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Life cycle analysis of energy consumption and CO_2 emissions from a typical large office building in Tianjin, China

Jia-Jun Ma [a], Gang Du [a], Zeng-Kai Zhang [a], Pei-Xing Wang [b], Bai-Chen Xie [a, *]

[a] College of Management and Economics, Tianjin University, Tianjin, 300072, China
[b] China Railway Construction Bridge Engineering Bureau Group, Tianjin, 300300, China

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ABSTRACT

Tiejian Tower, a large public building in Tianjin, China, is one of the many energy-efficient buildings the country has built to reduce energy consumption and carbon dioxide (CO_2) emissions. Based on first-hand data from the project and using an ecological input–output table, the embodied energy and CO_2 emissions for that building were estimated for its life cycle. Four scenarios were designed to assess the impacts of space heating and power mix, and sensitivity analysis was conducted to examine the major factors that can reduce CO_2 emissions. The operational stage consumed more energy than any other stage, and contributed the most to CO_2 emissions. The influence of energy-efficient equipment and their lifespan on energy consumption and CO_2 emissions varied greatly. Policies that encourage construction of buildings with longer lifespans and promote energy-saving measures can reduce energy consumption and carbon emissions in the buildings sector. The state should also supervise the operation of large buildings, involve large public buildings in future emissions-trading systems, and consider the power mix while planning such buildings.

1. Introduction

The buildings sector accounts for about a third of the total global emissions of carbon dioxide (CO_2) [1]. In the European Union, CO_2 emissions from buildings were almost 50% of the total emissions from a life cycle perspective [2]. In China, the energy consumed by the buildings sector – including that during the construction and operations phases – accounted for more than 36% of the national primary energy consumption in 2014 [3]. As the largest CO_2 emitter in the world, China has pledged not to allow its carbon emissions to go beyond what they will be around the year 2030, and the buildings sector, given its increasing share in national emissions, has a major role in achieving that goal. Among different categories of buildings, public buildings accounted for more than 26% of the total consumption of energy for operations (excluding district heating) in 2012 [4].

Buildings with a total floor area of more than 20 000 m^2 and occupied by public authorities or by institutions providing public services are referred to as large-scale public buildings (LPBs) in China. Tiejian Tower in Tianjin is a LPB with a floor area of about 57 000 m^2. The proportion of LPBs in the buildings sector increased rapidly because of the booming economy and the desire for better living standards in China. This trend made it even more difficult to reduce CO_2 emissions because the energy consumption of LPBs per square metre is 2–3 times that of conventional public buildings and about 5 times that of residential buildings [5]—there is no doubt that reducing the energy consumption of LPBs is indispensable to sustainable development.

To tackle the rapid growth in energy demand for heating and air conditioning of hotel buildings, China issued the first energy saving design standard for public buildings (GB50189-93) in 1994. Its revised version (GB50189-2005) was released in 2005, which indicated that the newly built public buildings should lower their energy consumption to 50% of that of comparable buildings in the 1980s. The current standard (GB50189-2015) raised the standard even higher, stating that energy consumption of new buildings should be 75% of that of comparable buildings in the 1980s, and also introduced or raised the standards for drainage systems, electrical systems, and renewable energy. Considering economic developments, three municipalities, namely Beijing, Tianjin, and Shanghai, promulgated even stricter energy-saving standards for the buildings sector.

Despite the improved energy-saving standards, energy

* Corresponding author.
E-mail addresses: xiebaichen@tju.edu.cn, xiebaichen@126.com (B.-C. Xie).

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consumption of buildings in cities has been rising in recent years. On one hand, the floor area of buildings has increased significantly; on the other hand, energy management during the operations stage of such buildings is far from mature [3]. To strengthen the management of operating energy for public buildings, the Ministry of Housing and Urban-Rural Development and the Ministry of Finance jointly released a document titled 'Implement opinion on promoting energy efficiency management for government office buildings and large-scale public buildings' in 2007. From then on, Beijing, Tianjin, and Shenzhen have been carrying out dynamic monitoring of energy consumption of some major energy-intensive buildings and have established three-grade energy consumption monitoring platforms. The target is to devise a system for supervising energy consumption of office buildings and LPBs and to reduce the total energy consumption of office buildings and LPBs by 20% [6]. From 2013, a few cities such as Beijing, Shenzhen, and Shanghai, as a pilot experiment, have made many LPBs with high energy consumption a part of the carbon trading system, and more LPBs are expected to follow once the national carbon emissions trading market is established in 2017.

Two of the largest cities in China, Beijing and Tianjin, are in northern China, a region in which heating accounts for a larger proportion of operating energy compared to that in other mega cities such as Shanghai and Shenzhen. At the same time, Beijing and Tianjin are the pioneers in developing energy-saving technologies and in formulating local regulations and standards; in many ways, these design standards and energy-saving practices are among the strictest in the country. Incorporating LPBs into the carbon trading system will promote energy conservation and emissions reduction in the buildings sector and will also help in achieving the national targets of emissions reduction. Research on carbon emissions from LPBs may also provide a scientific basis for perfecting the trading mechanism. Unfortunately, although China has substantial achievements in energy conservation to its credit and has built many energy-efficient buildings, the performance of such buildings has been seldom evaluated. Beijing, the capital of China, has a high proportion of service industry, whereas Tianjin is the largest industrial city. It is hard to duplicate the development mode of Beijing in other cities but, given their similar industrial structures, they may profit from the experience of Tianjin in energy conservation—which is why Tiejian Tower in Tianjin was selected for the present study as an example to conduct a detailed analysis of a building built recently and now operational.

Environmental assessments of buildings can provide the necessary information for reducing the environmental impacts of the buildings sector systematically and comprehensively [7]. Unlike general consumer goods, a building has a long life and continues to consume energy and emit CO_2 throughout its life [8]. The impacts of a building over its life cycle are interdependent: stricter energy-saving standards at the construction stage may result in more embodied energy, but will also lead to lower operating energy. In other words, energy-efficient buildings cost more in terms of construction energy [9]. Under some circumstances, buildings that adopt energy-efficient measures do not always save energy [10], and it is incomplete to judge the energy performance of a building only during its operations stage: life cycle analysis makes it possible to analyse the total energy consumption of a given building and may be of some help in achieving the right balance between embodied energy and operating energy.

The life cycle of a building, "from cradle to grave", is often divided into phases: production of materials and components, transportation to the building site, construction, use/operation of the building (including renovation, maintenance etc.) and demolition, disposal (recycling, landfill, incineration for energy recovery, etc.) [11–14]. Unfortunately, because of continuing data limitations, and due to the large range of construction techniques and material choices, none of the tools are currently capable of modelling an entire building or computing the environmental impacts in all life cycle phases and processes [15]. Despite all of that, life cycle analysis has been widely used in studying energy consumption and CO_2 emissions of public buildings in many countries including Japan [16], China [17–19], Thailand [20], and Australia [21]. Most of such studies take into account all embodied energy, recurring embodied energy, operating energy, and demolition energy in evaluating the performance of buildings. Process analysis and a hybrid method (a combination of input–output analysis (IOA) and process analysis) are the two popular approaches [12,22–24]. Although the hybrid method eliminates the flaws in the two methods it combines [23], accounting for the energy embodied during construction is highly data sensitive [25]: most of the existing literature confines the analysis of embodied energy to such major building materials as cement, steel, and glass as the sources of embodied energy but ignores many other materials and equipment inputs. In measuring operating energy, most of the literature either uses computer simulations or energy consumption parameters to estimate energy consumption [17,20,26] without considering the interaction between the users and the building. However, energy consumption in buildings is influenced by the behaviour of their occupants [27].

Earlier research was usually focused on energy consumption and potential CO_2 emissions of a specific public building or industry. These studies of typical buildings have considered not only the construction phase [28–30] and the operations phase [31,32] but also the entire life cycle [17,19,20]. Energy consumption and CO_2 emissions during the construction stage are mainly derived from the building materials [28,29], whereas those during the operations stage are derived from the energy consumption of HVAC system and other equipment inside the building [31]. Although such studies of conventional public buildings based on life cycle analysis are many, and some of them have focused on LPBs, few of them have paid any attention to energy-efficient public buildings. In extreme climates, cooling and heating contribute the most to energy consumption of LPBs. Better thermal insulation and a more efficient heat supply system are the general means to save energy. Some studies claim that ground-source heat pumps (GSHPs) and other technology and equipment that use renewable energy [33–35] are the effective means of saving energy. However, their effectiveness needs to be tested. Because Tiejian Tower has adopted many energy-saving and renewable energy technologies, its study will help in evaluating energy-efficiency measures over the building's lifespan.

To the best of our knowledge, the present study is the first attempt to study a large public building, namely Tiejian Tower, using life cycle analysis combined with ecological input–output analysis to assess its energy consumption and CO_2 emissions based on exhaustive first-hand project data and operating data. The results will provide detailed benchmarks for regions with similar climate and resource endowments in specifying standards of energy efficiency for buildings and for developing policies, and scenario development and sensitivity analysis may also help in identifying the contributions of related factors over the life cycle phases and in offering valuable suggestions to policymakers.

2. Methodology

As we all know, a relatively full life cycle of a building mainly consists of production of materials, construction (materials transport and construction-installation on-site activities), operation (including renovation, maintenance, etc.), demolition and disposal (recycling/reuse) [15,17]. The energy consumption for demolition often accounts for less than 1% of the life cycle [14,15], and many studies ignored the demolition accordingly [22,36,37]. As to the disposal stage, there is not a concrete and definite criterion for recycling or landfill of building waste in China. Moreover, the data about building materials recycling and landfill is insufficient in China and it is unpredictable from a long-term perspective. Considering the objective of this study and the availability of data, this paper mainly focuses on the construction stage, operation stage and maintenance stage for life cycle analysis of Tiejian Tower. The demolition and disposal stages are excluded. In this study, the energy consumption and CO_2 emissions during the construction stage are generated from the manufacturing of building materials, materials transport and on-site construction activities such as the use of construction machinery and construction-installation on-site processes. The energy consumption at the operation stage mainly comes from activities for work and comfort. The energy for maintenance stage is derived from the replacement of materials and components in renovation works.

2.1. Ecological input–output

Process analysis was widely used in estimating embodied energy and CO_2 emissions in the past [13,14]. However, that technique tends to underestimate the embodied energy of materials owing to truncation errors, the input–output hybrid analysis is being increasingly used for the purpose [23,38,39]. In their attempts to explore energy consumption and CO_2 emissions from different economic flows, many scholars have compiled databases on the embodiment intensity of different economic sectors [12,40,41]. However, these databases are based on versions of input–output of 2007 or earlier, which are thus out of date.

Referring to Chen and Chen [41], Zhou, Chen [42], as shown in Table 1, we compiled a simplified ecological input–output table with 31 sectors based on the input–output table for 2012 and the *Energy Statistical Yearbook 2013* (the details of the productive sectors are given in Table 2).

Based on Chen and Chen [41], an aggregate matrix equation for the ecological input–output model can be introduced as follows.

$$P + \varepsilon X = \varepsilon Y \tag{1}$$

in which.

$P = [P_{k,i}]_{m\times n}$,$P_{k,i}$ stands for the kth physical flow received by the ith primary sector;
$\varepsilon = [\varepsilon_{k,i}]_{m\times n}$,$\varepsilon_{k,i}$ represents the embodied intensity of the kth physical flow for products from Sector I;
$X = [z_{k,i}]_{n\times n}$,$z_{k,i}$ denotes products from Sector i to Sector j;
$Y = [y_{i,j}]_{n\times n}(y_{i,j}{=}y_i$ when $i = j$ and $y_{i,j} = 0$ when$i{\neq}j)$,y_i indicates the outputs of sector$i$.

With appropriate values of the net physical inputs matrix$P$, economic input–output matrix$X$, and total output matrix$Y$, the corresponding embodied physical flow intensity matrix is obtained as follows:

$$\varepsilon = P(Y - X)^{-1} \tag{2}$$

The net physical inputs per unit sectoral domestic output and technology coefficients matrix are introduced as follows, and with the identity matrix$I$,equation (2) can be written as

$$f = PY^{-1} \tag{3}$$

$$A = XY^{-1} \tag{4}$$

with the identity matrix$I$, equation (2) can be written as

$$\varepsilon = f(I - A)^{-1} \tag{5}$$

Consequently, the physical flow embodied in any economic product can be calculated by multiplying its economic value by the corresponding embodied intensity [41].

2.2. Stages in life cycle analysis

2.2.1. Building construction

The estimates of construction energy and CO_2 emissions in the present study are based on first-hand project data in the Bill of Quantities (BOQ), which quantifies the inputs during construction by documenting the quantity and the price of each item. The BOQ for construction stage consists of the building materials, transportation and on-site construction activities. According to Han, Chen [25], each item should be assigned to its productive sector in the input–output table. The construction of the building can be divided into six parts or aspects of engineering, namely structure and decoration engineering, electrical engineering, water supply and drainage engineering, fire protection engineering, heating, ventilation and air-conditioning system engineering, and intelligent system engineering. Based on the above classification and the embodiment intensity of different sectors, we can define the initial embodied energy and the initial embodied CO_2 emissions of each subproject as follows:

$$IEM = \sum_{i=1}^{n} IEM_i = \sum_{i=1}^{n} (\varepsilon_i \times I_i) \tag{6}$$

whereI_i denotes the economic cost of inputs$i$, andε_i is its corresponding embodiment intensity;IEM_i andIEM are embodied energy and CO_2 emissions of the inputs$i$ and of each subproject, respectively. The total initial embodied energy consumption and CO_2 emissions of the construction stage can then be obtained by the following equation:

Table 1
The ecological input-output table.

Input\Output			Industrial use				Final use	Gross
			Sector 1	Sector 2	……	Sector n		
Industrial input	Sector 1		$z_{1,1}$	$z_{1,2}$		$z_{1,n}$	f_1	y_1
	Sector 2		$z_{2,1}$	$z_{2,2}$		$z_{2,n}$	f_2	y_2
	……							
	Sector n		$z_{n,1}$	$z_{n,2}$		$z_{n,n}$	f_n	y_n
Net physical inputs	Carbon dioxide emission		$P_{CO2,1}$	$P_{CO2,2}$		$P_{CO2,n}$		
	Energy	Fossil	$P_{FE,1}$	$P_{FE,2}$		$P_{FE,n}$		
		Non-fossil	$P_{NFE,1}$	$P_{NFE,2}$		$P_{NFE,n}$		

Table 2
The classification of national economic sector.

Code	Sector	Abbreviation
1	Farming, Forestry, Animal Husbandry, Fishery & Water Conservancy	Farming
2	Mining and Washing of Coal	Ming C
3	Extraction of Petroleum and Natural Gas Production and Distribution of Hydroelectric and Nuclear Power	Extraction
4	Mining and Processing of Metal Ores and other Ores	Ming M
5	Mining and Processing of Nonmetal Ores and other Ores	Ming N
6	Manufacture of Foods, Tobacco and beverages	Foods
7	Manufacture of Textile	Textile
8	Manufacture of Textile Wearing Apparel, Footwear, Caps, Leather, Fur, Feather and Related Products	Textile W
9	Processing of Timber, Manufacture of Furniture	Timber
10	Manufacture of Paper and Paper Products, Printing, Reproduction of Recording Media	Paper
11	Processing of Petroleum, Processing of Nuclear Fuel	Petroleum
12	Manufacture of Chemical Products	Chemical
13	Manufacture of Non-metallic Mineral Products	Non-metal
14	Smelting and Pressing of Ferrous Metals	Smelting
15	Manufacture of Metal Products	Metal
16	Manufacture of General Purpose Machinery	General M
17	Manufacture of Special Purpose Machinery	Special M
18	Manufacture of Transport Equipment	Transport E
19	Manufacture of Electrical Machinery and Equipment	Electrical M
20	Manufacture of Communication Equipment, Computers and Other	Communication E
21	Manufacture of Measuring Instruments and Machinery for Cultural	Measuring I
22	Manufacture of Artwork and Other Manufacturing	Artwork
23	Manufacture of Recycling and Disposal of Waste	Recycling
24	Service to Machinery	Service M
25	Production and Distribution of Thermal Power and Heat Power	Power
26	Production and Distribution of Gas	Gas
27	Production and Distribution of Water	Water
28	Construction	Construction
29	Transport, Storage, Postal & Telecommunications Services	Transport
30	Wholesale, Retail Trade and Catering Service	Wholesale
31	Other	Other

$$TIEM = \sum_{a=1}^{6} IEM_a \tag{7}$$

2.2.2. Building operations

The energy consumption of a building in the operations stage mainly consists of the energy used for cooling, heating, hot water, lighting, working, and cooking etc. Tiejian Tower uses only two fuels, namely electricity and natural gas. As mentioned before, earlier studies usually used computer simulations to estimate the energy consumption during operations, which may lead to significant errors. As of July 2016, Tiejian Tower had been operational for more than two years, which makes it possible to obtain annual data on operations. Combining the different energy sources, the life cycle primary operating energy (LOE) will be given by the following equation:

$$LOE = (FEH + FEC + FEO + FCO) \times \eta_i \times LS \tag{8}$$

whereFEH, FEC, FEO represent energy consumption for heating, cooling, and other uses (including the energy for hot water), respectively;FCO represents energy consumption for cooking;LS represents the lifespan of the building; andη_i denotes the conversion coefficient of ith kind of energy to primary energy.

The life cycle CO_2 emissions (LOC) from the operations are given by the following equation:

$$LOC = (FEH + FEC + FEO + FCO) \times \mu_i \times LS \tag{9}$$

whereμ_i denotes the coefficient of CO_2 emissions for ith energy.

2.2.3. Building maintenance

A building usually has a long life, a large variety of materials are being used in building construction and some of them may have a life span shorter than that of the building [43]. What's more, high-replacement-rate materials often consume more energy [15]. As Tiejian Tower is a new building, no renovation has been undertaken so far. We assumed the lifespan of the building to be 50 years and estimated the recurring embodied energy consumption and recurring embodied CO_2 emissions during the maintenance stage from the following equation:

$$REM_i = \sum_{j=1}^{n} IEM_i (1-r)^{jt} \tag{10}$$

$$n = \mathrm{int}\left({}^{LS}/_{t} \right) \tag{11}$$

where$r$ is the annual average rate of decline in energy intensity and$t$ and$n$ represent the lifespan and the update frequency of ith input, respectively. The “int” in equation (11) denotes integral function.

2.3. Setting scenarios

Heating and cooling are the main applications that consume operating energy and contribute the most to energy consumption in Tiejian Tower. Because Tianjin is rich in geothermal resources, Tiejian Tower has adopted a system of GSHPs. Comparing such a system with the conventional district-heating system in terms of energy consumption may provide a benchmark to estimate the effectiveness of energy-saving measures from a long-term perspective. As electricity is the major form of operating energy, it is the power mix that fundamentally determines primary energy

Table 3
Main characteristics of the case study building.

Description	Designed Values	Standards[a]
Thermal characteristics	*U-values (W/m^2·K)*	*Requirement U-values (W/m^2·K)*
Roof (80 mm XPS board + 120 mm reinforced concrete)	0.38	≤0.55
External wall (70 mm rock wool board + 200 mm aerated concrete block (B05))	0.4	≤0.6
Separating wall (200 mm aerated concrete block)	0.94	≤1.5
Internal floors (70 mm rock wool board + 120 mm reinforced concrete)	0.52	≤0.6
Windows (12 mm low-e (low emissivity) argon insulating glass)	1.94	≤2
Green characteristics	*Elements*	
Water recycling	Greywater system	
Renewable energy	Ground source heat pump system	
Intelligent characteristics	*Elements*	
Intelligent system	Building Automation System, Office Automation System, Fire Automation System, Safety Automation System	
Others	*Values*	
Air-conditioning area	34828 m^2	
Cooling load	4200 KW	
Heating load	3400 KW	

[a] Tianjin public building energy efficiency design standards.

consumption and the corresponding emissions. In recent years, along with the introduction of superior technologies and the smart grid, the proportion of renewable power[1] in the grid has increased significantly. However, regions differ in their power mix because of the differences in their resource endowments, and confining the analysis to final consumption of electricity will lead to emissions from some regions being overestimated. It was therefore considered necessary to study the power mix of Tianjin in analysing CO_2 emissions from the energy required for the operations stage. Such estimates will also be valuable scientific benchmarks for allocating carbon quotas and for carbon trading.

To evaluate the impacts of heating and cooling requirements and of the power structure on energy consumption and CO_2 emissions for Tiejian Tower, with the technology employed and the power mix as key indicators, the present study constructed four scenarios.

Scenario 1 = (A1, B1)
Scenario 2 = (A1, B2)
Scenario 3 = (A2, B1)
Scenario 4 = (A2, B2)

where A represents heating and air-conditioning systems, with A1 representing the GSHPs system and A2 representing the conventional heating and air-conditioning system or the central air-conditioning and district-heating system, and B represents the different power mix: the details of B1 and B2 are given in Table 5.

3. Data

3.1. Introduction to the case study

Tiejian Tower is in Tianjin, the third largest city in China. Tianjin lies at the northern end of the North China Plain and is dominated by the monsoon circulation and a temperate monsoon climate. Tianjin's annual average temperature is about 12 °C. The city has four distinct seasons: spring is windy and dry; summer is hot and rainy, with July being the hottest month (average temperature 26–27 °C); autumn is cool and pleasant; and winter is cold with little snow, with January being the coldest month (average temperature −3 °C to −5 °C). These parameters place Tianjin in China's cold region, and Tianjin can serve as a reference for making policies related to energy savings for other regions with a similar climate.

Tiejian Tower was put into service on 26 September 2013. The building, a typical public building with offices, is built over 19 433 m^2 and has a total floor area of about 57 000 m^2. Many large companies have their corporate headquarters in Tiejian Tower. The support frame of the building is of reinforced concrete conforming to the current national standards. Labelled as a demonstration project of a green building, Tiejian Tower is also a typical intelligent and energy-efficient building. Table 3 summarizes the main characteristics of the building. To save energy, the windows-to-walls ratio of the tower is precisely limited to 0.58. According to the requirements of energy-efficient design, the exterior wall of the building is a combination of rock-wool board and porous concrete blocks and outside windows are of 12 mm low-e (low emissivity) argon insulating glass. To follow the precepts of ecological cities and green buildings, the abundant geothermal resources of Tianjin were harnessed by the building by choosing GSHPs for heating and cooling, which provides water at 7–12 °C in summer and at 40–45 °C in winter to the central air-conditioning system. To meet the energy demands for space heating and cooling, the system of GSHPs comprises 517 wells around the building, each at least 130 m deep. In addition, all the ground heat exchangers have adopted the double-U-shaped design. The building has adopted an intelligent control system to automate the control of lighting and other equipment intelligently. In this way, the operation of the building is almost entirely based on electricity except the energy used for cooking.

3.2. Data resources

The data required for compiling the ecological input–output table were taken from the *China Energy Statistical Yearbook 2013* and the input–output table for 2012. The table shows both the primary physical flows in terms of emissions outflows and resources inflows. The direct external energy inputs are divided into fossil sources (coal, crude oil, and natural gas) and non-fossil sources (hydro power, wind power, nuclear power, and others). The CO_2 emissions for the study were estimated from the emission factors proposed by the Intergovernmental Panel on Climate Change (only fossil fuels were included).

We assumed the lifespan of Tiejian Tower to be 50 years. This

[1] Renewable energy in the present study was confined to photovoltaic, hydro power, and wind power.

Table 4
Life span of materials and equipment for replacement calculations.

EE		HE		FE	
Components	Years	Components	Years	Components	Years
Cement and gypsum products	50	Plastic products	15	Plastic products	15
Generic devices	25	Metal products	50	Steel products	50
Equipment for power transmission and distribution	20	Compressor, valve, pump	25	Metal products	50
Electric Wire and Cable	20	Generic devices	25	Compressor, valve, pump	25
Lamps and lanterns	20	Instruments	20	Instruments	20
Other electrical equipment	20	Other electrical equipment	20		
SE		**WE**		**IE**	
Components	Years	Components	Years	Components	Years
Nonmetallic minerals	50	Rubber products	15	Electric Wire and Cable	20
Textile, Feather and Related Products	10	Plastic products	15	Communication Equipment, Computers	20
Woodwork	30	Ceramic products	50	Plastic products	15
Paint	20	Steel products	50	Metal products	50
Synthetic materials	30	Metal products	50	Instruments	20
Rubber products	15	Compressor, valve, pump	25		
Plastic products	15	Instruments	20		
Cement and gypsum products	50				
Brick and tile	50				
Glass	50				
Refractory material	15				
Steel products	50				
Metal products	50				

study estimated the embodied energy consumption and CO_2 emissions during the construction stage by first-hand project data from the BOQ, which quantifies all inputs in construction and also gives the price of each item. The number of inputs into different categories of engineering mentioned earlier were as follows: structure and decoration engineering, 380; electrical engineering, 110; water supply and drainage engineering, 150; fire protection engineering, 50; heating, ventilation and air-conditioning system engineering, 160; and intelligent system engineering, 280. The lifespans of materials and equipment were mainly assumed to be those given by Suzuki and Oka [16] and Scheuer, Keoleian [15]. The lifespan of the materials/equipment used in this study are indicated in Table 4.

As for the energy consumption for operations, monthly data were available from January 2014 to December 2015. The system of GSHPs is one of the typical energy-saving approaches used in Tiejian Tower that sets it apart from the average LPBs. Figures for the district-heating energy consumption intensity of such buildings were obtained from *China Building Energy Efficiency 2014* [4] and detailed information on the design of the Tiejian Tower's GSHP system and on the investments in different heating and air-conditioning systems was obtained from first-hand sources.

The power mix were estimated from the development plan of Tianjin and *World Energy Outlook*[2] It changes linearly over a given period but is kept constant after 2040. For example, in B2 the share of gas-fired power in the power mix is assumed to increase by 0.0625% annually from 2013 to 2020, by 0.05% annually from 2020 to 2040, and to remain constant at 25% after 2040. By referring to *China Building Energy Efficiency 2014* [4], we also assumed that generating and heating efficiencies change linearly over a given period, as shown in Table 5. We defined Scenario 1 (S1) as the base scenario, Scenario 2 (S2) as the high-speed clean scenario (the shift to clean energy is faster), Scenario 3 (S3) as the conventional scenario, and Scenario 4 (S4) as the clean scenario (the shift to clean energy occurs at normal speed).

Considering the downward trend of China's industrial energy intensity in recent years, the annual average rate of decrease in embodied intensity was assumed to be 3% before 2030 and, based on the changes in energy consumption in Japan and Germany,[3] 1% after 2030. As there has been no significant progress in traditional building materials, we assumed the embodied energy of the materials and equipment adopted in renovation and the terminal energy consumption of the equipment to be constant throughout the study period.

Table 5
Parameters of power mix and energy efficiency standards.

Contents	Year	2013	2020	2040
B1	Coal	0.97	0.75	0.4
	Gas	0.01	0.15	0.45
	Renewable	0.02	0.1	0.15
B2	Coal	0.97	0.7	0.6
	Gas	0.01	0.15	0.25
	Renewable	0.02	0.15	0.15
Energy efficiency standards	Coal (gce/kWh)	317	305	265
	Gas (gce/kWh)	202	169	162
	Heating (kgce/m^2)	16	15.4	13.4

4. Results

Together with energy consumption for operations, the total life cycle energy consumption of Tiejian Tower was estimated at 982.7 GWh (345.0 kWh/m^2 a year) and CO_2 emissions were estimated at 319 267.1 t (0.1 t/m^2 a year). The operations phase dominated the energy consumption and CO_2 emissions, which accounted for 73% and 64% of the life cycle energy consumption and emissions, respectively (Fig. 1). This difference in the two percentages indicates that emissions per unit of energy in the operations stage are lower than those at other stages, probably because of the relatively low energy efficiency in producing the building materials and equipment. Energy consumption in the operations stage is mainly due to heating, cooling, lighting, and appliances. Surveys

[2] BP, BP Energy Outlook 2030 (2012), 2035 (2016).

[3] IEA, World Energy Statistics, International Energy Agency, (2000–2014).

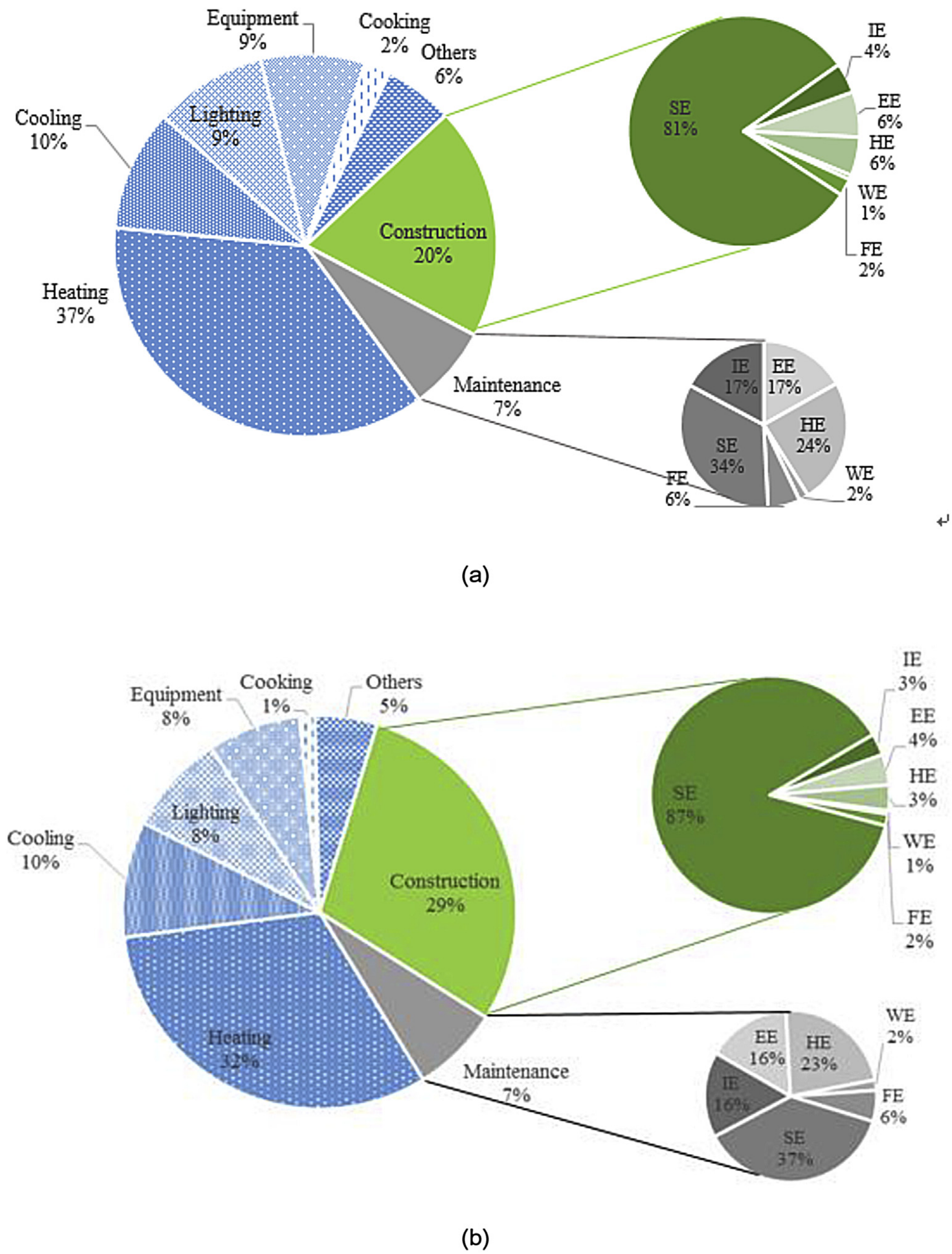

Fig. 1. Life cycle energy consumption (a) and CO_2 emission (b) of Tiejian Tower.

showed that heating accounts for over 50% of the total operating energy consumption and that of CO_2 emissions in winter. The contributions of cooling, lighting, and appliances are relatively small, and in their case too, the shares of energy consumption and emissions are very close.

The second largest contributor was the initial embodied energy, which accounted for 20% of the life cycle energy consumption and 29% of CO_2 emissions. Among the six categories of engineering, structure and decoration engineering consumed maximum embodied energy (81%) and also topped in CO_2 emissions from embodied energy (87%) but both claimed only 7% each at the maintenance stage. Although the types of engineering at the maintenance stage are similar to those at the construction stage, large gaps exist between the two in terms of energy consumption and CO_2 emissions. Although structure and decoration engineering retained its top rank during the maintenance stage as well, the shares of ventilation and air-conditioning system engineering, intelligent system engineering, and electrical engineering were significantly greater at the maintenance stage (Table 6 and Table 7). The estimated energy consumption of the structure and decoration engineering during the construction stage was estimated at 157.1 GWh and its CO_2 emissions were estimated at 81 652.1 t—these figures are, respectively, 11 times and 20 times the annual figures for the operations stage. Besides, as can be seen in Table 6, coal dominated the energy consumption, followed by petroleum and natural gas; the share of renewable energy was relatively low. The pattern was similar for CO_2 emissions. As can be seen in Table 7, energy consumption and CO_2 emissions at the

Table 6
Embodied energy consumption and CO_2 emission of sub-projects at construction stage (GWh).

Sub-projects	Coal	Crude oil	Natural gas	Hydropower	Wind power	Nuclear power	Others	Total	CO_2 (t)	Energy ratio	CO_2 ratio
EE	9.3	2.0	0.5	0.4	0.0	0.0	0.0	12.3	3910.9	6.4%	4.2%
HE	8.0	1.6	0.5	0.3	0.0	0.0	0.0	10.5	3234.2	5.4%	3.5%
WE	1.0	0.2	0.1	0.0	0.0	0.0	0.0	1.2	462.4	0.6%	0.5%
FE	3.6	0.7	0.2	0.1	0.0	0.0	0.0	4.6	1467.6	2.4%	1.6%
SE	123.7	21.9	6.4	4.1	0.5	0.5	0.1	157.1	81652.1	81.0%	87.4%
IE	6.1	1.3	0.4	0.3	0.0	0.0	0.0	8.1	2718.0	4.2%	2.9%

Table 7
Embodied energy consumption and CO_2 emission at the maintenance stage.

Sub-projects	CO_2 (t)	Energy consumption (GWh)
EE	3642.3	11.8
HE	5246.1	17.0
WE	452.4	1.3
FE	1344.5	4.3
SE	8635.2	23.6
IE	3706.4	12.0
Total	23027.0	70.1

maintenance stage were 70.1 GWh and 23 027 t, respectively, far less than those during the construction stage.

The sources of embodied energy consumption and CO_2 emissions during the construction stage are shown in Fig. 2. Non-metal building materials accounted for more than 40% of the energy consumption and nearly 60% of CO_2 emissions and were followed by the building materials from the smelting sector and the metal sector.

The present study extended its estimates of energy consumption and CO_2 emissions to such energy-efficient devices as LED lights, thermal insulation materials, low-e glass, and GSHPs. As is shown in Fig. 3, energy-efficient devices accounted for 7% each of the total energy consumption and CO_2 emissions during the construction stage, with GSHPs, at 6.9 GWh, being the largest contributor to embodied energy consumption, followed by low-e glass (4.0 GWh). However, CO_2 emissions from the production of low-e glass were higher than those from the construction of GSHPs. Both embodied energy consumption and CO_2 emissions from the thermal insulation materials and LED lights were relatively small.

Table 8 presents the energy consumption and CO_2 emissions under the four scenarios. The maximum consumption (1028.4 GWh) and emissions (350 369.3 t) were seen in S3, and those in S1 and S2 were less than those in S3 and S4, which means that the GSHPs system has achieved the target set for saving energy. However, the extent of savings was below the expectations. For example, S1 achieved only 4% savings in energy and reduced CO_2 emissions only by 9% compared to S3. Both energy consumption

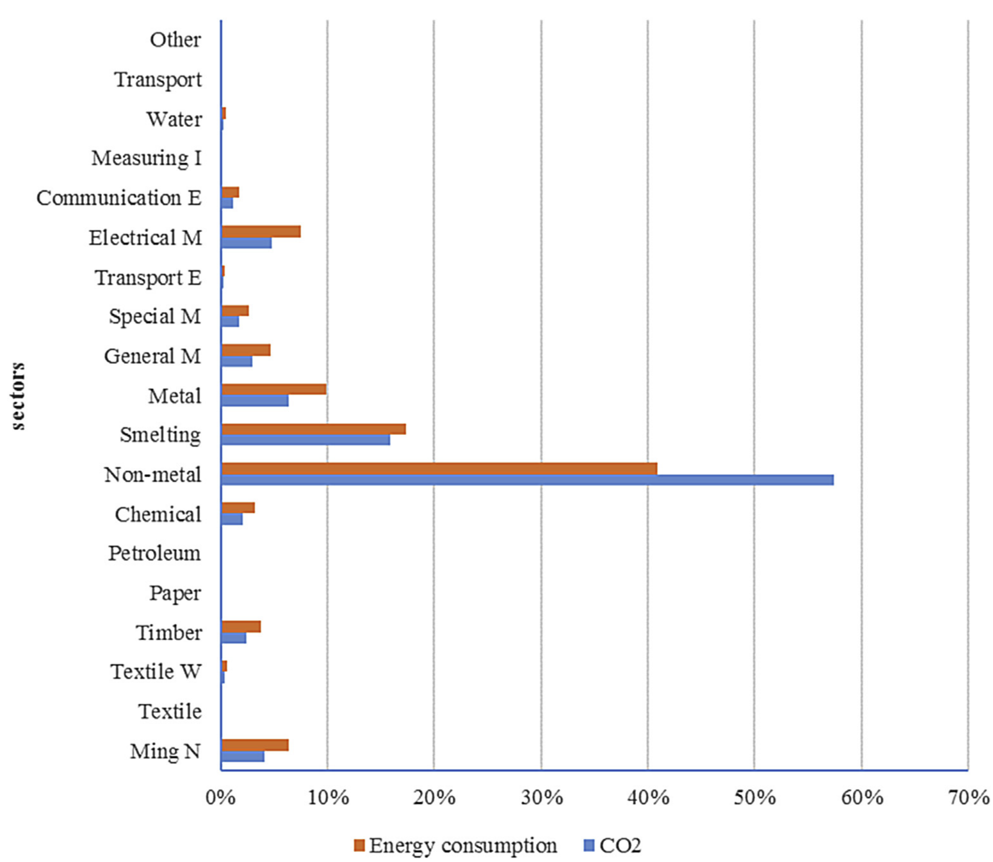

Fig. 2. Embodied energy and CO_2 emission components of sectors.

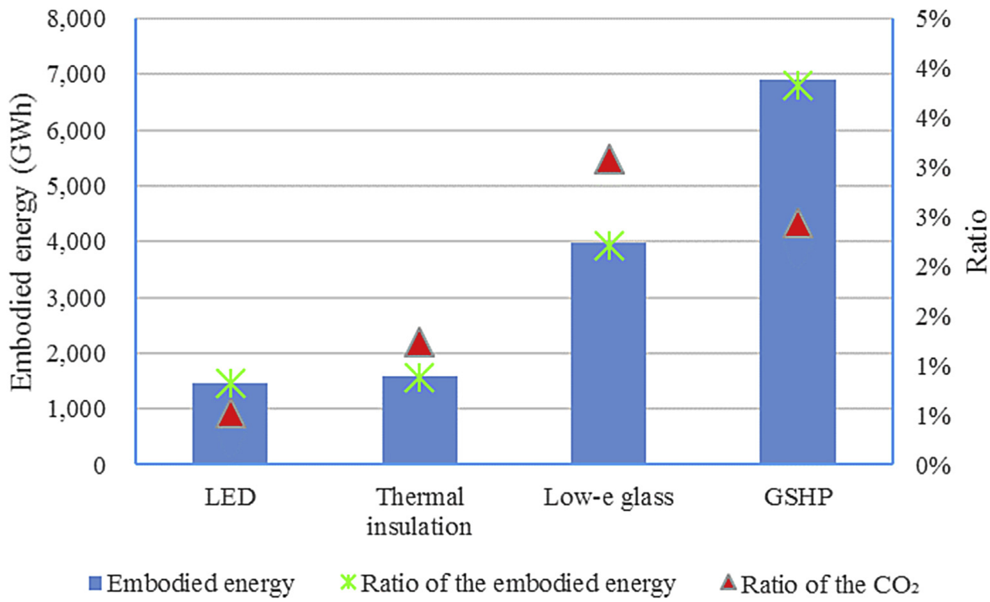

Fig. 3. Energy consumption and CO_2 emission of energy-efficient inputs for construction stage.

Table 8
Energy consumption and CO_2 emission under all scenarios.

Scenarios	Construction		Maintenance		Operation		Total	
	Energy (GWh)	CO_2 (t)	Energy (GWh)	CO_2 (t)	Energy (GWh)	CO_2 (t)	Energy (GWh)	CO_2 (t)
S1	193.9	93445.2	70.1	23027.0	718.8	202794.8	982.7	319267.1
	19.7%	29.3%	7.1%	7.2%	73.1%	63.5%	19.7%	29.3%
S2	193.9	93445.2	70.1	23027.0	631.8	159020.8	895.8	275493.0
	21.6%	33.9%	7.8%	8.4%	70.5%	57.7%	21.6%	33.9%
S3	192.8	93121.8	68.2	22449.9	767.4	234797.5	1028.4	350369.3
	18.7%	26.6%	6.6%	6.4%	74.6%	67.0%	18.7%	26.6%
S4	192.8	93121.8	68.2	22449.9	715.4	208641.5	976.4	324213.2
	19.7%	28.7%	7.0%	6.9%	73.3%	64.4%	19.7%	28.7%

and CO_2 emissions were the lowest in S2, being 8% and 15% less than those in S4 and 13% and 21% less than those in S3. These figures indicate that the effect of increasing the share of renewable energy in the power structure contributes substantially to energy conservation and emissions reduction. Furthermore, increasing the share of renewable energy reduces emissions more than saving energy does.

Table 8 also shows that operating energy accounted for more than 70% of the life cycle energy consumption in all the four scenarios: S3 recorded the highest value and S2 recorded the lowest; both initial embodied energy and maintenance energy were lower than operating energy in all the four scenarios, the share of embodied energy in scenario S2 being the highest. The shares in CO_2 emissions of embodied energy were higher than their corresponding shares in energy consumption. As a result, in no scenario was the share of operating energy greater than 70% in the total life cycle CO_2 emissions; in S2, it was only 57.72%. The ratio of CO_2 emissions to energy consumption at each stage under the four scenarios is shown in Fig. 5. The construction stage had the highest CO_2 emissions intensity of 482 t/GWh, whereas the operating stage had the lowest (about 282 t/GWh), and emissions intensity of the maintenance stage was close to that of the overall life cycle. Therefore, clean production and greater use of improved building materials are feasible ways to achieve the goals of emissions reduction.

5. Discussion

China plans to construct LPBs with a total footprint exceeding 100 million m^2 [4]. Based on the results presented above, life cycle energy consumption and CO_2 emissions from these buildings will be up to 1.7×10^6 GWh, or 212 million tonnes of carbon equivalent (TCE)—an increase of 560.1 million tonnes in CO_2 emissions, of which the energy consumed during the construction stage alone will amount to 42 million TCE. Undoubtedly, LPBs will result in huge energy consumption and CO_2 emissions from China in the future.

Although embodied energy in the case of Tiejian Tower is far less than operating energy, the latter is indispensable for saving energy. Production and use of materials such as cement, bricks, and glass lead to substantial CO_2 emissions, making the share of CO_2 emissions during the construction stage significantly higher than that of energy consumption. Energy-efficient materials and equipment add only small amounts to energy consumption during the construction stage. Related studies have shown that the total energy consumption can be reduced by 9% with better insulation materials and sealing alone [13] and, on average, GSHPs are 3–6 times more efficient than conventional electric heating systems [44]. In addition, more efficient lighting control systems and the use of LED lamps can effect more than 30% savings in electricity [4]. Theoretically, energy-efficient materials and equipment may have a great potential to save energy.

Somewhat unexpectedly, energy consumption for operations in Tiejian Tower continues to account for more than 73% of life cycle energy consumption despite the adoption of GSHPs, intelligent control systems, low-e glass, and other energy-efficient materials and equipment. The air-conditioning system accounts for 60% of the energy consumed during operations because of the heavy demand for heating in winter. To some extent, making the heating system more efficient is critical to reducing operating energy. Although Tianjin is one of the pioneer cities in constructing energy-monitoring systems for LPBs, most of the buildings do not use energy-monitoring devices. Sub-metering may not only provide an effective tool to monitor energy consumption, but also help to benchmark the performance of energy-saving buildings. To some extent, installing energy-monitoring systems in LPBs may be an effective way to control the increase in energy consumption.

This study is the first attempt to study an energy-efficient public building using life cycle analysis based on first-hand data. In order to explore the speciality of this building and obtain more universal conclusions from region and climate perspective, the energy consumption of Tiejian Tower will be compared with the results from related studies in this part. Concerning the feasibility, data availability, and the representation of different locations, the typical large-scale office buildings in Shanghai [18], Bangkok [20], Melbourne [21], Dalian [17] are selected for comparison. Table 9 presents life cycle energy consumption of these typical buildings as estimated in earlier studies. The functional unit of this comparison is defined as "one square meter of floor area per a year" and the lifespans of these buildings are 50 years. Then these results could be compared with each other. As is shown in Table 9, it is astonishing to see the extent of variation in the estimates. Energy consumption of the building in Dalian was the highest, probably because of the mild climate in other regions, which lowers the demand for heating, whereas winters in Dalian are harsher. Bangkok, on the other hand, is hot and humid all year round, and the demand for cooling is much higher. However, operating energy for the building in Bangkok is not the highest. A similar conclusion may also be reached by comparing the building in Shanghai with that in Dalian or in Tianjin. Energy for operating accounts for a large proportion of life cycle energy (Fig. 4), especially for buildings that require both heating and cooling. Thus, climate may affect the operating energy to a large extent.

Table 9 shows that the initial embodied energy for Tiejian Tower is much higher than the figures obtained in other studies. The reason is twofold: (1) the present study took into account all the material inputs and not just the major ones such as steel, cement, bricks, and glass; (2) Tiejian Tower has also adopted several energy-saving techniques, which further increased its embodied energy. As mentioned earlier, SE accounted for 81% of the total energy consumption during the construction stage and the major materials accounted for as much as 60% of the energy consumption for SE. In some passive residential buildings, embodied energy can represent up to 77% of the total embodied and operating energy [23]. With respect to LPBs, the share of operating energy is relatively small [21] (Fig. 4). Embodied energy of the building in Melbourne accounted for 46% of its total energy consumption, and then it is necessary to include the initial inputs as well in evaluating life cycle energy consumption of buildings. In addition, the embodied energy of any renovation and retrofitting or replacement of equipment amounts to 7% of the life cycle energy consumption. As frequent renovation may lead to material and energy being wasted and lack of repairs and maintenance may lead to increased energy consumption for the operations, the repairs and maintenance work needs to be regulated from a holistic perspective.

According to the scenario results, Tiejian Tower has adopted an intelligent building-management system, but it lacks itemized metering, which may explain why the building does not achieve the expected savings in energy in the operations stage: merely installing energy-efficient equipment is not sufficient by itself to save energy and to reduce CO_2 emissions. Strengthening the management of operating energy is also essential for achieving energy-saving goals. In addition, Tiejian Tower with the GSHPs system is unlikely to perform well until the power mix changes, and the share of embodied energy in CO_2 emissions share will decrease as the proportion of clean power in the power mix increases. These observations confirm the necessity to include construction energy in analysing energy consumption. Optimizing the power mix is effective in achieving the targets of energy saving and emissions reduction and the emissions trading system may affect the power mix to some extent, which, in turn, will reduce energy consumption and CO_2 emissions of the buildings sector.

A sensitivity analysis is conducted to assess the impact of changes in inputs and of uncertainties on different scenarios: the impact of lifespan and operating energy is described here, along with the findings of related studies [13,14].

The lifespan influences total energy consumption a great deal, and it is of little help to compare life cycle energy consumptions of buildings with different lifespans. In the present study, energy consumption and CO_2 emissions per unit building floor area were used for further comparison [17]. The impacts of changes in lifespan on S2 and S4 were greater than those on S1 and S3 (Fig. 6). Energy consumption (Fig. 6a) and CO_2 emissions (Fig. 6b) increased by 0.91% and 1.34%, respectively, under scenario S2 when the assumed lifespan was decreased by 1 year. When the lifespan was increased by 1 year, energy consumption and CO_2 emissions declined in all the scenarios. Among them, S2 performed the best, with a decline of 0.88% in energy consumption and of 1.28% in CO_2 emissions. The smallest changes were seen in S3 (a decrease of 0.65% in energy consumption and of 0.84% in CO_2 emissions). Changes in lifespan exerted a greater influence on CO_2 emissions than on energy consumption from a life cycle perspective.

Annual energy consumption and CO_2 emissions shared the same pattern of changes when the intensity of operating energy changed: when the intensity of operating energy increased by 1%, energy consumption increased by 0.73% (Fig. 6c) and CO_2 emissions increased by 0.64% (Fig. 6d) in all scenarios. The maximum increase in energy consumption (0.75%, Fig. 6c) and in CO_2 emissions (0.67%, Fig. 6d) was in S3 and the minimum, in S2, the corresponding

Table 9
Energy consumption of buildings in selected studies.

Year	Location	Average temperature (°C)	Floor area (m^2)	Lifespan (years)	Initial embodied energy ($kWh/m^2 \cdot a$)	Recurring embodied energy ($kWh/m^2 \cdot a$)	Operating energy ($kWh/m^2 \cdot a$)	Total ($kWh/m^2 \cdot a$)
2008	China, Shanghai	15.8	34620	50	21.7	–	111.7	133.3
2009	Thailand, Bangkok	27.5	60000	50	35.6	1.7	165.0	202.2
2009	Australia, Melbourne	16	75570	50	37.2	–	43.9	81.1
2012	China, Dalian	9	36500	50	46.7	–	327.2	373.9
	This study	12	57000	50	67.8	24.4	252.2	345.0

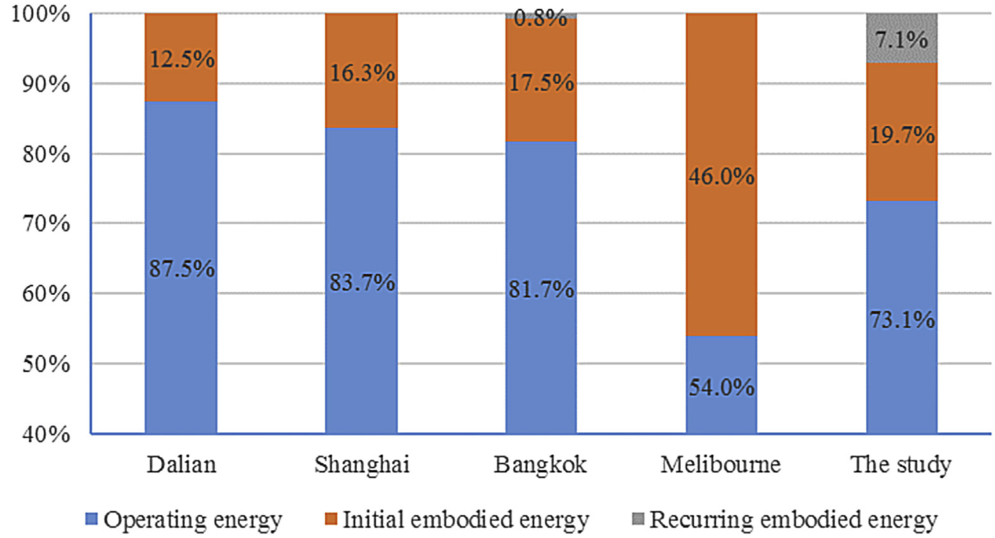

Fig. 4. Energy consumption structure of the buildings in selected studies.

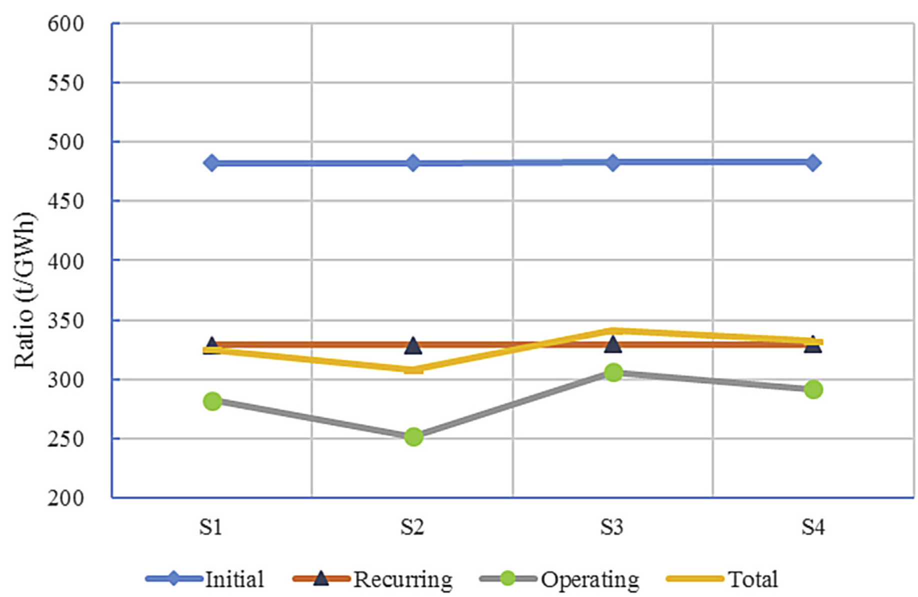

Fig. 5. CO_2 emission intensity of stages.

figures being 0.71% and 0.58%. The magnitude of change in energy consumption and CO_2 emissions was the same (0.73% and 0.64%) in all four scenarios when the intensity of operating energy decreased by 1%. Among the four, S3 showed the largest changes and S2, the smallest.

Although a longer lifespan means higher life cycle energy consumption and CO_2 emissions, it may levy the damage on environment due to the decrease of annual energy consumption per unit building floor area. With the rapid development of renewable energy, annual CO_2 emissions will decrease as the lifespan increases. In addition, buildings that are more energy efficient and use cleaner power resources are more sensitive to lifespan because they can save more energy over their entire life. CO_2 emissions are more sensitive to lifespan than energy consumption: a short lifespan leads to much greater waste, and CO_2 emissions increase. Therefore, developing a scientific long-term plan for the buildings sector, improving construction quality, and decreasing redundant construction will be effective measures for reducing energy consumption and CO_2 emissions [40].

In general, buildings that are more energy efficient or are larger consumers of clean power are less sensitive to operating energy intensity than conventional buildings. The energy intensity of China's building sector is 50% of that in Japan and USA. In the developed countries, energy intensity increases sharply when GDP per capita is relatively high, and China is close to that [4]. Therefore, China needs to explore appropriate ways to cope with the rapid increase in energy intensity and to meet its targets for energy conservation and for reduction in CO_2 emissions in the long run.

Although the present study offers some useful conclusions, some more issues need to be analysed further. First, the input–output model is a somewhat roundabout method, and the results are only approximations of embodied intensity. Secondly, the study is heavily dependent on the quality and quantity of data: although detailed data were available for the construction stage,

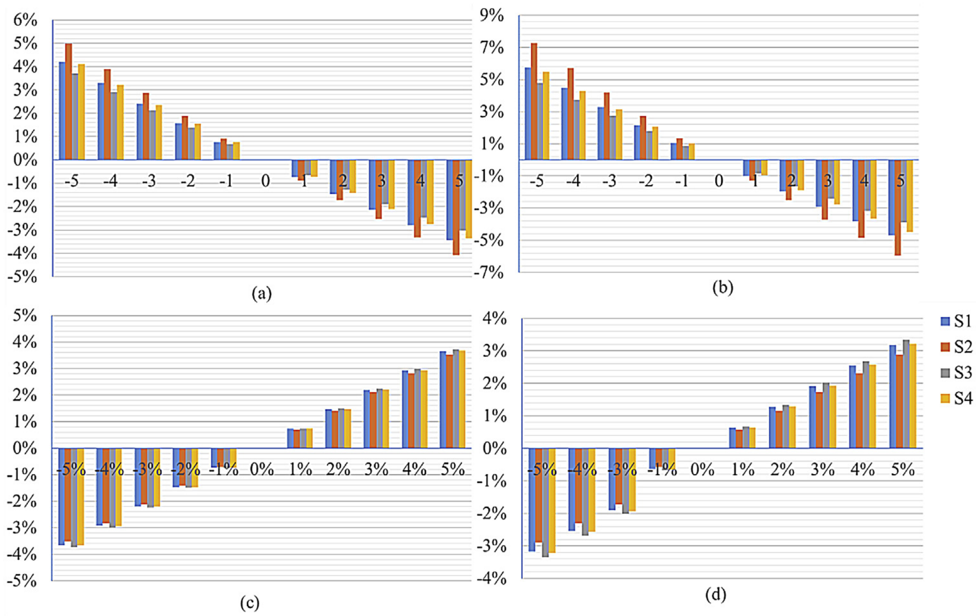

Fig. 6. (a) impacts of the change of lifespan on annual life cycle energy. (b)impacts of the change of lifespan on annual life cycle CO_2 emission. (c) impacts of the change of operating energy intensity on annual life cycle energy. (d) impacts of the change of operating energy intensity on annual life cycle CO_2 emission.

there is not distinctive data about transport, materials and construction activities, what's more, those for the operations stage spanned only the first two years (since the building is new)—long-term data may give somewhat different results. In addition, stages like demolition and disposal stages are ignored in this paper, though a full life cycle of buildings may provide more objective assessment of the building and obtain more valuable conclusions. Besides, during the life cycle of the building, CO_2 emissions are not the only emissions. The manufacturing process of building materials and the generating electricity also emit NO_x and SO_2, which can affect the local climate even more. Hence, taking all the atmospheric pollutants and water usage into consideration in the further study could make more sense. Besides, owing to space constraints, this paper did not explored the energy performance and energy saving measures for specific systems like insulation and HVAC system. The further study may focus on those specific issues. Lastly, the study ignored the economic perspective. Therefore, incorporating the data on costs and prices into the life cycle analysis could be the next step, along with allocation of a carbon quota from the life cycle perspective.

6. Conclusions and policy implications

6.1. Conclusions

First, input–output analysis is an effective approach to analyse energy consumption and CO_2 emissions related to buildings, it makes it possible to include embodied energy in life cycle analysis of buildings and to examine the contribution of different stages to energy consumption and CO_2 emissions. Overall, the Tiejian Tower consumes 982.7 GWh (345.0 kWh/m^2 a year) energy resources and emits 319 267.1 t (0.1 t/m^2 a year) CO_2 emissions in a life cycle. The operation phase accounts for 73% and 64% of the life cycle energy consumption and emissions respectively. Although Tiejian Tower has adopted a system of GSHPs, an intelligent control system, and high-efficiency glass for windows, the operation stage contributes most of the energy consumption (73%) and CO_2 emissions (64%) related to the building. It is essential to include the large-scale public office buildings in carbon trading. In addition, embodied energy plays an important role in energy consumption (20%), we should further strengthen energy-saving measures in the production of building materials. Furthermore, the introduction of energy-saving equipment and materials has only accounted for 7% of the embodied energy and CO_2 emissions.

Secondly, according to scenario analysis, energy efficiency is more effective in reducing emissions than in saving energy. In addition, from a long-term perspective, CO_2 emissions are greatly affected by the power mix. Greater injection of renewable energy into the grid and strengthening the supervision of the operations of public buildings are likely to be much more effective.

Finally, lifespan and the intensity of operating energy have significant effects on life cycle energy consumption and CO_2 emissions. Extending the lifespan of buildings is an effective measure to achieve the targeted reductions in energy consumption in the buildings sector. As energy consumption of public buildings continues to rise, widespread adoption of energy-efficient buildings and flexible application of renewable energy technologies are effective ways to reduce energy consumption and CO_2 emissions.

6.2. Policy implications

Public buildings offer a great potential to save energy. First, policies aimed at extending the lifespan of buildings will be more effective than those that offer greater incentives for adopting energy-saving techniques in reducing energy consumption and related CO_2 emissions. In recent years, China has become obsessed with the novelty, scale, and uniqueness of large-scale public buildings. This obsession has resulted in excessive energy consumption and wasted resources. Although energy efficiency helps in lowering operating energy, its positive effects are countered by the increase in embodied energy if the lifespan of energy-efficient buildings is not long enough.

Secondly, the state should also supervise the operation of public buildings more closely to obtain maximum benefits from energy-efficient technologies. Energy consumption during the operation of large public buildings is often more than what such buildings were designed for. Lack of supervision is always the most important reason for this gap between the expected and the actual energy consumption. The state should expand the scope of regulations related to energy consumption of public buildings, strengthen the mechanisms for monitoring energy consumption of buildings, and encourage the buildings to install meters that offer itemized billing.

Finally, large-scale public buildings should be involved in future emissions trading. China plans to establish a national carbon trading system in 2017. With the development of the economy, energy consumption and energy intensity of buildings are expected to increase. Making large public buildings a part of the proposed carbon trading system can be an effective way to improve the energy efficiency of such buildings. In addition, public buildings may be given a carbon quota based on life cycle analysis. The state should devise policies that accelerate the development of renewable energy and encourage the adoption of new technologies that extend the lifespan of buildings. These measures will conserve energy and decrease embodied CO_2 emissions from a life cycle perspective.

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