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Estimating urban residential building-related energy consumption and energy intensity in China based on improved building stock turnover model

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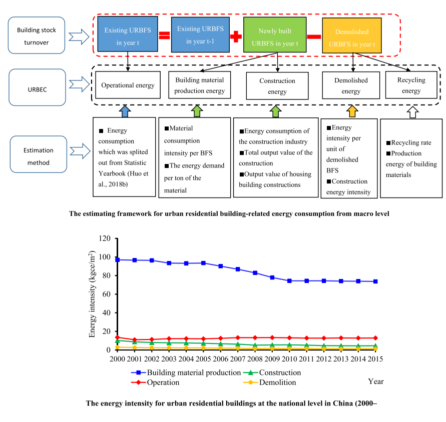
HIGHLIGHTS

- Proposed an urban residential building-related energy consumption (URBEC) and energy intensity estimation framework
- Proposed a China building floor space estimation method (CBFSEM)
- Estimated China's dwelling stocks, demolished and newly built residential BFS from 2000 to 2015
- Estimated urban residential building-related energy consumption and intensity of the building sector
- Validated the results of study by comparison; the deviations are well below 8%

GRAPHICAL ABSTRACT



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ABSTRACT

Accurate estimation of urban residential building-related energy consumption (URBEC) and energy intensity per unit floor area at the national level has significant implications for the analysis of carbon emission peaks. However, reliable data on China's building floor space (BFS) are lacking, resulting in unclear energy intensity levels. This study proposes a China BFS estimation method (CBFSEM) based on improved building stock turnover model. Using CBFSEM, it estimates the BFS of historic urban dwelling stock, the demolished and newly built dwelling from 2000 to 2015. It then estimates the corresponding energy consumption and intensity based on the obtained urban residential BFS data. Results showed that total URBEC in China increased dramatically from 217.1 Mtce in 2000 to 417.2 Mtce in 2015 with an average annual growth rate of 4.45%. China's total dwelling stock almost doubled, from 10.6 billion m^2 in 2000 to 27.4 billion m^2 in 2015 with an annual growth rate of 6.56%. The operational energy consumption accounted for approximately 70% of total URBEC and the building material production energy intensity was the highest in total URBEC, >60 kgce/m^2. A comparison with the *China Population Census* showed that the deviations were well below 8%, which indicated the reliability of the CBFSEM and the estimated results. In general, this study fills the gap in available data and addresses the shortage of estimation methods for BFS and energy intensity. It also provides the government with technical support and scientific evidence to promote building energy efficiency.

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1. Introduction

The building sector is one of the three largest energy-consuming sectors, in addition to the industry and transportation sectors, and is also an important source of greenhouse gas (GHG) emissions (Dong et al., 2017a, 2017b; Mi et al., 2017a, 2017b; Shan et al., 2018). Energy consumption in the building field accounts for approximately 46.7% of the total energy consumption in China (Lynn et al., 2017). China ranks second in building energy consumption in the world and first in residential energy consumption (IEA, 2016; Zhang et al., 2015). This sector will contribute to over 50% of energy savings needed to reach the goal to peak carbon emissions ahead of 2030 (Lynn et al., 2017). Therefore, energy conservation and emissions reduction in the building sector are directly related to China's commitment to peak the GHG emissions (Liang et al., 2014, 2017; Mi et al., 2017b; Zhang and Peng, 2017).

The urban residential building sector consumed 40% of the energy in China's civil building sector during the past decade (Huo et al.,2018a,b; Zuo et al., 2014; Zuo and Zhao, 2014). China is undergoing rapid urbanization and unparalleled urban construction (Sandanayke et al., 2018). The rapid urbanization, population growth, and residents' increasing disposable income require continued expansion of building floor space and the installation of energy-consuming devices (Fan et al., 2017). This consequently leads to the dramatic growth of energy use and emissions in the building sector, especially in the urban residential building sector (Huo et al., 2018b; Liu et al., 2017). Energy consumption intensity per unit floor area is a significant indicator to measure the energy efficiency of buildings. It is often used as a binding or guiding indicator in relevant building energy efficiency (BEE) standards (Zhao et al., 2016; Fang et al., 2017). Accordingly, the comprehensive analysis of urban residential building-related energy consumption (URBEC) and energy intensity at the national level can provide a clear image of China's building energy consumption (BEC) characteristics and changing trends. It can provide evidence for the government to evaluate the effect of the previous BEE programs or policies on energy savings and emissions reduction.

Scholars have previously attempted to investigate energy consumption with respect to the different stages of China's buildings during the buildings' lifetime; e.g., embodied energy consumption (Hong et al., 2016a, 2016b, 2017; Zhang and Wang, 2016a), operation energy consumption (Cai et al., 2009; Huo et al., 2018b, 2017; Yang and Jiang, 2007), and life-cycle energy consumption (Bastos et al., 2014; Cellura et al., 2014; Zabalza Bribián et al., 2009; Zhang and Wang, 2016b). In the life cycle analysis, they mainly focused on micro-level energy use and carbon emissions of single buildings with process-based life-cycle analysis approaches (P-LCA) (Gustavsson and Joelsson, 2010; Luo et al., 2015; You et al., 2011) and input-output based life-cycle analysis approaches (IO-LCA) (Chang et al., 2014; Shao et al., 2014). Those studies provided us with valuable information to understand energy usage in buildings. However, these micro-level studies could hardly reflect the overall historical characteristics of the building sector at the national scale due to inconsistent methods and data sources. Although some scholars have attempted to study macro-level energy use in the building field with some assumptions(Cai, 2014; Hong et al., 2017; Zhang and Wang, 2016b; Zhang et al., 2015), the status quo of China's energy consumption and energy intensity in the urban dwelling sector is still vague, due to the lack of reliable BFS data in China's statistical system and the inadequate methodologies for quantifying the BFS (e.g., newly built BFS, building stock, and demolished BFS) at the national level.

In this context, research on macro BFS has attracted increasing attention. The dynamic material flow analysis method was adopted to calculate the dwelling stock in China (Hu et al., 2010a, 2010b, 2010c). However, there exist some shortcomings associated with that data processing method because the statistical scope of the per capita floor space of buildings in the *China Statistical Yearbook* (*CSY)* only covers family households in urban areas but ignores collective households; this may lead to the overestimation of the building stock. In addition, Hu et al. (2010a, 2010b, 2010c) did not explore demolished and newly built BFS. Following this, scholars then obtained the BFS data directly from the *CSY* to predict the energy demand. For example, Zhou and Lin (2008) developed the bottom-up Long-range Energy Alternatives Planning (LEAP) model and adopted the statistical data on BFS to project the end-use energy consumption in China. Fridley (2008) adopted the same method as Zhou and Lin (2008) and calculated the BFS in China from 2005 to 2020. Shi et al. (2016) used the integrated energy consumption system model to predict energy consumption in the building sector using the BFS data from the *CSY*. Hong et al. (2016a, 2016b) conducted a study on China's building stock by directly using BFS data from *CSY*. Other studies that directly obtained the China BEC-related floor space data from the *CSY* include Zhou and Lin (2008), McNeil et al. (2012), Zhou et al. (2013), Tsinghua University Building Energy Conservation Research Center (TU-BERC) (2013), Cai (2014), and Yang et al. (2017).

In summary, most previous studies acquired building stock data directly from the *CSY* and then predicted the future BFS based on some assumptions and the national development plan. Obtaining the BFS data directly from the *CSY* is not recommended, because there are some deficiencies in China's statistical system (CABEE, 2017; Huo et al., 2018b). Moreover, the amount of floor space of China's demolished buildings is unknown due to the lack of statistical figures and actual survey data at the national level (CABEE, 2017). As for the newly built buildings, there is also no reliable time-series data due to the incomplete statistical caliber of the floor space of completed buildings listed in the *CSY*. Owing to the lack of BFS-related data and inadequate methodologies for quantifying the BFS, the energy intensity level has not been explored to date, hindering BEE work and national energy plans.

With this in mind, this study tries to fill these gaps, and aims to make the following contributions. First, we propose an estimation framework for URBEC and energy intensity and a set of universal China building floor space estimation models (CBFSEM) based on the improved building stock turnover model. The proposed models can provide a concise means of acquiring consistent data on China's energy consumption, energy intensity, and BFS of the urban dwellings. Second, we improved the building stock turnover model by adding the objective constraint and estimate the number of historical urban dwellings, demolished buildings, and newly built buildings from 2000 to 2015 using the CBFSEM. The quality of the data are good, which is valuable to government officials in terms of energy efficiency and planning in the building sector. Third, we compare the urban residential BFS results of this study with the data from the *China Population Census* to validate the reliability of our results and the CBFSEM. Finally, we adopt a macroscopic view to estimate the urban residential building-related energy consumption (URBEC) and energy intensity of the urban residential building sector based on the data obtained. As a result, we gain a clear and integrated image of energy consumption and intensity related to the Chinese urban residential building sector and can discern the characteristics of China's urban dwelling energy consumption as well as its developing trends. The CBFSEM not only eliminates the deficiencies with the inconsistent statistical caliber found in the statistical yearbook, but also derives reliable and high-quality BFS data. This will provide the government with accurate and valuable data to set reasonable energy efficiency policies and promote building energy savings efforts.

The rest of this paper is organized as follows: Section 2 is the review on deficiencies regarding the BFS in the *CSY*. Section 3 provides the methodology of URBEC and energy intensity estimation, as well as the CBFSEM. Section 4 presents the results and the model validation. Section 5 presents the analysis on URBEC and intensity, comparisons, and uncertainty analysis. Section 6 presents the conclusions, policy implications, limitations, and future directions.