Journal of Cleaner Production 194 (2018) 263–276

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Characterizing the essential materials and energy performance of city buildings: A case study of Macau

Qingbin Song [a, *], Huabo Duan [b], Danfeng Yu [b], Jinhui Li [c], Chao Wang [d], Jian Zuo [e]

[a] Macau Environmental Research Institute, Macau University of Science and Technology, Macau
[b] Smart Cities Research Institute, College of Civil Engineering, Shenzhen University, Shenzhen 518060, China
[c] School of Environment, Tsinghua University, Beijing 100084, China
[d] Guangdong Provincial Key Laboratory on Functional Soft Condensed Matter, School of Materials and Energy, Guangdong University of Technology, Guangzhou 510006, China
[e] School of Architecture & Built Environment, The University of Adelaide, Adelaide 5001, Australia

ARTICLE INFO

Article history:
Received 29 March 2018
Received in revised form
18 May 2018
Accepted 18 May 2018
Available online 19 May 2018

Keywords:
Buildings
Materials use
Energy consumption
Life cycle analysis
Macau

ABSTRACT

The lack of a clear understanding of the consumption of materials and energy in construction activities and by existing buildings has hindered sustainable urban development in Macau. This study is therefore designed to quantify the consumption of building materials and energy in Macau over past 16 years, from the perspective of life cycle analysis. The results show that there has been rapid growth in the annual consumptions of both materials and energy throughout the entire lifetime of buildings. In 2016, the construction of buildings contributed to almost all materials use during their lifetime, which in 2015 was approximately 10 times greater than in 1999, but the energy consumption of buildings only accounted for 7.8% of their total energy consumption. The amounts of material and energy consumption in the construction of buildings are about 1.375 tons/m^2 and 1176.72 MJ/m^2, respectively. Most energy was consumed during the operational lifetime of the buildings however, constituting 92.2% of the total energy consumption; this is particularly the case in the gaming industry. In 2016, the average energy consumption of residential buildings was 264.97 MJ/m^2·year, which actually increased. However, the management and recycling of building waste in Macau is still an area that is underdeveloped. Actually, nearly all building materials and energy are imported from neighboring regions in mainland China, resulting in potential resource and energy supply risks for Macau. The findings obtained in this study will enable policy makers, designers, and building users to make more sensible judgments in promoting the development of sustainable buildings in Macau and elsewhere.

1. Introduction

Recently, the relationship between the building sector and energy consumption has been constantly discussed, due to the large energy consumption of buildings (Cubi et al., 2015). It has been calculated that globally, buildings are responsible for 40% of all energy use and one third of greenhouse gas emissions (Huovila et al., 2009). In mainland China, the energy consumed by the building sector accounted for more than 36% of the national primary energy consumption in 2014 (BECRC, 2016; Song et al., 2016). In the U.S., residential buildings only contributed to about 22.2% of the total energy consumption (primary energy consumption, electricity retail sales, and electrical system energy losses) (Fumo, 2014). Energy security, environmental concerns, thermal comfort, and economic matters of buildings have become the driving factors for further research and development with the aim of reducing energy consumption and the associated greenhouse gas emissions (Hong et al., 2015; Chen and Ng, 2016; Marzouk et al., 2017).

Macau, a Special Administrative Region of China, is an internationally renowned city, with a burgeoning tourism industry (Song et al., 2017a). The rapid economic development and increasing population have sparked a high volume of construction activity in Macau. In 2015, there were a total 2750 building companies engaged in construction projects (1236 companies) and renovation projects (1514 companies), which is approximately 2.82 times the number of building companies that were engaged in the same activities in 2000. Currently, the energy consumption of buildings

* Corresponding author.
E-mail address: qbsong@must.edu.mo (Q. Song).

https://doi.org/10.1016/j.jclepro.2018.05.148
0959-6526/

during their operational phase has become the dominant component of their total energy consumption, accounting for more than 70% of their final energy use in 2016 (DSEC, 2017a). The energy consumption of buildings cannot be overlooked with respect to guaranteeing Macau's energy security and addressing problems caused by climate change. Accordingly, the energy consumption associated with buildings in Macau has inevitably displayed an upward trend along with the construction of large numbers of buildings (Song et al., 2017b, 2018).

Despite the improved energy-saving standards in building operation, the energy consumption of buildings in cities has been rising in recent years (Hong et al., 2016; Zhang et al., 2015). Currently, life cycle assessment (LCA) is one of the measurement instruments that is able to thoroughly assess energy consumption and environmental impact (Song et al., 2012; Song and Li, 2015; Mao et al., 2017). The LCA approach is considered to be one of the most popular methods to analyze the technical aspects of green and sustainable buildings (Duan et al., 2015; Kylili et al., 2017). Through LCA analysis, opportunities to reduce energy consumption and environmental impacts across all life cycle stages can be identified, which will help to avoid simply shifting the problem elsewhere.

In recent years, many LCA studies have been carried out in the building sector, by university researchers, urban designers, architects, engineers, and consultants (Hellweg and Canals, 2014). For example, Zhang et al., 2015 identified the energy consumption of the Chinese building sector by establishing an estimation model of building energy consumption from a life cycle perspective. However, an analysis of the literature shows that a large number of researchers applied LCA to case studies of buildings' energy systems and environmental impacts (Winther and Hestnes, 1999; Aste et al., 2010; Cellura et al., 2014). Very few studies focused on the lifecycle analysis in terms of materials and energy consumption from the perspectives of a whole city or country (Modeste et al., 2015), which will be more useful for realizing sustainable urban buildings, compared with a case study of only one or several buildings.

Especially, there is no clear and comprehensive understanding about the extent of Macau's materials and energy consumption, and the corresponding energy efficiency in the building sector (Song et al., 2017b). In addition, a considerable underestimation of energy usage associated with buildings has impeded the effective implementation of measures to improve building energy efficiency. Therefore, a consolidated knowledge base is required to inform decision makers about the best course of action to suit their situation, prior to opting for detailed analysis for retrofit alternatives.

This study is designed to characterize the use of materials and energy in the building sector in Macau during 1999–2016 from a lifecycle perspective. Through the use of LCA, we can gain a clear and integrated image of the overall materials and energy consumption attributable to buildings in Macau, and then uncover past changes and developing trends, from a macroscopic point of view. Furthermore, we have made some suggestions to improve building energy efficiency in Macau, and to promote sustainable urban development.

2. Materials and methods

2.1. Basic information regarding buildings in Macau

2.1.1. New buildings during the research period

Table S1 lists basic information on new buildings in Macau during the research period. The amount of new building areas shows an apparent declining trend from 1999 to 2002. After that, the building industry begins to soar again, reaching a historical peak at 1.93 million m^2 in 2007. Actually, at the same time as the building industry, the gaming industry also started to expand rapidly after the opening of gambling rights in 2002, leading to the construction of commercial buildings associated with this industry. However, since 2008, the global economic crisis has resulted in another declining trend in the building industry. Up until 2012 and 2013, the building industry gradually returned to an increasing trend due to economic development. Overall, the building industry experienced fast growth during the period of 1999–2015.

Fig. S1 presents the distribution of the different types of new buildings constructed from 1999 to 2015. Residential buildings accounted for 46.02% and 63.25% of the total building areas in 1999 and 2003, respectively. However, they only accounted for 13.77% in 2007, 11.06% in 2011 and 25.17% in 2015. "Other buildings" mainly refers to those associated with the gaming industry, which indicates that the gaming industry has become the most significant driver for new buildings, reaching a peak value of about 84.64% of all of the new building areas in 2007.

2.1.2. Buildings in use

Fig. S2 presents the average residential floor space per capita in Macau, which varies within a narrow range between 23.0 and 24.2 m^2. Though a great number of new buildings have been built in the past 10 years, the average residential floor space per capita has only increased by 1.2 m^2, and still there has been no great improvement. This is possibly a result of the fast population growth (increasing from 531.8 thousand in 2007, to 652.5 thousand in 2016) and the large ratio of new buildings being for other industries (more than 70% of all the new building areas). In comparison with the other countries and regions in Fig. S2, the average residential floor space per capita in Macau is also much lower, and is only higher than that of Hong Kong.

According to Fig. S3, due to the small area of Macau, building units of less than 50 m^2 in size occupy about 39.41% of all the building units in Macau, especially on Coloane Island (67.27%). Meanwhile the building units with areas of 50–99 m^2 constitute the majority (44.58%) of all building units.

2.2. LCA goals and scope

This study sought first to review and evaluate the life cycle materials and energy consumptions of the whole building sector in Macau, and then to provide some effective suggestions to promote and improve the energy efficiency of buildings in Macau.

For the LCA research, the system boundary determines which processes should be included within the LCA which should be consistent with the goal of the study. From the life cycle perspective, all of the related activities throughout the building's life cycle should be encompassed, including the production of building materials, building construction, building operation and building demolition.

Due to the small area and the lack of various resources, almost all building materials and most of the energy required in Macau were imported from other countries and region, especially Mainland China and Hong Kong. Therefore, in this study, we will mainly refer to the three stages of building construction, building operation and building demolition, as shown in Fig. 1. The boundaries of this study are restricted to the area of Macau, thus the transportation of the materials and energy from the import countries or regions into Macau will be excluded from our study. For the research period, we will consider the time from 1999 to 2016, which represents the potential materials and energy consumption trend of building sectors since Sovereignty over Macau was transferred back to China on 20 December 1999.