Energy Policy 38 (2010) 6597–6603

Contents lists available at ScienceDirect

Energy Policy

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

The embodied energy and environmental emissions of construction projects in China: An economic input–output LCA model

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ARTICLE INFO

Article history:
Received 14 January 2010
Accepted 15 June 2010
Available online 3 July 2010

Keywords:
Construction in China
Economic input–output LCA
Embodied energy and environmental emissions

ABSTRACT

A complete understanding of the resource consumption, embodied energy, and environmental emissions of civil projects in China is difficult due to the lack of comprehensive national statistics. To quantitatively assess the energy and environmental impacts of civil construction at a macro-level, this study developed a 24 sector environmental input–output life-cycle assessment model (I–O LCA) based on 2002 Chinese national economic and environmental data. The model generates an economy-wide inventory of energy use and environmental emissions. Estimates based on the level of economic activity related to planned future civil works in 2015 are made. Results indicate that the embodied energy of construction projects accounts for nearly one-sixth of the total economy's energy consumption in 2007, and may account for approximately one-fifth of the total energy use by 2015. This energy consumption is dominated by coal and oil consumptions. Energy-related emissions are the main polluters of the country's atmosphere and environment. If the industry's energy use and manufacturing techniques remain the same as in 2002, challenges to the goals for total energy consumption in China will appear in the next decade. Thus, effective implementation of efficient energy technologies and regulations are indispensable for achieving China's energy and environmental quality goals.

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1. Introduction

The environmental and energy challenges associated with turning society in a more sustainable direction are tremendous and urgent. Building and infrastructure construction, in step with developments in industry and transportation, has become an important energy consumer in China. This has resulted in an increase in environmental stress. In 2007, energy use in buildings accounted for 47% of the total energy consumption in China (Wang, 2005). Given the acceleration of urbanization as well as infrastructure construction, this percentage is projected to continue to increase in the future decades.

In terms of the life cycle energy use in buildings, operational energy is generally approximately 80% of the total energy consumption (BEERC, 2009). This has become the focus of recent studies. An investigation on the operational energy of commercial and residential buildings in China has found that the commercial building energy consumption statistics in the current National Bureau of Statistics of China underestimate energy consumption by 44% and the fuel mix is misleading. Energy efficiency improvements will not be sufficient to offset increases in energy intensity (particularly electricity) in commercial buildings (Bressand et al., 2007; Chen et al., 2008). In other studies, the resource consumption of urban residential buildings in China is calculated and compared with counterparts in the U.S., Canada, and Japan. It is shown that direct coal consumption will decline while electricity and natural gas consumptions will increase. Building design and operational energy technologies such as district heating should be compatible with urban planning so as to achieve better performance and energy savings (Fernandez, 2007; Zhang, 2004). To avoid the increased energy demand caused by urban housing development, design standards and codes should be revised to correspond with international norms and energy-efficient buildings should be adopted as a baseline (Guan et al., 2001; Lang, 2004; Rousseau and Chen, 2001). The widespread implementation of green building approaches as well as the effective reduction of building energy use cannot be achieved without various economic incentives such as tax rate reductions and low-interest loans. These may motivate both the supply and demand for energy-efficient buildings (Yao et al., 2005).

Researchers have been aware of the significant role embodied energy and its environmental impacts play in the creation of the energy-efficient society advocated by the Chinese government. The high energy consumption in both industrial and building

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0301-4215/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.enpol.2010.06.030

sectors has been analyzed and compared with the U.S. and Japan (Rao and Qian, 2006). Focusing on construction materials in China, the embodied energy of cement, steel, and glass and their direct and indirect environmental impacts have been calculated (Gong and Zhang, 2004). Direct and indirect household emissions of CO_2 in China were quantified with the help of input–output life-cycle assessment (I–O LCA) (Zheng et al, 2007). However, this study did not include other pollutants.

Generally, studies of building embodied energy as well other environmental impacts are rare in China, primarily because of barriers in obtaining quantitative data for analysis. Although I–O LCA models are very effective in quantifying embodied energy, the models are highly data-dependent, and the collection of economy-wide statistics in China is not mature nor complete enough, with the result that some critical data are not available. For example, energy consumption statistics are not available for all the 122 sectors in the I–O model, which introduces difficulties in establishing an energy intensity matrix for the I–O LCA model; environmental pollutants only cover SO_2 and PM, so a broad understanding of environmental impacts is lacking.

Embodied energy deserves systematic and complete analysis. Embodied energy in products is primarily the result of activity in industrial and transportation sectors. These sectors in China have room for improvement, with relatively minimal effect on citizens' daily life.

In this work, the embodied energy and environmental impacts of construction projects in China has been estimated. First, we briefly review the structure and development of I–O LCA models. Then, we discuss the 23 economic sectors related to the construction sector in the national economic system used in the model. Next, the derivation of the energy and environmental intensity matrices are reviewed. Finally, the implementation of the model in MATLAB® (Mathworks, 2009) and the detailed results and analysis are presented.

2. Methodology

2.1. Conceptual basis of LCA

Life-cycle assessment (LCA) is a methodology for evaluating the environmental load and energy consumption of processes or products (goods and services) during their life cycle from cradle to grave (ISO, 2006). For the building and infrastructure life cycle, it can be defined as a practical management approach with the goal of achieving an optimum cost and benefit solution through the process of design, building material extraction, material processing, construction, building operation, and disposal management. The approach takes into account the economic and functional considerations, as well as the environmental and safety requirements.

Generally speaking, there are three types of LCA models: process-based LCA, economic input–output LCA (I–O LCA) and hybrid LCA (Bilec et al., in print). The approaches vary in terms of differences in system scope and analysis, and each model has its own research process and character.

2.2. I–O LCA

I–O LCA addresses some of the drawbacks of process-based LCA model and greatly expands the system scope compared to the process-based LCA to include the entire economy of a country or region. It assesses the energy consumption and environmental impacts of goods and services from a nationwide perspective by taking advantage of a country's economic input–output matrix (Leontief, 1936). An economic input–output table is the economic relationship of each sector of a given country or region, which thus can facilitate mapping the supply chain of a given product. This makes it feasible to sum up the energy consumption and environmental impacts of each life-cycle phase (Hendrickson et al., 2006). The results of an I–O LCA model, however, represent the average level of performance of the sector, which therefore is often not suitable for a specific case study (Bilec et al., in print). I–O LCA models are mainly used to assess macro-level national economic activities, such as environmental impacts within certain industries. It can also serve as the foundation for a hybrid LCA model.

In an I–O LCA model, the final inventory vector "g" can be calculated by

$$g = S(I-C)^{-1}d$$

where C is the technical coefficient matrix, I is the identity matrix, S is the satellite matrix, and d is the total output vector. (Heijungs and Suh, 2002).

The dimension of each model component in this study is $C(24,24)$, $I(24,24)$, $S(14,24)$, and $d(24,1)$. The technical coefficient matrix "C" contains the coefficients that represent the economic interactions between the construction sector and the top 23 related sectors. The satellite matrix "S" includes total energy intensity, energy intensity in nine types of energy resources, and emissions intensity in four types of environmental emissions. The

Table 1
Sector codes and technical coefficients for the construction sector and the top 23 correlated sectors in China in 2002.

Sector code	Sector name	Technical coefficient
32056	Steel processing	0.10412164
1001	Crop cultivation	0.05265505
34060	Metal products	0.05132338
31049	Cement and lime products	0.04892172
63102	Wholesale and retail trade	0.04409941
20030	Furniture and products of wood, bamboo, cane, palm, straw, etc	0.03144237
35063	Other general industrial machinery	0.02954314
60100	Telecommunication	0.02920522
31053	Other non-metallic mineral products	0.02633046
2002	Forestry	0.02518606
39074	Other electric machinery and equipment	0.02440243
10012	Non-metal minerals and other mining	0.02417405
25036	Petroleum refining	0.02373305
26042	Synthetic chemicals	0.01840855
54094	Water freight and passengers transport	0.01655313
36065	Other special industrial equipment	0.01516916
52092	Highway freight and passengers transport	0.01421147
31052	Fireproof products	0.01405164
44086	Electricity and steam production and supply	0.01369923
74109	Business services	0.01228884
33059	Nonferrous metal processing	0.01100694
41081	Metal products	0.01055345
61101	Computing services and software	0.01046196
47089	Construction	0.00120362

Table 2
Planned and actual economic growth rates in China from 1995 to 2015.

Plan Period	9th Five-year	10th Five-year	11th Five-year	12th Five-year	
	1995–2000 (%)	2001–2005 (%)	2006–2010 (%)	2011–2015	
Plan	8.0	7.0	7.5	low	high
Actual	8.6	9.5	9.9[a]	8%	10%

[a] Predicted GDP growth rate for 2010 is 9.5%.

Table 3
Actual, target, and estimated energy intensities in China.

Type	Unit	2005	2009	2010	2015		
		Actual	Actual	Target	10% Reduction	15% Reduction	20% Reduction
Total energy	kgce/10^4 yuan	1219	1044	975	878	829	780
Coal	kg coal/10^4 yuan	1182	–	946	851	804	757
Coke	kg coke/10^4 yuan	122	–	97	87	82	78
Crude oil	kg crude oil/10^4 yuan	164	–	131	118	112	105
Gasoline	kg gasoline/10^4 yuan	27	–	21	19	18	17
Kerosene	kg kerosene/10^4 yuan	6	–	5	4	4	4
Diesel oil	kg diesel oil/10^4 yuan	60	–	48	43	41	38
Fuel oil	kg fuel oil/10^4 yuan	23	–	19	17	16	15
Natural gas	$m^3/10^4$ yuan	26	–	21	19	18	17
Electricity	kWh/10^4 yuan	1361	–	1089	980	926	871

Table 4
Embodied energy contributions from the top 23 sectors to the construction sector in 2007.

Sectors	Embodied energy (10^4 mt Coal eq.)
Crop cultivation	672
Forestry	351
Non-metal minerals and other mining	774
Furniture and products of wood, bamboo, cane, palm, straw, etc	284
Petroleum refining	3640
Synthetic chemicals	2110
Cement and lime products	4890
Fireproof products	1590
Other non-metallic mineral products	2970
Steel processing	12600
Nonferrous metal processing	1180
Metal products	888
Other general industrial machinery	427
Other special industrial equipment	179
Other electric machinery and equipment	186
Instruments, meters and other measuring equipment	76
Electricity and steam production and supply	2990
Highway freight and passengers transport	908
Water freight and passengers transport	974
Telecommunication	1120
Computing services and software	78
Wholesale and retail trade	589
Business services	126
Construction	4031

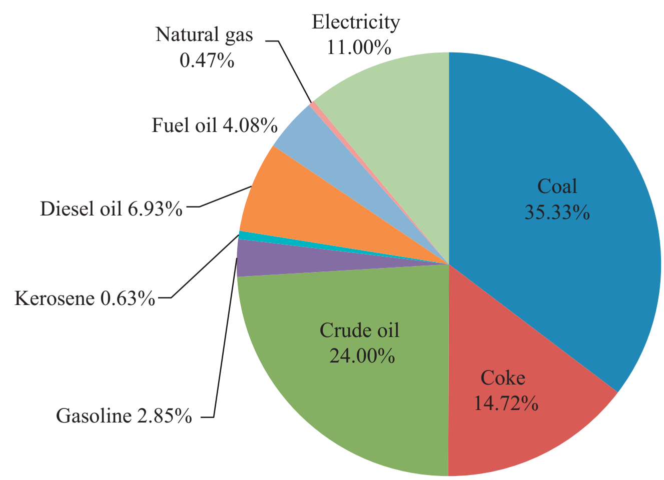

Fig. 1. Estimated percentages of energy types in the construction sector in China in 2007.

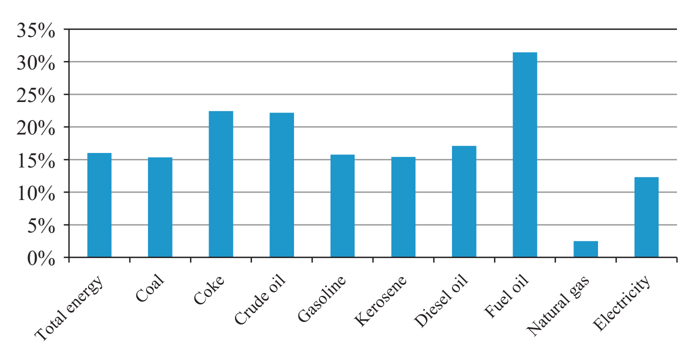

Fig. 2. Percentage of national energy consumption by source for the construction sector in China in 2007.

"d" vector represents the total economic output of the construction sector. The vector "g" is the inventory of the energy and environmental emissions related to the economic output in the "d" vector for the construction sector.

3. Model development

3.1. Correlated sectors

The criterion for sector selection was determined by their technical coefficients with the construction sector as shown in the latest Chinese input–output statistics from year 2002 (National Bureau of Statistics of China, 2006). The sectors' definitions, classifications, and system boundaries are those used in the national accounts and input–output table, in which the construction sector is defined to include building construction, infrastructure construction, equipment installation, and decoration. There are 122 sectors in the current Chinese economic statistics system, which covers the entire breadth of economic activities. Although sector divisions are not as specific as that in the 491 sector U.S. I–O data (BEA, 2009), it can provide enough information for developing an I–O LCA model. The difficulties lie in obtaining statistics on energy consumption and environmental emissions. The 122 economic sectors are the most detailed sector data available for China. Other data, such as energy use, are not as resolved and require some sectors or categories to be merged and calibrated in order to incorporate data of different resolutions.

Therefore, research outcomes may vary due to the assumptions and subjective rules used by researchers. This study choose the top 23 economic sectors correlated with construction, whose value represents 63% of the total economic activity in

China to represent the principal inputs for construction projects (see Table 1).

3.2. Energy and environmental emission intensity

In I–O LCA model, the energy and environmental emission intensities per unit economic activity are used to calculate the energy consumption and the mass of pollutants generated by a unit output of economic activity in each sector. The value of one sector's total economic output, energy consumption, and emissions are required to calculate the intensities. For China, the information on energy and emissions cannot be obtained directly from a national statistics system. In order to address this, the available data were processed in the following ways:

For energy consumption, the difficulties mainly lie in the differences in data collection. The energy consumption data for the Chinese economy are available from the China statistics year book in 48 sectors, which then needs to be distributed across the 122 economic sectors. In this model, the 122 sectors were mapped to the 48 sectors. It was assumed that the energy use of each sub-sector correlates with higher-level sector relative to its economic output.

A more complex situation presents itself in terms of environmental emissions because of the lack of relevant statistics in China. The US EPA's AP-42 uncontrolled emission factors were used to estimate the emission intensity of the energy use of the sectors. Empirical data on pollutant generation and emission control technologies in industrial sectors in China were used to modify the U.S. data to Chinese practices (National Pollution Investigation Office, 2008).

In the assessment of SO_2 emissions, the average sulfur content of coal is assumed to be 0.9%, given the character and quality of coal resources in China (Jilin Province Environmental Protection Bureau, 2009). Coke is mainly consumed by steel manufacturing, whose combustion thus is treated as an anthracite coal combustion (CCIA, 2008). For gasoline consumption, AP-42 emission factors for #4, #5, and #6 gasolines are averaged and the emission reductions through controls are considered. The overall average emission reduction rate for industrial sectors is 50% for SO_2 and 97% for PM. NO_x controls, however, are only applied in certain sectors, which are illustrated in detail in the results and discussion section.

Although considerations of practices in China have been included in the model, a thorough simulation is difficult to conduct and there are limitations in the model. For example, the I–O model in this study is a 23-sector model. In principle, the I–O LCA model should include all 122 sectors in the Chinese economic system. The lack of information on existing technologies and relevant statistics has caused this study to underestimate the embodied energy and environmental impacts of construction projects to a certain extent. For example, the average emission reduction rate for emission controls for industrial sectors

Table 6
Carbon dioxide emissions from the construction sector and the related sectors in 2007.

Sectors	CO_2 (10^4 mt)
Crop cultivation	992
Forestry	518
Non-metal minerals and other mining	1790
Furniture and products of wood, bamboo, cane, palm, straw, etc.	525
Petroleum refining	12000
Synthetic chemicals	2310
Cement and lime products	12600
Fireproof products	4100
Other non-metallic mineral products	7650
Steel processing	37500
Nonferrous metal processing	1220
Metal products	731
Other general industrial machinery	544
Other special industrial equipment	243
Other electric machinery and equipment	164
Instruments, meters and other measuring equipment	57
Electricity and steam production and supply	45200
Highway freight and passengers transport	1690
Water freight and passengers transport	1810
Telecommunication	2090
Computing services and software	99
Wholesale and retail trade	664
Business services	158
Construction	4961

Table 5
Environmental emissions of sulfur dioxide, oxides of nitrogen, and particulate matter from the embodied energy in the construction and related sectors in 2007.

Sectors	SO_2 (10^4 mt)	NO_x (10^4 mt)	PM (10^4 mt)
Crop cultivation	3.3	13.4	3.2
Forestry	1.7	7.0	1.7
Non-metal minerals and other mining	3.5	7.0	0.7
Furniture and products of wood, bamboo, cane, palm, straw, etc	1.1	1.6	0.2
Petroleum refining	25.0	29.5	4.2
Synthetic chemicals	4.5	8.1	0.8
Cement and lime products	25.1	36.3	4.8
Fireproof products	8.2	11.9	1.6
Other non-metallic mineral products	15.3	23.1	2.9
Steel processing	48.2	54.7	30.2
Nonferrous metal processing	2.2	3.3	0.6
Metal products	1.0	3.3	0.5
Other general industrial machinery	0.7	1.7	0.4
Other special industrial equipment	0.4	0.8	0.1
Other electric machinery and equipment	0.3	1.0	0.1
Instruments, meters and other measuring equipment	0.1	0.5	0.02
Electricity and steam production and supply	96.8	38.0	16.2
Highway freight and passengers transport	3.5	23.6	3.3
Water freight and passengers transport	3.7	25.3	3.6
Telecommunication	4.3	29.1	4.1
Computing services and software	0.2	1.3	0.3
Wholesale and retail trade	2.4	5.8	2.2
Business services	0.4	2.0	0.4
Construction	17.9	48.7	18.6

has been adopted, which may be different than those for pollutant-intensive sectors like steel processing and cement and lime products. Future studies in this field need to have more specific data and information, which are likely to be gathered and published by the government.

3.3. Assumptions for the scenarios evaluated

Given the current development path of Chinese society, the demand for both buildings and infrastructure will likely to continue for a long period of time. Therefore an outlook on the implications of providing this infrastructure in terms of energy and environmental impact is necessary for managing China's societal goals. To completely understand the role that the building sector and its correlated sectors play in total national energy consumption and environmental impacts, this study estimates the proportions of building embodied energy and energy-related emissions in Chinese society in 2015. The estimates for 2015 are based on the following assumptions.

Estimates of China's gross domestic product (GDP) and energy intensity in 2015 are used to project the energy consumption of Chinese society at that time. The prediction of GDP relies mainly on the economic development objectives stated in the five-year plans published by the Chinese government and the actual GDP growth rate. Table 2 compares the predicted and actual GDP growth rates over the last fifteen years. The five-year plans underestimated the annual growth rates. Therefore, for the 12th five-year plan period, the annual GDP growth rate is assumed to be between 8% and 10%.

For estimating the energy intensity, the 11th five-year plan sets a 20% reduction target for 2010 for energy consumption per unit GDP compared to 2005. Based on available data, the decrease in energy intensity between 2005 and 2009 is 14%. For the 12th five-year plan period, this study assumes three energy-intensity-reduction levels for 2015 compared to 2010, namely 10%, 15%, and 20% (see summary in Table 3).

In terms of environmental emissions, according to the 11th five-year plan, 2010 SO_2 emissions are targeted to be reduced by 10% compared to 2005 emissions. Given that the 11th five-year plan and 12th five-year plan are similar in terms of economic development and the proposed reduction in energy intensity, this study assumes that SO_2 emissions in 2015 will be 10% less than those in 2010. For emissions of NO_x, PM, and CO_2, the estimates of Zhang and the International Energy Agency (IEA) are used (Zhang et al., 2008, Zhang et al., 2009, IEA, 2007).

4. Results and analysis

The embodied energy of construction projects in China is 436 million mtce in 2007, which accounts for 16% of the total energy consumption of the country. According to the statistics of the Ministry of Housing and Urban–Rural Development (MHURD), PR China, building operation energy is 25% of the total national energy consumption. Building construction and operational energy consumption in China, therefore, represents 40% of the total annual energy use in China. However, this figure includes only the embodied energy from the top 23 sectors correlated with construction. If all 122 sectors are included in the model, embodied energy will be approximately 20–25% of the annual energy consumption and therefore about half of China's annual energy consumption would be related to buildings and infrastructure.

Table 4 shows that sectors of building materials manufacturing and heating and electricity supply are the dominant contributors to embodied energy. Since these sectors are emission-intensive,

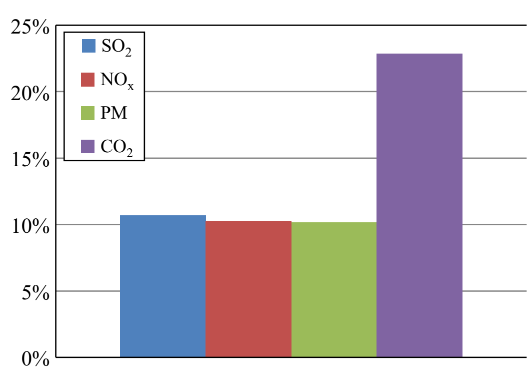

Fig. 3. Ratio of construction sector environmental emissions related to energy use compared to the total Chinese emissions in 2007.

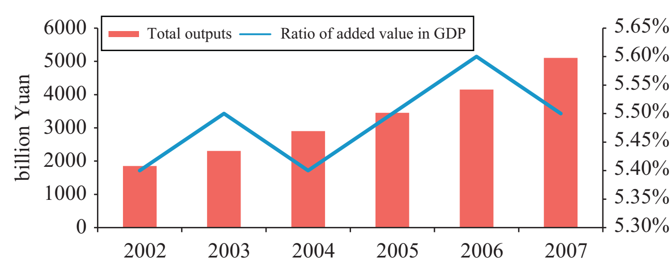

Fig. 5. Total outputs of the construction sector in Yuan and its added value as a percentage of gross domestic product from 2002 to 2007.

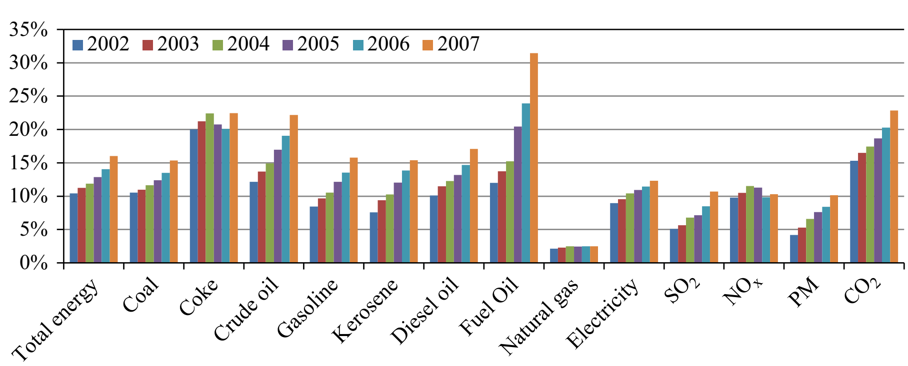

Fig. 4. Trend in embodied energy and environmental emissions in the construction sector from 2002 to 2007.

potential pollutant reductions can also be achieved. Reducing energy consumption by improving and upgrading existing manufacturing technologies is one way for China to reduce the embodied energy of construction projects. Another alternative for energy reduction lies in the construction sector itself, whose high energy consumption is driven by the demand for new buildings and infrastructure. Slowing down the increasing annual rate of output of the construction sector is feasible by minimizing the overlapping construction of small hydro-electric power plants, completing the construction of one-time or long-lived urban infrastructure, and creating a third-level market for real estate so as to decrease the demand for new housing construction.

It can be seen in Fig. 1 that embodied energy is largely derived from fossil energy, like coal, coke and crude oil, and contains less energy from cleaner sources such as natural gas. Therefore the embodied energy in construction is relatively pollution-intensive. Improving the emissions intensity of the construction sector could be achieved by shifting the energy use towards cleaner sources and renewable energy such as natural gas, solar, and wind power. Fig. 2 shows the percentage of national consumption for each type of energy, e.g., fuel oil is 31%, coke 22%, crude oil 21%, and natural gas is the least, at only 2%. Generally, the embodied energy breakdown of the construction sector remains relatively stable over time.

Tables 5 and 6 show SO_2, NO_x, PM and CO_2 emissions of each economic sector; Fig. 3 shows their percentage of the country's total emissions. Since the emissions of the manufacturing sectors are the main components of the total environmental impacts, the emissions of SO_2 and PM perform well compared to NO_x and CO_2. This is mainly due to emission reduction measures that the manufacturing industry sectors have adopted for these pollutants. In 2007, industry sectors generated 39 million tons of SO_2 while emitting 20 million tons to the atmosphere; a reduction rate of 50%. Similarly, the emission reduction rate of PM is 97%. However, the reduction measures for NO_x are not universal and only apply to three sectors: lime products, with an estimated pollution reduction rate of 7%, electricity and steam production and supply at a rate of 65%, and fireproof products at a rate of 4% (National Bureau of Statistics of China, 2008). Transportation sectors emit a notable amount of NO_x and in this sector, the national standard on vehicle emissions applies. Therefore, the significance of optimizing the logistics of an enterprise is two-fold: on the one hand, shortening the distance and using local materials can decrease transportation costs of construction projects and on the other hand, it can reduce energy use and emissions. Selecting low energy use and low emission modes of transport or improving the energy efficiency and emissions of transport can also decrease energy and emissions related to material' transport in the construction sector.

Emission control measures for CO_2 are rare in China. In the overall economy, since CO_2 is mainly generated in the combustion of coal, the emission trend for CO_2 in the 24 sectors is similar to that of SO_2. In 2007, the CO_2 emissions of the construction sector accounted for 25% of the national CO_2 emissions, and therefore construction and its correlated sectors play an important role in reducing the carbon intensity of the Chinese economy.

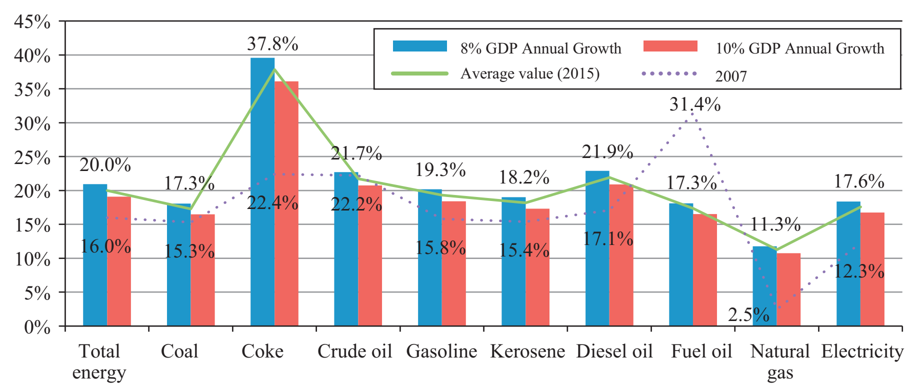

Fig. 6. Estimated percentage of the total national energy consumption that is embodied energy in the construction sector in 2015.

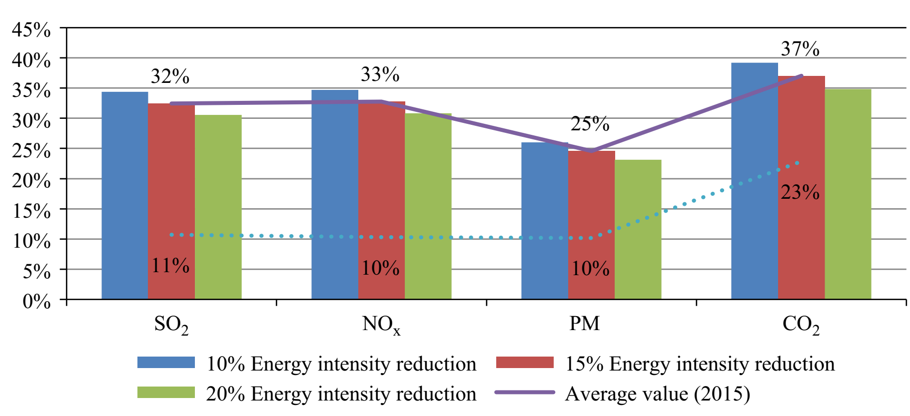

Fig. 7. Estimated percentage of the total national emissions that are emissions related to energy in the construction sector in 2015.

From 2002 to 2007, the embodied energy and environmental emissions of the construction sector gradually increased as a percentage of the total national energy use and emissions (see Fig. 4) except for coke and NO_x, which peak in 2004, decrease, and then increase in 2007. This generally steady increase is caused in part by the increasing the output of the construction sector as well as its percentage of total GDP (see Fig. 5). The correlations of sectors and manufacturing processes have not changed substantially over this period of time.

Both energy consumption and pollutant emissions will increase in 2015 in line with the expected increase in construction demand (see Figs. 6 and 7). In terms of energy use, coke shows a significant increase and is projected to represent more than one-third of the national coke consumption in 2015. Coke is used in steel making, so this increase in construction related coke use is understandable given the expected increase in construction volume. Fuel oil use in construction shows a notable decrease. This follows a trend in fuel oil use in the past ten years in China. Fuel oil intensity has been dropping faster than other forms of energy.

5. Conclusions

This study shows that the embodied energy as well as the environmental emissions of the construction sector represent a significant percentage of the total energy consumption and environmental load in China. Since buildings and infrastructure generally have a long life, operational energy is dominant in a buildings' life cycle energy use and therefore research on the embodied energy of construction in China is rare. This is also due to the lack of key data from the current national statistics system. Embodied energy involves more economic sectors (especially industrial sectors) than operational energy does, and its potential for energy reduction, from the viewpoint of available techniques, is easier to achieve and consequently deserves the attention and efforts of government, enterprises, and researchers. Effective measures could also be taken to reduce the increasing output of the construction sector, upgrading the energy infrastructure such that embodied energy would consist of a higher percentage of clean and renewable energy, optimizing the transportation system and avoiding uneconomic transportation of building materials and equipment, and developing energy-efficient and environmental-friendly techniques for manufacturing processes. It is possible for the government to develop policies and regulations that address energy efficiency and emissions in the construction sector such as regulating the diesel combustion emissions from non-road construction equipment or incentivizing energy efficiency in sectors such as steel and cement. This tool could be used to project the effects of such policies on embodied energy and the related emissions. Within the next five years, embodied energy and the environmental impacts of the construction sector will become more significant in China and greatly affect the sustainability of entire China's society.

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