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Revisiting drivers of energy intensity in China during 1997–2007: A structural decomposition analysis

Lin Zeng [a], Ming Xu [b,c,**], Sai Liang [b], Siyu Zeng [a], Tianzhu Zhang [a,*]

[a] School of Environment, Tsinghua University, Beijing 100084, China
[b] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041, United States
[c] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, United States

HIGHLIGHTS

- We analyzed energy intensity change from production and consumption perspectives.
- We extended the research scope of energy intensity to cover household consumption.
- Sectoral energy efficiency improvement contributed most to energy intensity decline.
- Impact of production structure change on energy intensity varied at different times.
- Growing export demand newly became main driver of China's energy intensity increase.

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ABSTRACT

The decline of China's energy intensity slowed since 2000. During 2002–2005 it actually increased, reversing the long-term trend. Therefore, it is important to identify drivers of the fluctuation of energy intensity. We use input–output structural decomposition analysis to investigate the contributions of changes in energy mix, sectoral energy efficiency, production structure, final demand structure, and final demand category composition to China's energy intensity fluctuation during 1997–2007. We include household energy consumption in the study by closing the input–output model with respect to households. Results show that sectoral energy efficiency improvements contribute the most to the energy intensity decline during 1997–2007. The increase in China's energy intensity during 2002–2007 is instead explained by changes in final demand composition and production structure. Changes in final demand composition are mainly due to increasing share of exports, while changes in production structure mainly arise from the shift of Chinese economy to more energy-intensive industries. Changes in energy mix and final demand structure contribute little to China's energy intensity fluctuation. From the consumption perspective, growing exports of energy-intensive products and increasing infrastructure demands explain the majority of energy intensity increase during 2002–2007.

1. Introduction

The latest International Energy Agency statistics show that China was the world's largest energy producer in 2010 with 2456 million tonnes of oil equivalent (mtoe) of total primary energy production (IEA, 2013). In addition, China has newly become the world's largest energy consumer with 1514 mtoe of total final consumption in 2010, 14 mtoe more than that the U.S. consumes (IEA, 2013). As a result, China has become the world's largest carbon dioxide (CO_2) emitter (Gregg et al., 2008). More than 85% of China's CO_2 emissions originate from fossil fuel combustion (Guan et al., 2012). To date, a number of studies have been conducted to analyze the historical trajectory of China's CO_2 emissions and its implications for achieving China's CO_2 mitigation targets (Minx et al., 2011; Steckel et al., 2011; Wang and Liang, 2013; Zha et al., 2010; Zhang et al., 2009; Zhang, 2009).

Currently, improving energy intensity is one of the most important actions to reduce China's CO_2 emissions as existing policy instruments in China predominantly focus on the upstream energy supply and consumption side instead of the downstream emission side. For example, Chinese government has mandated to reduce energy intensity (i.e., energy consumption per unit gross domestic product (GDP) measured by constant price, similarly hereinafter) by 20% during 2006–2010 as one of the constraint targets in its 11th Five Year Plan (FYP). The recent 12th FYP

* Corresponding author. Tel./fax: +86 1062796956.
** Corresponding author. Tel.: +1 734 763 8644; fax: +1 734 936 2195.
E-mail addresses: zenglin09@gmail.com (L. Zeng), zhangtz@tsinghua.edu.cn (T. Zhang), mingxu@umich.edu (M. Xu).

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(2011–2015) continues to mandate a 16% reduction of energy intensity.

China has experienced a dramatic decline in energy intensity from the onset of economic reform in the late 1970s until 2002. However, the energy intensity increased strikingly during 2003–2005 and declined slightly in 2006 (Liao et al., 2007; Wu, 2012). Analyzing driving forces of this energy intensity fluctuation can provide foundations for identifying the emphasis of China's energy and climate policy-making, which have been investigated by a number of decomposition studies (Huang, 1993; Lin and Polenske, 1995; Sinton and Levine, 1994; Sun, 1998; Zhang, 2003; Zhao et al., 2010). Technological change is regarded as the dominant contributor to China's energy intensity decline, while there is disagreement on the role of production structure change. Most of previous studies applied the index decompositions analysis (IDA) model to decompose the energy intensity changes from production perspective. Although it is flexible in formulation and has a relatively lower data requirement, the IDA method covers only the direct effect, ignoring the effects of the indirect energy demand and final demand (also named from consumption perspective). Meanwhile, IDA studies are normally for a sector of energy consumption, such as industry or transportation instead of the whole economy (Su and Ang, 2012b).

Several structural decomposition analysis (SDA) approaches have also been conducted to investigate China's energy intensity changes. The SDA model is based on input–output tables (IOTs) and could distinguish between a range of technological and structural effects that are impossible in the IDA model (Ma and Stern, 2008). In particular, SDA model can shape socio-economic drivers from both production and final demand perspectives.

Garbaccio et al. (1999) studied China's energy intensity decline during 1987–1992, disaggregating the economy into 29 sectors. Their main conclusion was that technical change within sectors accounted for most of the decline in energy intensity while structural change actually increased energy intensity. Chai et al. (2009) decomposed China's energy intensity change during 1992–2004 into error factors, technology change, and final demand structure change according to the 30-sector hybrid energy IOTs. They pointed out that China's energy intensity was also sensitive to final demand structure change during 1992–1997. Fan and Xia (2012) used a SDA based on 44-sector physical-monetary mixed energy IOTs to explore driving forces of China's energy intensity changes during 1987–2007. Five decomposed factors in their study were energy input coefficient, technology coefficient, final demand structure by product, final demand by category, and final energy consumption coefficient. They found out that industry structure and technology improvements have major influences on energy intensity changes. The two-polar decomposition method was used in their study, which is not an ideal decomposition (Su and Ang, 2012b). Furthermore, in existing SDA studies, sectors are highly aggregated to reveal sectoral detail of economic structure. This disadvantage limits effective policy decisions at sectoral or product scale.

With these limitations in mind, in order to provide an in-depth understanding of the driving forces of China's energy intensity fluctuation during 1997–2007, we carry out an ideal SDA applying the full D&L method proposed by Dietzenbacher and Los (1998). By closing basic monetary input–output tables with respect to households, changes of aggregate energy intensity (i.e., covers both production and household energy consumption) are investigated within the input–output analysis framework, which is a non-traditional approach compared to previous SDA studies. The share of household energy consumption in China's total energy consumption is around 10–11% (NBS, 2001, 2004, 2008a), which should not be neglected. Finally, we discuss the implications of our findings for China's energy and climate policies.

2. Methodology and data

2.1. Environmental input–output analysis (EIOA)

Energy consumption of the production sectors in a given period of time can be determined by the standard economic input–output model as follows (Miller and Blair, 2009):

$$e_t = rX = r(I-A)^{-1}y = rLy \quad (1)$$

where e_t is energy consumption for all production sectors, r is a row vector representing each production sector's energy efficiency (i.e., measured by energy usage per unit total output), X is a vector of total output from each sector, I is the identity matrix, A is the direct requirements matrix, $L=(I-A)^{-1}$ is the *Leontief Inverse Matrix* (Miller and Blair, 2009), and y is a column vector representing each sector's final demand (i.e., household consumption, government consumption, capital investment, stock change, and export).

China's 1997, 2002 and 2007 monetary input–output tables (MIOTs) are used (NBS, 1999, 2006, 2009) in this study. Different years have slightly different industry classifications—124 sectors for 1997, 122 sectors for 2002, and 135 sectors for 2007. The data are converted into a consistent industry classification with 101 economic sectors and then converted into 2002 constant prices using the GDP deflators from the world economic outlook database (IMF, 2012). Given the purpose of this study, we do not use sectoral price deflators for constant price conversion, although it represents an interesting avenue for future research. The Chinese MIOTs follow standard formats except for a final demand column called “others” which can be interpreted as errors representing different data sources (Liang et al., 2013a, 2013c, 2012, 2013d, Minx et al., 2011; Peters et al., 2007). We do not include this column in our calculation of total outputs. Thus, total output of each sector is given as the sum of the intermediate flows and the final demand excluding “others.”

In order to analyze the changes and driving forces of aggregate energy intensity of an economy within the input–output analysis framework, which is induced by both production and household energy consumption, we close the basic input–output model for household. This is known as the partially closed input–output model with endogenous consumption and has been studied by many researchers (Cloutier and Thomassin, 1994; Miller and Blair, 2009; Miyazawa, 1976; Miyazawa and Masegi, 1963; Wakabayashi and Hewings, 2007). The household sector is treated endogenously and assumed to behave like other industrial sectors with a linear and homogeneous consumption function (Batey et al., 1987; Miller and Blair, 2009).

It requires a column and a row for the new household sector. In the present paper, the household consumption (i.e., final consumption of urban and rural households), which is part of the final demand, is closed into the intermediate delivery matrix to represent the inputs of household sector (purchases of consumption commodities). Laborers′ remuneration, which is part of the value added, fills in the row value of household sector to show how its output (labor services) is used as an input by the other sectors. Strictly speaking, the row value of household sector should be the household income, which is not the same as laborers′ remuneration. However, laborers′ remuneration in input–output tables covers most of the household income in China. For example, the share of income from wages and salaries together with household operations in laborers′ remuneration is around 85.3% in 2007 in China (Chen et al., 2010). This assumption in our study leaves out other income sources such as properties income and transfer income. Detail of the partially closed input–output model is given in Appendix A. Thus, the modified MIOTs have 102 sectors for each. Aggregate energy consumption and energy intensity of the economy can be approximated as follows:

$$e_t{}^* = r^*(I-A^*)^{-1}y^* = r^*L^*y^* \quad (2)$$

$$e = \frac{e_t^*}{g} = r^*L^*\frac{y^*}{g} \quad (3)$$

where e_t^* is aggregate energy consumption for both production and household sectors, r^* is a vector representing each sector's energy efficiency, A^* is the new direct requirements matrix including the household sector, $L^*=(I-A^*)^{-1}$ is the new *Leontief Inverse Matrix*, y^* is the new final demand vector excluding household consumption, e is the aggregate energy intensity and g represents GDP.

Furthermore, to compare impacts on China's energy intensity between domestically produced and imported products, we follow the non-competitive imports assumption, i.e. treating the imported products as different from the domestic ones (Su and Ang, 2013). We derive the new direct requirements matrix A_d^* and final demand vector y_d^* in which only domestic goods are included by removing imports from the direct requirements table and from final demands (Liang et al., 2013c; Weber et al., 2008; Xu et al., 2011). This method assumes that imports are used in the same proportions in each sector and each final demand category. Details can be found in Weber et al. (2008). Thus, the resulted energy intensity based on these assumptions is an approximation, which can be approximated as

$$e = \frac{r^*(I-A_d^*)^{-1}y_d^*}{g} = \frac{r^*L_d^*y_d^*}{g} \quad (4)$$

The energy data are taken from China's Energy Statistical Yearbooks (NBS, 2001, 2004, 2008a). For 1997 and 2002, the energy data are in 42-sector format, including household energy consumption, while the 2007 energy data are in 45-sector format. In principle, there are two alternatives for dealing with the incompatibility of the data. The first is to aggregate the finer IO data to the level that matches the energy consumption data, while the other is to disaggregate the energy consumption data to the level that matches the IO data (Bouwmeester and Oosterhaven, 2013; Lenzen, 2011; Su et al., 2010). A concordance matrix is constructed to map the energy data to the 102 sectors according to the sector descriptions of the MIOT and energy data in our study (Peters et al., 2007). This procedure assumes that all economic sectors that map to one energy sector have the same sectoral energy efficiency.

2.2. Structural decomposition analysis

There are several socio-economic and technological factors, such as economic growth, economic structure, infrastructure investment and technology development, which affect levels of China's energy intensity in different directions and to varying degrees (Chai et al., 2009; Minx et al., 2011). SDA is a widely used method to examine the relative contribution of these factors to physical flows (Hoekstra and van den Bergh, 2002; Liang et al., 2013b; Liang and Zhang, 2011b; Wang et al., 2013; Xu et al., 2011).

To do so, we further decompose sectoral energy efficiency r^* to include an energy mix factor:

$$r^* = \tau E\hat{r}^* \quad (5)$$

where τ is a unit row vector conformable for matrix multiplication, E is a matrix representing shares of different energy types in each sector, and the hat symbol "^" indicates a diagonal matrix with the elements of the vector on its diagonal and all other elements are zeros. Energy types here include both domestically produced primary energy (i.e., coal, crude, natural gas and electricity) and the imported energy. The final demand vector y_d^* can further be decomposed into two composition components and an overall volume component:

$$y_d^* = y_{\text{sec}}y_{cat}g \quad (6)$$

where y_{sec} represents shares of sectors in each final demand category, y_{cat} indicates shares of each final demand category in GDP and g represents GDP. Particularly, there are four final demand categories in both y_{sec} and y_{cat}, that is government consumption, capital investment, stock change and exports, since the households are made endogenous and imports are removed from the final demand. These two final demand categories are not included in the final demand structure y_{sec} and final demand shares y_{cat} defined in our study. Thus, the full decomposition of energy intensity e can be expressed as

$$e = \tau E\hat{r}^*L_d^*y_{\text{sec}}y_{cat} \quad (7)$$

Table 1 lists all the decomposition factors in this analysis.

The change of energy intensity e from time $t-1$ to time t can be expressed as

$$\Delta e = \tau E_t\hat{r}^*{}_tL_{d,t}^*y_{\text{sec},t}y_{cat,t} - \tau E_{t-1}\hat{r}^*{}_{t-1}L_{d,t-1}^*y_{\text{sec},t-1}y_{cat,t-1} \quad (8)$$

The SDA of energy intensity changes above follows the commonly used additive identity splitting method (Dietzenbacher and Los, 1998) by adding and subtracting components like $\tau E_{t-1}\hat{r}_t{}^*L_{d,t}^*$ $y_{\text{sec},t}y_{cat,t}$ to the right-hand-side of the equation. One can rewrite the equation above by rearranging terms as

$$\Delta e = \tau\Delta E\hat{r}_tL_ty_{\text{sec},t}y_{cat,t} + \tau E_{t-1}\Delta\hat{r}L_ty_{\text{sec},t}y_{cat,t} + \tau E_{t-1}\hat{r}_{t-1}\Delta Ly_{\text{sec},t}y_{cat,t} + \tau E_{t-1}\hat{r}_{t-1}L_{t-1}\Delta y_{\text{sec}}y_{cat,t} + \tau E_{t-1}\hat{r}_{t-1}L_{t-1}y_{\text{sec},t-1}\Delta y_{cat} \quad (9)$$

The change in aggregate energy intensity e is finally decomposed into individual contributions, or effects, from changes in each of the five variables. Each term in the right-hand-side of the equation above represents how much the change of energy intensity e is caused by the change of energy mix (ΔE), sectoral energy efficiency ($\Delta\hat{r}^*$), production structure (ΔL_d^*), final demand structure among sectors (Δy_{sec}), and final demand composition (Δy_{cat}), when keeping other variables constant.

Table 1
List of decomposition factors.

Variable	Dimensions	Name	Definition
$\boldsymbol{e}$	1×1	Energy intensity	Energy use per unit GDP for the entire economy
$\boldsymbol{E}$	$k\times(n+1)$	Energy mix	Shares of different types of energy use in production sectors and household sector. $\boldsymbol{k}$ is the number of types of energy. $\boldsymbol{n}$ is the number of production sectors
$\hat{r}^*$	$(n+1)\times(n+1)$	Sectoral energy efficiency	Diagonal matrix representing energy efficiencies in production sectors and household sector measured by energy use per unit output
$\boldsymbol{L_d^*}$	$(n+1)\times(n+1)$	Production structure	Leontief Inverse Matrix representing production structure of the economy
$\boldsymbol{y_{sec}}$	$(n+1)\times m$	Final demand structure among sectors	Shares of sectors in each final demand category. $\boldsymbol{m}$ is the number of final demand categories
$\boldsymbol{y_{cat}}$	$m\times1$	Final demand composition	Shares of each final demand category in GDP

Note that the particular decomposition form presented above is not unique, as one can derive a number of alternative decomposition forms using the same method, such as

$$\Delta e = \tau \Delta E \hat{r}^{*}_{t-1} L^{*}_{d,t-1} y_{\sec,t-1} y_{cat,t-1} + \tau E_t \Delta \hat{r}^{*} L^{*}_{d,t-1} y_{\sec,t-1} y_{cat,t-1} + \tau E_t \hat{r}_t^{*} \Delta L^{*}_{d} y_{\sec,t-1} y_{cat,t-1} + \tau E_t \hat{r}_t^{*} L^{*}_{d,t} \Delta y_{\sec} y_{cat,t-1} + \tau E_t \hat{r}^{*}_t L^{*}_{d,t} y_{\sec,t} \Delta y_{cat} \quad (10)$$

All alternative decomposition forms are equivalently valid. This is the so-called non-uniqueness problem in SDA (Rose and Casler, 1996). The number of possible decomposition forms equals to the permutations of all variables. In this case, there are $5! = 120$ different but equally valid decomposition forms. No individual decomposition form is theoretically preferred. In particular, the original decomposition form and last one presented as Eqs. (9) and (10) above are referred as polar decompositions as they follow the original order of variables either from left to right or from right to left.

A common practice in SDA to address the non-uniqueness problem is to use the full D&L method which takes the average of the decomposition results of all possible decomposition forms (De Haan, 2001; Dietzenbacher and Los, 1998; Hoekstra and van den Bergh, 2002). This research follows the common practice. In addition, we also report the range of decomposition results from all the 120 possible forms and discuss the sensitivities of results.

From the consumption perspective, we also allocate the energy intensity changes during 1997–2007 to the four final demand categories, and break down the changes by sectors.

3. Results

3.1. Contributions of drivers to energy intensity changes

Fig. 1 describes the changes of China's energy intensity and total energy consumption in 1997, 2002 and 2007. Between 1997 and 2002, total energy consumption in China increased by only 7.1% from 1227 million tons of standard coal equivalent (mtce) to 1368 mtce, while energy intensity declined dramatically by 31.8% from 1.65 to 1.12 t of standard coal equivalent (tce)/10,000 Yuan.

In 2003, 2004 and 2005, the elasticity coefficients of energy consumption in China were 1.53, 1.59 and 1.02 respectively (NBS, 2008a), leading to a significant increase in the total energy consumption during 2002–2007. The amount was 2490 mtce in 2007, almost twice of that in 2002. As a result, the energy intensity increased by 6.2% from 2002 to 2007, which reversed the long-term declining trend since the late 1970s.

Fig. 2 presents the SDA results. Focusing on the entire period of 1997–2007, sectoral efficiency improvements contributed most, about 49.5%, to the overall energy intensity decline by keeping other factors constant, which was consistent with previous studies (Liao et al., 2007; Ma and Stern, 2008; Zhang, 2003). This was mainly due to the extensive application of energy-saving technologies and the advancement of management level. However, the effect of sectoral efficiency improvement on energy intensity decline was less notable and had been offset by that of economic structure change during 2002–2007.

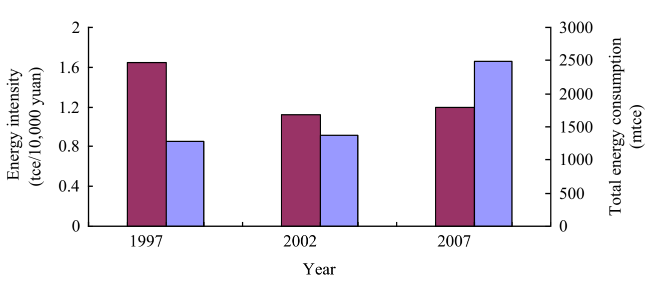

Fig. 1. China's energy intensity and total energy consumption in 1997, 2002 and 2007. (Sources: calculations based on (IMF, 2012; NBS, 2001, 2004, 2008a), the GDP data are converted into 2002 constant price).

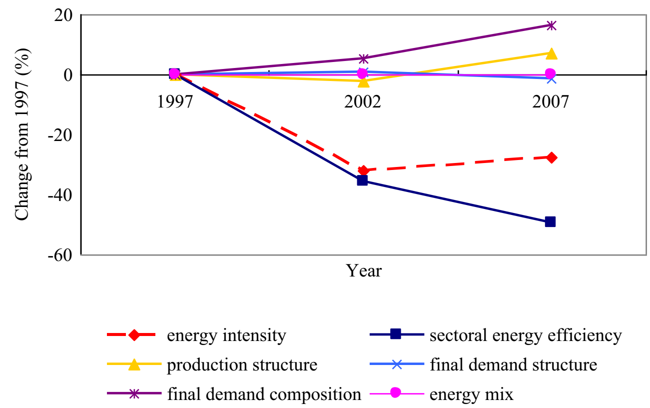

Fig. 2. Contribution of driving forces to the energy intensity fluctuation in China from 1997 to 2007. The dashed red line shows the percentage change in energy intensity from 1997 to 2007 (−27.5%). Other solid colored lines represent the contribution to energy intensity fluctuation from sectoral energy efficiency improvements (dark blue, −49.5%), production structure (orange, 6.9%), final demand structure (light blue, −1.5%), final demand composition (purple, 16.6%) and energy mix (pink, 0.0%). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

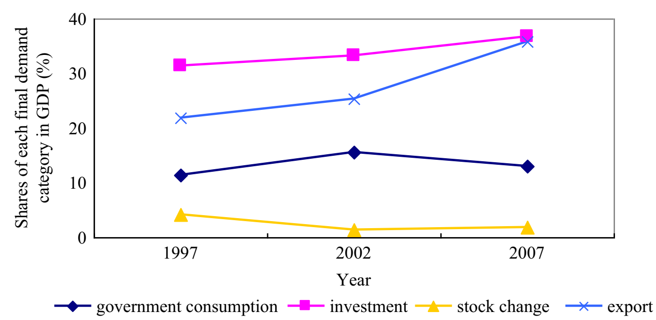

Fig. 3. Change of shares of each final demand category in total final demand (the shares do not add up to 1, since households are made endogenous).

By contrast, changes in final demand category composition caused a 16.6% increase of energy intensity during the period 1997–2007, if other factors remained constant. It also made the largest contribution to China's energy intensity increase during 2002–2007. Change in shares of the four final demand categories in total final demand (GDP) is shown in Fig. 3. Continually rising proportion of capital investment and export contributed most to this change, indicating that these two factors had a great effect on energy intensity fluctuation in the study period. Even though capital investment remained the largest part in total final demand, the share of export grew more rapidly compared to other final demands, which accounted for 35.9% of China's GDP in 2007, more than 1.6 times of that in 1997.

The contribution of changing production structure varied in different time periods. From 1997 to 2002, thanks to the significant adjustment of industrial structure, it would lead to a 2.4% decline in total energy intensity if holding all other factors constant. However, it had emerged as the second largest driver of China's energy intensity increase during 2002–2007. Similarly, it was also a new major CO_2 emission driver observed in previous studies (Guan et al., 2009; Minx et al., 2011). This structure change mainly arose from a shift to more energy-intensive industries, especially heavy manufacturing industries (Liang et al., 2013b). Compared with that in 2002, the proportion of secondary industry in GDP grew to 48.6% in 2007 (3.8% higher), while the proportions of the primary industry and third industry were down to 11.3% (2.4% lower) and 40.1% (1.4% lower), respectively (NBS, 2008b). Manufacturing were the fastest-expanding sectors, the share of which in China's GDP was 31.4% in 2002 and climbed up to 36.3% by 2007 (NBS, 2006, 2009). In particular, heavy manufacturing sectors named *nonferrous metals smelting and pressing*, *nonmetallic mineral products*, and *ferrous metals smelting and pressing* grew most rapidly. Energy consumption of these three sectors in 2007 was almost twice of that in 2002 (NBS, 2008a). Moreover, the accelerating process of industrialization and urbanization in China has resulted in energy-intensive products expanding recently. For example, 182.4 million tons of steel was produced in 2002. However, this figure jumped to 489.3 million in 2007. The output of iron and cement rose by 178.9% and 87.7% during 2002–2007, respectively (NBS, 2008b).

Final demand structure reflects the different consuming favorites of society to the products with different energy consumption, which has a direct impact on energy intensity. All else being equal, its change would firstly promote a slight rise of energy intensity during 1997–2002, and then lead to a fall by 3.5% during 2002–2007. The trend was similar to previous studies, but to a lesser extent (Chai et al., 2009). Energy mix was a relatively weak factor and in fact had little effect on China's energy intensity fluctuation during 1997–2007.

3.2. Allocation of energy intensity changes to final demand categories

From the consumption perspective, Table 2 shows an allocation of the energy intensity fluctuation to separate final demand categories. From 1997 to 2007, more than half of the energy intensity decline (0.23 tce /10,000 Yuan) was due to capital investment, while another 0.10 tce /10,000 Yuan or 22.2% of the decline was due to government expenditure. A 0.07 tce /10,000 Yuan (14.9%) was triggered by stock change, and the remaining 0.06 tce/10,000 Yuan (12.5%) was due to exports.

Though capital investment was the major driver for China's energy intensity fluctuation during 1997–2007, its contribution varied in different time periods. From 1997 to 2002, it made the largest contribution to the decline in China's energy intensity among the four final demand categories. Of the 0.28 tce /10,000 Yuan energy intensity decline triggered by capital investment, 82.4% was from construction activities, followed by two manufacturing sectors named *special purpose machinery* and *other transport equipment*. However, growing investment demand for construction and heavy manufacturing sectors caused an increase in energy intensity during 2002–2007. 41.3% of the energy intensity increase associated with capital investment was related to construction, and another 23.0% and 20.7% were caused by *manufacturing of automobiles* and *general purpose machinery*, respectively.

The export became the most important driver for the increase in China's energy intensity during 2002–2007, compared to the other final demand categories. Table 3 illustrates top sectors responsible for the energy intensity increase triggered by exports during 2002–2007. *Smelting and pressing of steel* resulted in about one-third of export-related energy intensity increase. Electronic products and machinery production were the remaining large contributors. China has now become the largest exporter in the world (UNSD, 2012). Not only the gross volume of exports was growing, their composition was also changing. While the demands for typical export commodities (such as toys, textiles and electronic devices) remained strong, demands for energy-intensive and capital-intensive products were also expanding rapidly. For example, the export of rolled steel increased more than 10-fold during 2002–2007. Exports for aluminum products grew from 188.7 in 2002 to 1853.4 thousand tons in 2007 (NBS, 2008a).

Table 2
Allocation of energy intensity fluctuation to separate final demand categories during 1997–2007 (units: tce /10,000 Yuan).

Final demand category	1997–2002	2002–2007	1997–2007
Capital investment	−0.28	0.05	−0.23
Government consumption	−0.05	−0.05	−0.10
Stock change	−0.05	−0.02	−0.07
Export	−0.14	0.09	−0.05
Total	−0.52	0.07	−0.45

Table 3
Top sectors responsible for the energy intensity increase triggered by exports during 2002–2007.

Sector	Percentage
Smelting and pressing of steel	33.5[a]
Manufacture of computer	10.5
Manufacture of other electronic and communication equipment	10.0
Manufacture of special purpose machinery	8.9
Manufacture of metal products	8.4
Manufacture of electronic component	7.1
Manufacture of knitted fabric and its products	6.2
Manufacture of basic chemical raw materials	6.1
Household electric appliances	6.0

[a] The figures are expressed as a percentage of the energy intensity increase triggered by exports (all sectors add to 100%).

4. Policy implications

4.1. Promoting technology innovation

Sectoral efficiency improvement is confirmed as the dominant contributor to China's energy intensity decline. However, efficiency savings have not been able to keep pace with the rapid energy consumption growth in recent years. In fact, nearly half of the production sectors had less notable efficiency improvements during 2002–2007. For example, energy efficiency of *mining and washing of coal* sector improved by only 7.0% while its energy consumption almost doubled during 2002–2007.

Chinese government has recently proposed a goal of doubling its 2010 GDP and per capita income by 2020. The rapid economic growth and speeding up of industrialization and urbanization will lead to an increase in total energy consumption in the near future. Strengthening the process of technological innovation would play a key role to improve China's sectoral energy efficiency. Possible measures may include using energy-efficient machinery and equipment, recovering waste heat, and so on.

Adjusting energy structure is also considered as an effective way to reduce energy intensity. However, the factor of energy mix contributes little to China's energy intensity changes in the study period. China's energy resource endowment determines its coal-based energy structure in the long run, and it is impossible to decrease the proportion of coal consumption dramatically in the near future. In order to save energy and reduce energy intensity, it would be desirable to adopt comprehensive measures to enhance the share of cleaner fossil fuels such as natural gas and promote renewable energy in energy supply mix. In particular, developing renewable energy to become a significant part of China's energy supply mix is important and promising, as it will not only provide non-fossil-based energy to meet increasing demands, but also drive efficiency improvement in traditional energy sectors through competition.

Efficiency improvement alone is unlikely to stabilize or reduce energy intensity in the context of our study. In order to meet the targets of reducing energy intensity in the 12th Five Year Plan and in a long term, the government should rely on not only technology development and efficiency improvement, but also structure changes in production and consumption.

4.2. Optimizing production structure

China's production structure change emerged as the second largest driver of China's energy intensity increase during 2002–2007, indicating the potential of decreasing energy intensity by optimizing the production structure. The adjustment of production structure should focus on encouraging energy-efficient and low-carbon industries and controlling energy-intensive industries. Industries that previously experienced rapid development should be regulated to avoid surplus production, such as the construction material industry and the metallurgy industry. China should also continue the effort of phasing out outdated technologies in energy-intensive industries.

4.3. Greening final demand structure

Since exports is the largest driver of China's energy intensity increase from the consumption perspective, in order to curb excessive growth of exports and rationalize export structure, products with high level of embodied energy such as steel and aluminum should be discouraged.

Extensive capital formation for construction and heavy manufacturing in China is likely to continue. Material use efficiency in construction should be improved to avoid high energy consumption from upstream sectors such as steel, cement, and glass. Stringent building standards should be put in place and green-architecture should be promoted. Chinese government should also restrict other high energy-consuming fixed investment activities.

In addition, the energy intensity of endogenous household consumption sector increased by 6.2% from 2002 to 2007, mainly due to increasing energy consumption and population migration brought by rapid urbanization (Minx et al., 2011). Chinese government should pay more attention to energy use in household consumption, such as encouraging lifestyle changes, promoting green labeling in consumer products, and promoting energy-efficient appliances.

4.4. Adopting integrated policy making

There are interactions among various policies targeting reducing energy intensity, as a particular policy can potentially lead to unintended environmental consequences, but also co-benefit opportunities throughout supply chain linkages (Liang et al., 2013c; Liang and Zhang, 2011a). Various policies aiming at reducing energy intensity should be comprehensively evaluated and integrated to minimize the cost of policy implementation, which may need a “Leading Group” formed at the uppermost level of the government (Liang et al., 2013c).

5. Uncertainty analysis

The inherent uncertainties of the EIOA method mainly come from time-lag, the assumption of linear relationships between sectors, and the assumption of homogeneous products in each sector. Implications of these uncertainties to EIOA results have been extensively discussed (Huang, 1993; Lenzen, 2000; Liang and Zhang, 2013; Weisz and Duchin, 2006).

Three aggregation issues exist in SDA **s**tudies, namely sector aggregation, spatial aggregation, and temporal aggregation. Choice of the level of sector aggregation is dictated by economic and energy data availability. A higher level of sector disaggregation is to be preferred when data availability is not an issue, which can retain full information of data and enhance policy decisions at sectoral scale (Lenzen, 2011; Su et al., 2010). Spatial aggregation means geographical area for which data are presented. For big countries with uneven geographical economic developments such as China, SDA studies using regional level data are better in capturing the true situation when compared to those using national level data (Su and Ang, 2010). The temporal aggregation issue is about making choices in terms of time periods. It is found that decomposition studies using shorter time period lengths provide valuable information about the path taken by each effect over time (Su and Ang, 2012a).

There are also different assumptions for imports and exports when performing the SDA studies. In the present study, we follow

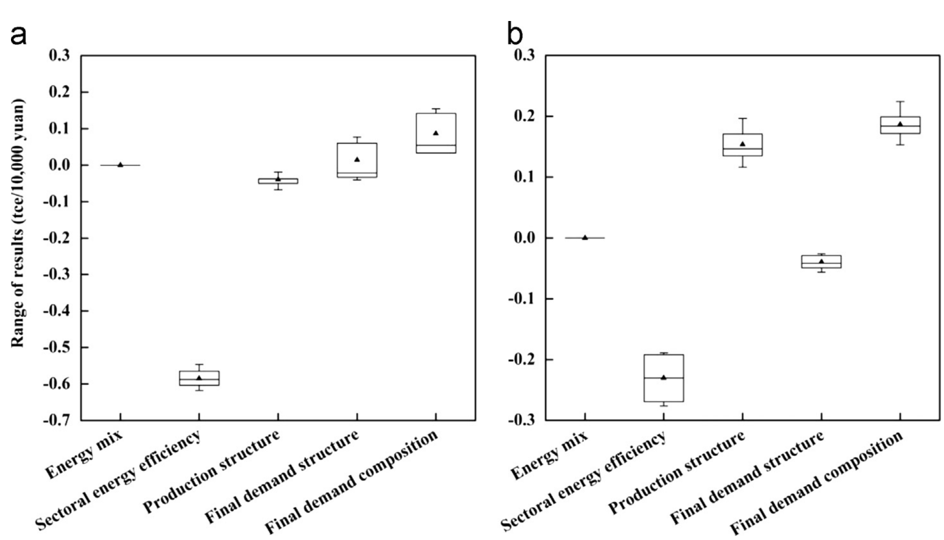

Fig. 4. Descriptive statistics for the contributions of five factors to energy intensity changes across 120 alternative decomposition forms between two time periods. Lines in each box represent median values of each factor's contribution, with top lines as the 75th percentiles and bottom lines as the 25th percentiles. Solid triangles in each box represent average values of each factor's contribution. The end of whiskers represents minimum and maximum values of each output variable. (a) 1997-2002 and (b) 2002-2007

the non-competitive imports assumption and the uniform export assumption (i.e., assume the same input structures for processing and normal exports)(Su and Ang, 2013; Su et al., 2013). Choice of the imports and exports assumption will have impact on decomposition results, which should not be neglected, especially when focusing on the energy consumption and related CO_2 emissions embodied in international trade.

A full D&L decomposition method was applied in our research using the average of all 120 equivalent exact decomposition forms to achieve ideal decomposition. However, this method is cumbersome when the number of decomposition factors is large (Dietzenbacher and Los, 1998; Seibel, 2003). To overcome this problem, some approximate D&L techniques have been proposed, such as by taking the average of the two polar decompositions (Dietzenbacher and Los, 1998) or of any pair of "mirror image" decompositions (De Haan, 2001). These approximate D&L techniques fail the factor-reversal test and are therefore not ideal. Other ideal SDA methods like LMDI (i.e., logarithmic mean Divisia index) is preferred in this situation due to its relative simple formulae (Su and Ang, 2012b).

The descriptive statistics for the individual contribution of five factors (i.e., energy mix, sectoral energy efficiency, production structure, final demand structure among sectors, and final demand composition) to the energy intensity fluctuation across 120 alternative decomposition forms are presented in Fig. 4. Even though we find a large range in our results across all possible decomposition forms, the observed effects remain prominent in all cases.

6. Conclusions

By closing the input–output model with respect to households, we conducted structural decomposition analysis to investigate underlying drivers of China's energy intensity fluctuation during 1997–2007. Results show that sectoral energy efficiency improvements contributed the most to the decline of the aggregate energy intensity between 1997 and 2007. The increase in China's energy intensity during 2002–2007 was instead explained by changes in final demand composition and production structure. The change in final demand composition was mainly due to increasing share of exports. The change in production structure was mainly caused by the expanding of energy-intensive industries. China's energy intensity was not sensitive to the changes of final demand structure and energy mix in the study period. From the consumption perspective, growing exports of energy-intensive products such as steel, and increasing infrastructure demands for construction activities and heavy manufacturing industries explained the majority of energy intensity increase during 2002–2007.

In order to achieve the targets of reducing energy intensity in the 12th FYP and in the long term, apart from turning to efficiency improvement and technical progress, Chinese government should pay more attention to the adjustment of production structure and the guidance of the final demand consumption. In addition, various policies aiming at reducing energy intensity should be comprehensively evaluated and integrated to minimize the cost of policy implementation.

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Appendix A. Partially closed input–output model

According to Miyazawa's formulation (Miyazawa, 1976), the basic structure of the partially closed input–output model with endogenous consumption is as follows:

$$\begin{bmatrix} A & h^c \\ h^r & 0 \end{bmatrix} \begin{bmatrix} X \\ x_{n+1} \end{bmatrix} + \begin{bmatrix} y^{\sim} \\ y^*_{n+1} \end{bmatrix} = \begin{bmatrix} X \\ x_{n+1} \end{bmatrix}$$

where $A=(a_{ij})_{n\times n}$ is the direct requirements matrix, $X=(x_i)_{n\times 1}$ is a vector of total outputs of industrial sectors, x_{n+1} is the total household income, $\tilde{y}$ is a vector of final demands other than household consumption, y^*_{n+1} is the exogenous income of the household sector, $h^c=(h^c_i)_{n\times 1}$ is a vector of consumption coefficients, $h^r=(h^r_j)_{1\times n}$ is a vector of labor input coefficients. The consumption coefficient h^c_i is defined as $h^c_i = y^c_i/x_{n+1}$, where y^c_i is the commodity of sector i consumed by the household sector. The labor input coefficient is defined as $h^r_j = w_j/x_j$, where w_j represents the income of the household sector earned from sector j.

Appendix B. Supplementary materials

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2013.11.053.

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