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Commercial building energy use in six cities in Southern China

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HIGHLIGHTS

- The worst modern buildings use more energy than the worst old buildings.
- Government office buildings did not use more energy than private office buildings.
- Commercial buildings in China use less energy than buildings in the US.
- Modern commercial buildings don't use more energy than old buildings.

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ABSTRACT

With China's continuing economic growth, the percentage of government offices and large commercial buildings has increased tremendously; thus, the impact of their energy usage has grown drastically. In this survey, a database with more than 400 buildings was created and analyzed. We researched energy consumption by region, building type, building size and vintage, and we determined the total energy use and performed end use breakdowns of typical buildings in six cities in southern China. The statistical analysis shows that, on average, the annual building electricity use ranged from 50 to 100 kW h/m^2 for office buildings, 120 to 250 kW h/m^2 for shopping malls and hotels, and below 40 kW h/m^2 for education facilities. Building size has no direct correlation with building energy intensity. Although modern commercial buildings built in the 1990s and 2000s did not use more energy on average than buildings built previously, the highest electricity intensive modern buildings used much more energy than those built prior to 1990. Commercial buildings in China used less energy than buildings in equivalent weather locations in the US and about the same amount of energy as buildings in India. However, commercial buildings in China provide comparatively less thermal comfort than buildings in comparable US climates.

1. Introduction

For the past two decades, the Chinese government has continued to expand its efforts to promote building energy efficiency and green building construction. After more than 10 years of effort, the MHURC (Ministry of Housing and Urban-Rural Construction) has developed building energy standards for residential and public buildings throughout China. Although building codes are readily available in China, all savings are theoretical until the codes are fully implemented. A continuing debate concerns whether the real energy use of buildings has met these building codes and whether modern buildings in China use an equivalent or higher amount of energy compared to buildings in developed countries with equal service levels. A meaningful debate of these concerns, regarding either energy conservation potentials or evaluating the impact of recent building energy standards, relies on a database of measured building energy consumption for residential and public buildings by region, building type, and vintage.

2. Materials and methods

2.1. Literature review

Efforts have been made to analyze building energy consumption statistically. The China National Bureau of Statistics (NBS)

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publishes energy data every year. However, a report developed by the Lawrence Berkeley National Laboratory (LBNL) showed that commercial energy consumption in the current NBS statistics was underestimated by 44%, the fuel mix was misleading and energy efficiency improvements will not be sufficient to offset strong increases in the energy (particularly electricity) intensity of commercial buildings (Bressand et al., 2007). China's building sector consumes one quarter of the total energy in the country and with an estimated total area of over 50 billion m^2 the annual energy use is around 6700 TW h as indicated by Jiang et al. (2007) from Tsinghua University. Although data on the residential sector are relatively rich (Brockett et al., 2002; Chen et al., 2007), few data sources are from recent field surveys, and most of these surveys rely on data published by the NBS that were calculated indirectly from forecasting and estimations. Researchers have claimed, "China's current building energy use data are too fractured and incomplete" (Guan et al., 2001).

Another large-scale investigation of the current energy efficiency of buildings in China has been conducted in 22 provincial capitals and major cities. The surveys were carried out within four groups: consumers, producers, services, and consultancy supervisors (Liang and Li, 2006). The survey results reveal that only 20.6% of the total buildings have met the requirement of standard GB 50189-2005 (new buildings must save 50% of their energy consumption from heating, air conditioning and lighting compared to buildings built in the 1980s).

Other research also aims at studying the energy consumption of commercial buildings in China. Zhou and Lin from LBNL evaluated the impact of a variety of scenarios of gross domestic product (GDP) growth, energy elasticity, and energy-efficiency improvement on energy consumption in commercial buildings in China using a detailed China End-Use Energy Model. The results suggest that commercial energy consumption in China's current statistics is underestimated by about 44% (Zhou and Lin, 2008). Xiao et al. (2012 analyzed the energy consumption of office buildings in several provinces and municipalities directly under the control of the Central Government of China, utilizing data from the first national survey of about 4600 samples which was conducted in 2007. Their results revealed that electricity use intensity excluding district heating of office buildings in each city or province in China appeared two different groups, most of them distributed on the lower range from 33.6 to 77.5 kW $h_e/(m^2\ a)$ (here 1 kW h_e means 1 kW h of electricity, distinguished from 1 kW h heating (illustrating as kW h_h) or 1 kW h cooling (kW h_c)), excluding district heating energy use, while some of buildings fell within a higher range from 51.8 to 107.0 kW $h_e/(m^2\ a)$ (Xiao et al., 2012).

The Chinese government has shown an increasing awareness of this problem in recent years, particularly for government offices and large "public" buildings, such as shopping malls or high-end office buildings. Because the energy intensity of these buildings is 10–20 times that of residential buildings, even though they represent less than 4% of the total building floor area, they represent roughly 20% of all building energy use. In previous studies by the MHURC, buildings in Beijing, Chongqing, Wuhan, and Shenzhen showed energy intensities of at least 70 kW h/(m^2 year) and more commonly from 180 to 400 kW h/(m^2 year) (China Ministry of Housing and Urban-Rural Construction (MHURC), 2007).

2.2. Methods of building database

With China's continuing economic growth, the percentage of government offices and large commercial buildings is expected to increase, and the impact of their high-energy use can only be expected to grow in the future. Therefore, the MHURC established a project to determine the current energy use characteristics of government buildings and large public buildings with a coordinated effort to conduct energy consumption surveys in five cities in Southern China, three in the hot-summer cold-winter region (Chongqing, Chengdu, and Wuhan) and two in the hot-summer warm-winter region (Fuzhou and Shenzhen). The local institutions in the five cities working on this project are the Shenzhen Academy of Building Research, the Fuzhou Sixin Technology Development Promotion Center, the Wuhan Office of Building Energy Conservation, the Xihua University in Chengdu, and the Chongqing Construction Technology Development Center.

After the MHURC recognized the value of having a consistent database of measured building energy use, it sponsored a task force in 2006 to develop a "Standard for Building Energy Consumption Surveys" that will serve as a template for the surveys in the five pilot cities. The ultimate objective of the project is to establish a system for energy-conserving operational management of government offices and large public buildings, subsequent analysis of the energy consumption survey data, research into energy-efficiency ratings and the development of energy use indices. The survey standard was later used in the building survey of five major cities in Southern China.

The energy survey was completed in 2008. The original objective was to survey all of the commercial buildings in the territories of five major cities. While some cities completed the survey, other cities failed to do so because of limited resources. In Shenzhen, the Shenzhen Academy of Building Research visited all 5000 commercial buildings in the cities and verified their building area and electricity usage. Additionally, the institution conducted a detailed energy audit in selected buildings to identify energy efficiency improvement opportunities. Other cities have also conducted detailed energy audits in a selected number of buildings. These audits helped the local and central governments to understand the depth of the problems and potential resolutions. Each city summarized their survey results in a report submitted to the MHURC (Chongqing Municipal Construction Technology Development Center, 2008; Fuzhou New Technology Promotion Center for Scientific & Technological Development, 2008; Shenzhen Institute Of Building Research, 2008; Wuhan Energy Conservation Office, 2008; Xihua University, 2008).

These reports provided valuable information on the building energy intensity and usage patterns in China. In several cities, the raw data of annual energy consumed in each individual building were listed. However, the surveys were not completed in a consistent way. Some cities spent a lot of effort on collecting detailed HVAC performance data, while other cities sorted through legal documents to clarify the legal ownership and divided the building floor area by different functions. Conclusions regarding building energy intensity and the breakdown of the energy end uses cannot be drawn from these data.

However, a separate effort in Shanghai was completed by the Shanghai Energy Supervisory Center that surveyed 11 large commercial buildings in Shanghai (Shanghai Energy Conservation and Supervision Center, 2007). These large commercial buildings included government buildings, hotels, museums, stadiums, and shopping malls. Most of these buildings were built within the last 10 years, and some are landmarks in Shanghai. The intention of the survey was to better understand the energy use intensity of these high profile buildings and to determine whether any retrofit opportunities exist. Therefore, the survey collected detailed information on the building envelope and HVAC equipment. In accordance with the Energy Supervisory Center, the Shanghai Tongji University surveyed about 95 other buildings in Shanghai (Chen et al., 2006).

This study provides an analysis of all of these survey efforts. We compiled the survey data into one database including more than 400 buildings. The database contains the building floor area, function, annual energy consumption, and detailed HVAC information. However, not all of the data from local intuitions were available for this analysis. Certain monthly information was not published, and only data reported to the MHURC and published by the Shanghai Energy Supervisory Center were used in the database to understand the building energy intensity patterns in Southern China.

We divided the energy usage in terms of electricity and gas usage but did not combine them because of the controversies regarding the conversion of site energy to source energy. In southern China, generally, gas was used for heating and domestic hot water, and electricity was used for cooling, lighting and equipment plug load. The energy information in this study is site energy, which is the energy consumed directly at the site. We converted heating gas and electricity to a single unit so that users can easily compare their magnitudes. However, readers are discouraged to simply combine the data. Although the breakdown of the end use energy was difficult because sub-meters do not exist in most commercial buildings in China, we estimated the cooling electricity usage from the comparison of heating season data with cooling season data. Limited gas usage information was collected during the survey because cooling loads in southern China are much higher than heating loads, and less attention is given to gas usage relative to electricity usage.

Furthermore, this study compared the energy usage in China with other developed and developing countries. We compared the energy intensity of southern China buildings with buildings in the US and in India at similar climates. Generally, we found that buildings in China used significantly less energy per unit area than buildings in the US. One explanation is that Chinese buildings did not provide an equal level of service in terms of lighting and thermal comfort as buildings in developed countries. Another reason is that commercial buildings in China were operated more carefully than buildings in the US because the labor cost is lower and owners can afford more operators. Thus, buildings with an equivalent level of services built after the 1990s following the same western standards had relatively low energy intensity levels.

2.3. Cities and weather conditions

The six cities are major cities in southern China with three cities on the coastline and three cities along the mid-stream and upstream of the Yangtze River. Shanghai is the largest City in China, and its first high-rise building was built in the 1930s, which still exists today. The current building stock is a combination of old buildings built before 1980 and new buildings built afterwards. Shenzhen is the newest city in China, and all of its buildings were built after 1980. Chengdu, Chongqing, Fuzhou, and Wuhan are historic cities with thousands of years of history. However, the majority of their commercial buildings were built after 1949. All of the cities are located in cooling-usage dominated areas. Under the classification of the China building codes, Shanghai, Wuhan, Chongqing, and Chengdu are in the "hot summer cold winter" climate, while Shenzhen and Fuzhou are in the "cold summer and warm winter" climate. Although the first four cities are in the hot summer cold winter climate, Chengdu is not as hot as the other three cities during the summer because of its unique location next to the mountains, on the west, and a river. In Chengdu, small commercial buildings barely need mechanical cooling because of its foggy weather during the summer. Table 1 is the number of cooling and heating degree-days in these cities and equivalent cities with similar the summer conditions in the US. The heating load of the commercial buildings of six cities during the summer was generally small and can be offset by the internal heat gain, if the buildings are insulated properly.

In the US, the cooling degree-days calculation uses 18 °C as the reference temperature. In China, the cooling degree-days reference temperature is 26 °C. In China, mechanical cooling is normally turned off when the outside temperature is below 26 °C. A study has calculated the 18 °C basis cooling degree-days in China, and we used that information to find the equivalent cities in the US during the summer (Zhang et al., 2002).

2.4. Building data sample

The MHURC designed the building survey standard, and each city was required to follow the standard when sending out the survey request. The survey standard was clear on the utility information but vague on building description because the level of knowledge and expertise at the regional offices were different, and it was difficult for the MHUC in Beijing to design detailed survey forms for each city. The standard included building utility bills, functions and the building area with no requirement on the buildings envelope and mechanical systems. Officials in each city office designed their own survey forms and used their judgments to decide the level of details in the survey. For example, some regional offices collected all building information in their cities, while other regional offices only collected data from a small portion of the buildings. Some building data had a detailed breakdown of building functional areas, while other data only had the total building area. Although more detailed information was collected in the field, not all of the information was available to share, and some data were withheld to protect the owner's privacy. Table 2 is a list of the information available to the study.

Table 2
List of building information from each city.

	Shanghai	Chengdu	Wuhan	Shenzhen	Fuzhou	Chongqing
Name	✓	✓	✓		✓	No
Area	✓	✓	✓	✓	✓	✓
Year built	✓	✓			✓	✓
End use			✓			
Monthly data	✓[a]	✓[b]				
Gas data	✓	✓[c]	✓			[d]
Electricity	✓	✓	✓	✓	✓	✓
Building envelop	✓					

[a] Seventy percent of the buildings have monthly gas and electricity data.
[b] Average monthly data for each type of building are available.
[c] Ten percent buildings have annual gas consumption data.
[d] Total energy was provided, but no gas consumption alone.

Table 1
Weather conditions in six cities (Zhang et al., 2002).

	Shanghai	Chengdu	Wuhan	Shenzhen	Fuzhou	Chongqing
Cooling degree days (26 °C)	203	60	286	365	274	174
Cooling degree days (18 °C)	1075	887	1249	2074	1605	1288
Heating degree days (18 °C)	1648	1276	1549	289	605	1086
US equivalent cities	Charlotte, NC	Washington DC	EL Paso, TX	West Palm Beach, FL	Orlando, FL	Tallahassee, FL

Although the data have missing information and gaps, we were able to collect a relatively large number of building samples in these six cities. Table 3 is the summary of the sample size of these buildings and their types. In total, the sample size of the database is 402. There are 12 types of buildings, and more than half of these buildings are government or private office buildings. The dataset covers all major types of commercial buildings in China, but the sample sizes of libraries, stadiums, and airport terminals are too small to be statistically significant.

Many modern buildings in China are mixed-use, especially those buildings in busy commercial districts. The lower parts of this type of building are typically used as shopping malls and restaurants. The upper parts are used for office space and residential apartments. If only 1 m is used in the building, it is difficult to separate the energy use between the upper portions and lower portions of the buildings; thus, the survey results for the energy intensity in this type of building is not as useful as buildings with a single function. Retailers who lease spaces in the lower floors normally pay for electricity by square meter instead of kWh and have little incentive to save energy.

The supermarkets in the table refer to grocery stores less than 5000 m^2; none of the Wal-Mart type of supermarkets were included in the survey. In general, grocery stores that serve foods had indoor temperatures that were slightly lower than other shopping stores, and their lighting intensities were normally higher than those of offices. No separate restaurant has been included in the survey data. In China, very few large commercial buildings are dedicated to food services only. Restaurants typically occupy a portion of shopping malls or office buildings. The hospitals in the sample all have inpatient departments and pharmacies. The database does not include medical clinics without inpatients. The three multi-function buildings in the samples are buildings with a mix of hotels, offices, shopping areas, and restaurants. Although few of these buildings exist in the survey, large commercial buildings of this type are increasingly being built in China.

Regarding the year the buildings were built, the samples range from the 1930s to 2000s. The 1930s samples include the famous, historic Shanghai International Hotel, which is the tallest building in China before 1970. The majority of the buildings in the sample

Table 3
Building sample size and building types.

	Shanghai	Chengdu	Wuhan	Shenzhen	Fuzhou	Chongqing	Total
Government buildings	4	19	12	13	41	27	116
Offices	42	1	3	14	47		107
Hotels	5	14	4		30	5	58
Shopping mall + offices	27			4	15		46
Shopping mall		8	4		7	16	35
College		15				5	20
Hospital		2			2	3	7
Supermarket		4			2		6
Multi-function	2					1	3
Airport terminal	1						1
Library					1		1
Stadium	1						1
Total	83	63	23	31	145	57	402

Table 4
Year built and floor area of the building sample.

Year built	Floor area	Shanghai	Chengdu	Wuhan	Shenzhen	Fuzhou	Chongqing	Total
1930s	20,000–40,000	1						1
	> 40,000	1					5	6
1950s	< 5,000					2	2	4
	20,000–40,000	1						1
1960s and 1970s	< 5,000					12	2	14
	< 10000					1		1
	10,000–20,000					3		3
	20,000–40,000					5		5
	> 40,000	2				1		3
1980s and 1990s	< 5,000					2		2
	< 10,000					4	2	6
	10,000–20,000	4				6	5	15
	20,000–40,000	13				40	4	57
	> 40,000	36				17	1	54
2000s	< 5,000					3	6	9
	< 10,000					5	5	10
	10,000–20,000	1				4	8	13
	20,000–40,000	6				23	15	44
	> 40,000	18				17	2	37
Unknown	< 5,000		4	1				5
	< 10,000		13		4			17
	10,000–20,000,		13	4	8			25
	20,000–40,000,		17	11	10			38
	> 40,000		16	7	9			32
Total		83	63	23	31	145	57	402

were built in the 1990s and 2000s after China began its economic reform. For the sample buildings, Table 4 shows the size, building year and floor areas. In general, buildings built in the 2000s are bigger than those built beforehand. The data samples in Shenzhen did not label the year the buildings were built. However, they were all built after 1980 because the city did not exist prior to that.

The majority of the buildings have a floor area larger than 20,000 m^2. Those smaller than 5000 are supermarkets and government office buildings. Some government office buildings built before 1990 are still small in size; in the recent 10 years, new government buildings are becoming increasingly larger. Among the buildings built after 1980, 82% are larger than 20,000 m^2. Large buildings are not energy efficient in southern China if the heat generated from the core spaces cannot dissipate efficiently. Furthermore, if the building depth is too large and cannot use day lighting efficiently, the power used by artificial lights will increase.

3. Results and discussions

Fig. 1 shows the electricity energy intensity of four major types of buildings in the six cities. The four major types are government buildings, offices, hotels, and shopping malls. The plot does not include the average energy intensity of other building types, such as schools and museums, because the sample sizes are small and statistically insignificant.

3.1. Government office buildings

One of the major objectives of the survey is to determine how much energy government buildings use because of a growing concern that government buildings are more wasteful than private sector buildings. In each city, nearly every government building, belonging to the central and local government, has been surveyed. The function of different government office buildings and their occupancy schedules were similar. Few of these buildings are mixed-use. It is meaningful to compare their energy intensities with each other in the first place.

The average electricity intensity of government office buildings was from 40 to 80 kW h/m^2. However, regional differences exist. As previously mentioned, Chengdu is much cooler in the summer than the other five other cities. The energy intensities in Chengdu were lower than the intensities in the other five cities. On average, Chengdu's electricity usage was about half as much as that in other cities. One explanation is that a large portion of the electricity was used for cooling in the other cities of Southern China. If this assumption is true, about 30–50% of all electricity was used for mechanical cooling in these buildings. However, the percent of electricity used for cooling from this assumption seems to be too high to be true.

Another explanation is that buildings in Chengdu are not as good as buildings in other cities regarding service. Moreover, we observed similar regional difference for other types of buildings. The electricity used in Chengdu in private offices, hotels, and shopping malls was much lower than that in the other cities. Social development may be another factor that has an impact on the energy usage. While Shanghai and Shenzhen are two of the richest cities in China, their energy intensities were the highest among the six cities. For example, the cooling degree-days of Fuzhou are 50% higher than Shanghai, but the buildings in Shanghai used nearly equal amounts of electricity as buildings in Fuzhou.

3.2. Private offices

In the six cities, we found that the energy intensities in private offices were almost the same as the government buildings. The average building energy intensity of private offices was between 50 kW h/m^2 and 100 kW h/m^2, which were about the same as the government buildings. The data do not support the common perception that government buildings are more wasteful than the private buildings.

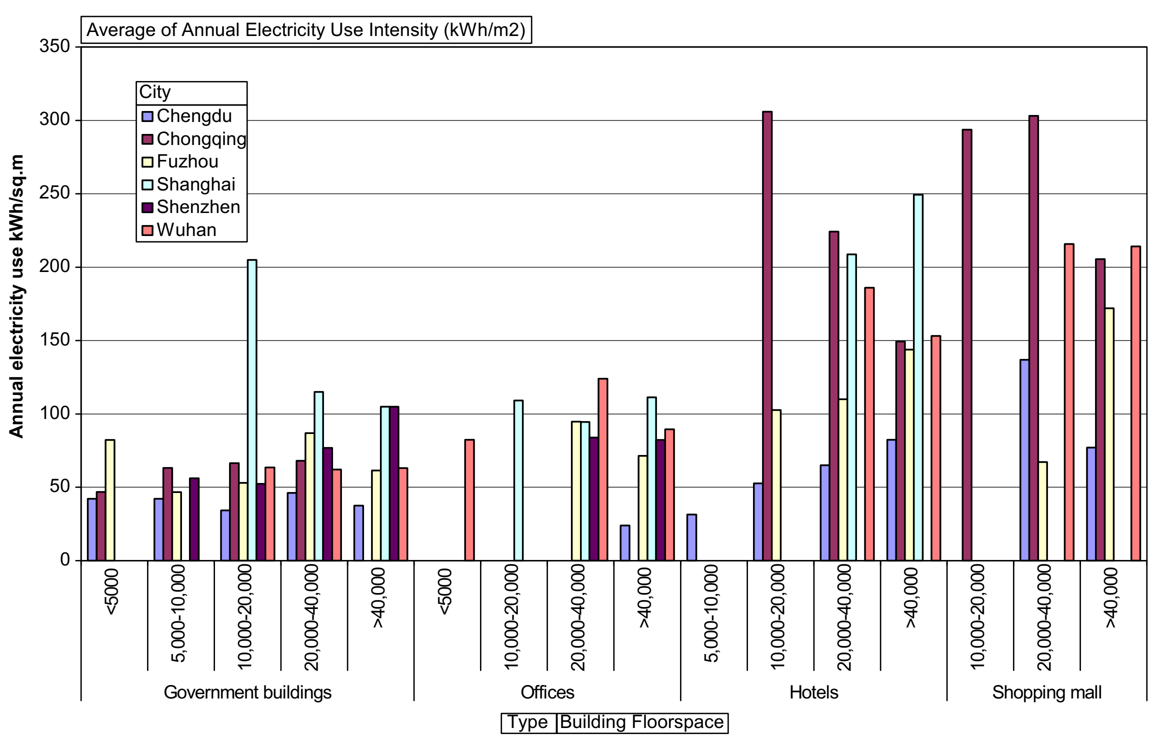

Fig. 1. Average annual electricity use per floor area of four major types of buildings.

We analyzed this problem further by comparing the maximum and minimum energy intensities of the two sectors. Table 5 shows the average, the minimum and the maximum electricity usages of government office building versus private office buildings in five cities. While government buildings in Shanghai, Chengdu, and Wuhan used more electricity than private buildings, we observed the opposite result in Shenzhen and Fuzhou. Comparing the maximum and minimum of the survey drew similar conclusions. The high energy consuming buildings in government sector were not worse than that in the private sector. The lowest electricity-intensive government buildings was not better than the lowest electricity-intensive private office buildings either. We did not find compelling evidence that the government buildings used more electricity on cooling and lighting than private buildings.

3.3. Hotels and shopping malls

The electricity consumption of hotels and shopping malls was much higher than that of the office space. On average, excluding hotels in Chengdu, the electricity use per year ranged from 200–300 kW h/m^2. In shopping malls, the lighting power density was typically higher than that of office buildings. This not only increased the direct use of electricity but also increased the cooling load from the internal heat gain. The electricity use of hotels was higher than offices because they provide food services and their lighting power density in the public areas was high. We found that the electricity usage in hotels was very sensitive to weather conditions. For example, hotels in Chongqing used much more electricity than hotels in Chengdu.

3.4. Building size

In Fig. 1, we classified the buildings by their floor areas. People are worried about the impact of building size because modern China buildings are becoming increasingly larger. Low-rise buildings are replaced by high-rise buildings because of land shortages and because developers prefer to construct large building complexes serving multiple functions. In heating dominated areas, large buildings are more energy efficient because the heat loss through the envelope per floor area is smaller than that of small buildings. In cooling dominated areas, large buildings have a smaller direct solar heat gain, and the heat transferred through the buildings envelope per floor area was smaller. However, the internal artificial lighting electricity and internal heat gain increase as buildings become larger. Furthermore, the fan energy used to remove the heat from the core space increases. Overall, in cooling dominated areas, small buildings tend to be more energy efficient than large buildings.

However, in Fig. 1, we did not observe that electricity use intensity changes so much with floor area. We also analyzed the

Table 5
Comparison of public and private offices.

	Annual electricity use (kW h/m^2)	Shanghai	Chengdu	Wuhan	Shenzhen	Fuzhou
Government offices	Average	135.0	40.6	62.8	59.5	68.0
	Maximum	205.0	96.8	73.4	105.0	248.2
	Minimum	104.7	24.6	47.3	30.0	15.7
	Sample size	4	19	12	13	41
Private offices	Average	108.0	24.0	98.7	83.1	86.8
	Maximum	179.1	24.0	124.0	139.5	342.2
	Minimum	62.1	24.0	82.4	47.9	5.1
	Sample size	42	1	3	14	47

Table 6
Government office building annual electricity use intensity.

Government buildings	Floor area (m^2)	Shanghai	Wuhan	Shenzhen	Fuzhou	Chongqing	Total
Average annual electricity use (kW h/m^2)	< 5,000				82.3	46.9	70.08
	< 10,000			56.2	46.8	63.3	54.07
	10,000–20,000	205.0	63.5	52.4	53.0	66.5	63.82
	20,000–40,000	115.0	62.2	76.9	87.0	68.1	75.83
	> 40,000	105.0	63.2	105.0	61.5		76.53
	All	135.0	62.8	59.5	68.0	58.6	66.35
Maximum annual electricity use (kW h/m^2)	< 5,000				248.2	87.1	248.21
	< 10,000			71.4	83.5	96.2	96.19
	10,000–20,000	205.0	73.4	85.6	87.0	95.7	205.00
	20,000–40,000	125.4	69.2	76.9	125.0	121.5	125.35
	> 40,000	105.0	71.4	105.0	82.0		104.96
	All	205.0	73.4	105.0	248.2	121.5	248.21
Minimum annual electricity use (kW h/m^2)	< 5,000				15.7	16.5	15.71
	< 10,000			38.8	21.4	30.4	21.40
	10,000–20,000	205.0	47.3	30.0	19.2	42.0	19.22
	20,000–40,000	104.7	50.0	76.9	66.4	5.1	5.13
	> 40,000	105.0	54.9	105.0	40.9		40.91
	All	104.7	47.3	30.0	15.7	5.1	5.13
Sample size	< 5,000				19	10	29
	< 10,000			4	10	7	21
	10,000–20,000	1	4	7	7	6	25
	20,000–40,000	2	6	1	3	4	16
	> 40,000	1	2	1	2		6
	Subtotal	4	12	13	41	27	97

statistical correlation between average annual electricity use intensity and building sizes for different building types. We assume the electricity use intensity is not correlated with building sizes for different building types. The P value for government office building, private office building and shopping malls are 0.200, 0.804 and 0.164, respectively. All the P values are greater than 0.05, which means the assumption is accepted. Hence for each type of buildings in a given city, we did not observe clear trend in energy intensity variation with building sizes as far as the statistics in this research indicate. Tables 6–8 list the annual electricity use of government office buildings, private office buildings, and shopping malls, respectively. Additionally, the average maximum and minimum annual electricity use intensities of the six cities are listed in the tables.

3.5. *Electricity use variations—High and low electricity-intensive buildings*

Fig. 2 shows the comparison between the highest and lowest electricity-intensive buildings for the four major building types in the six cities. The energy intensities varied extensively for all building types in the six cities, suggesting large potentials for improving building energy efficiency. The variations in office buildings were much higher than shopping malls and hotels. The electricity use of the highest office buildings was about 10 times higher than that of the lowest buildings. The survey has no detailed information on the comfort and indoor air temperature, and thus, it is hard to judge whether the lowest energy intensity buildings are indeed the best buildings or not. The general impression from the field visits is that the lowest energy intensity buildings are energy efficient, but perhaps they did not meet the basic requirements regarding comfort and lighting. Typically, low energy intensity office buildings are those built in the Soviet style, with a corridor in the middle and offices on the sides with windows. These buildings in Southern China have no heating systems, and only use window air conditioners for cooling.

Large hotels and shopping malls are different from the office buildings. The majority of these buildings were built after 1990, and they are similar in service level to each other because of the increasing living standard. These buildings have to provide a high

Table 7
Office building annual electricity use intensity.

	Floor area (m^2)	Shanghai	Wuhan	Shenzhen	Fuzhou	Total
Average annual electricity use (kW h/m^2)	< 5,000		82.4			82.40
	5,000–20,000	109.1				109.11
	20,000–40,000	94.6	124.0	83.9	94.7	93.72
	> 40,000	111.4	89.6	82.2	71.4	95.36
	All	108.0	98.7	83.1	86.8	95.03
Maximum annual electricity use (kW h/m^2)	< 5,000		82.4			82.40
	5,000–20,000	144.2				144.18
	20,000–40,000	139.3	124.0	115.8	342.2	342.20
	> 40,000	179.1	89.6	139.5	135.5	179.08
	All	179.1	124.0	139.5	342.2	342.20
Minimum annual electricity use (kW h/m^2)	< 5,000		82.4			82.40
	5,000–20,000	86.1				86.07
	20,000–40,000	62.1	124.0	47.9	6.1	6.08
	> 40,000	64.3	89.6	53.1	5.1	5.11
	All	62.1	82.4	47.9	5.1	5.11
Sample size	< 5,000		1			1
	5,000–20,000	4				4
	20,000–40,000	8	1	7	31	47
	> 40,000	30	1	7	16	54
	Subtotal	42	3	14	47	106

Table 8
Shopping malls annual electricity use intensity.

	Floor area (m^2)	Shanghai	Wuhan	Fuzhou	Chongqing	Total
Average annual electricity use (kW h/m^2)	5,000–20,000				293.7	293.67
	20,000–40,000		215.7	67.3	303.1	223.48
	> 40,000		214.2	172.0	205.5	197.20
	All		214.9	97.2	288.6	228.04
Maximum annual electricity use (kW h/m^2)	5,000–20,000				394.5	394.46
	20,000–40,000		225.7	199.1	398.0	397.96
	> 40,000		252.9	213.3	246.5	252.90
	All		252.9	213.3	398.0	397.96
Minimum annual electricity use (kW h/m^2)	5,000–20,000				212.6	212.61
	20,000–40,000		205.7	8.9	176.0	8.93
	> 40,000		175.4	130.6	164.5	130.62
	All		175.4	8.9	164.5	8.93
Sample size	5,000–20,000				4	4
	20,000–40,000		2	5	10	17
	> 40,000		2	2	2	6
	Subtotal		4	7	16	27

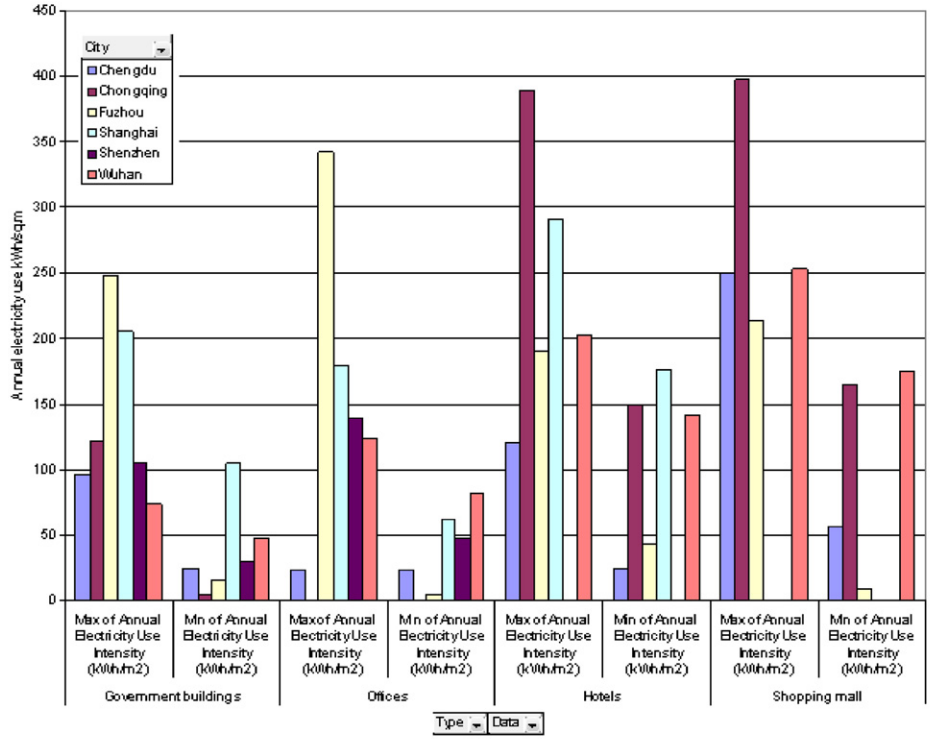

Fig. 2. Highest and lowest building energy intensities of different building types.

Table 9
Annual electricity use intensity of shopping malls.

	Year built	Shanghai	Wuhan	Shenzhen	Fuzhou	Chongqing	Total
Average annual electricity use (kW h/m^2)	1950				40.9	73.2	57.1
	1970s or before				73.8	65.8	72.7
	1980–1990s	125.4			67.5	67.5	70.7
	2000s	138.2			66.8	53.7	66.2
	Unknown		62.8	59.5			61.1
	All	135.0	62.8	59.5	68.0	58.6	66.3
Maximum annual electricity use (kW h/m^2)	1950				52.6	78.2	78.2
	1970s or before				138.4	87.1	138.4
	1980–1990s	125.4			128.4	95.7	128.4
	2000s	205.0			248.2	121.5	248.2
	Unknown		73.4	105.0			105.0
	All	205.0	73.4	105.0	248.2	121.5	248.2
Minimum annual electricity use (kW h/m^2)	1950				29.2	68.2	29.2
	1970s or before				15.7	44.5	15.7
	1980–1990s	125.4			21.4	42.0	21.4
	2000s	104.7			19.2	5.1	5.1
	Unknown		47.3	30.0			30.0
	All	104.7	47.3	30.0	15.7	5.1	5.1
Sample size	1950				2	2	4
	1970s or before				13	2	15
	1980–1990s	1			12	5	18
	2000s	3			14	18	35
	Unknown		12	13			25
	All	4	12	13	41	27	97

level of thermal comfort and lighting quality to attract clients. However, even for these two types of buildings, the highest energy intensities were about twice as much as the lowest energy intensities. Because large hotels and shopping malls in the survey were all equipped with air conditioning systems, the difference in the energy intensity can only be attributed to how the buildings had been designed and whether they were used efficiently.

3.6. *Year of construction*

Tables 9–11 summarize the energy intensities of buildings built in different years for three types of building: government offices, offices, and hotels. The sample sizes of other building types were not large enough, and we did not include them in the analysis. In northern China, buildings built before the 1990s are

Table 10
Electricity use of government office buildings built at different years.

	Year built	Shanghai	Wuhan	Shenzhen	Fuzhou	Total
Average annual electricity use (kW h/m^2)	1970s or before	74.5			66.9	70.7
	1980–1990s	111.7			82.5	96.4
	2000s	102.6			97.0	99.6
	Unknown		98.7	83.1		85.8
	All	108.0	98.7	83.1	86.8	95.0
Maximum annual electricity use (kW h/m^2)	1970s or before	74.5			66.9	74.5
	1980–1990s	179.1			263.8	263.8
	2000s	160.2			342.2	342.2
	Unknown		124.0	139.5		139.5
	All	179.1	124.0	139.5	342.2	342.2
Minimum annual electricity use (kW h/m^2)	1970s or before	74.5			66.9	66.9
	1980–1990s	62.1			6.1	6.1
	2000s	64.3			5.1	5.1
	Unknown		82.4	47.9		47.9
	All	62.1	82.4	47.9	5.1	5.1
Sample size	1970s or before	1			1	2
	1980–1990s	28			31	59
	2000s	13			15	28
	Unknown		3	14		17
	All	42	3	14	47	106

Table 11
Electricity use of office building built at different years.

	Year built	Shanghai	Wuhan	Fuzhou	Chongqing	Total
Average annual electricity use (kW h/m^2)	1930	175.9				175.9
	1950	265.8				265.8
	1970s or before	290.6		113.3		135.5
	1980–1990s	196.2		103.1	223.1	120.1
	2000s			135.6	246.6	172.6
	Unknown		169.5			169.5
	All	224.9	169.5	114.1	241.9	146.3
Maximum annual electricity use (kW h/m^2)	1930	175.9				175.9
	1950	265.8				265.8
	1970s or before	290.6		170.9		290.6
	1980–1990s	208.0		138.7	223.1	223.1
	2000s			189.8	388.8	388.8
	Unknown		203.1			203.1
	All	290.6	203.1	189.8	388.8	388.8
Minimum annual electricity use (kW h/m^2)	1950	265.8				265.8
	1970s or before	290.6		42.9		42.9
	1980–1990s	184.3		70.1	223.1	70.1
	2000s			51.4	149.3	51.4
	Unknown		142.2			142.2
	All	175.9	142.2	42.9	149.3	42.9
Sample size	1930	1				1
	1950	1				1
	1970s or before	1		7		8
	1980–1990s	2		15	1	18
	2000s			8	4	12
	Unknown		4			4
	All	5	4	30	5	44

less energy efficient than those built later because of the lack of insulation in the building envelopes. In southern China, insulation is not a large issue because these office building are cooling dominated. If we only compare the average annual electricity use, the differences between buildings built in different years are small. For example, in Table 9, the average annual electricity used in modern office buildings in both Fuzhou and Shanghai is only slightly higher than those built in the 1980s or before. Similar patterns were observed in government office buildings and hotels. The average electricity use of hotels and government offices built in the 2000s is sometimes higher than that of those built before the 2000s, and sometimes it was lower. We analyzed the statistical correlation between average annual electricity use intensity and vintage for different building types. We assume the electricity use intensity is not correlated with vintage for different building types. The *P* values for government office building, private office building, and shopping malls are 0.269, 0.459 and 0.466, respectively. All the *P* values are greater than 0.05, which means the assumption is accepted. Thus, there is no direct correlation between building energy intensity and vintage so far witnessed according to the statistical significance in this research.

The comparison of minimum annual electricity use draws a similar conclusion. Buildings with lower energy intensity were dependent upon the year they were built. The lowest electricity-intensive buildings built in the 2000s are not necessarily better than those built in the 1950s. For example, in Shanghai, the hotel

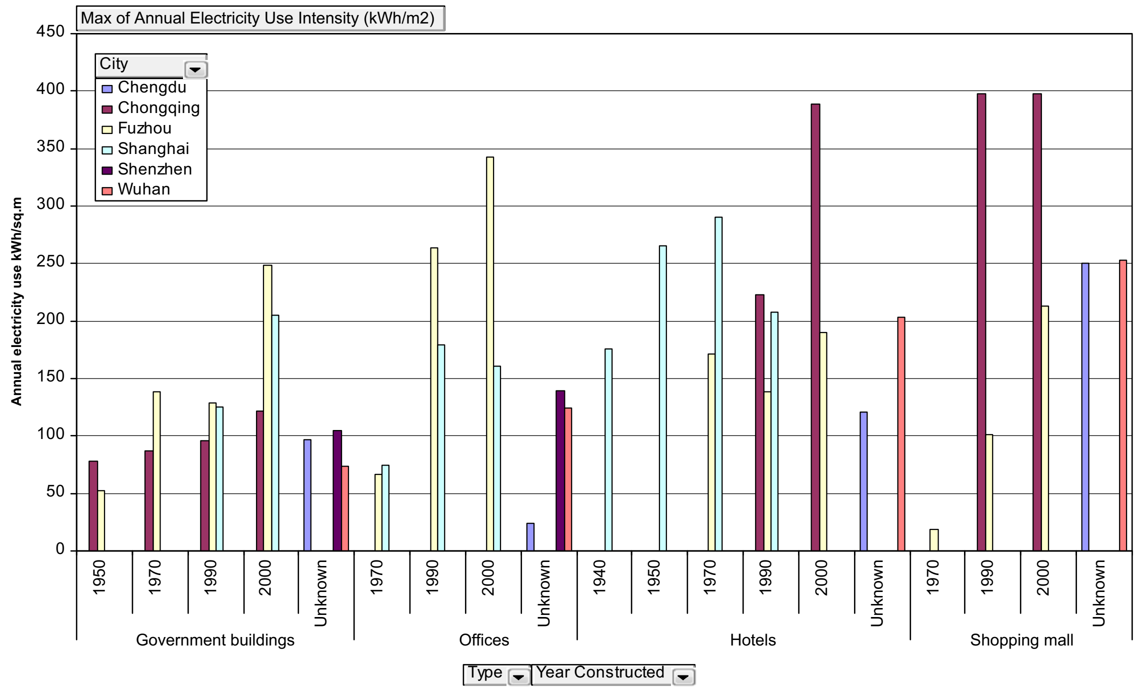

Fig. 3. Most energy intensive buildings are becoming increasingly intensive.

built in 1930 used nearly equal amounts of electricity as hotel buildings built after 1990.

However, when we compared buildings with the highest electricity use, we observed a clear trend that the intensities are becoming increasingly higher. We selected the maximum values of the electricity intensity of buildings built at different years and plotted them in Fig. 3. Fig. 3 shows that the energy intensities of the highest electricity-intensive buildings became increasingly higher over the years. The same trend applies to government buildings, offices, hotels, and shopping malls, for virtually all cities. For example, in Chongqing, the highest electricity-intensive government buildings built in the 1950s used about 75 kW h/m^2 of electricity. The highest electricity-intensive building of the same type built in the 2000s used about 120 kW h/m^2 of electricity a year. The same trend occurred for hotels in Shanghai. The most energy intensive buildings built in the 1940s used about 175 kW h/m^2 of electricity per year, and the most energy-intensive buildings built in the 2000s used about 275 kW h/m^2 of electricity per year.

Although the average building energy intensity of buildings built in different years did not change, the least energy-friendly buildings are getting worse. This phenomenon can be explained by visiting these major cities. A number of modern buildings use full curtain walls with low-quality glazing systems. The solar heat gain of these glass boxes is tremendous. This type of buildings did not exist in China 30 years ago. The lighting power intensities of several high-class shopping malls and hotels are much higher than those high-end buildings built 30 years ago.

3.7. Comparing China with US and India

It is interesting to compare the energy intensities of Chinese buildings with the rest of the world. The comparison will not only determine whether Chinese buildings are using less or more energy than buildings in developed countries, such as the US, but also how much and why. The comparison with India will demonstrate whether economic development is the reason for the difference in the building energy intensities in different countries. Generally, building technologies in developed countries are more advanced than those in developing countries. However, the elevated requirements in comfort and dependence on automated systems in developed countries may make their buildings less energy efficient than buildings in developing countries. Low cost labor in developing countries enables developers to hire more operators and be more resource sensitive. In this study, we used the US as an example of a developed country and India as an example of a developing country.

In the US, the Commercial Buildings Energy Consumption Survey (CBECS) is a national sample survey that collects information on the stock of US commercial buildings, their energy-related building characteristics, and their energy consumption and expenditures (U.S. Department of Energy, 2007). We used the US data from the recent survey completed in 2007.

Because we wanted to remove the influence of weather from the comparison and the US is a large country with drastically different weather locations, we chose southern states in the CBECS survey to compare with buildings in southern China. Although the southern US is a still large geographical area and the weather pattern may differ from place to place, this is the highest resolution we can obtain from the CBECS dataset. The southern states in the CBECS include DC, TX, FL, and NC. Many cities in the southern states have a similar number of cooling degree-days as the cities in southern China. The US matching cities in Table 1 are from the southern states.

In the CBECS dataset, commercial buildings include all buildings in which at least half of the floor space is used for a purpose that is not residential, industrial, or agricultural, so they include building types that might not traditionally be considered "commercial," such as schools, correctional institutions, and buildings used for religious purpose. Correctional facilities and churches were not included in the Chinese survey. Although the definition of US commercial buildings is slightly different from that in China, we were still able to find matches for the majority of building types.

In India, the equivalent weather zone to the cities in southern China is the "subtropical humid area" of India. Northeastern India

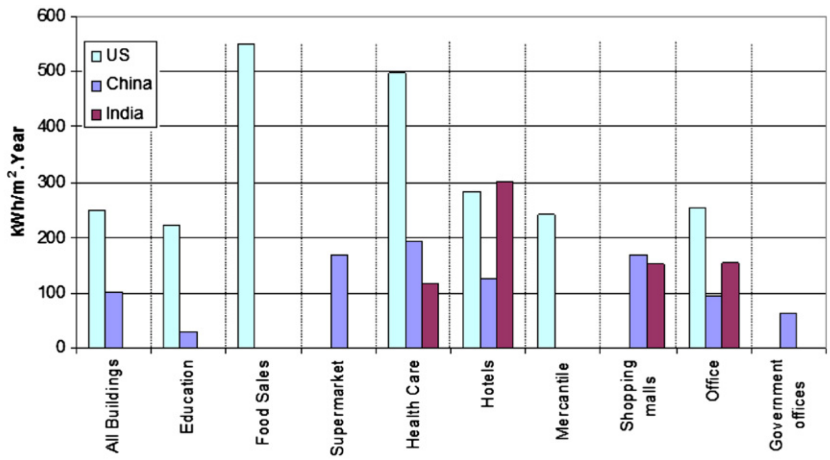

Fig. 4. Building energy intensities of US, India, and China.

and much of Northern India are subject to a humid sub-tropical climate. In 2008, the Bureau of Energy efficiency, Ministry of Power of India, completed a survey of 40 buildings across different use types of office buildings, including IT parks, shopping malls, hotels, and hospitals (Spatial Decisions, 2008). IT Parks had no direct comparison, and we did not use that data. The survey calculated the average energy intensity of these types of buildings.

We compiled the data from the three countries and plotted the building energy intensity of similar building types in Fig. 4.

Although the building stocks in the survey are slightly different, in general, the findings indicate that the energy intensities of the buildings in India were very close to those in China. Both were lower than those of buildings in the US. In China, it is indicated that the overall average energy intensity of all of the commercial buildings was about half as much as that of the US.

The education buildings in China had the lowest energy intensity among all commercial buildings in the three countries because, in southern China, the education facilities normally lack heating and cooling systems. Compared with food sales in the US, the supermarkets in China used about one-third of the energy, which is induced by the data analysis. The energy intensity of the US health care facilities was more than twice as high as that of China and India. Hotels in India and hotels in the US used similar amounts of energy. Hotels in China used about half as much energy as hotels in the US considering the information we can acquire so far

Shopping malls in the US used about 20% more energy than shopping malls in China and India. However, the difference was not as large as other types of commercial buildings. Office buildings in China used about half the amount of energy as office buildings in the US.

Although buildings in the US, China, and India have different average energy use intensities, one thing is common for all three countries. All three countries have large variations in building energy intensities among the same type of buildings at a single location. The variation of Chinese buildings is shown in Tables 6–10 and 11. The maximum values were typically three times the minimum values. The building energy intensities in India and in the US also had large variations. For example, in India, the ranges were 8.14 to 18.55 units/ft^2 for offices, 11.87 to 28.43 units/ft^2 for shopping malls, 3.62 to 10.08 units/ft^2 for IT parks, 30.13 to 37.20 units/ft^2 for hotels, and approximately 11.70 units/ft^2 for hospitals (Spatial Decisions, 2008). The large ranges indicate the potential to improve building energy performance either through design or operation in all three countries.

3.8. End use analysis

Building end use information can be used to understand how buildings were operated and where energy was used. Ideal end use data should include the breakdown of the lighting, cooling, heating, equipment plugs, operating schedule, and seasonal differences. The end use data can be used to develop benchmarks and prototypical models of commercial buildings.

Detailed end use data are difficult to collect because of the lack of sub-meters that separate the cooling electricity use from lighting and plug equipment. Normally, building electricity systems are not designed for sub-metering. Sometimes, it is impossible to add separate meters because the wiring diagram does not support the sub-meters. This is not only a typical problem in China but also a problem in the US and other countries.

However, the end use data can be estimated indirectly from monthly electricity bills. In southern China, the cooling systems are normally turned off during the winter, and the heating systems are turned off during the summer. Few buildings use four pipe cooling and heating systems; thus, simultaneous heating and cooling is seldom a problem. In transitional seasons, electricity is used mainly for lighting, equipment and ventilation because both chillers and boilers are switched off.

Only a small portion of the dataset has monthly utility information. We were able to collect monthly electricity bills for 85 buildings in Shanghai and 50 buildings in Chengdu. From this pool of data, we estimated the breakdown of cooling, heating, lighting and equipment for different types of commercial buildings for the two cities.

3.8.1. End use in cool climate—Chengdu

Fig. 5 is the median value of the monthly electricity usage per square foot in five major types of commercial buildings. The gas use was added to electricity use at the site energy level to calculate the total energy use (Xihua University, 2008). Although researchers should not add them together through simple unit conversion, these are the only monthly data we received from the survey report. The chart demonstrated that, although Chengdu is in Southern China, people do not use cooling as much as expected. For example, education buildings, buildings in colleges and middle schools, did not use any heating and cooling energy throughout the year, and this is also a common phenomenon in education buildings in China. The energy intensity was the lowest among all of the building types. Conversely, hotels used excessive gas heating in the winter to keep guest rooms comfortable.

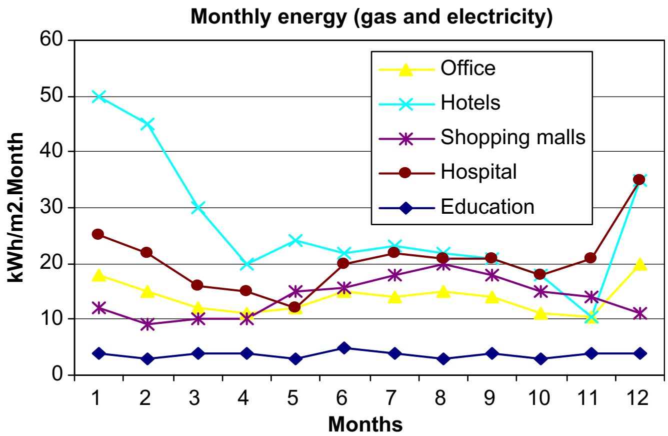

Fig. 5. Median value of monthly energy usage of different building types in Chengdu.

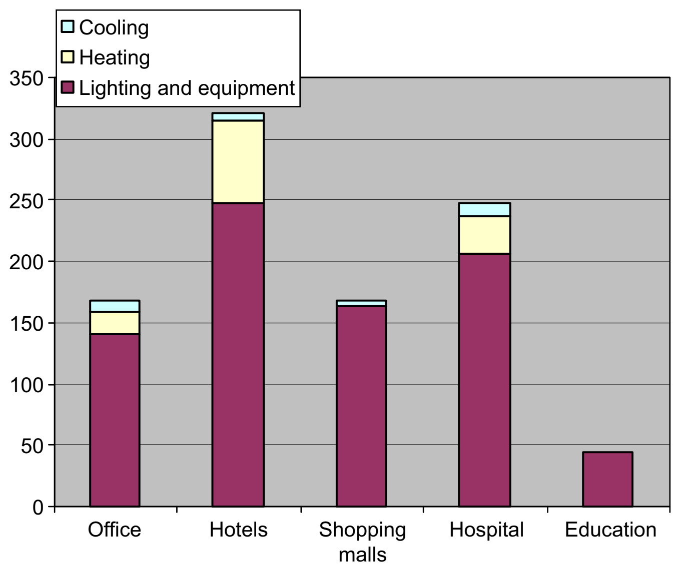

Fig. 6. Energy end use breakdown of different building types in Chengdu (*unit*: kW h/m^2).

Moreover, the total energy use during the winter was higher than that during the summer. Offices, hospitals, and shopping malls did not use much energy for building heating during the winter. The heating requirements of these types of buildings were generally lower than hotels.

Fig. 6 shows the breakdown of the energy used for cooling, heating, lighting, and equipment. Across the major building types, electricity was predominately used for lighting and equipment, more than 80% for offices and hospital, 90% for education schools, and 70% for hotels. Only a small fraction was used for heating and cooling. For hotels and offices, the total heating energy was higher than the cooling energy because of cooler weather during the summer. Shopping malls did not use heating energy throughout the year because of the high internal load from artificial lightings. The cooling energy was small compared to the electricity used for lighting and equipment.

3.8.2. *End use in hot climate—Shanghai*

We drew a similar conclusion from the data in Shanghai, although Shanghai is much hotter than Chengdu and more economically developed. Because Shanghai is more developed

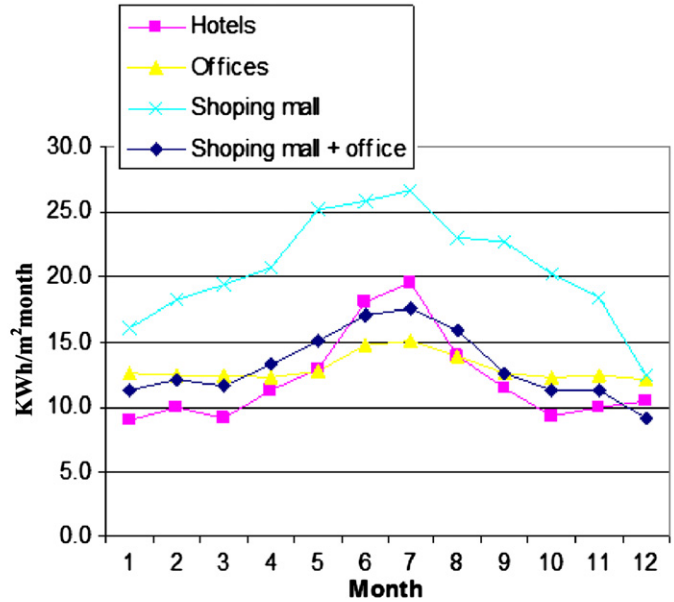

Fig. 7. Monthly building electricity use of different building types in Shanghai.

economically than Chengdu, the comfort level in the buildings is generally higher than in Chengdu. The data from Shanghai include both total energy use and a breakdown of the gas and electricity use. We used the monthly gas use to estimate how much gas was used for domestic hot water and how much was used for space heating because during hot summers when no heating was required.

Fig. 7 shows the monthly electricity use of buildings in Shanghai. The electricity demand peaked during the summer in the month of July. However, the electricity use of different types of building evolved differently during the transitional seasons. For example, the electricity use for offices and hotels was unchanged between Feb, March and April though the weather was becoming increasingly warm. However, the electricity use in shopping malls increased gradually in those three months. The different pattern between shopping malls and offices was because of the lack of operable windows and natural ventilation in shopping malls. Unlike office buildings and hotels, many shopping malls in Shanghai did not use natural cooling during transitional seasons and mechanical cooling was used. Therefore, the cooling electricity consumption increased gradually with the rising outdoor temperature.

Fig. 8 shows the monthly gas use of four types of buildings in Shanghai. We used the unit of kW h/m^2 for gas because it is easy to compare with electricity use. The conversion rate is 1 kW h=0.03413 thm, and the terms cannot be simply added together to calculate total energy because of the site and source energy issue. The gas use of the hotel was significantly higher than that of the three other types of buildings because of the domestic hot water demands. Both shopping malls and offices used gas for heating. While office buildings in Chengdu required heating, the shopping malls did not. Although Shanghai is as cold as Chengdu during the summer, shopping malls in Shanghai use more gas for heating than in Chengdu. This finding was most likely because of the high living standard in Shanghai.

Additionally, we noticed that the monthly heating gas use was not symmetrical with July at the center. The gas usages in January and February were higher than the gas usages in November and December because January and February were much colder than November and December in Shanghai.

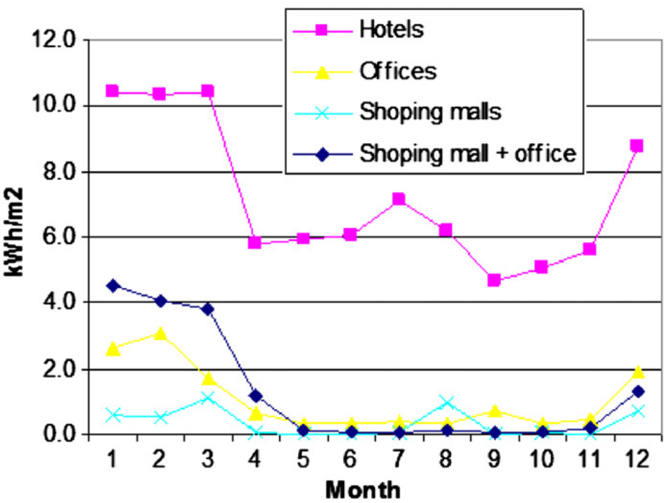

Fig. 8. Monthly gas consumption of different building types in Shanghai.

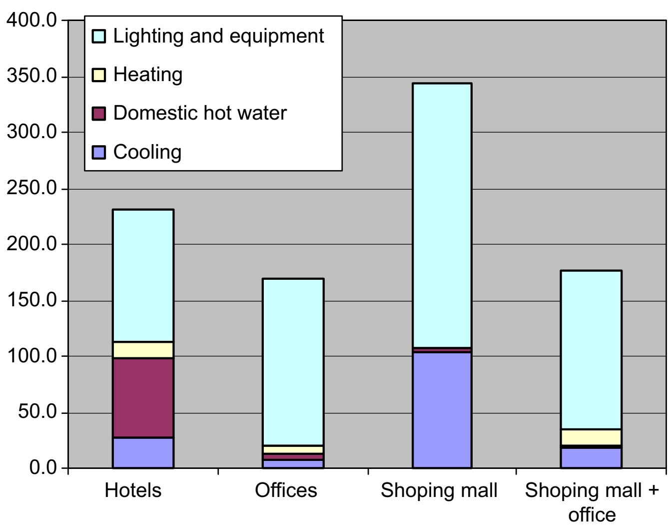

Fig. 9. Energy end use breakdown of the total building energy usage in Shanghai (*unit*: kW h/m^2).

Fig. 9 shows the breakdown of the total building energy usage. The general pattern of the overall energy usage was high during both the winter and summer and low in the transitional seasons for hotels, offices and mixed-use shopping malls and offices. Shopping malls used less energy during the summer than the transitional seasons because of the high internal heat gain from lighting and people.

4. Conclusion and recommendation

This study used the data collected from recent building energy surveys by the MHOUC and Tongji University in Shanghai to study building energy usage patterns in southern China statistically. Building energy data from six major cities were combined to form a single database. The paper presents the statistical results of the building energy use for different sizes, functions, year of construction and locations.

In any country, commercial buildings are gathering places for a large number of people, and they often serve multiple functions and are owned and operated by multiple institutions and individuals. The survey was the first step in an effort at the national level in China to document building energy usage on large scales. The data collection was not perfect because of the complexity of buildings. This report presents the statistical data on the exact energy usage of buildings in southern China and the variations among different vintages. The maximum, average, and minimum energy intensities of various types and sizes of the buildings can be referenced for future policy making or setting up standard inputs for building simulations. We draw the following conclusions from the building energy survey and analysis.

- Building size has no direct correlation with building energy intensity. In southern China, large buildings were equally efficient or less efficient compared to small buildings.
- On average, modern commercial buildings built in the 1990s and 2000s did not use more energy than buildings built previously. However, the comfort level of these modern buildings was generally higher than older buildings.
- On average, modern buildings had the same level of energy intensity as the old buildings. The highest electricity-intensive modern buildings used more energy than the highest electricity-intensive buildings built previously. Over time, the highest electricity-intensive of the newly built buildings use more energy than the highest electricity-intensive building built previously. This finding is not a surprise for visitors that have been to modern cities in southern China. The majority of curtain wall buildings with central HVAC systems were built in the 1990s and 2000s.
- Government office buildings did not use more energy than private office buildings. Private office building owners did not have incentives to save energy because normally the tenants pay the electricity bill themselves.
- Commercial buildings in China used less energy than buildings in the equivalent weather locations in the US. This finding was partially because of the difference in comfort levels and the different efficiencies in building operations. Commercial buildings in China used similar amounts of energy as their Indian counterparts.
- In southern China, electricity was predominately used for lighting and plug loads. However, the energy used for cooling and heating was increasing as China becomes more economically developed. Comparing the end use patterns of Shanghai and Chengdu supported this finding.

The building energy survey is an essential step to improve building energy performance for both engineers and policy makers. The argument that you cannot manage if you cannot measure applies equally as well in China as anywhere else. Through this first step, we learned lessons that future researchers could refer to.

It is important to create a platform or data center that encourages all of the survey participants to share information with each other. The MHURC did not develop a uniformed data requirement for each city, and each city was reluctant to provide the detailed survey information they collected in exchange.

Collecting building information itself is equally important as collecting energy data. Monthly energy data will be more useful than yearly energy data. This round of the survey missed many important details regarding the buildings themselves, and few cities have monthly data. Differences exist in the typical commercial buildings compared with those in western countries, and many of the large commercial buildings are mixed-use. Without detailed floor area data of each function that buildings serve, the aggregated energy usage is not very useful.

The building energy survey is a tedious job with a large number of people involved. It is costly and difficult to survey all buildings. If the survey is only a single event, the information collected will be easily lost after the work is completed. The energy survey should pay more attention to a handful of representative buildings over a longer period of time rather than trying to collect sparse data from all buildings.

Acknowledgements

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