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Life-cycle energy of residential buildings in China

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HIGHLIGHTS

- We developed a hybrid LCA model to quantify the life-cycle energy for urban and rural residential buildings in China.
- Operation energy in urban and rural residential buildings is dominant, varying from 75% to 86% of life cycle energy respectively.
- Compared with rural residential buildings, the life-cycle energy intensity of urban residential buildings is 20% higher.
- The life-cycle energy of urban residential buildings is most sensitive to the reduction of daily activity energy.

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ABSTRACT

In the context of rapid urbanization and new construction in rural China, residential building energy consumption has the potential to increase with the expected increase in demand. A process-based hybrid life-cycle assessment model is used to quantify the life-cycle energy use for both urban and rural residential buildings in China and determine the energy use characteristics of each life cycle phase. An input–output model for the pre-use phases is based on 2007 Chinese economic benchmark data. A process-based life-cycle assessment model for estimating the operation and demolition phases uses historical energy-intensity data. Results show that operation energy in both urban and rural residential buildings is dominant and varies from 75% to 86% of life cycle energy respectively. Gaps in living standards as well as differences in building structure and materials result in a life-cycle energy intensity of urban residential buildings that is 20% higher than that of rural residential buildings. The life-cycle energy of urban residential buildings is most sensitive to the reduction of operational energy intensity excluding heating energy which depends on both the occupants' energy-saving behavior as well as the performance of the building itself.

1. Introduction

Buildings are responsible for significant material and energy consumption in industrial societies. They account for one-sixth of the world's freshwater withdrawals, one-quarter of its wood harvest, and two-fifths of its material and energy flows (Augenbroe et al., 1998). In China, the residential building sector consumed 193 million metric tons of standard coal in 2007, which represented 11% of national end-use energy consumption and ranked second after the industrial sector (Chen et al., 2008). This figure is likely to increase in the future because of the potential demand for new housing caused by rapid urbanization in conjunction with the pursuit of more comfortable living environments. It is predicted that Chinese residential energy consumption will more than double by 2020, from 6.6 EJ in 2000 to 15.9 EJ in 2020 (Zhou et al., 2009). China's urbanization rate was 33% in 2007 (CIUDSRC, 2009) and is expected to be 55% in 2020 (Fang, 2009). The urban population is expected to grow by 20 million every year, accompanied by the construction of 2 billion square meters of buildings annually through 2020 (Zhou et al., 2008). Thus, it can be seen that residential building energy consumption plays a critical role in the sustainable development of Chinese society.

Since the initiation of building energy efficiency programs in China in the early 1980s, residential building has been one of the core focus areas. The system of design standards and technical specifications is well established and facilitates the design and construction of energy-efficient residential buildings (Lang, 2004). The energy reduction mandated for building design has increased from 30% to 50% of the 1980 energy benchmark. Since the land area of China is large and diverse, five climate zones for building design have been established. Residential buildings in the severe cold and cold zones are responsible for a large percentage of heating energy use. Heating energy use reduction depends on both

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energy-efficiency techniques such as the thermal insulation of the building envelope (Wang et al., 2007), and economic incentives for heating system upgrades, including preferential fiscal and tax policies (Li, 2009). In the southern part of China where heating systems are not typically installed, passive techniques such as natural ventilation and effective shading are more widely used so as to reduce cooling energy use (Jiang et al., 2009). In addition, it is estimated that educating occupants could reduce energy consumption by 14% (Ouyang and Hokao, 2009). End-use energy of residential buildings in China is primarily calculated from the “bottom-up”. Using this approach, space heating, water heating and appliances are estimated to use 32%, 27% and 21% of operational energy respectively (Zhou et al., 2008). The percentage varies from urban to rural residential buildings, but not significantly. The comfort level in residential buildings in China, in general, is much lower compared to developed countries. In 2004, the average energy consumption (excluding heating energy) of urban residential buildings in China was 8 kg coal equivalent (kgce) per square meter; in comparison, the energy consumption per square meter in the U.S. and Japan is 21 and 28 kgce (BEERC, 2008).

Earlier studies of residential buildings in China mainly focused on operation energy. Relevant research on life cycle energy use is not common and is usually regionally specific. Aden et al., (2010) and Gong et al., (2012) quantified life cycle energy and GHG emissions for residential buildings in Beijing city. Lei et al., (2010) calculated the life cycle energy of urban residential buildings in China; however, analysis for rural residential buildings are still insufficient. Therefore the calculation of urban and rural residential buildings' energy consumption from cradle to grave in China is needed. On the one hand, residential buildings have a long use phase, usually 50–70 years. The embodied energy in materials and construction is less than operational energy. However, reducing embodied energy will not substantially affect a resident's life style, which may make developing effective public policy and government interventions easier. Besides, the analysis of life-cycle energy consumption including embodied energy is highly data-dependent and cross-sectoral, in that the total embodied energy of residential buildings includes contributions from many sources such as building materials, construction machinery, and transportation vehicles.

This study developed a process-based hybrid LCA model to completely understand the life cycle energy of both urban and rural residential buildings in China. The hybrid model is an integration of economic input–output life-cycle assessment (I–O LCA) and process LCA model (Bullard et al., 1978; Suh et al., 2004). The foundation of the I–O LCA model is the economic input–output analysis techniques developed by Leontief (1970). Using economic input–output analysis, the “total product chain” inputs of certain goods or services can be calculated (Leontief, 1986; Hendrickson et al., 1998), which makes quantifying the “total product chain” energy and environmental impacts feasible. Complete system boundary, time- and cost-saving, and reproducible study results are significant strengths of I–O LCA models (Hendrickson et al., 2005). Process LCA models, by contrast, closely model a certain product or service, and the model scope expands to the point where the flow between processes are negligible (Bilec et al., 2010). The advantage of this model lies in the detailed process-specific analyses, specific product comparisons, and model results tailored to a product. Thus, this study adopted process-based hybrid LCA model to embrace a comprehensive system boundary for building embodied energy, while reflecting the specificity of operation energy for residential buildings in China.

Residential building energy consumption in China is not a new topic, but to date no studies have comprehensively assessed the life-cycle energy for both urban and rural residential buildings at national scale using a hybrid LCA approach. This study presents an overview of life-cycle energy of residential buildings in China with complete building embodied energy consideration and detailed building operation energy breakdown. The study's results demonstrate characteristics and differences of urban and rural residential building energy use, and help identifying critical opportunities for building energy reduction in the rapid urbanization in China.

2. Model overview

A life cycle energy analysis model was created to assess the residential building sector, see Table 1 and Fig. 1. The embodied energy in residential buildings was calculated by an economic input–output life-cycle assessment model (I–O LCA) based on the 42-sector 2007 China economic benchmark data (NBSC, 2009a). Building operation and end-of-life energy were calculated by the published process data (BEERC, 2008). It should be noted that the building operation energy included heating, cooling, lighting,

Table 1
Summary of the residential building life-cycle energy analysis model.

	Material extraction and manufacturing	Transportation	Construction	Operation	Demolition
Model	I–O LCA (2007 China economic sector benchmark)			Process data (2006)	Process data (2003, 2005)
Building type	Urban residential buildings; Rural residential buildings				
Building lifespan	50 years, from 2008 to 2057				
Energy inventory	Total energy consumption, coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, electricity, biogas, agricultural waste, and firewood				

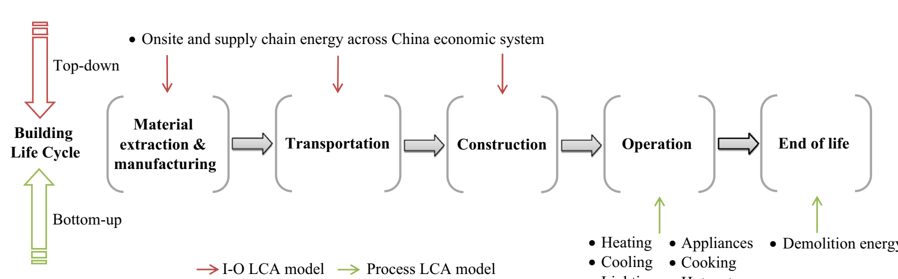

Fig. 1. System boundary for residential building life-cycle energy quantification.