Energy Policy 41 (2012) 644–653

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Residential energy consumption in urban China: A decomposition analysis

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ARTICLE INFO

Article history:
Received 18 June 2011
Accepted 8 November 2011
Available online 2 December 2011

Keywords:
Residential energy consumption
Index Decomposition Analysis (IDA)
China

ABSTRACT

Residential energy consumption (REC) is the second largest energy use category (10%) in China and urban residents account for 63% of the REC. Understanding the underlying drivers of variations of urban REC thus helps to identify challenges and opportunities and provide advices for future policy measures. This paper applies the LMDI method to a decomposition of China's urban REC during the period of 1998–2007 at disaggregated product/activity level using data collected from a wide range of sources. Our results have shown an extensive structure change towards a more energy-intensive household consumption structure as well as an intensive structure change towards high-quality and cleaner energy such as electricity, oil, and natural gas, which reflects a changing lifestyle and consumption mode in pursuit of a higher level of comfort, convenience and environmental protection. We have also found that China's price reforms in the energy sector have contributed to a reduction of REC while scale factors including increased urban population and income levels have played a key role in the rapid growth of REC. We suggest that further deregulation in energy prices and regulatory as well as voluntary energy efficiency and conservation policies in the residential sector should be promoted.

1. Introduction

Residential energy consumption (REC) is the second largest energy use category (10%) in China although it lags behind the industry by far (Figs. 1 and 2).[1] Urban residents account for most of the REC (63%).[2] With urban population expected to grow by 20 million per year and residential building area increasing by 2 billion square meters every year through 2020, residential energy consumption (REC) is likely to continue its rapid growth (Zhou et al., 2009). Other factors may also contribute to a rapid growth of REC, including elevated income levels, changing consumer preferences, as well as penetration of electric appliances and private transportation vehicles. On the other hand, continued energy price reforms, energy efficiency policies and energy conservation awareness may help to restrain further REC growth.

Understanding the underlying drivers of variations of China's REC thus helps to identify challenges and opportunities and sheds some light on China's future energy policy. Residential building energy consumption contributes significantly to total REC. Some studies (Ouyang and Ge (2009); Chen et al., 2008; Yoshino et al., 2006) explored the evaluation or saving of energy consumption in residential building sector. Meanwhile, the transitions of fuel types, electricity-using appliances, private vehicle ownership, and house heating also exert important influences on changes in REC (Sathaye and Tyler, 1991; Glicksman et al., 2001; Taylor et al., 2001; Brockett et al., 2002; Riley, 2002; Deng, 2007; Ni, 2008; Zhou et al., 2009). The other factor affecting REC that has attracted much attention is the energy efficiency. Some studies have illustrated the energy efficiency indicators in residential sector (Haas, 1997), the impact of refrigerator efficiency standards on the environment, manufacturers and consumers (Tao and Yu, 2011), and the efficiency improvement of residential building energy consumption (Yu et al., 2009; Li, 2009; Zhong et al., 2009; Morrissey and Horne, 2011; Zhao et al., 2009). Our study differs in that we provide a comprehensive analysis of drivers behind China's urban REC at disaggregated product/activity level over the period of 1998–2007. In this study, we look at the major energy-using products in the following four categories: (1) private transportation; (2) electrical appliances; (3) central heating; and (4) activities using coal, natural gas, coal gas and liquefied petroleum gas (LPG).

The rest of the paper proceeds as follows. Section 2 reviews previous studies on REC. Section 3 discusses our selection of index decomposition method and applies the selected method to a REC model. Section 4 discusses the data. Section 5 presents our findings. Section 6 concludes the paper with some policy suggestions.

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[1] However, some of the industrial energy consumption can also be attributed to consumers because the products that the industry produces eventually are also consumed by them.

[2] REC by urban residents account for 63% of China's total REC in 2007 (CSY, 2008; China Urban Construction Statistical Yearbook, 2008; BERC, 2008). However, this figure does not account for the non-commercial energy consumed in the rural area.

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doi:10.1016/j.enpol.2011.11.027

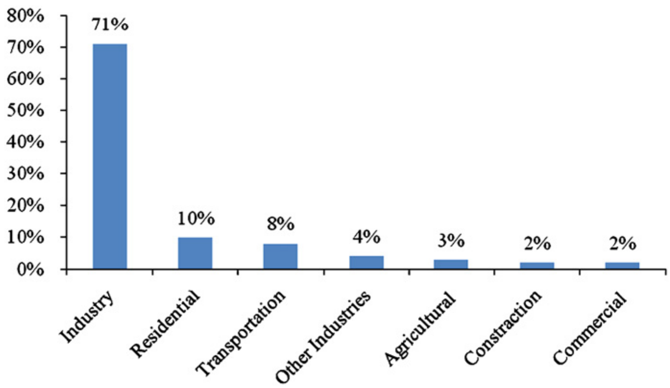

Fig. 1. China's total primary energy consumption in 2007.
Data source: China Energy Statistical Yearbook (2008).

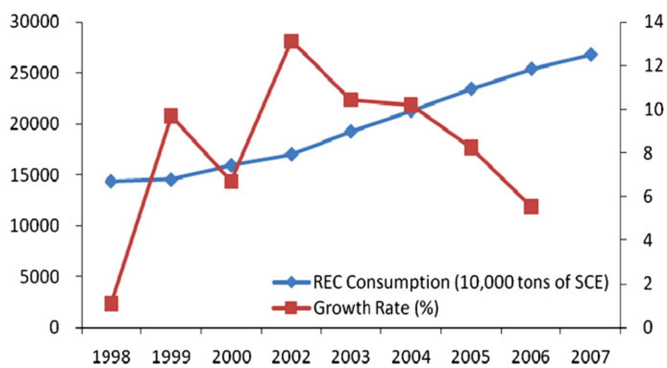

Fig. 2. China's residential energy consumption from 1998 to 2007.
Data source: CSYs (1999–2008), SCE—standard coal equivalent.

2. Literature review

There is an extensive literature on China's industrial energy consumption and total energy consumption. Besides the sheer importance of the industrial sector, the quality of the statistical data also contributes to the large number of studies in this area. Consistent and detailed data on residential energy consumption, however, is less prevalent. The existing studies are primarily case studies that rely on surveys. Much of the existing studies focus one of the following four themes: improvement of residential building energy efficiency, change of REC structure, factors affecting the ownership and use of private vehicles, and impacts of household characteristics on energy saving and emission based on direct and indirect energy consumption.

2.1. Improvement of residential building energy efficiency

Studies have explored housing energy efficiency from different perspective. First, promoting retrofit is a key factor for the improvement of residential building energy efficiency. Li (2009) explored some renovation measures. Zhao et al. (2009) put forward the technical scheme of heat metering and energy efficiency retrofit of existing residential buildings in northern heating areas of China. Second, implementing incentive policy is also important. Zhong et al. (2009) showed that the performance-based incentives were more important. Third, residential building envelope should be efficient. Yu et al. (2009) illustrated that envelope shading and exterior wall thermal insulation were the best strategies to decrease the air conditioner electric consumption, and there was a large potential to decrease the energy consumption of the existing strip residential building by reconstructing envelope. Fourth, energy efficiency standards are also a crucial factor. Glicksman et al. (2001) and Taylor et al. (2001) have pointed out low energy efficiency standards are a major reason for escalating energy demand for house heating; increased total floor area and growing income have both contributed to the growing energy consumption for residential house heating.

2.2. Change of REC structure

Sathaye and Tyler (1991) looked at the transitions of REC from traditional biomass to commercial fuel types. Asia's households have witnessed dramatic increases in the use of commercial fuels in recent years. Most strikingly, electricity has come to penetrate most households. The results of the household surveys conducted in China, India, the Philippines, Thailand, and Hong Kong suggest that changing patterns of activity and livelihood in these households underlie this growth of commercial fuel consumption. Zhang (2004) illustrated also that the direct consumption of coal in China's residential sector had been decreasing while the consumption of electricity and gases (natural gas, coal gas and LPG) had been growing since 1990s. Meanwhile the annual energy consumption per household in China on the secondary energy basis tended to increase, while that on the primary energy basis kept on decreasing.

Meanwhile, the electricity consuming products have showed new trends. Brockett et al. (2002) conducted a survey on electricity consuming products in households in five Chinese cities. They found that the wealthier cities have a higher rate of electric appliances ownership illustrating an income or expenditure effect, while land-rich but poorer areas had larger households, affecting total lighting consumption. The small size of households combined with average low income of a developing country had constrained adoption of appliances such as dishwashers and clothes dryers which were both common in developed countries. The survey highlighted the commonalities of Chinese food structure by the widespread ownership of rice cookers and the predominance of direct gas flame for cooking. It also identified the trend away from coal towards electricity and gas fuel had taken place in all cities driven by the structural change of energy-using activity.

2.3. Factors affecting the ownership and use of private vehicles

Riley (2002), Deng (2007) and Ni (2008) have studied the impact of demographic and economic changes as well as policy differences on ownership and use of private vehicles. Riley (2002) illustrated that rapid economic development, and the relaxation of policies designed to restrict private vehicle ownership seemed to be the primary factors influencing motor vehicle growth in China. Deng (2007) pointed out that income effect was strong at both national level and within regions. Meanwhile, changes and fees imposed on private car owners by authorities at different levels might have a strong influence on car ownership level. Ni (2008) made a survey in Shanghai, China, and argued that in terms of the purchase and use behavior, variables such as gender, perceptions of different aspects of the utility of different travel means, as well as personal or household income were significant.

2.4. Impacts of household characteristics on energy saving and emission based on direct and indirect energy consumption

Golley et al. (2008) conduct a cross-sectional study on China's urban direct and indirect energy consumption based on a household survey. Their focus is to identify impacts of household characteristics on energy consumption and associated emissions and they find that while richer households do indeed emit more per capita, poorer households tend to be more emission intensive—that is, generating higher emissions per Yuan spent.

Wei et al. (2007) and Golley et al. (2008) also consider indirect energy consumption defined in terms of the energy inputs needed in the production of goods and services consumed ultimately by households. Based on the application of a Consumer Lifestyle Approach, Wei et al. (2007) quantify the direct and indirect energy use and related carbon emissions during the period of 1999–2002 and find that residents' lifestyle can have an important and significant impact on energy use and related carbon emissions.

In sum, the above studies mainly have explored specific characteristics of China's REC. Our study differs in that we provide a comprehensive analysis of drivers of China's REC growth by looking the major energy-using products in the four categories: (1) private transportation; (2) electrical appliances; (3) central heating; and (4) activities using coal, natural gas, coal gas and liquefied petroleum gas (LPG).

At the same time, our study focuses on the direct energy consumption at disaggregated product/activity level. We provide a time-series analysis of China's urban REC during the period 1998–2007 based on bottom-up modeling, thus sheds new light on how urban REC structure has changed over time and what driving forces underlies the change. Similarly, Zhou et al. (2009) project China's REC up to 2020 based on a single-year decomposition of REC on electrical appliances and house heating in 2000, and assumptions about future development in population, urbanization, residential living area, household size, appliance penetration, as well as end-use energy efficiency. We provide a time-series analysis of urban REC based on 17 energy-using products/activity.

3. Method

Two broad categories of decomposition techniques, input–output techniques – structural decomposition analysis (SDA) and disaggregation techniques – index decomposition analysis (IDA), have been widely used to identify the magnitude of some predetermined driving factors of changes in observed energy indicators. Both approaches have several variants. Hoekstra and Van den Bergh (2003) investigate the different types of indexes that are used in IDA and SDA. The SDA approach is based on input–output coefficients and final demands from input–output tables while the IDA framework uses aggregate input and output data that are typically at a higher level of aggregation than input–output tables. This basic difference also determines the advantages and disadvantages of the two methods. One advantage of SDA is that the input–output model includes indirect demand effects – demand for inputs from supplying sectors that can be attributed to the downstream sector's demand – so that SDA can differentiate between direct and indirect energy demands. Chai et al. (2009) show that impact of indirect energy demand can be substantial. Rose (1999), Hoekstra and van den Bergh (2003) and Hoekstra (2005) provide overview of the Environmental SDA literature.

IDA is only capable of capturing impacts of direct energy demands; however, we consider the IDA approach sufficient for a study of residential energy consumption in which case the direct energy use is the area that consumers have the most power to act. The IDA approach has gained some favorable momentum in recent years partly due to readily available data and flexibility of application to disaggregation at different levels, which eases empirical applications and comparisons. Empirical studies using IDA have been conducted at different disaggregation levels and covered a wide range of countries and country groups in North America, Europe and Asian regions. Ang and Zhang (2000) and Liu and Ang (2007) present excellent accounts of empirical IDA applications. Among the variants of IDA approaches including Laspeyres index decomposition approaches and Divisia index decomposition approaches, several scholars (Ang and Zhang, 2000; Ang and Liu, 2001; Ang, 2004) have argued that the logarithmic mean Divisia index (LMDI) approach is a preferred method with the advantages of path independency, ability to handle zero values and consistency in aggregation. Details about the LMDI approach can be found in Ang and Liu (2001).[3]

The index decomposition technique has been widely used in the areas of energy economics and environmental economics. Variants of the IDA approach have been applied to a large number of analyses of industrial energy consumption, total energy consumption and energy-related emissions, etc. (Ang and Zhang, 2000; Liu and Ang, 2007), but it is rarely applied to REC which is largely due to data scarcity. Achão and Schaeffer (2009) applied the LMDI method in its additive form[4] to residential electricity consumption in Brazil by disaggregating residential consumers by consumption classes and regions of the country and decomposing electricity consumption by four electrical appliances: television, refrigerator, freezer, and washing machine. In this study, we also use the LMDI approach in its additive form to explore the driving factors behind the rapid growth of China's urban REC, however, with a more comprehensive dataset, we are able to study 17 energy-using products in four broad categories which constitute a complete residential energy consumption structure.

The total annual urban REC is factored into the following expression:

$$E=\sum_j\sum_i \frac{E_{ij}}{Y_{ij}}\frac{Y_{ij}}{Y}\frac{Y}{L}\frac{L}{P}P=\sum_j\sum_i PR S1\, S2\, EP\, PO \quad (1)$$

where E is the total annual urban REC in China, E_{ij} is the urban REC due to ith energy-using product in jth category, Y_{ij} is the energy expenditure on E_{ij} (in constant prices), Y is the total energy expenditure on urban REC, L is the total urban living expenditure, P is the total urban population, j is the four categories: private transportation; electrical appliances; central heating; and other energy-using activities; i is the 17 energy-using products: private vehicle, motorcycle, ten electrical appliances, central heating, activities using coal, natural gas, coal gas, and LPG, respectively.

For ease of presentation, we introduce five intermediate terms –PR, $S1$, $S2$, EP and PO – to represent the five terms in the first half of Eq. (1), respectively.

Applying LMDI in its additive form, the change in total urban REC between any two years (t and $t-1$) –ΔE_{tot}– is decomposed as follows:

$$\Delta E_{tot}=E_t-E_{t-1}=\Delta E_{PR}+\Delta E_{S1}+\Delta E_{S2}+\Delta E_{EP}+\Delta E_{PO} \quad (2)$$

where E_t, E_{t-1} is REC in Year t and $t-1$ respectively,

$$\Delta E_{PR}=\sum_j\sum_i w_{ijt}\ln\left(\frac{PR_{ij,t}}{PR_{ij,t-1}}\right) \quad (3)$$

$$\Delta E_{S1}=\sum_j\sum_i w_{ijt}\ln\left(\frac{S1_{ij,t}}{S1_{ij,t-1}}\right) \quad (4)$$

$$\Delta E_{S2}=\sum_j\sum_i w_{ijt}\ln\left(\frac{S2_t}{S2_{t-1}}\right) \quad (5)$$

$$\Delta E_{EP}=\sum_j\sum_i w_{ijt}\ln\left(\frac{EP_t}{EP_{t-1}}\right) \quad (6)$$

$$\Delta E_{PO}=\sum_j\sum_i w_{ijt}\ln\left(\frac{PO_t}{PO_{t-1}}\right) \quad (7)$$

[3] In the SDA literature, the method proposed by Dietzenbacher and Los (1998) dominates. This method leads to the same results as the IDA method proposed by Sun (1998). This was shown in Hoekstra and van den Bergh (2003).

[4] Ang (2004) provides details on the additive and multiplicative decomposition techniques and presents the mathematical link between the two.

where ΔE_{PR}, ΔE_{S1}, ΔE_{S2}, ΔE_{EP}, and ΔE_{PO} are called price effect, structure effect 1 (intensive structure effect), structure effect 2 (extensive structure effect), expenditure effect, and population effect, which represent the REC change due to energy price changes, change of energy expenditure share on household product i in total REC expenditure, change of REC expenditure share in total living expenditure, change of per capita living expenditures and change of population size, respectively.

And w_{ij} is the logarithmic weighting scheme, specified in the following:

$$w_{ijt} = L(E_{ij,t},E_{ij,t-1}) = \frac{(E_{ij,t}-E_{ij,t-1})}{\ln(E_{ij,t}/E_{ij,t-1})} \tag{8}$$

Hence, Eq. (2) can be expressed as follows:

$$\begin{aligned}\Delta E_{tot} = E_t - E_{t-1} &= \sum_j \sum_i \frac{E_{ij,t}-E_{ij,t-1}}{\ln E_{ij,t}-\ln E_{ij,t-1}} \ln\left(\frac{PR_{i,t}}{PR_{i,t-1}}\right) \\ &+ \sum_j \sum_i \frac{E_{ij,t}-E_{ij,t-1}}{\ln E_{ij,t}-\ln E_{ij,t-1}} \ln\left(\frac{S1_{i,t}}{S1_{i,t-1}}\right) \\ &+ \sum_j \sum_i \frac{E_{ij,t}-E_{ij,t-1}}{\ln E_{ij,t}-\ln E_{ij,t-1}} \ln\left(\frac{S2_{t}}{S2_{t-1}}\right) \\ &+ \sum_j \sum_i \frac{E_{ij,t}-E_{ij,t-1}}{\ln E_{ij,t}-\ln E_{ij,t-1}} \ln\left(\frac{EP_{t}}{EP_{t-1}}\right) \\ &+ \sum_j \sum_i \frac{E_{ij,t}-E_{ij,t-1}}{\ln E_{ij,t}-\ln E_{ij,t-1}} \ln\left(\frac{PO_{t}}{PO_{t-1}}\right)\end{aligned} \tag{9}$$

4. Data—urban REC and expenditures

Research on China's REC has suffered from the lack of consistent and detailed data. Previous studies have collected data through surveys (Sathaye and Tyler, 1991; Brockett et al., 2002; Ni, 2008). Our study takes a bottom-up approach to modeling China's urban REC using data from a wide variety of sources. In this study, we only examine urban residential sector for the following reasons: (1) data on quantities and prices of various commercial energy consumption are relatively complete for the urban residential sector but incomplete for the rural areas; (2) non-commercial energy such as biomass still accounts for a substantial proportion of rural residential energy consumption; however, statistics is rather incomplete and subject to substantial measurement error. For the REC in urban areas we consider oil consumption for private transportation, electricity consumption for electrical appliances, directly purchased heat for central heating, and, directly purchased coal and gases for other energy-using activities (mainly cooking and individual heating). This section describes modeling of energy consumption and expenditures for each of these elements. Data sources and some modeling results are summarized in Appendix A and B. Oil, electricity, coal, natural gas, coal gas and LPG are all converted to million tons of standard coal equivalents (Mtce) where aggregation is needed and conversion factors are provided in Appendix C. All expenditures are in 1998 constant prices.

4.1. Private transportation

Energy consumption and expenditure on private transportation are modeled as follows:

$$E_{Ti} = N_{Ti} * e_{Ti} * M_{Ti} \tag{10}$$

$$Y_{Ti} = p_{Ti} * E_{Ti} \tag{11}$$

where E_{Ti}, N_{Ti}, e_{Ti}, M_{Ti}, Y_{Ti} and p_{Ti} represent annual energy consumption of urban private transportation i (i=private vehicles, motorcycles), annual number of urban private vehicles and motorcycles, fuel efficiency of private vehicles and motorcycles (L/100 km), annual average mileage of private vehicles and motorcycles, annual expenditure on REC of urban private transportation i and annual average retail gasoline price, respectively.

4.2. Electrical appliances

Urban energy consumption and expenditure on electrical appliances are modeled as follows:

$$E_{Ai} = N_{Ai} * C_{Ai} * T_{Ai} \tag{12}$$

$$Y_{Ai} = p_e * E_{Ai} \tag{13}$$

where E_{Ai}, N_{Ai}, C_{Ai}, T_{Ai}, Y_{Ai} and p_e represent annual energy consumption of urban residential electrical appliance i (i=air-conditioner, washer, refrigerator, electric cooking, color TV, monochrome TV, home computer, water heater, range hood, microwave oven, electric fan), annual number of urban electrical appliance i, annual average capacity of electrical appliance i, annual average using time of appliance i, urban expenditure on energy consumption of electrical appliance i and annual average retail electricity price, respectively.

4.3. Central heating

Urban energy consumption and expenditure on central heating are modeled as follows:

$$E_c = A_c * e_c \tag{14}$$

$$Y_c = A_c * p_c \tag{15}$$

where E_c, A_c, e_c, Y_c and p_c represent urban energy consumed for central heating, total central heating area in urban areas, annual energy consumption per unit central heating area, expenditure on urban central heating and urban central heating price (per unit area), respectively.

4.4. Other energy-using activities

Although central heating has penetrated rapidly in urban areas in recent years, individual heating systems are still widely used where central heating is unavailable or inadequate especially in southern provinces where central heating is not officially provided. On the other hand, cooking has not been completely electrified. Coal products and gases are still widely used for heating and cooking purposes. Energy-using activities not included in Sections 4.1, 4.2 and 4.3 are modeled by fuels. The expenditure on the ith fuel – Y_{oi} – is modeled as follows:

$$Y_{oi} = p_{oi} * E_{oi} \tag{16}$$

where p_{oi} and E_{oi} are the price of fuel i (i=coal, natural gas, coal gas, and LPG) and urban residential consumption of fuel i, respectively.

4.5. Lighting

Data on urban residential lighting energy consumption is very limited. We are thus forced to leave out lighting in our primary analysis. To examine the extent to which our analysis is robust to the omission of lighting, we conduct a sensitivity analysis in the next section using available urban lighting data during 2002–2004. The expenditure Y_l on urban residential lighting energy consumption E_l is calculated by

$$Y_l = E_l * p_e \tag{17}$$

where p_e is annual average retail electricity price.

5. Results and discussion

5.1. Results

5.1.1. Energy price effect promotes REC decrease

Table 1 and Fig. 3 present the complete decomposition results. As expected, the price effect (ΔE_{PR}) is mainly negative. The Chinese government has launched a series of reforms in the energy sector in an effort to improve the economic efficiency. One essential element is the price deregulation which has resulted in an overall increase in energy prices (Ma and He, 2008; Zhao et al., 2010). Our results illustrate that rising energy prices have had a dampening impact on the urban REC. The total urban REC would have increased much more rapidly without recent deregulation reforms in energy prices.

5.1.2. Scale effect (expenditure effect and population effect) promotes REC increase

The expenditure effect (ΔE_{EP}) and the population effect (ΔE_{pop}) are both scale effects indicating the positive impacts of rising income levels and urbanization. In fact, the expenditure effect dominates positive contribution to the overall urban REC growth and it is so robust as to more than double the dampening effect of price increase. On the other hand, growing population and rapid urbanization have also significantly contributed to the increased REC in cities. China's urbanization rate has increased from 33.35% to 44.94% within a decade (1998–2007). Such results are similar to that of Riley (2002), Deng (2007) and Ni (2008). (These three references only identified the factors affecting the ownership and use of private vehicles.)

Table 1
Decomposition of China's urban REC (1998–2007, Mtce).

	ΔE_{tot}	ΔE_{PR}	ΔE_{S1}	ΔE_{S2}	ΔE_{EP}	ΔE_{PO}
Absolute contributions	65.2	−27.3	−34.4	35.6	71.8	19.5
Relative contributions (%)	100	−41.9	−52.7	54.6	110.2	29.9

5.1.3. Extensive structural effect (larger share of energy expenditure) promotes REC increase

The positive *extensive* structural effect (ΔE_{S2}) shows that residential consumption has been more energy-intensive during the study period. The *extensive* structural effect (ΔE_{S2}) actually embodies two effects: (1) the structural shift in residential consumption between energy-using activities and those that do not directly use energy in final consumption, and (2) the energy efficiency changes in energy-using products. Assuming no structural shift and improved energy efficiency of energy-using products over time, we would expect a negative *extensive* structural effect. The positive result shows that the impact of a structural shift towards more energy-using activities on household expenditure structure has overcompensated that of energy efficiency gain and thus results in a larger share of energy expenditure.

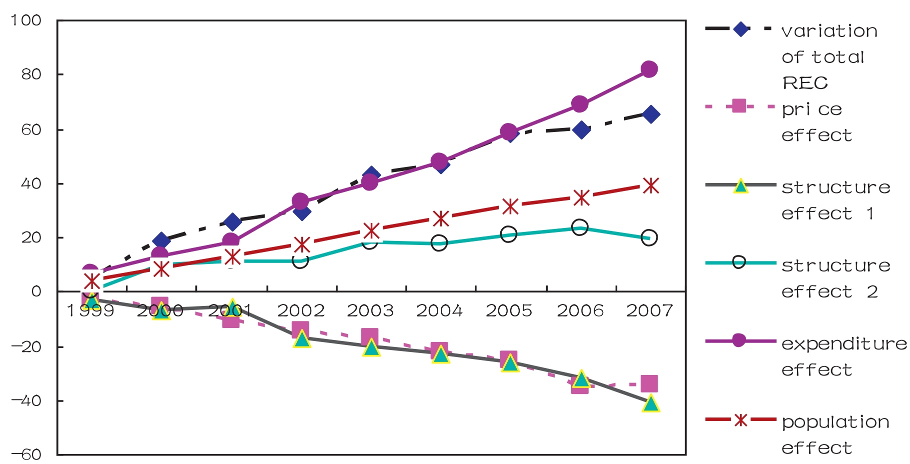

Fig. 3. Comparison of accumulated decomposition effects (Mtce).

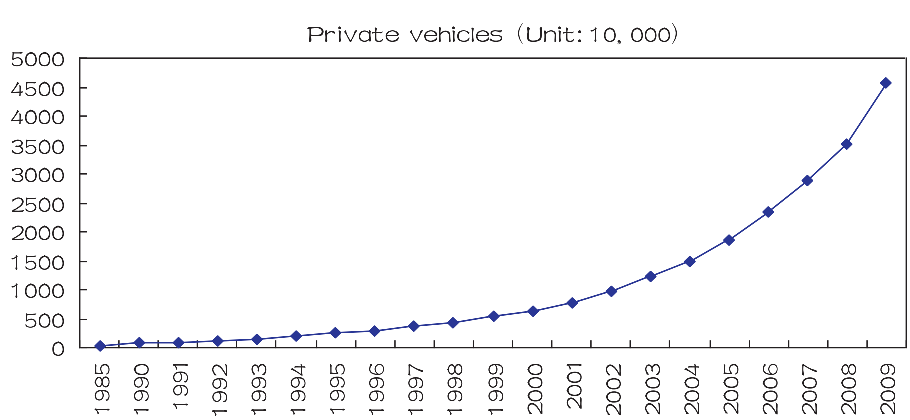

Fig. 4. Total private vehicles in China: 1985–2009.
Data source: CSY (2010).

The share increase of energy expenditure is mainly driven by the ownership increase of private vehicle, motorcycle, and air conditioner. China is experiencing one of the highest annual motorization growth rates in the world (Riley, 2002). Fig. 4 reflects further that China's private vehicles increased very quickly from 1985 to 2009.

5.1.4. Intensive structural effect (consumption structure change of energy products and energy-using products) promotes REC decrease

The *intensive* structural effect (ΔE_{S1}) is attributed to price differences between various energy products (coal, gases, oil, electricity and heat) and the structural shift between energy-using products that use different energy products. With a fixed energy expenditure budget, a structural shift towards using more expensive energy products (e.g. oil and electricity) will result in a negative overall *intensive* structural effect (ΔE_{S1}), and vice versa. The price differences between energy products may be affected by a variety of factors including marginal productivity, environmental impacts, society technological conditions, regulatory pricing schemes, etc. In general, high-quality and cleaner fuels such as electricity and oil are more expensive than low-quality and dirtier fuels like coal. A negative *intensive* structural effect (ΔE_{S1}) would reflect a structural change towards more consumption of the former and less of the latter.

This is indeed borne out by the detailed decomposition results for each product (Table 2 and Fig. 5). The results reflect a changing lifestyle and consumption mode in pursuit of a higher level of comfort and convenience as evidenced by increased energy expenditure on private vehicles, motorcycles, air-conditioning, personal computers, microwave ovens and central heating, and decreased shares on basic and traditional electric appliances including refrigerator, TV, washing machine, cooking appliances and electric fan. Another striking feature of the structural change is that shares of low-quality and environmentally polluting fuels for heating and cooking purposes such as coal have declined while the share of the more efficient and cleaner fuel—natural gas, has increased.

Historically, individual heating systems (as compared to central heating) dominate residential heating. Three quarters of the total floor area in urban residential buildings were heated by stoves with efficiency of less than 10% (McElroy et al., 1998). In the 1980s and even the early 1990s, coal provided more than 80% of the total urban residential energy and a large proportion was consumed for direct cooking and heating purposes. However, the percentage has been declining with the proliferation of gas fuels including natural gas, coal gas and LPG, largely as a result of increased government investment in these areas. By 1999, 80% of urban homes had access to gas for cooking and coal-burning households have increasingly turned to the use of cleaner fuels and more efficient heating and cooking technologies (He, 2002). Our results have confirmed this changing pattern.

Table 2
Structure effect 1 decomposition by products (1998–2007, Mtce).

Rank	Items	Absolute contribution	Relative contribution (%)
1	Private vehicle	12.72	(46.54)
2	Central heating	4.87	(17.82)
3	Air conditioner	4.53	(16.58)
4	Motorcycle	2.89	(10.57)
5	Personal computer	1.41	(5.16)
6	Natural gas	1.12	(4.10)
7	Microwave oven	0.63	(2.31)
8	Water heater	−0.16	0.59
9	Microwave oven	−0.20	0.73
10	Washing machine	−0.30	1.10
11	Electric fan	−0.36	1.32
12	Color TV	−0.73	2.67
13	Electric cooking	−0.85	3.11
14	Liquefied petroleum gas	−1.30	4.76
15	Coal gas	−2.60	9.51
16	Refrigerator	−8.68	31.76
17	Coal	−40.35	147.64
Total		−27.33	100

5.2. Sensitivity analysis

Lighting still accounts for about one quarter of total residential electricity consumption in urban areas (Liu et al., 2003). We thus perform a sensitivity analysis using the available data (2002–2004) to examine the extent to which the omission of

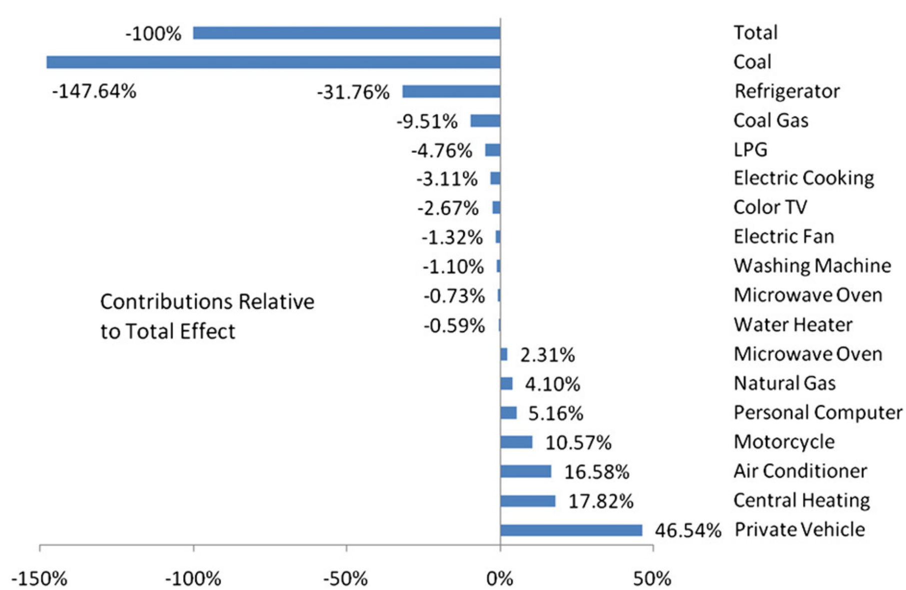

Fig. 5. Structural effect 1 by products.

lighting may affect the decomposition results. Table 3 presents the comparison between decomposition results with residential lighting included and those with residential lighting excluded. The differences are rather limited and thus the omission of residential lighting will not affect our overall discussion in any significant way.

5.3. Further discussion

Our study shows that scale effects are the main drivers behind the increase of REC in urban China. With elevated income levels and rapid urbanization, China's urban REC is likely to continue increasing rapidly. In addition, a more energy-intensive consumption structure – an increased share of energy expenditure in total living expenditure – also contributes to the increase. Increased ownership of energy-using products is likely to increase the energy intensity of residential consumption. Fig. 6 illustrates the ownership of major residential energy-using durables in urban areas during 1999–2007. While washing machine, refrigerator and air conditioner have almost reached the saturation point and color TV is even over saturated, there is still substantial room for ownership of transportation vehicles, microwave ovens, personal computers and water heaters to increase.

The results also reveal a negative impact on REC due to a structural change towards more consumption of high-quality and cleaner fuels such as electricity and oil and less consumption of low-quality and dirtier fuels like coal, and a significant dampening effect due to increased energy prices. China's energy market has gone through an unbalanced deregulation process (Ma and He, 2008; Zhao et al., 2010). Typically, price deregulation was earlier for the coal industry than for the electricity, oil and heat industry. China's coal price has become market oriented while electricity and oil prices are still tightly regulated and subject to periodical adjustments by the government. The price differences between fuel products partially reflect the unbalanced price reforms among other factors. Changes in pricing schemes inevitably lead to structural shifts and changes in the total REC. Further price deregulation for electricity and petroleum products will generally reinforce the negative price effect and negative *intensive* structural effect.

Table 3
Sensitivity analysis of total effects 2002–2004 (Mtce).

	ΔE_{tot}	ΔE_{PR}	ΔE_{S1}	ΔE_{S2}	ΔE_{EP}	ΔE_{PO}
2002–2004 (without lighting)	14.48	−7.26	−6.29	6.32	13.36	8.35
2002–2004 (with lighting)	14.56	−7.26	−6.23	6.18	13.46	8.41
Error (%)	0.55	0	0.96	2.27	0.74	0.71

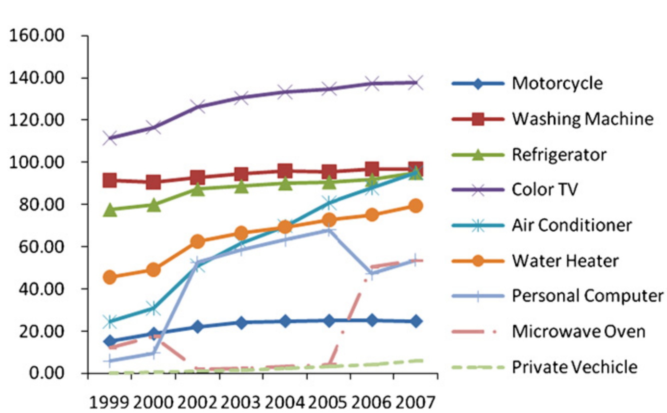

Fig. 6. Ownership of energy-used products per 100 households.
Data source: CSYs (2000–2008); data for 2001 is missing.

6. Conclusion and policy suggestions

In this paper, we study the underlying forces driving the fast-growing residential energy consumption in urban China. By applying the logarithmic mean Divisia index to a dataset of 17 energy-using products compiled from a wide range of sources, we are able to detail the changes of China's socioeconomic landscape and life style, as well as impacts of these changes. Rapid urbanization, elevated income levels and increased ownership of energy-using durables have all contributed significantly to an overall increase of urban REC in China. With these factors continuing current growing trajectories, urban REC will also likely to continue increasing. On the other hand, price reforms in the energy sector have helped to constrain the consumption growth.

Given that changing consumption style is one of the major contributors to increased residential energy consumption, further deregulation in residential energy prices, regulatory energy efficiency policies as well as voluntary efficiency programs that encourage energy conservation in the residential sector should be promoted.

6.1. Energy price deregulation

China's electricity was subsidized for a long time. Cheap electricity prices might hamper the energy-saving efforts in China's residential sector. Since 1985, China's electricity price has been deregulated step by step characterized by a few milestone policies including "*Interim Provision on Promotion Fund-Raising for Electricity Investment and Implementing Multiple Electricity Prices*" in 1985, and "*Notice on Adjustment of Power Price*" in 2003. As we have presented in this paper, price increase attributed by deregulation has helped to dampen China's urban REC. However, residential electricity price is still substantially subsidized. The recently proposed tiered residential electricity price scheme that aims to promote residential electricity conservation should therefore be encouraged.

6.2. Energy-efficiency standards and policies

During the past few years, the Chinese government has carried out a series of policies to improve energy efficiency in vehicles (Wu et al., 2003; Wang et al., 2010), and electrical appliances (Lin, 2002). China adopted its first mandatory national fuel consumption standard in 2004 which includes Phase I and Phase II fuel consumption limit and proposed to develop a new fuel consumption standard (Phase III) (Wang et al., 2010). China also introduced the first set of minimum energy efficiency standards for eight types of appliance products in 1989 and revised a series of standards in late 1990s and early 2000s (e.g. refrigerator standard, fluorescent lamp ballast standard, air conditioner standard, fluorescent lamp standard, etc.). The China Certification Center for Energy Conservation Products also established the energy conservation label program under which an endorsement label would be granted to products that meet both the quality assurance and energy performance specifications. Lin (2002) estimated that these regulatory standards and voluntary endorsement labels would contribute to a 9% reduction in REC by 2010. On the other hand, policies can also be made to provide incentives for producers of household appliances, especially for air conditioner, and personal computer, to innovate with more energy-efficient products. Similarly, the energy efficiency improvement of residential heating is another important area that should be attracted attention by the Chinese government. Chinese government has taken some measures, such as promoting combined power and heat generation, to improve energy efficiency in residential heating in the past few years (Glicksman et al., 2001; Lang, 2004). However, the heating energy consumption per unit area in China is still 2–3 times more than that of Western European or North American countries with similar climatic conditions due to poor insulation technologies and standards (Glicksman et al., 2001; Lang, 2004; Li, 2009). Although the Chinese government has implemented a series of energy efficiency policies and programs, a more aggressive set of policies are needed to further improve energy efficiency given that there are still significant efficiency gaps.

6.3. Energy-saving consciousness

We have shown in this study that the changing life style and consumption mode can have a significant impact on REC, which implies that energy-saving consciousness can play an important role. Chinese residential energy saving (RES) consciousness has improved in recent years attributed to increased environmental publicity (Liu, 2009; Feng, 2008). However, some issues remain—differences in the energy saving consciousness across different areas or different income level, limited information about energy saving methods, lacking economic incentives (Liu, 2009; Feng, 2008). The Chinese government has taken a number of actions to promote energy saving including ‘‘*Energy Saving Law*’’ in 1997, and ‘‘*National Actions to Implement Energy Saving Programs*’’ in 2007. However, the actual impact is so far limited and there is still large potential for further improvement (Feng, 2008). The key measures in future would include: provide more guidance and information regarding residential energy saving methods, improve public awareness through effective educational, illustrative, and persuasive programs and build in economic incentives, such as tiered energy prices, feed-in tariffs, peak-load smart prices, etc.

6.4. Limitation and further research

The limitation of the paper is that due to the lack of consistent time series data on energy efficiency measures, the current study is unable to capture the impacts of variations of energy efficiency. For instance, data on average capacity and average using time of electrical appliances (C_{Ai} and T_{Ai}) is only available for the year of 2004 and is used for the entire study period to calculate energy consumption. The structure effects (1 and 2) for electrical appliances thus only reflect the impact of the changes in total ownership over time and omit the impact of the changes in average capacity and average using time caused by a variety of factors including efficiency improvement (smaller capacity), change of preference for larger capacity, conservation efforts (less average using time), changes in weather conditions (changes in using time), etc. Similarly, data on fuel efficiency (e_{Ti}), average mileage (M_{Ti}) and central heating efficiency (e_c) are also available for a single year but are used for the entire study period. Consequentially, the impacts of efficiency change due to higher fuel economy standards and promotion of combined power and heat generation, as well as the impacts of usage change are not captured in the present analysis. It is reasonable to assume that energy efficiency has improved over time and consistent data on energy efficiency advancement can significantly improve the current study.

Acknowledgments

This study is funded by the National Natural Science Foundation of China (Project nos. 70773040 and 71073053). The authors want to thank Chao Ouyang for her help in data collection, thank Professor Sufang Zhang's for her help in grammar correction. The authors especially appreciate the anonymous reviewers for their valuable comments.

Appendix A. Data description and sources

See Table A1.

Appendix B. Energy consumption (Mtce) and expenditure (RMB 100 million)

See Table B1.

Appendix C. Energy conversion parameters

See Table C1.

Table A1

Variables	Description	Data sources
N_{Ti}	Annual number of urban private vehicles and motorcycles	China Statistical Yearbooks (CSYs), 1999–2008
e_{Ti}	Fuel efficiency of private vehicles and motorcycles (1998)	EF (2006)
M_{Ti}	Annual mileage of private vehicles and motorcycles	Yuan et al. (2000)
p_{Ti}	Annual average gasoline price (Yuan/l)	BMCDR (1998–2007)
N_{Ai}	Annual number of urban electrical appliances	CSYs, 1999–2008*
C_{Ai}	Annual average capacity of electrical appliances (2004)	NDRC (2004)
T_{Ai}	Annual average using time of appliances (2004)	NDRC (2004)
p_e	Annual average retail electricity price	Zhang and Tan, (2005), China Electric Power Yearbooks (2003–2008)
A_c	Annual urban central heating area	China Urban Construction Statistical Yearbooks (1999–2008)
e_c	Annual average energy consumption per unit of central heating area	Annual Development Report on China's Building Energy Saving (BERC, 2008)
p_c	Annual urban central heating price (per unit area)	CPIN (1999–2008)
p_{oi}	Prices of coal, natural gas, coal gas and LPG	CPIN (1999–2008)
E_{oi}	Annual urban residential consumption of coal, natural gas, coal gas and LPG	China Urban Construction Statistical Yearbooks (2008)
E_l	Annual urban residential electricity consumption on lighting (2002–2004)	NDRC (2004)
L	Annual urban living expenditure	CSYs (1999–2008)
P	Annual urban population	CSYs (1999–2008)

Table B1

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
PV										
E	0.4	0.6	0.9	1.1	1. 8	2.9	4.8	8.3	10.7	15.5
Y	8.5	12.7	26.9	31.1	49.6	86.3	158.7	289.9	461.0	669.8
MC										
E	2.9	3.5	4.8	5.4	6.3	7.1	7.7	8.6	8.8	8.9
Y	63.3	79.2	139.8	148.9	175.9	214.1	254.3	302.4	379.6	385.6
AC										
E	1.5	2.0	2.7	3.3	5.0	6.4	7.5	9.6	10.6	11.8
Y	50.6	68.6	98.6	121.7	190.6	246.7	284.0	367.2	407.5	442.8
LT										
E	–	–	–	–	0.7	0. 8	0.8	–	–	–
Y	–	–	–	–	28.0	30.4	30.8	–	–	–
WS										
E	0.4	0.4	0. 5	0.5	0.5	0.5	0.6	0.6	0.7	0.7
Y	12.7	14.2	16.1	17.4	19.3	21.0	21. 7	24.2	25.0	25.4
RF										
E	13.7	14.7	16.8	17.8	20.3	21.6	22.8	25.5	26.2	27.9
Y	454.2	514.4	606.7	657.2	769.5	837.2	865.8	974.9	1005.5	1044.7
CT										
E	1.3	1.4	1.6	1.7	1.9	2.1	2.2	2.5	2.6	2.7
Y	41.5	48.6	58.1	63.7	73.3	81.1	84.4	95.4	99.2	99.8
PC										
E	0.2	0.3	0.5	0.7	1.2	1. 7	2.1	1.9	2.2	2.6
Y	5.6	9.7	18.2	26.4	44.9	64.8	78. 6	73.5	85.2	97.4
WH										
E	1.7	1.9	2.3	2.5	3.2	3.6	3.9	4.6	4.8	5.2
Y	57.8	67.3	83.1	93.3	122.9	140.5	149.0	174.5	184.0	195.4
RH										
E	0.6	0.6	0.8	0.8	1.0	1.1	1.1	1.3	1.4	1.4
Y	18.6	21.8	27.7	30.2	36.2	40.6	42.7	49.5	51.8	53.4
MO										
E	0.1	0.2	0.3	0.4	0.6	0.8	0.9	1.2	1.3	1.4
Y	4.5	7.1	11.8	15.8	24.0	30.8	35.3	45.1	48.9	51.8
EC										
E	1.3	1.5	1.6	1.8	1.7	1.9	2.1	2.3	2.5	2.7
Y	43.8	51.5	59.0	66.2	64.7	73.0	78.1	88.1	94.9	100.2
EF										
E	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7
Y	14.2	16.0	18.0	19.4	22.7	24.2	24.4	26.9	27.0	26.6
CH										
E	4.5	5.1	6.1	7. 7	8.7	10.5	12.1	14.0	15.0	17.0
Y	58.1	80.6	113.6	164.5	211.9	253.7	297.5	256.9	278.1	346.5
CG										
E	2.4	2.5	3.2	2.5	2. 5	2.9	2. 6	2.3	1.9	1.9
Y	83.7	80.0	92.4	82.9	89.6	100.4	91.3	85.1	86.7	87.6
NG										
E	2.6	2.9	3.3	3.3	4.7	5.0	6.0	6.9	7.6	8.8
Y	28.6	35.3	44.4	41.9	58.4	76.1	86.3	101.5	104.1	126.7
LPG										
E	9.4	8.6	9.1	9.6	11.3	13.4	12.1	12.1	11. 9	12.5
Y	120.5	125.6	148.3	167.5	197.6	271.0	270.9	305.0	376.3	380.2
CL										
E	34.8	36.1	42.0	44.5	36.3	39.2	35.7	33.7	29.2	21.7
Y	126.0	128.3	143.7	164.5	140.3	144.6	145.9	157.3	148.1	104.3

Note: PV: private vehicle; MC: motorcycle; AC: air conditioner; LT: lighting; WS: washer; RF: refrigerator; CT: color television; PC: personal computer; WH: water heater; RH: range hood; MO: microwave oven; EC: electric cooking; EF: electric fan; CH: central heating; CG: coal gas; NG: natural gas; LPG: liquefied petroleum gas; CL: coal.

Table C1
Data Source: CSY (2009), China Energy Statistical Yearbook (2009).

Type of energy	Unit	Standard coal equivalent (tce in kilograms)
petrol	Kilogram (1 l=0.725 kg)	1 kg=1.4714 tce
Electric power	Kilowatt hour	1kWh=0.1229 tce
Raw coal	Kilogram	1 kg=0.7143 tce
Coal gas	Cubic meter	1 m^3=0.5 tce
Natural gas	Cubic meter	1 m^3=1.33 tce
LPG	Kilogram	1 kg=1.7143 tce

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