studies do not usually apply AWD because it is more intensive and requiring more data. In this paper, we overcome the data limitation through reviewing literature and carry out a survey as described in section 2. Consequently, we intend to adopt AWD decomposition to analyze the effects of changes in residential end-uses on carbon intensity in China. Here, the carbon intensity approach is selected instead of the carbon emission approach. That is because the carbon intensity approach had the advantage of the presentation of cumulative decomposed effects from year 1 to any year in the time-series decomposition while in the carbon emission approach it is difficult to realize [41].Residential carbon intensity can be expressed as the summation of the product of carbon emission coefficient, final energy share, final energy intensity and activity level as follows:

$$G_t = \frac{C_t}{P_T} = \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{C_{ijt}}{E_{ijt}}\frac{E_{ijt}}{E_{it}}\frac{E_{it}}{A_{it}}\frac{A_{it}}{P_t} = \sum_{i=1}^{m}\sum_{j=1}^{n}R_{ijt}e_{ijt}I_{it}a_{it} \tag{5}$$

For a four-term index decomposition, changes in the residential carbon intensity index may be attributed to changes in the primary fuel mix used for electricity generation and heat generation, changes in the final fuel mix, changes in energy intensity and changes in structure or mix of residential energy services consumed. This relationship can be expressed as in Equation (6). The AWD formulation for decomposing residential carbon intensity can be seen in Appendix A. Table A1 provides the definition of variables in AWD.

$$\begin{aligned}(1+\Delta\%G_{tot}) = {} & (1+\Delta\%G_{emissions})*(1+\Delta\%G_{fuel-structure})*(1+\Delta\%G_{end-intensity}) \\ & *(1+\Delta\%G_{end\text{-}mode})(1+D)\end{aligned} \tag{6}$$

3.2 Data Source

It is known that the Chinese National Bureau of Statistics made substantial adjustments to energy statistics since the year 1996 in 2010. In order to avoid results distortion caused by inconsistent statistical coverage, we use the latest data in 'Energy Balance of China (Standard Quantity)' from 'China Energy Statistical Yearbook 2009' [25] to compute the changes in residential carbon emissions in urban and rural areas from 1996 to 2008[3]. Carbon coefficients and oxidation rate of coal, crude oil, gasoline, kerosene, diesel oil, LPG and natural gas were

[3] The data excludes non-commercial biomass energy.

taken from the literature [26,47], and the rest from IPCC2006 [35].

The annual activities measurement described in section 2.2 and income level used for adjusting the research data originate from the "Comprehensive Statistical Data and Materials on 60 Years of New China"[48], the "China Statistical Yearbook"[49] and the Wind database[50]. The monthly temperature of each province used for calculating the HDD and CDD come from the "China Meteorological Administration" [51].

4. Results and Discussions

4.1 The changes of urban and rural residential carbon intensity in China

As depicted in Fig. 3, aggregate carbon intensity in urban areas is obviously higher than that in rural area with the former about two or three times than the latter. The huge lasting gap between urban and rural areas is caused by their differences in consumption level and lifestyle. Also, in terms of time-series trends, the carbon intensities of both urban and rural areas can be divided into two phases: 1996-2001, 2002-2008. In the first stage, residential carbon intensity fluctuates slightly in both urban and rural areas, of which the rural one rises by 9.6% while urban one declines by 15.8%. To some extent, this phase coincides with the period over which abnormal inverse correlation exists between economic development and energy consumption in China, and this may be due to a number of reasons [50]. In the following stage, however, both intensities present obviously upward trends with less degree in urban areas than that in rural areas. The residential carbon intensities in urban and rural areas increased by 56.3% and 102% respectively during the period 2002-2008, accompanied respectively by an average annual growth rate of 6.6% and 10.6%. The feature of the secondary phase reflects economic changes in China during this period. Since its accession to the WTO in 2001, China's economic system gradually integrates with international standards and maintains an annual economic growth rate more than 10%.

In case of the sustained rapid growth of China's economy, there is a potential for the continued increase of the residential carbon intensities in both urban and rural areas in the future. Therefore, it is essential to study the driving factors of the evolution of residential carbon intensity and then exam the direction of energy saving and carbon reduction.

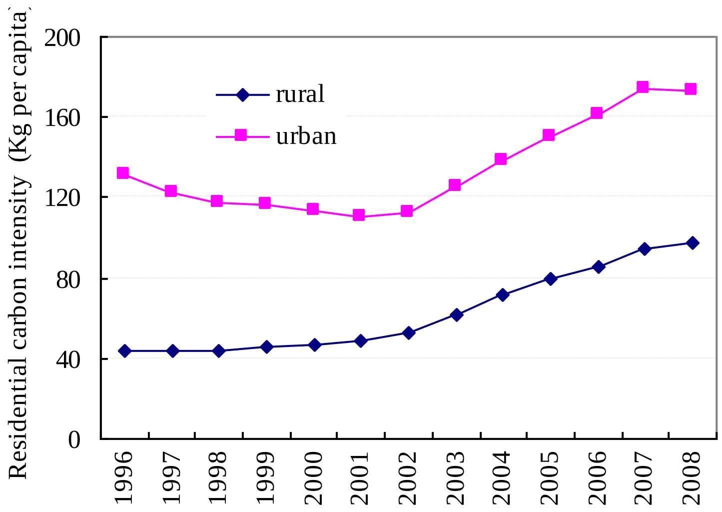

Fig. 3 Trend of residential carbon intensity in urban and rural China during 1996-2008

4.2 Decomposition results analysis

After calculation using the AWD method, changes in four terms, i.e. carbon emission coefficient, final fuel mix, end-use energy intensity and end-use mode, are identified as attributing factors on changes in residential carbon intensity (see Fig.4 and Fig. 5). In the decomposition results, the biggest absolute value of residual is only 0.04, which indicates that the results calculated by AWD are credible and the residual can be neglected. How the changes in the four attributing terms influence the changes in residential carbon intensity will be discussed as follows.

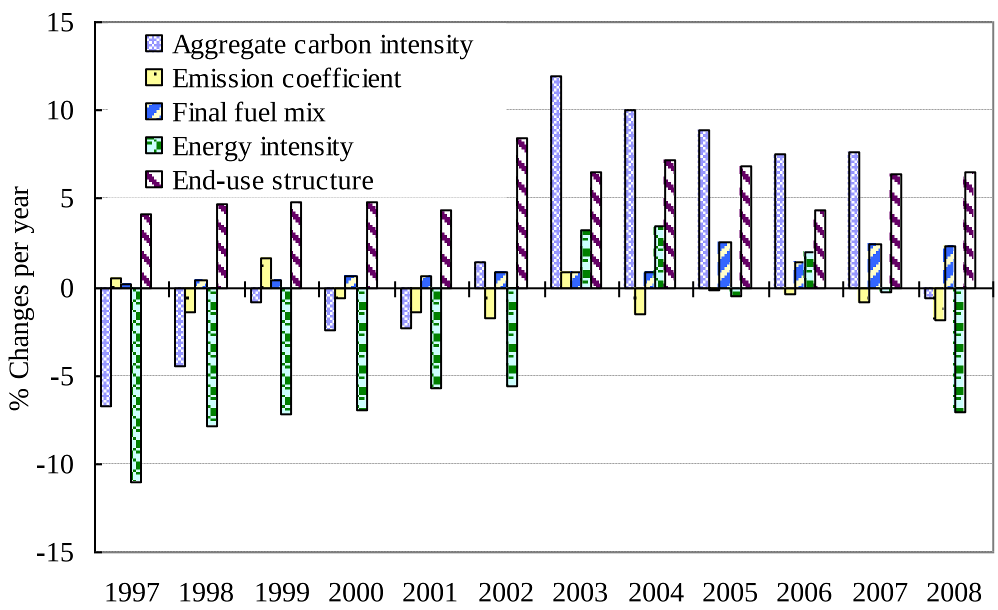

Fig. 4 Result of decomposition of aggregate carbon intensity from residential sector for urban China for the period 1996-2008

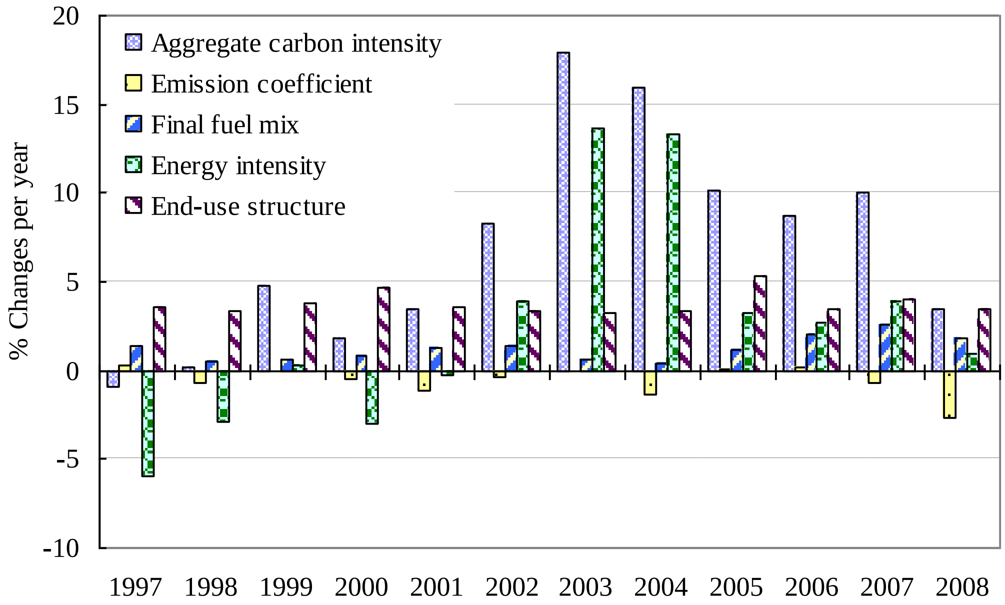

Fig. 5 Result of decomposition of aggregate carbon intensity from residential sector for rural China for the period 1996-2008

4.2.1 Carbon emission coefficients effect

Despite its different impact patterns in urban and rural areas, the changes in carbon emission coefficients have an inconspicuous and yet overall negative effect on changes in residential carbon emission intensity, which partly offsets the increase in carbon intensity. The change of emission coefficient is derived from two aspects, i.e. the change in emission coefficient of electricity generation and that of heat generation. Given that only city dwellers have access to heat for space heating for now in China, the effect of emission coefficients in rural areas is confined merely to the former aspect. In this context, the effect of emission coefficients on urban and rural areas is impacting carbon emission intensity in separate ways.

Technology progress has been driving up the efficiency of power generation. Moreover, the development of hydro power and nuclear power has optimized the source structure of total electricity production in the studied years. As a result, the emission coefficient for electricity production in China has been reduced from about 59kg/GJ in 1996 to 48kg/GJ in 2008 according to our calculation (see Fig. 6). Because people in rural areas have no access to central heating, the negative effect of the emission coefficient is only caused by the decrease of the emission coefficient of electricity production. The effect for urban China, however, includes changes in both primary fuel mix of electricity generation and that of heat generation.

Fig. 4 also shows that, for several particular years, the emission coefficients effect in urban China is positive and drive the increase of residential carbon intensity, especially in year1999 and year 2003. This situation is mainly caused by the fluctuation in the primary fuel mix of heat production. That can be proved from the Fig. 6 that shows the emission coefficient of heat generation presents a sudden increase just in year 1999 and year 2003. Consequently, the potentials for energy conservation partly lie on optimizing the primary fuel mix of electricity generation and heat generation, and the heat generation may have more potentials.

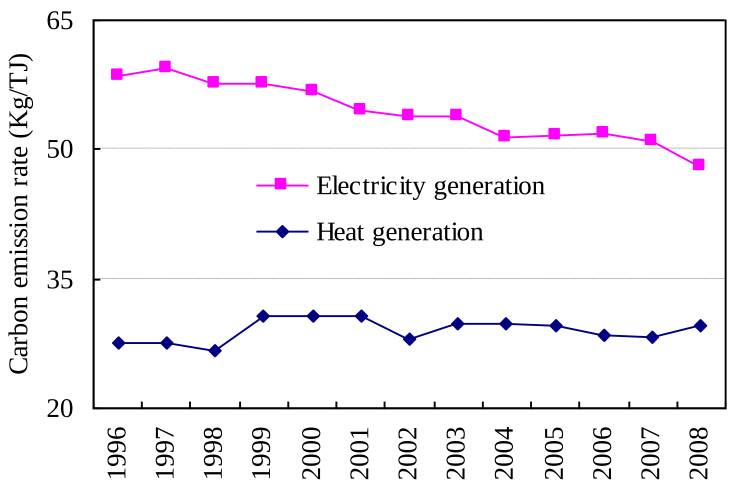

Fig. 6 Changes in carbon emission coefficient of electricity and heat generation for the period 1996-2008

4.2.2 Final energy structure effect

The changes in the final energy structure have a positive effect on the aggregate residential carbon intensity and remain a strengthening trend. The change in the final energy structure experiences an upgrade and evolution for kinds of commercial energy. On the one hand, the carbon-intensive coal has been replaced by the LPG in rural areas while the low-carbon natural gas gains popularity in urban areas, which leads to a lower level of carbon emissions per unit energy for the residential sector and partly offsets the increase of the residential carbon intensity. On the other hand, however, electricity that was applied merely to the lighting and household appliances in an earlier stage is now widely used as an efficient commercial energy on a daily basis in air-conditioning, cooking and water-heating, etc. (see Fig. 7).

As the result of being a replacement for other forms of energy, electricity proportion of the total residential energy consumption has increased since 1996 by 19% and 9% respectively in rural and urban areas. In fact, due to the intensive carbon emissions and heat-waste in the process of its generation, electricity should eventually been acknowledged as an energy source with a high carbon density. The average carbon emission coefficient of electricity ranges from 48 kg/GJ to 59kg/GJ, which is much higher than the 24.78kg/GJ of the most intensive primary energy coal. As electricity proportion goes up, the actual carbon density of the residential final energy structure escalates, neutralizing the former negative effect of energy structure evolution on carbon density and eventually exerting a positive effect with a strengthening trend. That implies the indirect emissions produced by electricity consumption should not be disregarded for the final purpose of energy-saving and emission-mitigation of residential sector and at the national level.

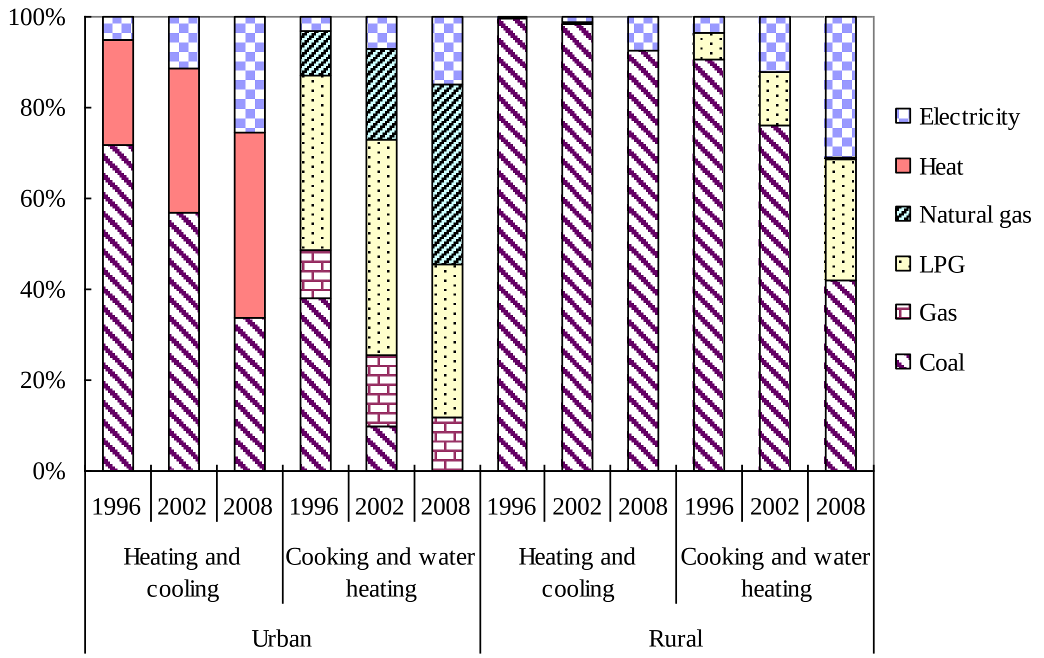

Fig. 7 Final energy structures of two end-use activities in urban and rural China

4.2.3 End-use energy intensity effect

Overall, end-use energy intensity has a significant impact on residential carbon intensity and the effect goes both ways. The intensity offsets the increase of residential aggregate carbon intensity over the years 1997-2002 for urban areas and over the years 1997-2001 for rural areas, and then drives the increase of carbon intensity in both areas over the rest of the years. As shown in Fig. 4 and Fig. 5, the height of the blue asterisks bar is always lower than the green dices bar during the whole period, which means that the driving effect of end-use energy intensity on the decline of carbon intensity overwhelms the other way around. Therefore, cutting down end-use energy intensity could effectively reduce the residential carbon intensity.

End-use energy intensity is reflected by the change of energy consumption per end-use activity, which is closely related to energy efficiency of end-use equipment, the amount of final activity, use-frequency and use-pattern. In order to clarify how the effect of end-use energy intensity works through those end-use applications, both positive and negative effects of end-use energy intensity are respectively decomposed by stage, according to the cumulative effect method calculating described in the Appendix.

When further decomposing energy intensity effects towards end-use activities, analysis is divided into a decrease stage and an increase stage respectively, i.e. 1996-2002 and 2002-2007 for urban areas, 1996-2001 and 2001-2008 for rural areas (see Fig. 8).We can find that the changes of energy consumption caused by “space heating and cooling” and “cooking and water-heating” are vital driving factors in turning around the negative effect of energy intensity to positive regardless of whether it is an urban or rural area. It could be attributed to people’s increased request for comfortable room temperature and wholesome diet which escalates the energy consumption mentioned above. It is infeasible to control people’s concern for healthcare, while encouraging residents to lower excessively high standards of comfort by reducing energy consumption of air conditioning per unit area (for instance, the indoor temperature should not be too high in winter) could be considered as an effective way to slow down carbon emission intensity.

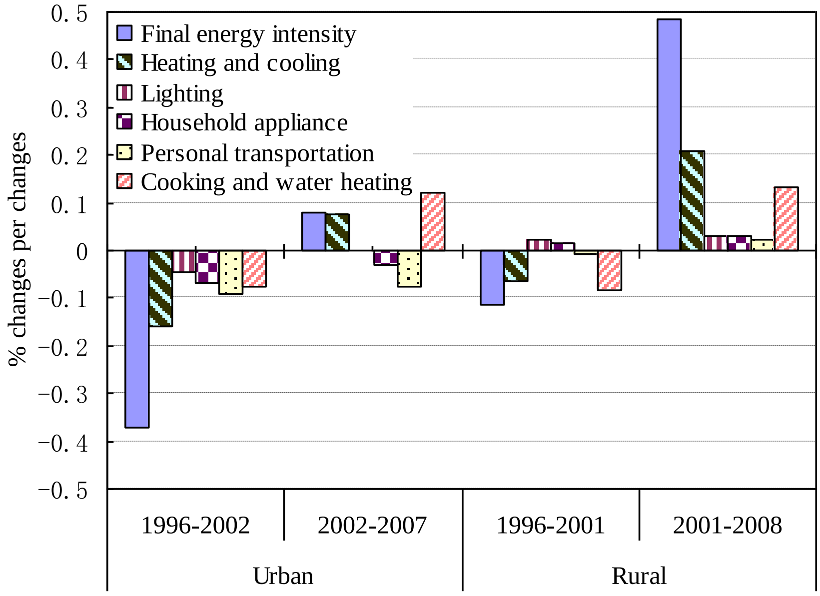

Fig. 8 Result of staged-decomposition of final energy intensity effect for urban and rural China

Besides, for urban dwellers, the declines in energy intensity of private transportation and electrical appliances over the two stages enhance the decrease of end-use energy intensity and consequently contribute to a decrease of aggregate carbon emission intensity. This could be attributed to the rocketing ownership of private cars and household appliances in the context of the escalating living standards of urban residents. However, the relative decline of the average utilized level per unit leads to a reduction of the practical energy consumption per unit of equipment, which, of course, is also related to other factors such as the implementation of energy efficiency policies and rising oil prices. For rural areas, the effects of "space heating and cooling" and "cooking and water heating" mainly determine whether the effect of end-use energy intensity is positive or negative. The effect of private transportation and household appliances is basically positive, which is related to the increase of rural residents' real effective demand for them.

4.2.4 End-use activity mode effect

Unlike the final energy intensity effect, the changes of end-use activities have a significant and continuous positive impact on residential carbon intensity. This result strongly suggests that the mode of end-use activity is the main constraint on the reduction of residential carbon intensity. The escalating living standards of Chinese residents caused by the rapid development of China's economy has brought end-use activity to a whole new level, exerting a continuous positive effect on end-use activity mode and making the rising trend of end-use activity level inevitable. Therefore, it seems infeasible to reduce residential carbon intensity through the effect of end-use activity mode at least in the short term.

We further decompose end-use activity mode effect of rural and urban residents from 1996 to 2008 (see Table 1) using the same way we did to final energy structure effect. The results show that, for urban residents, heating and cooling and private transportation rank top two in regard to contributing to end-use mode effect, with the contribution rate being 41% and 39% respectively. This result indicates that the increase of the car ownership and the floor space per capita, especially the increase of central heating area, have a huge influence on residential carbon emission intensity. In rural areas, however, heating and cooling and household electric appliances are the top two contributors for end-use activity effects, with the contribution rate being 41% and 38% respectively. It can be seen that, the increase of floor space per capita and the quantity of electric appliances exert a significant impact on the increase of residential carbon emission intensity. Thus, slowing down the growth speed of these aspects would be essential to control the end-use mode effect on residential carbon intensity.

Table 1 Contribution rate of different activities to the end-use mode effect for urban and rural China from 1996 to 2008

	Lighting	Private Transportation	Heating & cooling	Household appliance	Cooking & water heating
Urban	4.47	39.48	40.69	13.48	1.88
Rural	7.75	9.39	41.17	38.46	3.23

5. Conclusions and Policy Implications

5.1 Conclusions

Based on the AWD decomposition, this study innovatively from an end-use perspective analyzes the changes and driving factors of residential carbon emission intensity in urban and rural China during the period from1996 to 2008. Main conclusions are as follows:

(1) There is a huge continued gap between urban and rural areas in the residential carbon emission intensity. Also, obvious increasing trends exist in no matter urban or rural areas, especially for the recent stage from 2002 to 2008.

(2) Carbon emission coefficient effect is basically but slightly negative, so it does make contribution, which is though only limited to the emission reduction in residential sector. Furthermore, different impacting ways for urban and rural areas are found due to whether or not having an access to central heating. The effect for rural areas is almost negative but for urban areas in particular years is positive because of the offset from the heat generation.

(3) Changes in final energy structure have a positive effect with intensifying trend, mainly due to the substitution of electricity for other energy, which means electricity is actually such a high-carbon energy that it causes the higher carbon emission intensity.

(4) End-use energy intensity has significant both positive and negative effects on residential carbon intensity and the effect on the decrease outweighs that on the increase, of which “heating and cooling” and “cooking and water-heating” have vitally determinative contributions to the effect direction, private transportation and electrical appliances always contributes to a decrease for urban and an increase for rural areas respectively.

(5) End-use activity mode has significant continuous positive effects on the residential carbon emission intensity, of which the private vehicles and the housing area per capita in urban areas, and household appliance ownership and housing area per capita in rural areas have the most significant contribution respectively.

5.2 Policy Implications

With the rapid economic growth, residential carbon intensity will inevitably continue to grow, so it is necessary to take measures to control the growth rate of carbon emissions in residential sector. Based on the conclusions of this study, the following policy implications are proposed:

(1) Optimizing primary fuel mix for electricity and heat generation especially for the latter is necessary to ensure the emission reducing contribution of emission coefficients. However, since the carbon emission effect is inconspicuous and cannot substantially increase

in short term, it needs to take into consideration the cost-benefit comparison when trying to adjust emission coefficients.

(2) The indirect carbon emissions by electricity should not be ignored when encouraging energy evolution in residential sector. From the other side, taking measures to diminish electricity waste is an effective way to reduce carbon emission in residential sector, for example, increasing the cost of unnecessary electricity use or imposing tiered electricity price.

(3) Given the current needs that people prefer more comfortable temperature environment and wholesome diet, it is unfeasible to change the preference but it is necessary and effective to control extravagant standards of comfort. So related measures such as imposing strict room temperature limit should be considered.

(4) Measures aiming to reduce the energy usage per unit vehicle and appliance in urban households are effective and should be encouraged. For example, traffic restriction in metropolises and reducing tax of energy-saving appliances can be good choices.

(5) When the government adopts measures to stimulate consumptions and improve living standards, such as the Home Appliances Subsidy Program, it is desirable to consider the proper extent of implementation, so as to prevent the resulting significant growth of household carbon emissions.

In brief, providing guidance for households to save energy are recommended as the first priority of policy-making to slowdown the increases speed of residential carbon emission.

6. Further Perspective

This paper has just solved the problem of data availability through approximate estimation based on data from literatures and a small quantity of questionnaires, which is fine for preliminary analysis of carbon intensity from end-use perspective but may be improper when accurately analyzing every detail of energy-use behaviors. Besides, China as a large multi-regional country, each region has special lifestyle and energy-use character, so regional research on residential carbon emission may be more important for local public policy makers. Our future work is to examine these from more detailed aspects.

Appendix: AWD Formulation for Decomposing Residential Carbon Intensity

Aggregate carbon intensity in residential sector may be expressed as the summation of product of carbon emission coefficient, final energy share, final energy intensity and activity level as follows:

$$G_t = \frac{C_t}{P_T} = \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{C_{ijt}}{E_{ijt}}\frac{E_{ijt}}{E_{it}}\frac{E_{it}}{A_{it}}\frac{A_{it}}{P_t} = \sum_{i=1}^{m}\sum_{j=1}^{n}R_{ijt}e_{ijt}I_{it}a_{it} \tag{A.1}$$

For a four-term index decomposition, changes in the residential carbon intensity index may be attributed to changes in the primary fuel mix used for electricity generation and heat generation, changes in the final fuel mix, changes in energy intensity and changes in structure or mix of residential energy services consumed. This relationship can be expressed as follows:

$$\begin{aligned}(1+\Delta\%G_{tot}) = (1+\Delta\%G_{emissions})*(1+\Delta\%G_{fuel-structure})*(1+\Delta\%G_{end-intensity})\\ *(1+\Delta\%G_{end\text{-}mode})(1+D)\end{aligned} \tag{A.2}$$

With AWD decomposition, the terms in above formulation are denoted in Equations (3a)-(7a).

$$\begin{aligned}(1+\%\Delta G_{tot})_{0t} = &\exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}\left(c_{ij0}+\alpha_{ijt}\Delta c_{ij}\right)\ln\left(R_{ijt}/R_{ij0}\right)\right]\times\\ &\exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}\left(c_{ij0}+\beta_{ijt}\Delta c_{ij}\right)\ln\left(e_{ijt}/e_{ij0}\right)\right]\times\\ &\exp\left[\sum_{i=1}^{m}\left(c_{i0}+\gamma_{it}\Delta c_{i}\right)\ln\left(I_{it}/\mathrm{I}_{i0}\right)\right]\times\\ &\exp\left[\sum_{i=1}^{m}\left(c_{i0}+\omega_{it}\Delta c_{i}\right)\ln\left(a_{it}/\mathrm{a}_{i0}\right)\right]\end{aligned} \tag{A.3}$$

$$(1+\%\Delta G_{emi})_{0t} = \exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}\left(c_{ij0}+\alpha_{ijt}\Delta c_{ij}\right)\ln\left(R_{ijt}/R_{ij0}\right)\right] \tag{A.4}$$

$$(1+\%\Delta G_{str})_{0t} = \exp\left[\sum_{i=1}^{m}\sum_{j=1}^{n}\left(c_{ij0}+\beta_{ijt}\Delta c_{ij}\right)\ln\left(e_{ijt}/e_{ij0}\right)\right] \tag{A.5}$$

$$(1+\%\Delta G_{int})_{0t} = \exp\left[\sum_{i=1}^{m}\left(c_{i0}+\gamma_{it}\Delta c_{i}\right)\ln\left(I_{it}/\mathrm{I}_{i0}\right)\right] \tag{A.6}$$

$$(1+\%\Delta G_{mod})_{0t} = \exp\left[\sum_{i=1}^{m}\left(c_{i0}+\omega_{it}\Delta c_{i}\right)\ln\left(a_{it}/\mathrm{a}_{i0}\right)\right] \tag{A.7}$$

The underlying condition is that $0 \le \alpha_{ijt},\ \beta_{ijt},\ \gamma_{it},\ \omega_{it} \le 1$,

$$\alpha_{\text{ijt}} = \left[\frac{\frac{c_{ij0}}{R_{ij0}} \Delta R_{ij} - c_{ij0} \ln\left(\frac{R_{ijt}}{R_{ij0}}\right)}{\Delta c_{ij} \ln\left(\frac{R_{ijt}}{R_{ij0}}\right) - \left(\frac{c_{ijt}}{R_{ijt}} - \frac{c_{ij0}}{R_{ij0}}\right) \Delta R_{ij}} \right] \tag{A.8}$$

$$\beta_{\text{ijt}} = \left[\frac{\frac{c_{ij0}}{e_{ij0}} \Delta e_{ij} - c_{ij0} \ln\left(\frac{e_{ijt}}{e_{ij0}}\right)}{\Delta c_{ij} \ln\left(\frac{e_{ijt}}{e_{ij0}}\right) - \left(\frac{c_{ijt}}{e_{ijt}} - \frac{c_{ij0}}{e_{ij0}}\right) \Delta e_{ij}} \right] \tag{A.9}$$

$$\gamma_{\text{it}} = \left[\frac{\frac{c_{i0}}{I_{i0}} \Delta I_{i} - c_{i0} \ln\left(\frac{I_{it}}{I_{i0}}\right)}{\Delta c_{i} \ln\left(\frac{I_{it}}{I_{i0}}\right) - \left(\frac{c_{ijt}}{I_{it}} - \frac{c_{i0}}{I_{i0}}\right) \Delta I_{i}} \right] \tag{A.10}$$

$$\omega_{\text{it}} = \left[\frac{\frac{c_{i0}}{a_{i0}} \Delta a_{i} - c_{i0} \ln\left(\frac{a_{it}}{a_{i0}}\right)}{\Delta c_{i} \ln\left(\frac{a_{it}}{a_{i0}}\right) - \left(\frac{c_{ijt}}{a_{it}} - \frac{c_{i0}}{a_{i0}}\right) \Delta a_{i}} \right] \tag{A.11}$$

The Equations (12a)-(16a) show how these cumulative effects from year 1 to year k derived from objective variable and four decomposing terms.

$$GTOT_{1k} = (G_{tot})_{1,2}(G_{tot})_{2,3} \cdots (G_{tot})_{k-1,k} \tag{A.12}$$

$$GEMI_{1k} = (G_{emi})_{1,2}(G_{emi})_{2,3} \cdots (G_{emi})_{k-1,k} \tag{A.13}$$

$$GFUL_{1k} = (G_{ful})_{1,2}(G_{ful})_{2,3} \cdots (G_{ful})_{k-1,k} \tag{A.14}$$

$$GINT_{1k} = (G_{int})_{1,2}(G_{int})_{2,3} \cdots (G_{int})_{k-1,k} \tag{A.15}$$

$$GMOD_{1k} = (G_{mod})_{1,2}(G_{mod})_{2,3} \cdots (G_{mod})_{k-1,k} \tag{A.16}$$

Table A.1 Variables definitions in this paper

Variables	Definitions
G_t	Aggregate carbon intensity(carbon emissions per capita) from residential sector of urban or rural China in year t
C_t	Total carbon emissions from residential sector of urban or rural China in year t
C_{it}	Carbon emissions from end use i in year t
C_{ijt}	Carbon emissions from the use of final energy type j for end use i in year t
P_t	Population in urban or rural area in year t
E_t	Total energy consumption from residential sector of urban or rural areas in year t
E_{it}	Energy consumption from end use i in year t
E_{ijt}	Energy consumption from the use of final energy type j for end use i in year t
A_{it}	Measure of end-use activity i in year t
R_{ijt}	Rate of carbon emissions from the use of primary energy type j for end use i in year t, given by C_{ijt} / E_{ijt}
e_{ijt}	Share of final energy use from final energy j by end use i in year t, given by E_{ijt} / E_{it}
I_{it}	End-use energy intensity for end-use I in year t, given by E_{it} / A_{it}
a_{it}	Activity level per capita of end-use i , given by A_{it} / P_t
c_{it}	Carbon emission share from end use i in year t, given by C_{it} / C_t
c_{ijt}	Carbon emission share from the use of final energy type j for end use i in year t, given by C_{ijt} / C_t
$(1+\%\Delta G_{tot})_{0t}$	Index of actual change in aggregate residential carbon intensity between year 0 and year t, where 0 is the base year of a period that can be adjacent two year or longer period.
$(1+\%\Delta G_{emi})_{0t}$	Index component of estimate of the change in residential carbon intensity due to a change in primary fuel emissions rate from the generation of electricity and heat between year 0 and year t
$(1+\%\Delta G_{str})_{0t}$	Index component of estimate of the change in residential carbon intensity due to a change in final energy use structure between year 0 and year t
$(1+\%\Delta G_{int})_{0t}$	Index component of estimate of the change in residential carbon intensity due to a change in end-use energy intensity share between year 0 and year t
$(1+\%\Delta G_{mod})_{0t}$	Index component of estimate of the change in residential carbon intensity due to a change in end-use mix between year 0 and year t
$\%\Delta G_{emi}$	Carbon emission effect
$\%\Delta G_{str}$	Final energy structure effect
$\%\Delta G_{int}$	End-use energy intensity effect
$\%\Delta G_{mod}$	End-use activity mode effect
$(1+D)_{0t}$	Residual of estimation
$GTOT_{1k}$	Index of cumulative changes in aggregate residential carbon intensity between year 1 and year t, where 1 is the first year of a period
$GEMI_{1k}$	Index component of estimate of the cumulative changes in residential carbon intensity due to a cumulative change in primary fuel emissions rate from the generation of electricity and heat from year 1 to year t
$GFUL_{1k}$	Index component of estimate of the cumulative changes in residential carbon intensity due to a cumulative change in final energy use structure from year 1 to year t

$GINT_{1k}$	Index component of estimate of the cumulative changes in residential carbon intensity due to a cumulative change in end-use energy intensity share from year 1 to year t
$GMOD_{1k}$	Index component of estimate of the cumulative changes in residential carbon intensity due to a cumulative change in end-use mix from year 1 to year t

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