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Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China's building sector

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A B S T R A C T

With respect to global climate change, energy consumption and carbon emissions of the building sector has become an increasingly crucial issue in the sustainable development of China. While process-based analyses have been performed in previous research, in the present study, we propose a hybrid input-output approach that could account for supply-chain energy and emissions by China's building sector. In terms of energy and emission sources, three scopes are defined, primarily aimed at the entire life-cycle of building sector. By dividing the life-cycle into construction, operation, and disposal stages, both scope-based and stage-based analyses are made using domestic statistical data, within the range 1997–2012. The results demonstrate that supply-chain energy and emissions of Scope 3 contribute significantly to the overall life-cycle impacts of building sector, which might be underestimated in a process-based assessment. Although the operation stage appears to be the one with the largest consumption and emissions in the lifespan of a single building, attention should also be paid to the construction stage. The energy and emissions during construction make up the largest share (over 60%) in the life-cycle of the building sector due to the large number of building projects every year. Energy and carbon-intensive components are also evaluated, and possible measures for energy-saving and carbon reduction are discussed. Accordingly, this study provides some useful methods and relevant analysis results, which will be critical for the future of sustainable development of China's building industry.

1. Introduction

1.1. Research background

According to The Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) [1], the global average temperature increased by 0.85 °C from 1880 to 2012. In light of the serious consequences of global climate change, the issue of greenhouse gas (GHG) emissions has attracted increasing attention [2]. As a developing country with a large population, the total energy consumption and carbon emissions of China are among the highest in the world [3–5]. In tandem with the rapid development of its economy, China has a significant responsibility for reducing global carbon emissions, and has already made a commitment to reduce carbon emissions per GDP by 40–45% by 2020, compared with the level in 2005 [6].

Because it is one of the most energy and carbon-intensive industries, the building sector accounts for roughly 30–40% of the total energy consumption worldwide, and this sector contributes over one third of global CO_2 emissions [7–9]. Different from developed countries, except for the huge amounts of energy and emissions for daily operation of buildings, China is presently dealing with an excessively large number of building projects during the process of urbanization [10]. This consequently leads to a dramatic growth of energy use and emissions for construction work [11]. Accordingly, comprehensive analyses of the energy consumption and carbon emissions of China's building sector throughout the life-cycle have been imperative for energy-saving and carbon reduction.

1.2. Life-cycle assessment of buildings

Life-cycle assessment (LCA) has become a widely acknowledged tool for the research of environmental impacts. With respect to the

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lifetime of a building, components such as materials production and transportation, building construction and operation, demolition work, and waste treatment are usually taken into account for both macro-level and micro-level analyses. Process-based and input-output based approaches (P-LCA and IO-LCA) are two fundamental ideas in analysis [11–14]. P-LCA is able to achieve detailed information for each process involved in each scope [11], but P-LCA has certain truncation error due to the definition of system boundary of buildings [15]. On the other hand, IO-LCA can capture the energy and carbon footprint from the entire supply-chain [13]. However, IO-LCA also introduces uncertainties, because the sectors in I–O analysis can only represent typical processes [12].

Previous studies have made many attempts to investigate life-cycle energy use and carbon emissions of single buildings, using process-level data. For example, Gustavsson and Joelsson [16] compared the life-cycle primary energy use and CO_2 emissions of wood-framed buildings and concrete buildings. You et al. [17] assessed the life-cycle emissions of urban residential buildings in China, covering processes of materials production, on-site construction, building operation, and demolition. Davies et al. [18] and Luo et al. [19] analyzed the embodied energy and carbon of office buildings based on case studies. Abanda et al. [20], Islam et al. [21], and Chau et al. [22] have also conducted studies reviewing the life-cycle energy and carbon assessment of buildings. I–O based case studies were also made by some researchers. Han et al. [23] proposed an I–O model for carbon analysis of construction activities and compared several methods for groundwork. Shao et al. [24] analyzed the energy use and carbon emissions for construction of six case study buildings in Beijing, China, based on the bill of quantities (BOQ). Chang et al. [25] calculated the embodied energy for different types of buildings using the average materials consumption data in the construction phase. Besides, facing the crucial issues regarding energy-efficiency and carbon mitigation, a large number of strategies were proposed for building life-cycles. Lomas [26] and Abdallah et al. [27] proposed measures for carbon reduction and energy conservation in existing buildings. Čuláková et al. [28] investigated energy-saving and carbon reduction strategies for construction of building structures. Ng et al. [29] summarized possible approaches for buildings that would remain low-energy and low-carbon throughout their life-cycle.

However, due to the inconsistency of methods and databases, micro-level studies focusing on selected buildings could hardly reflect the overall characteristic of regional buildings with respect to history. Unfortunately, although IO-based methods are well applied to study environmental performance of national economy at macro-level [30–32], research on the regional building sector is relatively less, especially for LCA studies. Nässén [15] assessed the energy use and carbon emissions during the construction stage of buildings. Acquaye and Duffy [33] estimated the GHG emissions of the Irish construction sector. Onat el al [12]. investigated the life-cycle carbon footprint of U.S. buildings according to the World Resource Institute (WRI) standard. Using multi-regional I–O analysis, Hong et al. [34] found that the construction industry contributed 29.6% of the total energy use in China for 2007.

1.3. Objectives and organization

In light of the above mentioned gaps in knowledge, the present study aimed to achieve a comprehensive analysis of life-cycle energy consumption and carbon emissions of China's building sector (entire national inventory of buildings) from a macro-level perspective. As introduced in Section 1.2, both P-LCA and IO-LCA have their advantages and limitations. Hence, a hybrid method covers their complementary strengths might be a good practice. Given that the life-cycle pertains to the entire inventory of buildings, it might be called the conglomerate building life cycle. First in Section 2, a hybrid IO-LCA approach and relative data processing procedure are proposed which could account for both on-site and supply-chain activities. Then in Section 3, Chinese statistical data for 1997–2012 are analyzed, and the scope-based and stage-based results for conglomerate life-cycle of the building sector are discussed. Finally, possible measures for energy-saving and carbon reduction are exemplified. A summary of the analytical framework of the present study is illustrated in Fig. 1.

2. Methodology and data

2.1. Research scopes

The building life-cycle was divided into three stages in the present study, namely construction stage, operation stage, and disposal stage. Both the direct physical inputs (direct energy consumption and carbon emissions by building sector) and indirect inputs (from the upstream supply-chain) were considered, using a hybrid approach consisting of process method and input-output analysis. Moreover, in order to conduct a comprehensive analysis of the energy consumption and carbon emissions, the research scopes were set to three different levels proposed by WRI [12,14,35]. Scope 1 referred to the on-site energy consumption and carbon emissions produced by fossil fuel combustion. Scope 2 represented the energy consumption and carbon emissions from the production of purchased electricity and heat, namely the fossil fuel combustion in power plants. Scope 3 referred to all the other energy consumption and carbon emissions generated from the economic supply-chain such as building materials preparation and transportation. Fig. 2 illustrates the relationship of the three scopes and the life-cycle stages of buildings in detail.

Based on process-level data of direct energy use of the building sector, the energy consumption and carbon emissions of Scope 1–2 could be calculated using a simple P-LCA approach, whereas these of Scope 3 had to be estimated using a IO-LCA approach to account for physical inputs of upstream activities. Furthermore, for Scope 2,

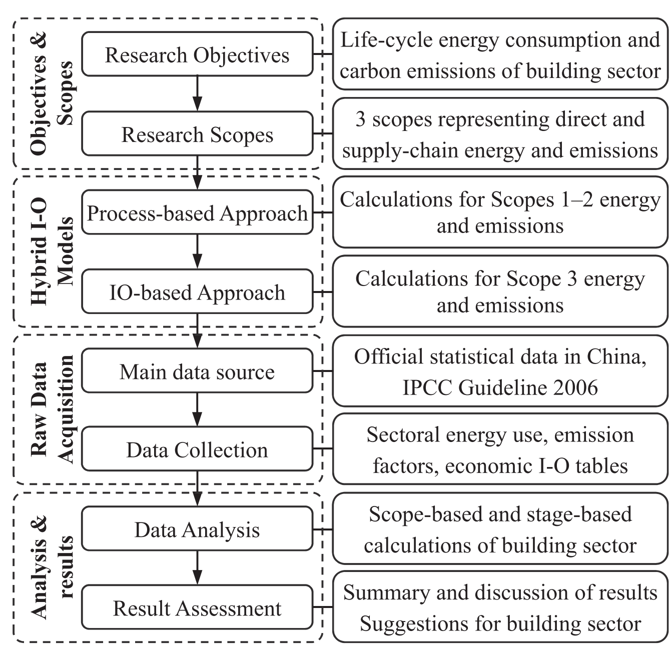

Fig. 1. Analytical framework of the present study: The definition of scopes is presented in Section 2.1, data source is introduced in Section 2.4.