The energy and environmental implications of construction in China

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Abstract Input-output life cycle assessment (LCA) and hybrid LCA models were developed to calculate the energy and environmental impacts of construction projects, rural and urban residential buildings, and an education building in China. Results show that the embodied energy and emissions of construction projects are approximately 30% of national totals. Although operation energy dominates the total life-cycle energy for both urban and rural residential buildings, its share varies significantly (from 75% to 86%) due to the gap in urban and rural living standards and differences in building structure. In the case of the specific building, results of the process-based hybrid model are moderately higher (5% to13%) than the I-O model values and the hybrid model is more specific to the building characteristics.

1 Introduction

The resource depletion and environmental emissions of the building sector are significant. The construction sector consumed 40% of the materials entering the global economy [1] and and emitted 33% of the total greenhouse gases globally [2]. In China, building energy consumption has increased more than 10% annually during the past 20 years. In 2007, building energy consumption accounted for 21% of total national energy consumption [3], which is projected to increase to 35% in 2020 due to the improving living standards [4]. To alleviate the energy and emission loads of buildings, the reduction in energy required for new building design has increased from 30% to 50% (65% in some cities like Beijing, Shanghai and Chongqing) of the 1980 building energy benchmark. The codes, design standards, and technical specifications have been established to facilitate the design and construction of energy-efficient buildings [5]. On the other hand, energy retrofits of existing buildings are encouraged and supported by various economic incentives such as preferential fiscal and tax policies.

Recent research in China has focused on energy and environmental performance of buildings in their operation phase, and explorations of the embodied energy and pollution emissions of construction are relatively rare and scattered. Since an input-output model has the strength of a comprehensive national study boundary, it is capable of assessing the energy and environmental impacts of goods and services in China. However, the model application in buildings is limited by the availability of comprehensive statistics. The sector divisions in the economic input-output table are too coarse to target specific products or services. For example, building construction, civil engineering construction, building installation, and building decoration are grouped together in the construction sector which makes the calculation of embodied impacts by building or infrastructure type difficult. In addition, the statistics on sectoral energy consumption and environmental emissions does not exactly match the sectoral definitions in the economic I-O table, so it is difficult to develop the satellite matrix in the I-O model. On the other hand, the scope of the Chinese statistical system is narrow and the emissions of NO_x and CO_2 are not recorded.

To completely understand the energy and environmental impacts of construction in China, this study calculated the embodied energy and emissions of construction project(s) at three levels:

1) Macro-level: the embodied energy and emissions of construction projects in 2002, 2005 and 2007, and the predicted embodied performance for 2015.
2) Medium-level: the 50-year life-cycle energy of rural and urban residential buildings built in 2007.
3) Micro-level: the embodied energy and emissions of a high-rise education building with a typical reinforced concrete frame and frame-shear wall structure.

2 LCA models

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. Originally developed in the late 1960’s and formally defined in the 1990’s, LCA has experienced 40 years of development in both methodology and research scope.

Generally speaking, there are three types of LCA models: process LCA, input-output LCA (I-O LCA) and hybrid LCA. The approaches vary in terms of differences in system scope and analysis, and each model has its own research process and character [3].

The process LCA model focuses on the process chain of products to calculate the energy and material flow of each (overall) life phase(s). This model yields specific data and a tailored process diagram of products, but suffers the disadvantages of incompleteness, subjective system boundaries, and intensive time and capital inputs. Besides, model application is affected by the confidentiality and unavailability of certain data.

The I-O LCI model improves the comprehensiveness and strengthens the replicability of study results. Based on the economic I-O technique and publicly accessible data on sectoral economic and energy performance, the I-O LCI model is relatively easy to establish. However, the model has the weakness of aggregation. Since similar products are grouped into a sector regardless of their specific manufacturing processes [6], the model results reflect the energy and environmental impacts of given production at the national average level, and may obscure the performance of unique materials or techniques.

The hybrid LCI model was developed to combine the advantages of both process and I-O models while mitigating their respective limitations. There are two types of hybrid LCI models: process-based hybrid models and I-O-based hybrid models. The former identifies the direct energy and materials required by the product system, calculates the embodied impacts with an I-O model to present a more complete system for upstream production, calculates the production impacts by process models and finally sums up the results. The latter requires the extraction of energy pathways from the I-O data, and then replaces the energy path generated by the I-O model with reliable and accurate process data [7]. The I-O-based hybrid model has been considered as a nearly perfect tool for life cycle assessment. However, such models need sufficient process data, even though expanding the process LCA portion results in increased data requirements [8].

3 Embodied energy and emissions of construction in China

Based on the Chinese economic benchmark data in 2002, 2005, and 2007, I-O models were developed to calculate the embodied impacts of construction projects. The sectoral energy intensity and SO_2 intensity were calculated according to the statistical yearbook, while the intensities of NO_x and CO_2 were estimated by the US EPA's AP-42 uncontrolled emission factors [9]. The emission control technologies in industrial sectors in China [10] were considered to bridge the U.S. data and Chinese practices. The detailed data processing for I-O model is in [3].

In addition, the projected construction embodied energy and emissions for 2015 were calculated with upper and lower scenarios. The targets from the "12th five-year plan (2011-2015)" and the actual performance of Chinese society in the "11th five-year plan (2006-2010)" period were used to estimate the range of model variables and the national total value of each impact.

From 2002 to 2007, the amount of each type of energy increases significantly except for fuel oil (see Table 1). The total energy consumption of construction projects in 2007 has almost doubled compared to 2002. Coal, coke, natural gas, and electricity increased significantly, while the growth of oil consumption was relatively slow; fuel oil consumption decreased from 2002 to 2005 and then rebounded in 2007. The steep increase in embodied energy caused by the strong demand for construction projects was a reflection of the rapid growth of Chinese society. The economic outputs of the construction sector in 2007 are approximately 5000 billion yuan, approximately two times greater than in 2002. However, there was not a corresponding linear response in the embodied energy of construction projects. This was because of the energy saved by the decreased sectoral energy intensity offset the increasing demand. The overall energy intensities of industrial sectors decreased 15% to 72% from 2002 to 2007. Although demand in the construction sector in 2015 is predicted to increase by 54% to 118% compared with 2007, the embodied energy would increase by 18% to 61%, and the challenges from embodied emissions would be reduced. Thus, development in China would not necessarily come at the cost of severe energy consumption and environmental pollution. On the other hand, the share of embodied energy and emissions in the national total would be reduced in 2015; this implies that China would adjust the structure of the national economy in the next five-year plan period and in particular increase the share of 'clean industry', such as the high-tech industry, in the GDP.

It is shown in Figure 2 that coal is dominant in the embodied energy of construction projects, the proportion of each type of oil energy decreases from 2002 to 2007, and the share of diesel oil is more significant than gasoline and kerosene. Although the proportion of natural gas gradually increases, it is still insignificant. The embodied energy profile results from the coal-intensive energy consumption of China. Compared with petroleum and natural gas, coal reserves in China are large. In 2008, China’s coal reserve is 13.3% of the world’s total, while petroleum is 1.2% and natural gas is 1.3% [11]. Besides, based on 2008 data [12], the production cost of coal in China is 733 yuan·mtce^{-1}, this is much lower than the average value of crude oil and natural gas, 2855 yuan·mtce^{-1}.

Tab.1: Embodied energy and emissions of construction projects in 2002, 2005, 2007, and the projected impacts in 2015

Impacts	Unit	2002	2005	2007	2015	
					upper	bottom
Total energy	10^4 mtce	42800	57500	80200	129000	94300
Coal	10^4 tons	41200	60600	87100	140000	102000
Coke	10^4 tons	5720	7920	11900	19100	14000
Crude oil	10^4 tons	8120	9430	12000	19200	14000
Gasoline	10^4 tons	825	997	1230	1980	1450
Kerosene	10^4 tons	197	229	315	506	370
Diesel oil	10^4 tons	1950	2580	3130	5030	3680
Fuel oil	10^4 tons	1290	1180	1450	2330	1700
Natural gas	100 million m^3	76	106	181	290	212
Electricity	100 million kWh	4320	6030	8930	14300	10500
SO_2	10^4 tons	732	640	738	584	418
NO_x	10^4 tons	447	625	847	904	581
CO_2	10^4 tons	158000	226000	324000	446000	326000

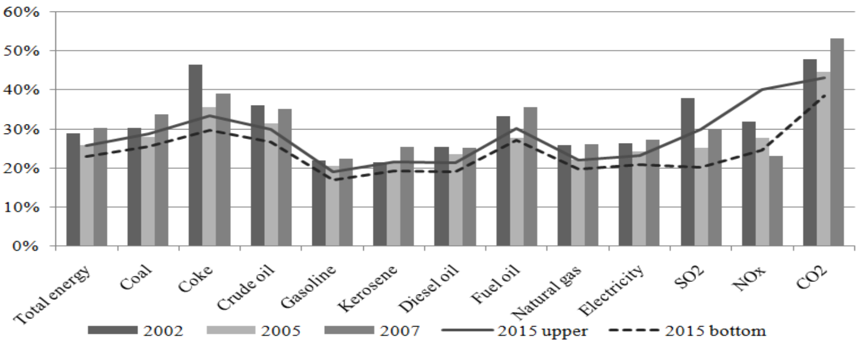

Fig.1: Shares of construction embodied energy and emissions in the national totals

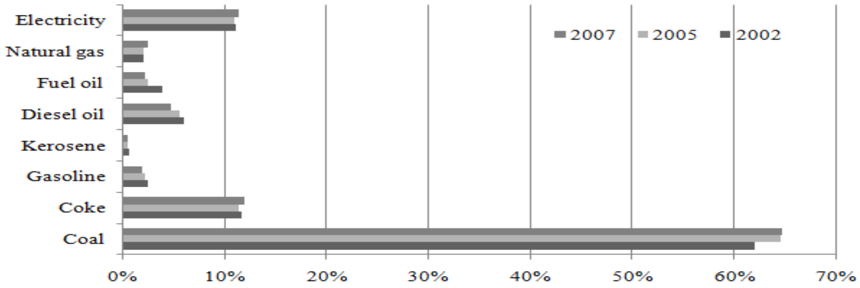

Fig.2: Structure of embodied energy of construction projects in China

4 Life-cycle energy of urban and rural residential buildings

A hybrid LCA model was developed to calculate the life-cycle energy of rural and urban residential buildings built in China in 2007. The I-O model based on 2007 Chinese economic benchmark data was used to quantify the embodied energy of building pre-operation phases, such as material extraction, manufacturing, transportation and construction. The historical energy-intensity data of former studies were adopted for the estimation of building operation and demolition energy [13]. Given that the emissions in rural residential buildings' operation phase is largely derived from the combustion of various biomass energy such as agricultural residue, biogas and firewood, and nation-wide emission factors are hard to obtain, this study only focuses on the life-cycle energy of residential buildings.

It can be seen from Table 2 that the embodied energy of urban residential buildings exceeds that of rural residential buildings (intensities of 233 kgce·m^{-2} and 114 kgce·m^{-2} respectively). This is because urban residential buildings in China are more structurally complex and are more material intensive. The total operation energy of urban and rural residential buildings are similar, as is their energy intensities (about 700000 mtce·m^{-2}). The demolition of structurally massive generally high-rise buildings (steel and reinforced concrete) requires more energy than light-weight, generally low-rise buildings (brick, brick-wood, bamboo and clay). Urban residential buildings consume more energy in demolition and overall urban residential buildings are more energy intensive: 974 kgce·m^{-2} compared to 816 kgce·m^{-2} for rural residential buildings.

Tab.2: 50-year life-cycle energy of residential buildings unit:10^{4} mtce

	National	Urban	Rural
Material,transportation, service	19200 [18%]	12200 [23%]	7010 [13%]
Construction	959 [0.9%]	609 [1.0%]	350 [0.7%]
Operation	85200 [80%]	40200 [75%]	45000 [86%]
Demolition	613 [0.6%]	345 [0.6%]	268 [0.5%]
Life-cycle energy	106000	53400	52600
Energy intensity (kgce/m^2)	888	974	816
Building area (m^2)	1190	548	695

Figure 3 presents the structure of urban and rural residential building life-cycle energy. Coal and electricity, 43% and 33% respectively, are significant for urban residential buildings; natural gas is 17%. The high share of coal derives mainly from building material manufacturing and building heating. Electricity and natural gas are used for daily living activities such as lighting, cooling, cooking, and water heating. Each type of petroleum based fuel takes less than 2% of life-cycle energ. Urban residential buildings do not consume biomass energy. For rural residential buildings, coal represents 52%, electricity 7%, and natural gas 3% of total life cycle energy. Biomass such as stalks and firewood are 22% and 10% respectively. Coal dominates energy use, which is primarily because of building heating. There is no regional central heating network in rural areas, and heating is primarily by household coal-burning stoves. On the other hand, cooking is primarily fueled by stalks and firewood and partially by coal. Compared with urban areas, home appliances such as air conditioning, microwave ovens, and washing machines are not widely used in rural households. This limits the share of electricity in life-cycle energy use. Furthermore, the overall proportion of biomass energy in operation energy for rural residential buildings was 40% in 2006. This is a significant decline from 80% in the mid-1980s' and 60% in 1998. The trend may continue, with natural gas and coal likely substitutes.

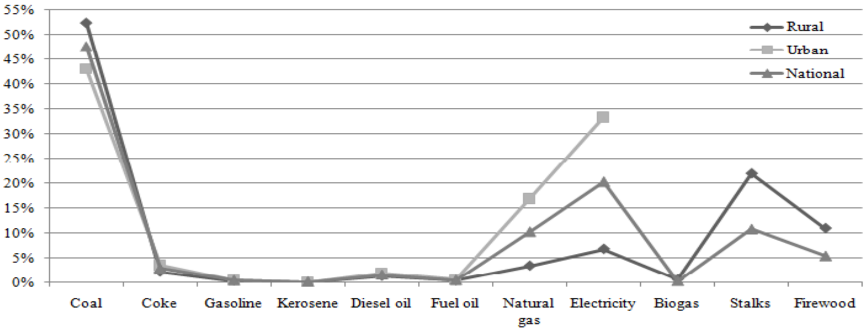

Fig.3: Structure of life-cycle energy use for urban and rural residential buildings

As Figure 4 shows, daily life activities are the dominant end use for urban residential buildings' life-cycle energy. Production in construction-correlated sectors ranks second. Individual household heating is third, followed by regional boiler heating, combined heat and power heating, construction, and demolition. Therefore, the preferences for energy saving in urban residential buildings are: (1) Reducing daily life energy intensity: cultivating awareness of potential energy saving habits in building use, such as turning off appliances and lights when there are no occupants in the room, taking advantage of natural ventilation in summer, etc. (2) Reducing the energy intensity of construction-correlated sectors: improving the sectoral energy efficiency across society could reduce the embodied energy of residential buildings effectively, which the Chinese government endeavors to achieve in the "11th five-year plan" period and the coming "12th five-year plan" period. (3) Lower relevant heating energy intensities: in the northern urban areas, approximately 30% of the total heated area uses individual heating units. However, its energy intensity is 1.5 to 2 times as much as the that of combined heat and power heating and regional boiler heating. Thus, improving the efficiency of individual household heating will facilitate the reduction of life-cycle energy of urban residential buildings. Advancing the retrofits of existing central heating supply systems and utilities to reduce the distribution heat loss and avoid excess heat are also significant for district heating systems. (4) Reducing the energy intensity of the construction sector: by lowering energy costs, contractors could realize additional profit. (5) Reducing demolition energy intensity: improvement in energy efficiency in building demolition may accompany waste recycling and reuse, which may also reduce the embodied energy of new building construction.

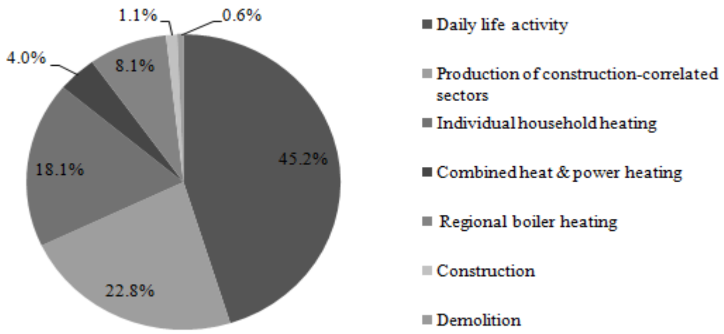

Fig.4: **Percentage breakdown of life-cycle end use energy of urban residential buildings in China**

5 Embodied energy and emissions of an education building

The education building located in Shijiazhuang, China has a total floor area of 49166 m^2. The building has two parts: the main building and the podium. The main building is 81 meters high (19 stories above ground and 2 stories underground) and has a beam-slab raft foundation and frame-shear wall structure. The podium has 6 stories above ground and 2 stories underground with single-column and strip foundations and a reinforced concrete frame structure. The stucture is designed for a seismic intensity of 7. Construction started in June 2010 and is expected to be completed in November 2011.

A process-based hybrid LCA model was developed to calculate the embodied energy and emissions of the building (see Figure 5). An I-O model based on 2007 Chinese economic benchmark data was used to calculate the embodied energy and emissions of building materials manufacturing and fuel production. The process model was developed for transportation, concrete batching and construction activities.

The embodied energy of the education building is calculated to be 309965 GJ and the energy intensity is 6.3 GJ·m^{-2}. Compared with the study results for buildings in the U.K., Australia, and Japan, the energy intensity of the case building is higher than the mean value of residential buildings (5.5 GJ·m^{-2}) but much lower than the mean value for commercial buildings, 9.2 GJ·m^{-2} [14]. This in general is because the residential buildings are usually wood frame construction, while the commercial buildings have high-rise concrete or steel structures. Unlike the commercial buildings which conventionally have luxurious appointment and costly equipment, the education building has few interior partitions and no HVAC system or automatic sprinkler system.

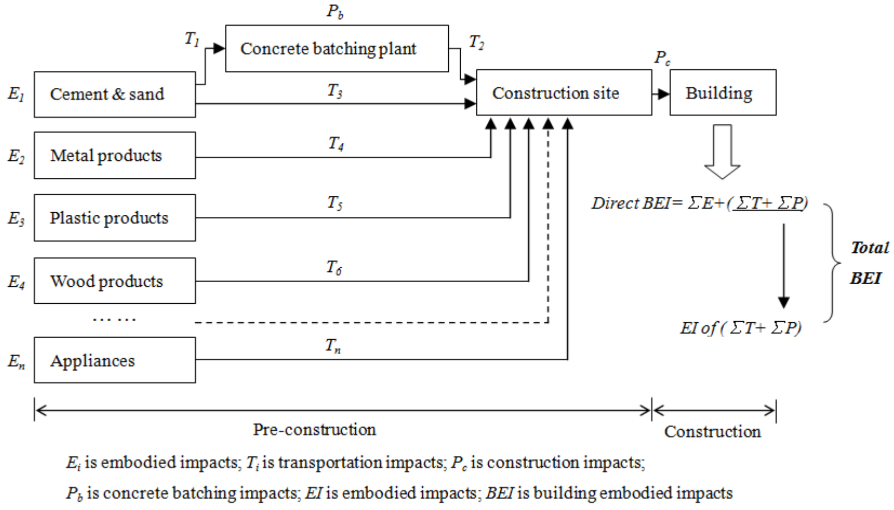

Fig.5: **Process-based hybrid LCA model for the embodied impacts of case building**

Embodied energy is dominated by building material manufacturing, representing 90%, with the share of transportation and construction 4% and 6% respectively (see Figure 6). This proportion is very close to the average value of 18 case studies in Sweden and Denmark examined by Nässén et al.: 91% for material manufacturing, 3% for transportation and 6% for construction [15]. For the case building, the low proportion of transportation energy results from the local purchase of building materials such as cement, sand, steel, brick, plastics, and ceramic products. Most of them are produced in the neighboring counties and cities, within 100 kilometers of the construction site.

The embodied emissions of the education building are shown in Table 3 and the intensity of SO_2, NO_x and CO_2 is calculated to be 2.1 kg·m^{-2}, 2.5 kg·m^{-2} and 794 kg·m^{-2} respectively. Given the high proportion of material manufacturing energy in building embodied energy, its emissions are significant, approximately 90% of the total embodied SO_2 and CO_2, and 76% of embodied NO_x. Although the transportation energy is less than the construction energy, the emissions of transportation are more significant. This is because transportation relies heavily on diesel consumption.

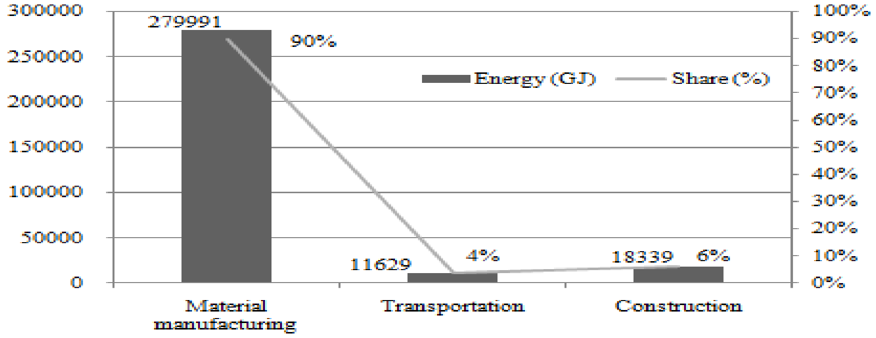

Fig.6: **Embodied energy consumption for each building phase**

Tab.3: **Embodied emissions of education building**

Emissions	SO_2 (kg)	NO_x (kg)	CO_2 (ton)
Material manufacturing	94100 [90%]	92400 [76%]	34800 [89%]
Transportation	2230 [2%]	14400 [12%]	1210 [3%]
Construction	8040 [8%]	14400 [12%]	3000 [8%]
Total	104000	121000	39000

The total cost of the education building is 78.4 million yuan in 2009. Based on the CPI of China from 2007 to 2009, it is equivalent to 74.5 million yuan in 2007. With the developed I-O model, the national average embodied impacts for the 74.5-million-yuan construction project are calculated and then compared with the results of process-based hybrid model (see Table 4). It can be seen that the values of the hybrid model are moderately higher than the I-O model. The embodied energy calculated by the process-based hybrid model is 5% higher than the results of I-O model. This is much smaller than the gap calculated by Crawford for four case buildings in Australia, who found 18% to 56% higher process-based hybrid model values [16]. This might be caused by several reasons such as the caliber of the sector classification in the I-O table, the scope of the construction sector, the consistency of sectoral energy consumption statistics with sectoral economic data, and the representativeness of the case building. The gap of the process-based hybrid model and the I-O model established by Chinese energy and economic statistics needs further validation.

Tab.4: Embodied energy and emissions for different LCA model

Inventory	Quantity			Intensity			Gap (%)
	Unit	Hybrid	I-O	Unit	hybrid	I-O	(Hybrid-IO)/hybrid
Energy	mtce	1060	10100	kg ce·m^{-2}	215	205	5
	GJ	310000	295000	GJ·m^{-2}	6.3	6.0	5
SO_2	ton	104	91	kg·m^{-2}	2.1	1.9	13
NO_x	ton	121	106	kg·m^{-2}	2.5	2.2	12
CO_2	ton	39000	36200	kg·m^{-2}	794	735	7

6 Conclusions

This study calculated the embodied energy and emissions for the construction sector, urban and rural residential buildings, and a specific high-rise education building with a typical structure in China. It can be seen that if China continues its effort to reduce energy consumption and increase environmental protection in the future, rapid urbanization and infrastructure construction would not necessarily exert a significant energy and emission burden to the society. Reduced sectoral intensities could offset the increased demands for construction.

The life-cycle energy of urban and rural residential buildings is dominated by operation energy. Compared with the buildings in urban areas, rural residential buildings have an alternative energy choice, biomass. However, the overall proportion of biomass energy in operation energy declined from 80% in the mid-1980s' and 60% in 1998 to 40% in 2006. This undoubtedly increased the utility energy loads in China. For urban residential buildings, the decrease in operation energy mainly depends on cultivating awareness of potential energy saving and efficient habits of building use.

It can be seen from the education building that the improvement in building embodied energy and emissions in China highly relies on the energy and emissions reduction of manufacturing sectors. The local purchase of building materials is helpful to reduce embodied emissions, especially for NO_x. Since this study found that the results of the process-based hybrid model are only moderately higher than the I-O model values, we conclude that the I-O model could be used for roughly estimating the embodied impacts of typical construction projects.

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