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An Overview of the driving forces behind energy demand in China's construction industry: Evidence from 1990 to 2012

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Abstract

The rapid urbanization in China has produced a large demand for energy in the past decades. It is therefore urgent to have an understanding of the driving forces behind the energy increase in the construction industry. This study applies structural decomposition analysis (SDA) to quantify the effects of driving factors from insight into consumption and production. The results show that the energy consumption trajectory of China's construction industry is the result of competition between the effect of increasing final demand and improvement in energy efficiency. Although the effect of consistent efforts in structure optimization by the central government was significant from 2007 to 2012, the potential to save much energy still lies in structure optimization in energy, production, and final demand. According to the projection, structural upgrades in economy would be the most important factor for energy reduction in 2020. Scenario analysis further indicated that the percentage change of energy increments in 2020 can be reduced at 22% of 2010 level under the optimistic scenario. Sector aggregation analysis revealed that more aggregates would increase uncertainty to some extent and result in a misinterpretation of the importance of the underlying factors. According to the quantitative analysis in this study, the percentage change of total embodied energy consumption in the construction industry should be limited below 25% of 2010 level at the end of the 13th Five-Year Plan.

1. Introduction

China is on path to rapid urbanization and industrialization. As the result of such intensive construction, the growth rate of energy consumption in buildings is more than 10% in the past decades [1]. Being the primary energy consumer in the society, the construction industry accounted for 16% of total economy's energy consumption in China in 2007 [2] and projected to be 20% in 2015 by Chang and Wang [3]. Therefore, considering the requirement for sustainable development in China, it is urgent to understand the driving forces behind the energy increase in the construction industry. The aim of this study is to provide an overview of the driving forces and energy use trajectory of the construction industry by utilizing both economy analytical methods and time-series input-output tables. Such investigation could not only facilitate specific policy decisions on energy and environmental issues in relation to the building sector but also switch the urbanization process towards more sustainable development.

An effective method to comprehensively understand the relative contribution and mechanism of different driving forces is decomposition analysis, which breaks down the total changes into sub-effects induced by a number of factors. This method quantifies these effects on total energy demand individually at the industrial or national level [4–7].

In general, many different methods based on decomposition theory have been proposed by different researchers [8–12]. Index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two of the most popular approaches in previous studies. Of these, IDA is the most time-efficient and has the advantage of lower requirements for specific economic data to explore the driving factors hidden behind the economic system. However, without the use of an input-output table, IDA fails to provide detailed information on the economic structure and supply chain. This implies that only direct effects from the changes of factor can be assessed by index decomposition [5,13,14].

These theoretical deficiencies have been addressed by employing the SDA model, which is designed to quantify the effects of driving factors based on the input–output analysis in the entire economy. SDA enables decomposition analysis to understand the hidden linkage and indirect interactions at the sectoral level and to reflect the structural changes from insight regarding consumption and production [15,16]. The contributions from different factors have been assessed quantitatively and separately with the decomposition of all directly related factors. Although the SDA model has been restricted to the availability of economic data and can only be represented additively due to the use of input-output table, it has been widely employed to examine the driving forces leading to Chinese environmental loading issues [17–21]. SDA has also been applied on the industrial and city scale in China with the results playing a significant policy role [13,22,23]. Therefore, given the data specificity and information completeness, this study used SDA as the basic model to conduct decomposition analysis.

However, very few studies have applied the SDA model to China's construction industry, which currently has large energy demands because of the booming property market. Lu et al. [24] used Logarithmic Mean Divisia Index decomposition method to quantify incremental carbon emissions of China's construction industry from 1994 to 2012. The findings indicated that the change of energy structure and intensity comprised the major leading factors for emission mitigation in the construction industry. Hatayama and Tahara [25] utilized decomposition analysis to predict metal consumption (e.g. steel, aluminum, copper, and zinc) in the building stock. Hong et al. [26] decomposed energy interactions of the construction sector to identify critical energy-intensive paths in the upstream supply chain. Liu et al.[27] made a structural analysis of China's construction industry based on the Panzar-Rosse model. In fact, China's construction industry is an ideal subject to investigate energy consumption trajectory because it not only generates significant environmental impact but is also characterized by its extensive and sizable construction projects. Thus, exploring the driving forces behind the increase in energy consumption is not only fundamental to provide comprehensive analyses and projections for future energy consumption but also critical to enhance sustainable development of energy application in the construction industry. This study seeks reasoned explanations and policy implications regarding the characteristics of the construction industry from 1990 to 2012. The contribution of this paper consists of the following two aspects. First, a national level investigation of the trajectory of the energy use embodied in China's construction industry will provide an indication of potential barriers and possible means of improving the development of sustainable construction in China. Second, a systematic analysis of the driving forces behind the energy demand will provide a holistic understanding of leading driving factors. This can not only facilitate decision makers to determine the direction of further improvement but also promote the development of relevant policies at both national and industrial levels.

2. Methodology

2.1. Data source and consolidation

Two categories of data are required in this study: time-series inputoutput tables and year-based energy consumption data. First, all of the input-output tables are collected from the Chinese National Bureau of Statistics. These tables are all edited into the 28-sector format (see Appendix A) because sector classification was different from 1990 to 2012. Moreover, to keep the price consistent among the different tables, the monetary flows are all concerted into 1990 constant prices via price indexes. Second, all the year-based energy consumption data are obtained from Chinese energy statistical yearbook. However, the classification of the economic sector in the yearbooks is not consistent with input-output table. In fact, the I-O table compiled by the National Bureau of Statistics is more specific on the detailed monetary flow data while the direct energy input data are collected at a more aggregate level. Therefore, it is necessary to disaggregate the sectoral energy consumption data and make them specifically match the sector classification of the input-output tables. Such disaggregation is based on the assumption that the sub-sectoral energy consumption data is proportional to its economic output. Four types of energy have been considered—coal, oil, natural gas, and other types of primary energy (e.g. nuclear, solar, wind, biomass energy, etc.). To avoid the problem of double-counting, national energy balance tables have been used to remove the energy consumed in the energy transformation, intermediate consumption, and losses in coal washing and dressing.

2.2. Model development

The input-output analysis was introduced by Leontief and completed in 1970. It has served as a validation method to analyze "externalities" of products or services by quantifying the inter-industrial interdependence relationship in the entire economic system using publicly available data [28]. Such analytical tools are an efficient tool and technique to measure environmental impacts from a top-down perspective for many years [29–32]. In general, the input-output analysis can be expressed as:

$$F = C\,I(- U)^{-1} D \quad (1)$$

Where C is a 4*28 vector representing the direct energy input from four types of primary energy sources to all sectors, I is the identity matrix, U is the 28*28 matrix representing the intermediate use coefficient matrix in the input-output table, D is a 28*1 vector representing the total final demand of the construction sector since this study applies SDA model on one specific industry/sector rather than a national level.

F is the target environmental impact related to the final demand in the vector *D* for the construction sector.

The form of decomposition is flexible according to various perspectives. In general, the total changes can be decomposed into the effects from three separate factors: the change of industrial energy intensity (ΔC), the change of production structure ($\Delta(-I\ U)^{-1}$), and the change of final demand (ΔD). However, the total change in energy intensity is the sum of energy intensities of various energy types. This overall effect may be caused by the structural change and energy efficiency improvement. Therefore, to measure each individual effect and distinguish the difference between them, an intermediate variable was used in the study by Chang, Lewis [33]: $^{t\,t(-1)} = C_t \sum_i n=1\ \mathrm{C}i\ t(-1)$, where = 4 types of primary energy sources.

C

$$^{-1}\overline{\textstyle\sum_{i=1}^{n}}\quad \mathrm{C}_{it}$$

(2)

Eq. (2) indicates that the energy consumption structure is static at the initial year (t-1), and the total amount of energy is equal to the current year (t). Consequently, we have:

$\Delta C\ C\ Cv = -t\ \ t\ t(-1)$ (3)

$\Delta C_s = Ct\ t(-1) - Ct$ (4)

Where ΔC_v describes the change in total energy intensity, and ΔC_s describes the change of energy structure. Similarly, another variable for differentiating structural change and growth effect for final demand can be defined: $^{t\,t(-1)} = D_{t-1} \sum_i n=1_n Di\ t(-1)$, i = categories of final demand

D

$\sum_{i=1} D_{it}$ (5)

$\Delta D\ D\ D_v = -t$ $t\ t(-1)$(6)

$\Delta D_s = D_t\ t(-1) - D_t$ (7)

Eq. (5) indicates that the final demand structure is maintained in the initial year (t-1) whereas the total volume of final demand is the same as the current year (t). The ΔD_v represents the change of final demand volume, and ΔD_s represents the structural change of final demand. Consequently, the total change in environmental loading F from base year 0 to later year t can be expressed as:

Table 1

Mathematical expressions for four typical structural decomposition models.

	Residual term included		Residual term excluded	
Model	Laspeyres index approach	Paasche index approach	The polar decomposition	The fourth model
Features	Estimated based on the initial year (t=0)	Estimated based on the current year (t=1)	Estimated based on the mixture of Laspeyres and Paasche approach	Estimated by calculating the average of all first-order

				decomposition solutions
$E1$	$E_1 = \Delta C\, I_v(- U^0)^{-1} D^0 + \Delta\varepsilon$	$E1 = \Delta C\, Iv(- U^t)^{-1} D^t + \Delta\varepsilon$	$E_1 = \frac{1}{2}\Delta C_v (I - U^t)^{-1} D^t + \frac{1}{2}\Delta C_v (I - U^0)^{-1} D^0$	$E_1 = \frac{1}{3!}\sum_{i=1}^{3!}\left[\Delta C_v (I - U^T)^{-1} D^T\right]_i$
$E2$	$E_2 = \Delta C\, I_s(- U^0)^{-1} D^0 + \Delta\varepsilon$	$E2 = \Delta C\, Is(- U^t)^{-1} D^t + \Delta\varepsilon$	$E_2 = \frac{1}{2}\Delta C_s (I - U^t)^{-1} D^t + \frac{1}{2}\Delta C_s (I - U^0)^{-1} D^0$	$E_2 = \frac{1}{3!}\sum_{i=1}^{3!}\left[\Delta C_s (I - U^T)^{-1} D^T\right]_i$
$E3$	$E_3 = C^0[\Delta\, I(- U)^{-1}] D^0 + \Delta\varepsilon$	$E_3 = C\, \Delta\, I^t [(- U)^{-1}] D^t + \Delta\varepsilon$	$E_3 = \frac{1}{2} C^0 \left[\Delta (I - U)^{-1}\right] D^t + \frac{1}{2} C^t \left[\Delta (I - U)^{-1}\right] D^0$	$E_3 = \frac{1}{3!}\sum_{i=1}^{3!}\left[C^T \left[\Delta (I - U)^{-1}\right] D^T\right]_i$
$E4$	$E_4 = C\, I^0(- U^0)^{-1} \Delta D_v + \Delta\varepsilon$	$E4 = C\, I^t (- U^t)^{-1} \Delta Dv + \Delta\varepsilon$	E_4 $\frac{1}{2}$ 0 $0\ -1$ $= C\, I(- U\ )$ $\Delta D_v + \frac{1}{2}$ t $t\ -1$ $C\, I(- U\ )$ ΔD_v	$E_4 = \frac{1}{3!}\sum_{i=1}^{3!}\left[C^T (I - U^T)^{-1} \Delta D_v\right]_i$
$E5$	$E_5 = C\, I^0(- U^0)^{-1} \Delta D_s + \Delta\varepsilon$	$E5 = C\, I^t (- U^t)^{-1} \Delta Ds + \Delta\varepsilon$	$E_5 = \frac{1}{2}$ $^0(- \ ^0)^{-1}$ $_s + \frac{1}{2}$ $^t(- \ ^t)^{-1} C\, I$ $U\ \Delta D\ C\ I\ \ U\ \Delta D_s$	$E_5 = \frac{1}{3!}\sum_{i=1}^{3!}\left[C^T (I - U^T)^{-1} \Delta D_s\right]_i$

$$\Delta F = E\,\Delta C(\ _s) + E\,\Delta C(\ _v) + E\,\Delta\, I[\ (- U)^{-1}\ ] + E\,\Delta D(\ _s) + E\,\Delta D(\ v) + \Delta\varepsilon \tag{8}$$

$E1$ $E2$ E_3 $E4$ $E5$

Here, $E(\Delta)$ is the individual effect on total change ΔF caused by the change in a specific factor. However, the computational process for identifying these individual effects is complicated.

The possible solutions have been extensively described in previous reports. In summary, the mathematical model can be divided into two categories by considering whether a residual term is included in the calculation (see Table 1). Table 1 shows mathematical expressions of different driving factors according to four typical decomposition analysis models.

The Laspeyres and Paasche index approaches calculate the individual effect of a specific factor by assuming the value of the remaining factors that are held constant at the initial year and current year, respectively. Such assumptions can generate the residual term ($\Delta\varepsilon$) that is a mixed effect because of the simultaneous changes from two or more factors. Table 1 illustrates that the residual term representing such interaction effects have a direct impact on the total changes. Seibel [34] argued that the residual term could be neglected when the calculation period is short and the identified factors are not subject to sudden change. In contrast, large residual terms leading to considerable bias in final result must be considered.

In fact, the decomposition form is not unique because the effects for all the factors can be evaluated either for base time 0 or current time *t*. Such a technical problem associated with structural decomposition is capable of resolving in the fourth model by averaging all the first-order decomposition solutions. For a detailed discussion and computing processes related to this method, please see De Haan [35] and Dietzenbacher and Los [36]. The third model (the polar decomposition) is another effective method addressing the problem of nonuniqueness in decomposing results. It has been commonly used in many studies [21,37,38]. This method eliminates the residual term by comprehensively considering the effect from the Laspeyres and Paasche indexes.

Finally, totally nine input-output tables (1990, 1992, 1995, 1997, 2002, 2005, 2007, 2010, and 2012) are collected from the National Bureau of Statistics, this study thereby divides the investigated time period into eight separate intervals.

3. Results analysis

It is important to briefly discuss the annually embodied energy use before analyzing the driving forces related to energy increases in the construction industry in the past two decades. Fig. 1 shows that the energy consumption from the construction industry increased stably from 1990 to 2002 but has grown sharply from 2005 to 2012. Such large increases in energy consumption further emphasize the importance of investigating the hidden driving factors for the construction industry.

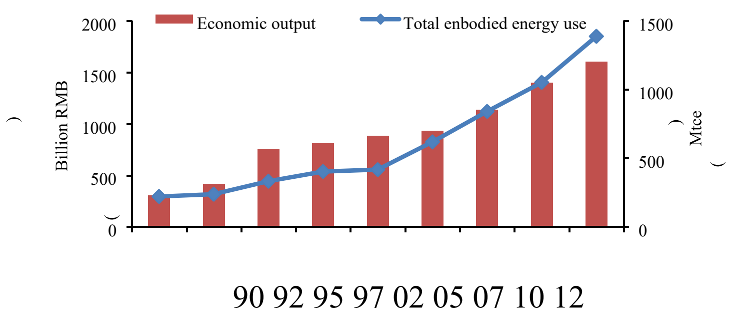


Fig. 1. Annual economic output and energy use of the construction industry.

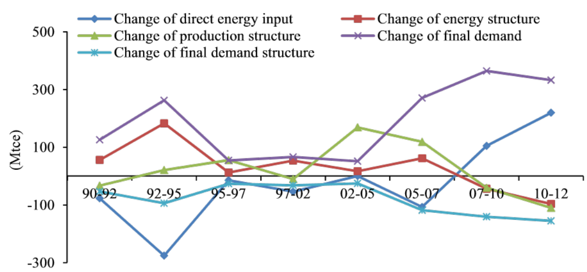
As mentioned in the methodology section, the structural decomposition analysis of the construction industry from 1990 to 2012 has been conducted through four major methods. The results of the comparative analysis are shown in Table 2. The first two approaches estimate the target individual driving factor by assuming that the others remain constant at either base year values or current year values. Such subjective manipulation could generate incalculable residual terms that are bound to add uncertainty. On the other hand, the results of the last two approaches were almost the same. The third method simplified the computational process by considering mixture effects and assigning equal weight on the initial year and the current year in the decomposition formula. More importantly, this method considers mixture effects of driving factors and eliminates the residual terms during calculation. The last method averages all first-order decomposition forms and thereby resolves the problem of non-uniqueness. However, this approach has drawbacks on the complicated calculation process that are applied. Therefore, this study employed the third method to further analyze the hidden driving forces during different time periods.

Table 2

Results of decomposition analysis by different models. (Mtce).

	Laspeyres index approach	Paasche index approach	Polar decomposition	The fourth model
Change of direct energy input	−204.2	−1427.0	−815.6	−808.0
Change of energy structure	129.9	913.9	522.0	517.1
Change of production structure	158.8	479.6	416.7	412.8

Change of final demand	1168.9	1212.3	1190.6	1179.5
Change of final demand structure	−209.1	−216.9	−213.0	−211.0
Total	1044.3	961.9	1100.6	1090.3



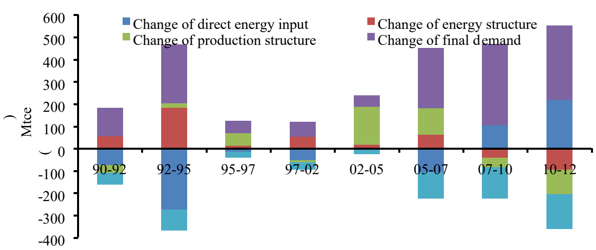


Fig. 3. Contribution of five driving factors in the total energy consumption change. Fig. 2. Trends of five driving factors from 1990 to 2012.

The total energy increments calculated by four methods are consistent with each other. It was calculated to be almost 1100 million tonnes of coal equivalent (Mtce). The result implied that there was a competition between the effects of energy input efficiency improvements and the increasing final demand. Furthermore, the structural change in energy and production also has positive impacts on the embodied energy consumption whereas the reduction effect of structural change in final demand was relatively small. From the production perspective, efficiency gains in energy intensity were the only factor balancing the energy increment in the construction industry. In fact, the efficiency improvement in energy intensity reduced by 815.6 Mtce (−369%) in total consumption of 1990 level. In contrast, the structural change in energy and production leads to an increase in embodied energy use of the construction industry by

938.7 Mtce (425%). From a consumption-based perspective, the energy use driven by the final demand can be investigated separately based on different demand categories provided by the input-output table. According to the result, the construction industry of China is a typical demand-driven industry—energy consumption has increased by 1190.6 Mtce (539%) due to the increased volume of final demand from 1990 to 2012. Further decomposing the final demand by different categories highlighted that the gross fixed capital formation contributed 1131 Mtce (512%). In China, investments in fixed capital formation are closely related to infrastructure construction, retrofit, refurbishment, and real estate activities, which are certain to create large energy demands. In contrast, the consistent efforts to optimize the final demand structure have reduced energy consumption by 213 Mtce (96%) from 1990 to 2012. In summary, the change in the volume of final demand and energy intensity were the major factors contributing to the growth or decline in embodied energy consumption of the construction industry. The effects of structural optimization on energy, production, and final demand were relatively minor.

Figs. 2 and 3 present a detailed analysis in eight separate time intervals. In the 1990s, the central government was committed to economy development and infrastructure construction, which aimed to transform the construction industry into the main power for China's economy growth. This policy orientation led to rapid growth in final demand and energy use in construction.

More specifically, from 1990 to 1992 the change in the volume of final demand and energy structure resulted in a 57.0% and 25.3% increase in total embodied energy use whereas energy intensity reduction, structural optimization in production, and change in final demand structure together offset the total embodied energy consumption by 73.7% of the 1990 level. In total, the energy consumption increased 8.7% from 1990 to 1992.

From 1992–2002, all the five affecting factors were consistent with the former 2-year interval. The volume growth of the final demand is the largest driving force. It resulted in an increase of embodied energy consumption by 161.7% (384 Mtce) followed by effects from structural changes in energy consumption (105.1%) and production (28.0%). In contrast, the major reduction factor is the efficiency improvements in energy intensity. This achieved a 144.7% (343 Mtce) reduction in total. Subsequently, the structural change in final demand was a minor effecting factor contributing 64.0% (205.5 Mtce) of the reduction in energy consumption of the construction industry.

Starting in 2000, the total embodied energy consumption has grown sharply due to the booming property market. From 2002– 2005, energy use embodied in the construction industry was driven mostly by changes in production structure (40.6%) with smaller effects due to the increasing volume of final demand (12.4%) and energy intensity (0.1%). The overall energy increment was 213 Mtce (51.2%), which represented the largest percentage change during the period from 1990 to 2012.

To alleviate this negative environmental impact from the intensive urbanization all over the country, the central government took a series of measures to achieve energy reduction and conservation during the 10th (2001–2005) and 11th (2006–2010) Five-Year Social and Economic Development Plans. For instance, the 11th Five-Year Plan put forward a plan to optimize the energy consumption structure in China's economy and made a 20% reduction in total domestic energy use mandatory. This aimed to restructure the economic growth pattern from resource-intensive to resource-efficient. More specifically, China adjusted the production structure by shifting from an energy-intensive industry towards more energy-efficient industry to achieve a structural energy saving. The Ministry of Housing and Urban-Rural Development improved the energy efficiency of the construction industry through two major strategies—one is the adoption of innovative techniques in building material production, and the other is promoting more applications of low energy-intensive materials during the construction process.

Consequently, such a policy orientation is effective for the following three periods. From 2005–2007, the change in volume of the final demand and production structure were two primary factors leading to 43.9% and 19.2% energy increases versus 2005 levels, respectively. In comparison, changes in energy intensity and final demand structure were the major drivers of reduction—this cut 36.4% of the embodied energy consumption in total. Unfortunately, such energy saving measures could not outweigh the effects of energy-driven factors.

The consistent efforts on structural optimization by the central government paid off from 2007 to 2012. The structural adjustment in energy, production, and final demand has a continuous and significant positive impact in energy reduction. It balanced the total energy increase by reducing energy demand by 31.0%. The growth in the final demand volume was the most dominant factor (36.9%) for energy increase during this period. More importantly, the amount of energy reduction induced by the structural optimization was continuously increased during the time period from 2010 to 2012. Such consistency not only demonstrated the effectiveness of relevant energy conservation policies implemented by the central government at the national and industrial levels but also provided a quite promising picture for further energy reduction from the structural optimization in energy, production, and demand in the construction industry.

In sum, by comprehensively reviewing the driving forces behind eight time periods from 1990 to 2012, the embodied energy consumption of the construction industry was investigated in accordance with several dominant trends. First, the total energy demand is driven by consistently increasing volume of final demand. Based on an average

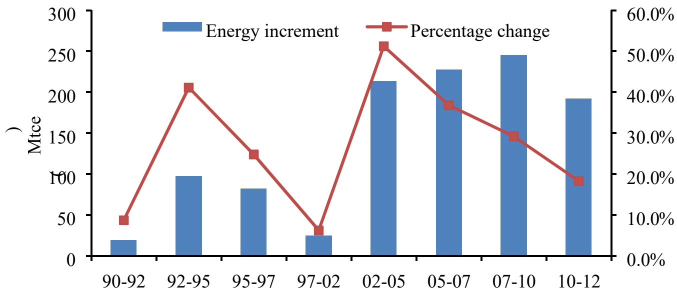


Fig. 4. Summary of energy increment and its percentage change for different periods.

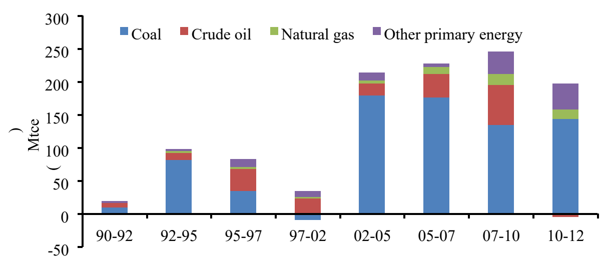


Fig. 5. Change in total energy consumption from 1990 to 2012 by different fuel types.

Table 3

Data required for projection.

Sector	Energy consumption growth rate	Proportion in GDP	Energy source	Growth rate
Agriculture	1.3%	3%	Coal	3.0%
Industry	3.2%	50%	Oil	4.0%
Iron and steel	2.9%		Natural gas	5.7%
Non-metallic minerals	1.1%		Others	3.4%
Chemicals	2.2%			
Transportation	5.4%			

Service	3.3%	47%	Total	3.2%

Note: all the data listed in this table are obtained and estimated based on the World Energy Outlook 2007-China and India Insights, Chapter 9.

Table 4

Scheduled and actual annual growth rate of economy in China from 1991 to 2015.

	8th Fiveyear 1991–1995	9th Fiveyear 1996–2000	10th Fiveyear 2001–2005	11th Fiveyear 2006–2010	12th Fiveyear 2011–2015
Schedule	6.0%	8.0%	7.0%	7.5%	7.0%
Actual	12.30%	8.60%	9.70%	11.20%	8.20%

annual increasing rate of 0.8%, the urbanization rate in China is estimated to reach a historic high of 51.5% at the end of "The Twelfth Five-Year Plan" [39]. Such rapid urbanization brings a long-standing and considerable energy demand to China. Relatively speaking, the effort of improving energy intensity is also significant in energy reduction in the construction industry. This has offset a large amount of energy consumption driven by the high levels of final demand growth. Second, according to Fig. 4, the trend of percentage change in the incremental energy consumption in different investigated periods revealed that although the energy consumption surged from 2002, the annual growth rate continued to reduce from 2005 due to the implementation of energy conservation regulations and policies. Third, the energy reduction in the construction industry can be further achieved by taking steps to optimize the structure of energy consumption, production, and final demand.

Fig. 5 examines the energy increase in the construction industry according to different fuel types. It is clear from this figure that the coal consumption is dominant in all energy sources followed by oil and other primary energy—this highlights that the construction industry is a typical fossil fuel energy-oriented sector. The downward trend of the coal consumption during 1992–2002 has been reversed due to the surging economic output from the construction industry in 2002. Further examination of the driving forces indicated that such a surge in the energy consumption is the result of increased energy intensity and final demand volume. However, this substantial consumption of coal was consistently reduced afterwards due to the great efforts in structural optimization by the central government.

4. The projection of the 13th (2015–2020) Five-Year Plan

Given the large potential of energy reduction in structural optimization during the period from 2005 to 2012, it is therefore necessary to investigate to what extent such energy saving can be achieved with the development of modern economy and technology in the near future. Moreover, measuring the potential driving forces in the projected scenario can also help the central government achieve equitable energy reduction policies in consumption. Therefore, this study made a projection scenario for the future energy consumption in China's construction industry. The input-output table from 2010 has been adopted as the initial year to predict the economic data. Similarly, the energy consumption data obtained from the 2011 Chinese Energy Statistical Yearbook are used as the baseline to predict energy consumption patterns and volume in 2020.

To project the energy consumption trajectory, a number of assumptions adopted by the World Energy Outlook 2007 have been used in this study to estimate the volume and pattern of energy consumption. Tables 3, 4 summarized four categories of data required for projection. First, the annual growth rate for major energy-intensive sectors has been assumed (e.g. iron and steel, non-metallic minerals, chemicals, and transportation). Second, the basic economic structure involved in agriculture, industry, and service was also determined. The proportion of economic output from service sector increased to 47% whereas the percentage of agriculture and industry reduced to 3% and 50%, respectively. This adjustment adopted by the World Energy Outlook 2007 highlights the switch in China's economic structure from manufacturing-based to service-based. Third, the annual growth rate of different primary energy sources has been assumed. The primary energy consumption including coal and oil is projected to grow by 3.0% and 4.0% per year from 2010 to 2020, respectively. Clean energy sources such as natural gas and renewable energy in other primary energy will grow faster (5.7% and 3.4%, respectively) according to the structural optimization in future energy consumption. The annual growth rate of total energy consumption is assumed to be 3.2%. Fourth, the GDP growth rates in the past two decades have been reviewed to predict the volume of economic output in 2020 (Table 3). Given the difference between the scheduled and actual rate over the past two decades as well as the economic downturns since 2006, the average annual growth rate is assumed to be 6.5% for the 13th FiveYear Plan period. To predict future production structure, the RAS method has been proved to be an effective technique to reconstruct the input-output table. It has been used to estimate the inter-industrial coefficient in 2020. The data required by RAS method are calculated based on the assumption that the sectoral data of intermediate sales and total interindustry purchases are proportional with their total gross outputs.

The percentage changes in the total energy consumption according to different driving factors are shown in Fig. 6. The total embodied energy consumption in the construction industry would reach 1408 Mtce by 2020 with a 34.0% increase of 2010 level and a 537.4% increase of 1990 level. The energy reduction from structural optimiza-

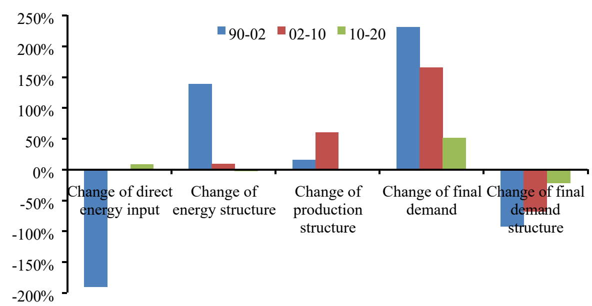


Fig. 6. Percent change in the total embodied energy consumption for five driving factors.

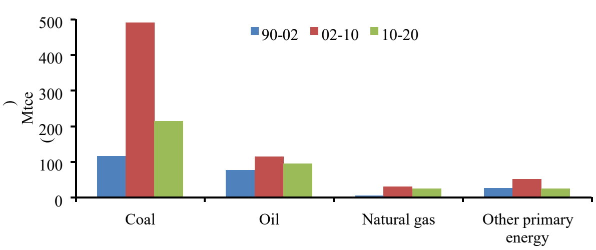


Fig. 7. Change of the energy increments by different fuel types.

tion is significant—the structural change in energy, production and final demand are three major factors causing energy reduction. Such result is also in-line with the energy reduction trend since 2005, implying the importance of structural upgrading for achieving sustainable construction in the modern economy. These three factors together reduce 24.7% (260 Mtce) of 2010 level. It is also worth noting that although the volume of final demand is the largest driver for energy increments, it experiences a slowdown in this scenario, especially versus the trend from 1990 to 2002 and 2002–2010. Fig. 7 shows the change of energy increments for different fuel types. Based on the assumed growth rate in the economy and energy use, the consumption of carbon-intensive energy sources (e.g. coal and oil) has been significantly reduced in comparison to the level of 2010.

5. Scenario analysis

5.1. Scenario analysis for the projection

Given that the assumptions used in the projection are crucial for robust model results, this study therefore conducted scenario analysis based on the bottom-level assumptions and variables. Moreover, energy increase from the construction industry is inevitable in China due to the rapid urbanization process and requirement for improving people's living standard. According to the projection in the Section 4, the structural optimization has been demonstrated as the major reduction drivers for the energy consumption of the construction industry. Therefore, the focus of concern in this scenario analysis is to explore how the structural optimization suppresses the energy increment from a production-based perspective with the same projected GDP growth rate. Table 5 shows the changes of basic data under different scenarios. Reference scenario is consistent with the assumptions in original projection. Optimistic scenario is adopted to enhance the positive effect from the structural optimization on energy reduction. Therefore, the proportion of economic output in service is assumed to increase by 10% while the share of industry reduces by 10%. Simultaneously, a 10% increase is assumed for the annual growth rate of clean energy and renewable energy, and the growth rate for energy-intensive sectors (e.g. Iron and steel, non-metallic minerals, and chemicals) is assumed to reduce by 10%. By contrast, pessimistic scenario puts emphases on the negative effect from structural changes on energy consumption. Accordingly, the sharing of economic output in industry is adjusted to 55%, the growth rate of clean energy and

Table 5

Basic profile of different scenarios.

	Reference scenario	Optimistic scenario	Pessimistic scenario
Agriculture	(3%)	(3%)	(3%)
Industry	(50%)	(45%)	(55%)
Iron and steel	2.9%	2.6%	3.2%
Non-metallic minerals	1.1%	1.0%	1.2%
Chemicals	2.2%	2.0%	2.4%
Service	(47%)	(52%)	(42%)
Natural gas	5.7%	6.3%	5.1%
Other primary energy	3.4%	3.7%	3.1%

Note: the number of percentage presented in the bracket is the sharing of economic output in the national GDP.

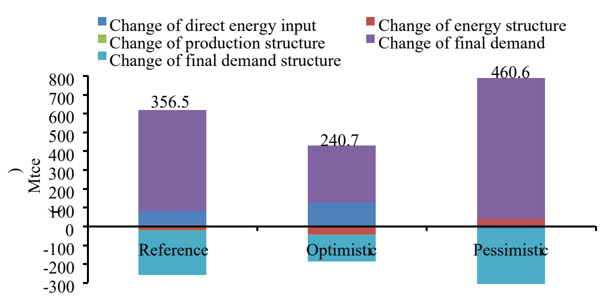


Fig. 8. Energy increments of different driving factors in three scenarios.

renewable energy declines by 10%, and the growth rate for energyintensive sectors increases by 10%.

According to Fig. 8, the energy increment calculated under the pessimistic scenario was 460.5 Mtce with a 43.8% increase of 2010 level, which was 29.2% higher than the result obtained in the reference scenario. In contrast, the result calculated in optimistic scenario was 240.7 Mtce with a 22.9% increase of 2010 level, which was 32.5% lower than the original projection. This finding provides an insight into how the structural optimizations in production and energy consumption affect the total energy use of the construction industry. It can be seen that the energy increase driven by the volume of final demand has been restrained significantly due to the structural optimization of production and energy in the optimistic scenario. Fig. 9 shows the energy increment according to different primary energy sources. Similarly, optimistic scenario performed best regarding the suppression of energy increments in different primary energy sources. On one hand, as a typical carbon-intensive source causing global warming, coal was consumed the least in the optimistic scenario. On the other hand, the proportion of clean energy (natural gas) and renewable energy in total energy consumption has been improved from 6.8% and 6.9–8.9% and 7.1%, respectively. In summary, the results of scenario analysis indicate that the steering of production structure from heavy manufacturing to service-based economy as well as the adjustment of energy consumption structure by improving the proportion of clean and renewable energy have significant positive effect on energy reduction

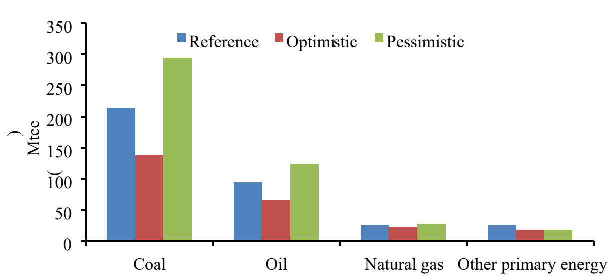


Fig. 9. Energy increments of different primary energy sources in three scenarios.

of the construction industry.

5.2. Scenario analysis in sector aggregation

The uncertainties in the input-output analysis come from two major sources. One is the theoretical assumptions before analysis including the assumption of proportionality, homogeneity, and identity of production technology. The other is due to transformation and reconstruction in the compilation of input-output tables. In general, the methodological uncertainties are mostly unavoidable and hard to estimate in the computational process. In contrast, uncertainties from subjective compilation can be quantified and improved based on uncertainty analysis. Moreover, Weber [14] also emphasized that the level of sector aggregation has a direct impact on results accuracy—this is the most critical factor influencing the uncertainty in structural decomposition. Unfortunately, very few studies have discussed this problem systematically due to a lack of public data. Therefore, this study focused on sector aggregation.

Broadly speaking, sector aggregation is the result of the tradeoff between the level of detail in analysis and the availability of environmental data from the statistical yearbook. Generally, the I-O table compiled by the National Bureau of Statistics is more specific on the detailed monetary flow data. However, direct energy input data are recorded at a more aggregate level, where the sector classification standard is not consistent with the I-O table. Moreover, due to the improvement of sector classification standards in the past two decades, the compilation of input-output table has been changed across different years. Sector aggregation has to be performed to keep the consistency in table format across the time series.

The level of sector aggregation thus directly affects the final results of the I-O analysis because the number of sectors has been predetermined in structural decomposition analysis. As a result, the sector aggregation strategy needs to be implemented to match these two systems

[40]. One strategy is to aggregate the I-O sectors to match the energy sector data. This strategy not only guarantees the accuracy of sector aggregation but also avoids extra assumptions. The other approach disaggregates energy consumption data to match the I-O table that retains all economic information while bearing the drawbacks on the subjective estimation of energy use among the subsectors.

Thus, this study employed multi-scale I-O tables to conduct uncertainty analysis. To create I-O tables with different number of sectors, the sectoral outputs with similar production process or analogous chemical properties were integrated as one specific sector for uncertainty examination purpose. Generally, the I-O table with 28 sectors (presented in this study) has been recombined into tables with 18 sectors, 8 sectors, and 4 sectors respectively to verify the impact of changes in the level of sector aggregation (Appendix A). In the inputoutput table in 18-sector format, the sectors in relation to the manufacturing process of metal products, machineries, equipment, instruments have been combined into a uniform sector titled as "other manufacturing" whilst a number of service sectors related to culture, education, health, research, finance, and insurance were integrated as the "other services sector". In the 8-sector situation, the whole manufacturing industry has been macroscopically divided into two categories, namely energy-intensive and energy-efficient manufacturing sectors. This division was in-line with the sector classification by Weber [14] which to some extent reflects energy interactions between the construction sector and the manufacturing sectors within different levels of energy intensity. In the 4-sector scenario, the integration process was consistent with the current industry classification standard where the entire modern economy was categorized into agriculture (the primary industry), manufacturing (the secondary industry), construction, and service sectors (the tertiary industry). In this situation, economic interactions among sub-sectors were ignored intentionally.

Fig. 10 shows that all scenarios agree on the dominant driving

Fig. 10. Changes of driving factors by different scenarios.

forces for energy increment in the construction industry. Besides, the sequence of importance for driving factors underlying each scenario is consistent with original findings except the result calculated by a 4sector format table. In this scenario, the effect of structure change in production is stronger than the effect of change in the energy structure. This is inconsistent with other scenarios. Such inaccuracy may lead to a misunderstanding of the importance of the factor under study. Moreover, the results of the I-O analysis with 8 and 4 sectors have been changed considerably due to the loss of detailed information on economic data. Therefore, it is advisable and necessary to perform decomposition analysis based on sufficient economic information.

6. Discussions and policy implications

From 1990–2012, energy consumption in the construction industry changed dramatically due to the booming property market. It is likely that this trend will continue for a long time due to the rapid urbanization process and resulting increase in standard of living. The results indicate that although the change in energy intensity contributed markedly to the energy reduction of the construction industry at the aggregate level, it is still insufficient to offset the rapid growth in final demand. Therefore, it is important to adopt more ambitious strategies to offset further increases.

In principle, reductions in energy intensity are the result of technological improvement and energy structural optimization—this is the major tool used for energy savings in the construction industry. The predicted results show that by further improving the sharing for renewable and clean energy sources, energy use would be reduced by 22 Mtce (2.1%) in 2020.

In fact, the structural optimization in production from 1990 to 2012 was enabled by both improvements in energy productivity in the heavy industry as well as movement of energy-intensive sectors towards energy-efficient service sectors. The proportion of the service industry increased from 31.5% to 43.1% in the past two decades. This is projected to be nearly half of the national total economic output in 2020. Had such a situation stayed constant, the total energy reduction from the structure shift would be expected to be 238 Mtce (22.7%). This would make it the most important factor for energy reduction in 2020.

Based on the results of this study, it is clear that the energy increase in China's construction industry is mostly driven by the growth of final demand. Such high demand is the result of the investment-driven and rigid demand for residence. However, it is really difficult to predict the volume of final demand for the construction industry. On one hand, in the foreseeable future, the trends in population growth will slow due to the family-planning policy started in the 1980s. As a result, such supply shortage in property market will be alleviated. Moreover, with several rounds of macro-control on property market by the central government from the year 2005, profit margins have been further narrowed. This suppresses the enthusiasm of investors and returns the market to rationality. On the other hand, although total population decreases in China, the cityward migration associated with rapid urbanization would also generate stronger demand for urban residential buildings, which may result in larger energy footprints for per unit building floor area compared to rural residential buildings. Besides, the rising middle class in urban areas also yields demand for more spacious houses. Such comfort-oriented purchases would also cause new constructions, and thus increase building energy consumption.

In addition, traditionally human behavior is regarded as an important factor to achieve the energy conservation and sustainable development during building operational phase rather than embodied phase. However, Hong et al. [41] demonstrated that human activities also have a direct impact on environmental emissions during the building construction phase. They indicated that an improvement of onsite management skill and worker productivity could lead to a more energy-efficient construction process. Therefore, human behavior (e.g. workers and staff activity) is also of great importance during building embodied phase. In fact, according to the results obtained in this study, the energy consumption per capita of the construction industry has increased from 0.22 t of coal equivalent (tce) in 1990 to 0.32 tce in 2012. Therefore, improving energy efficiency of human beings during the construction process is an effective method to reduce energy consumption of the construction industry.

In summary, although the embodied energy use of China's construction industry has shown consistent increases from 1990 to 2012, the role of driving factors has changed across different time periods. The structural change in energy and production has gradually switched their roles from energy-driven factors to energy-reducing factors. This is due to the consistent efforts in structural optimization by the central government. It is also worth noting that the urbanization rate in China will reach a historic high of 51.5% at the end of the 12th Five-Year Plan [39]. Therefore, focus should not only remain on structural optimization and energy intensity improvements but also controlling or restricting the volume of consumption demand by the central government.

More specifically, the central government should first encourage industrial sectors to adopt advanced production technologies. Technical innovation effectively improves energy productivity and efficiency. Since construction activity is highly related to the number of energy-intensive sectors due to its heavy use of cement and steel (e.g. manufacture of non-metallic mineral products and smelting and pressing of metals), more energy-efficient and value-added products should be advocated to these energy-intensive suppliers for reducing energy intensity. For instance, prefabricated products provide a controlled condition to facilitate the standard design of building materials, units, and components—these advances could not only improve energy efficiency but also achieve a higher added value during the construction process.

Second, as a typical fossil energy-oriented sector, the construction industry should take action to optimize its energy consumption structure. In fact, the change in energy structure is also one major factor leading to energy increase in the past two decades. This highlights the deficiency that such factors had on energy use in the construction industry. One effective way to achieve this optimization is to improve the share of environmentally-friendly energy. This would replace the conventional carbon-intensive energy with renewable and clean energy sources. For instance, shale gas is a promising energy source which is abundant in China. According to Wang, Chen [42], this energy source is projected to replace coal power and change the US energy landscape in the future.

Third, the central government should consistently put great efforts into industrial structural upgrading—not only by switching the economy from heavy manufacturing to service based, but also transiting the entire supply chain toward a more sustainable and high value added economy. More specifically, it is crucial to set measurable targets at the beginning of the 13th Five-Year Plan. According to the quantitative analysis in this study, the optimistic scenario indicates that the percentage change of energy increments in 2020 is 22% of 2010 level by conducting an ambitious structural optimization in production and energy consumption. Accordingly, given the consistently positive effect from the implementation of energy reduction policies and ambitious of the central government in energy reduction as well as the declined trend of incremental energy consumption as shown in Fig. 4, it is reasonable to expect that the percentage change of the incremental energy consumption from the construction industry could be restrained below 25% of 2010 level at the end of the 13th Five-Year Plan. Such target is to large extent dependent on technology innovations and a favorable environment created by the central government for further upgrades.

7. Conclusions

This study employed structural decomposition analysis to explore the driving forces behind energy use in China's construction industry from 1990 to 2012. A systematical review of the major trends and improvements in energy consumption has been presented. Moreover, critical factors have been identified for further policy consideration. The findings of this study are as follows:

(1) A comparative analysis of different decomposition methods shows that the polar decomposition is prior to other models. This is especially based on its advantages in eliminating residual terms and simplifying computational processes.

(2) The driving factors during the past two decades represent a competition between the effects of increasing demand and a reduction in energy intensity. In contrast, the effects of structural optimization in energy, production, and final demand were comparatively minor from 1990 to 2005. However, such determinant was proved to be more significant in energy reduction

after 2005 due to the consistent efforts in structure optimization by the central government. The results also indicated that the construction industry is a typical fossil fuel-oriented sector in which the consumption of coal has increased almost 2-fold of 2002 level from 2002 to 2012 due to the flourishing property market.

(3) The projection of energy use changes in the construction industry from 2010 to 2020 shows that the structural optimization in energy, production and final demand are three major factors causing energy reduction. This is because of the consistent efforts in structural optimization and technological improvement by the central government.

(4) The scenario analysis firstly explored the positive effect of the structural optimization on energy reduction from a productionbased perspective. Result shows that the percentage change of energy increments in 2020 is 22% of 2010 level in the optimistic scenario. Secondly, results from different levels of sector aggregation have been examined under 18, 8, and 4-sector format scenarios. The results revealed that more aggregates would increase uncertainty to some extent and result in a misinterpretation of the importance of the underlying factors. Therefore, it is advisable and necessary to perform decomposition analysis based on sufficient detailed economic data.

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Appendix A

28 sectors.

	Name		Name
S1	Agriculture	S15	Manufacture of metal products
S2	Mining and washing of coal	S16	Manufacture of general and special purpose machinery
S3	Extraction of petroleum and natural gas	S17	Manufacture of transport equipment
S4	Mining and processing of metal ores	S18	Manufacture of electrical machinery and equipment
S5	Mining and processing of nonmetal ores	S19	Manufacture of communication equipment, computers and other electronic equipment
S6	Manufacture of foods and tobacco	S20	Manufacture of measuring instruments and machinery for culture activity and office work
S7	Manufacture of textile	S21	Other manufacturing
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather(down) products	S22	Production and distribution of electric power, heat power, gas, and water
S9	Processing of timber, manufacture of furniture	S23	Construction

S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity	S24	Transportation, storage, posts and telecommunications
S11	Processing of petroleum and coking	S25	Wholesale trade, retail, hotel, and restaurants
S12	Chemical industry	S26	Culture, education, health, and research
S13	Building materials and non-metallic mineral products	S27	Finance and insurance
S14	Smelting and pressing of metals	S28	Other services

18 sectors.

	Name		Name
S1	Agriculture	S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity
S2	Mining and washing of coal	S11	Chemical industry
S3	Petroleum and natural gas mining and processing	S12	Building materials and non-metallic mineral products
S4	Mining and processing of metal ores	S13	Other manufacturing
S5	Mining and processing of nonmetal ores	S14	Production and distribution of electric power, heat power, gas, and water

S6	Manufacture of foods and tobacco	S15	Construction
S7	Manufacture of textile	S16	Transportation, storage, posts and telecommunications
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather (down) products	S17	Wholesale trade, retail trade, hotel, and restaurants
S9	Processing of timber, manufacture of furniture	S18	Other services

8 sectors.

	Name		Name
S1	Agriculture	S5	Production and Distribution of Electric Power, Heat Power, gas, and water
S2	Mining and quarrying	S6	Construction
S3	Energy-intensive manufacturing industry	S7	Transportation, Storage, Posts and Telecommunications
S4	Energy-efficient manufacturing industry	S8	Other Services

4 sectors.

	Name		Name
S1	Agriculture	S3	Construction

S2	Industry	S4	Service

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