# Measurement of Energy Consumption in Buildings

Rang Tu

## Contents




**Abstract**

Building energy consumption, which consists of residential and commercial buildings, accounts for around 20–40% of the total delivered energy consumption worldwide. It is vital to analyze the current building energy consumption to find out the main energy consumption targets with energy saving potentials, and hence to provide guidelines for efficient building energy system design and retrofitting.

This chapter revolves around the energy consumption of commercial buildings and residential buildings in China and selected foreign countries. First, the current building energy consumption of China, which is divided into four categories, is analyzed. Then, the detailed energy consumption of each part of the energy system in commercial buildings is discussed. Afterward, ways to increase the efficiency of air conditioning systems are particularly analyzed. Next, it presents



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an analysis of and a comparison between the energy consumptions regarding different energy consumption end users of residential buildings in China downtown and selected countries, namely USA, Japan, and Italy. The differences of air conditioning energy consumptions among these countries are explained from the prospect of types of air conditioning systems, namely centralized and split air conditioning systems.

This chapter helps to understand the energy consumption situations of commercial and residential buildings and the directions for increasing the efficiency of air conditioning systems are proposed.

**Keywords**
Energy consumption · Commercial buildings · Residential buildings · Air conditioning systems

## Introduction

Commercial buildings and residential buildings are two major sources of building energy consumption as per IEA (International Energy Agency), EIA (U.S. Energy Information Administration), and IEEJ (The Institution of Energy Economies, Japan). As shown in Fig. 1, among the worldwide total energy consumption of the main end users including building, industry, transportation, building energy consumption takes a larger part compared with other parts, which is around 35% [1]. The reduction of building energy consumption is meaningful for the energy conservation.

The building energy consumption is closely related to GDP. Relationships between annual area average building energy consumption and the capita GDP for

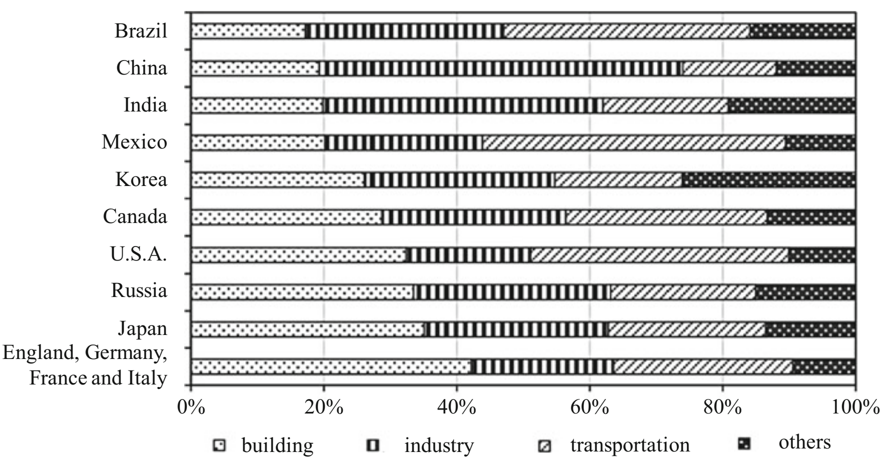



**Fig. 1** Portion of each energy end users in different countries in 2010 [1, 2]

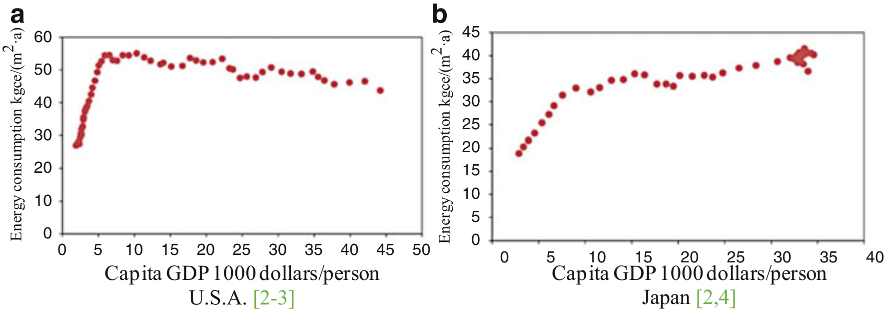



**Fig. 2** Capita GDP and annual area average energy consumption for USA and Japan ((1) area average building energy consumption is the total building energy consumption divided by building area; (2) the energy consumptions of different energy sources are converted into weight of standard coal (kgce: kilogram of standard coal). In other countries, standard oil (oe) is used and 1 kgoe = 1.429 kgce)

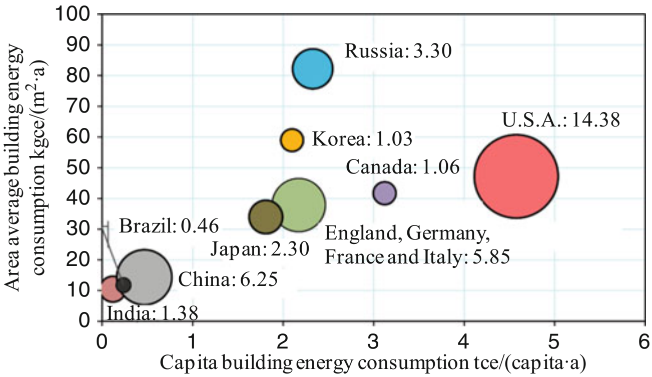



**Fig. 3** Building energy consumption of different countries in 2010 [2] (IEA, World Energy Outlook 2012; EIA, Annual Energy Outlook 2012; IEEJ, Handbook of Energy and Economic Statistics in Japan 2012.)

USA and Japan in Fig. 2 [2–4] illustrate that annual area average building energy consumption increases sharply when capita GDP is low while the variation trend becomes relatively steady afterward.

The annual building energy consumptions, namely total energy consumption (in the unit of $1 \cdot 10^8$ tec, represented by the size of circles), area average building energy consumption, and capita building energy consumption, of different countries are shown in Fig. 3, from which it easily can be seen that the area average and capital building energy consumptions are lower in developing countries than that of developed countries. Besides, there are differences among developed countries. For example, the capita building energy consumption of USA is as two to three times as that of Japan, Korea, and the four European countries. Russia has the highest area average building energy consumption and similar capital building energy consumption compared with Japan and European countries.

This chapter focuses on the energy consumption of commercial buildings and residential buildings in China and selected foreign countries. The building energy consumption situations of China is firstly introduced, including the building energy consumption categories and the yearly development of energy consumption. Afterward, the commercial building energy consumption and residential building energy consumption are discussed based on the field investigation of China and selected foreign countries. Ways to increase energy efficiency of air conditioning systems for both building types are proposed. This chapter is a literature review of previous related researches, including Annual report on China building energy efficiency in 2013, 2014, and 2017, of Building Energy Research Center in Tsinghua University.

## Building Energy Consumption of China

China is a developing country and has several climate zones, including severe cold zone, cold zone, hot-summer and cold-winter zone, hot-summer and warm-winter zone, and mild zone. Centralized heating system is applied in the downtown area of North China in winter. And the residential buildings in rural area have different features with those in downtown area. Considering the differences of winter heating methods between North and South China, building and life styles between rural and downtown areas and people activities, and energy consumption between commercial and residential buildings, the building energy consumption is mainly divided into four parts, which include downtown centralized heating in North China (A), commercial buildings excluding North China centralized heating (B), downtown residential buildings excluding North China centralized heating (C) and rural residential buildings (D). The above four building energy consumption categories in 2015 in China are shown in Fig. 4. The total energy consumption is represented by the area of the four squares; the area average energy consumption is represented by the height of the four squares; the building area for each energy consumption category is denoted by the width of the four squares.

According to the definitions of the four building energy consumption categories, the total building area is the sum of B, C, and D, which was 57.3 billion $m^2$ in 2015. The progressions of building areas of B, C, and D from 2001 to 2015 are shown in Fig. 5. Building area of A is included in that of B and C, which was around one quarter of the total area.

Although building area for B only occupies one fifth of the total building area, the area average building energy consumption is the highest. The total energy consumption generated by each of these four categories are similar and that of B has grown into almost the largest energy consumption part according to the increase of building scales and area average building energy consumption shown in Fig. 6.

Commercial buildings are mainly used for public activities of people. The economic development, serving quality and features of public activities can be

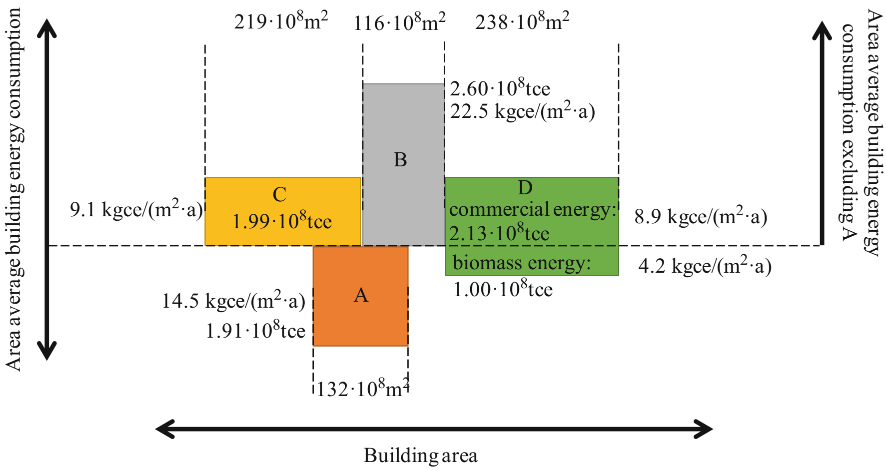



**Fig. 4** Building energy consumption in China (year 2015) [5]

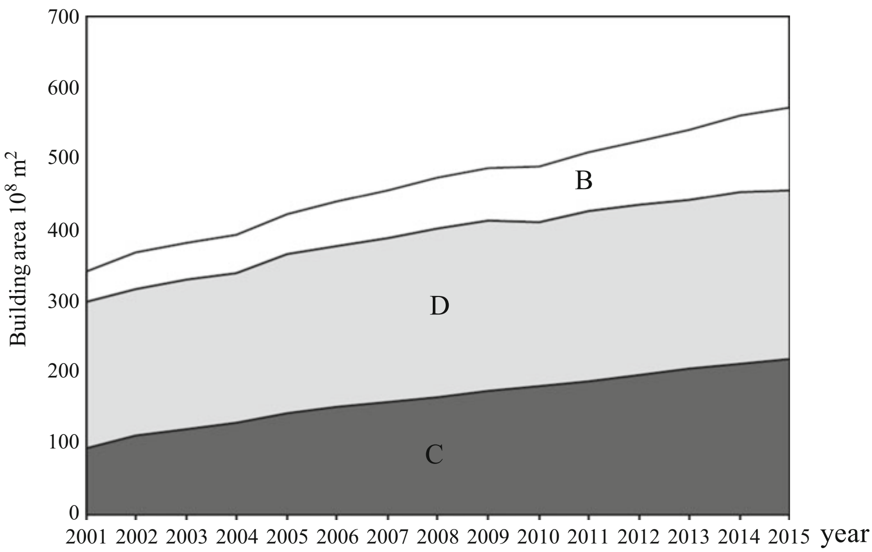



**Fig. 5** Building area of China from 2001 to 2015 [5]

reflected by the corresponding capital building area. The capital areas of commercial buildings for different countries are shown in Fig. 7.

Energy consumption of downtown residential buildings excluding North China centralized heating should also be analyzed. China is experiencing fast urbanization and increase of downtown population (from $4.59 \cdot 10^8$ in 2000 to $7.71 \cdot 10^8$ in 2015). Besides, downtown residential building area is growing rapidly as shown in Fig. 8.

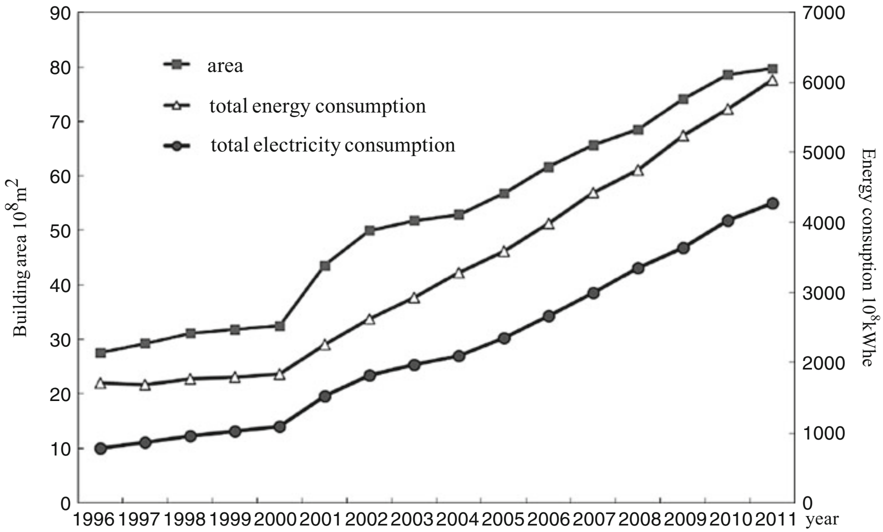



**Fig. 6** Building area and building energy consumption of commercial buildings excluding North China centralized heating [6] (the energy consumptions of nonelectricity energy sources are converted into equivalent electricity in the unit of kWhe)

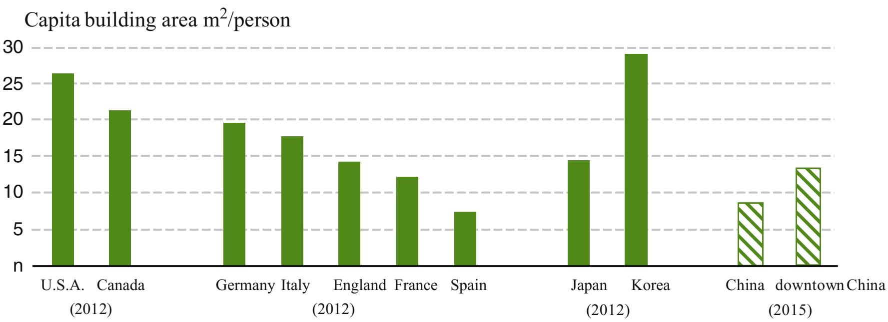



**Fig. 7** Capital commercial building area for different countries [5] (capital area of China is the total commercial building area of China divided by total population; capital area of downtown China is the total commercial building area of downtown China divided by total downtown population)

Similarly, capita residential building area reflects the economic level as well as the living pattern of a country. Shown as Fig. 9, the capita area of residential building in USA is over 70 $m^2$, which is much higher than that of other countries. China, on the other hand, has the largest residential building capita area among the BRIC countries, which is around 30 $m^2$/person.

With the increase of downtown population and downtown residential building area, the energy consumption of residential buildings in China has been increasing. Shown as Fig. 10, the energy consumption of residential buildings increased from $0.72 \times 10^8$ tce in 2001 to $1.99 \times 10^8$ tce in 2015, in which electricity consumption

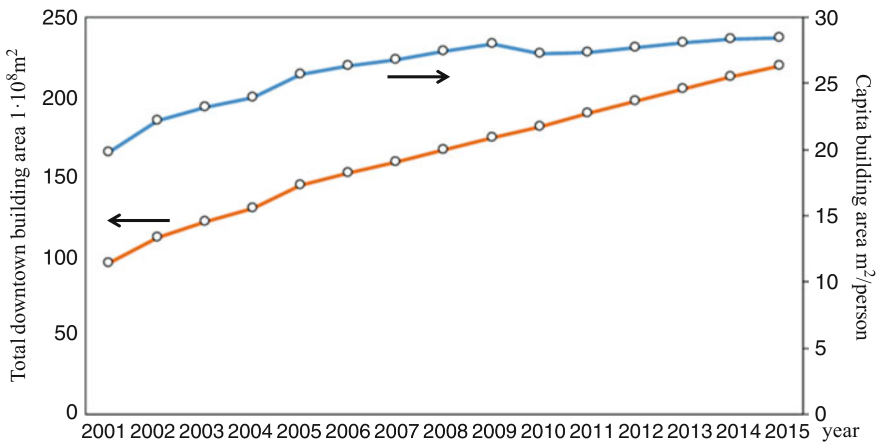



**Fig. 8** Total downtown residential building area and capita building area of China [5]

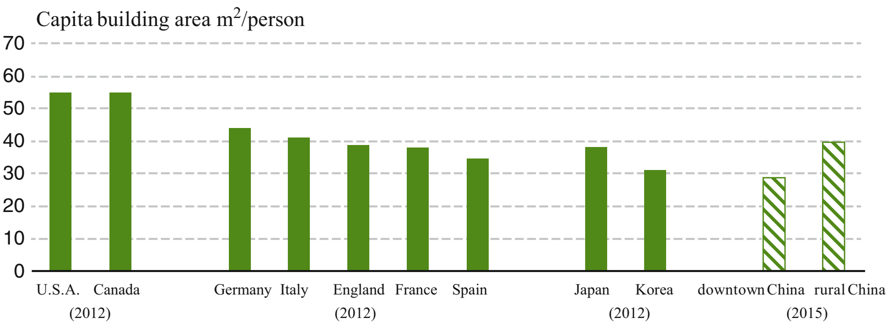



**Fig. 9** Capital residential building area for different countries [5]

increased from 1231 × $10^8$ to 4300 × $10^8$ kWh. The annual household average energy consumption slowly increased from around 500 kgce/(hh·a) in 2001 to around 750 kgce/(hh·a) in 2015.

The total energy consumption and area average or capita energy consumption of commercial buildings and residential buildings are discussed in this subsection. The next two chapters mainly focus on the energy consumptions of different parts in the building energy system.

## Building Energy Consumption of Commercial Buildings

Commercial buildings refer to architectures for public activities, such as office buildings, schools, hotels, shopping malls, hospitals, train stations or airports, stadiums, etc. Energy consumptions in commercial buildings come from air

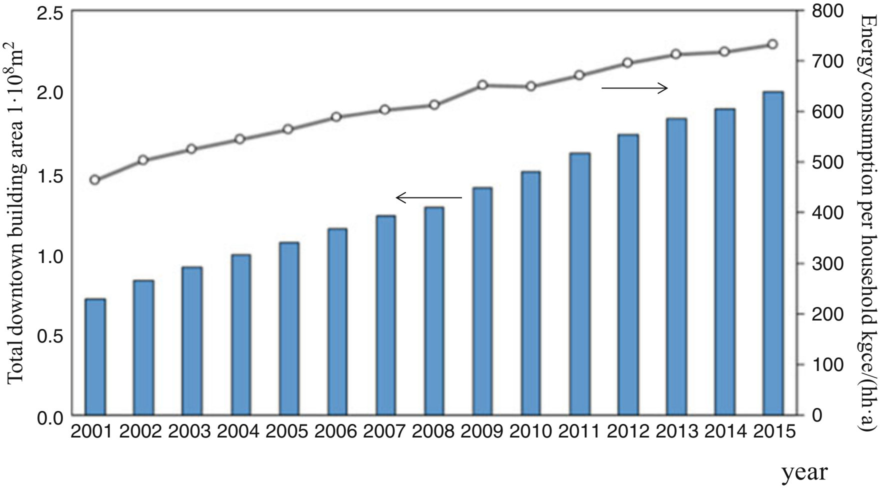



**Fig. 10** Annual energy consumption of residential buildings from 1996 to 2011 [5]

conditioning systems, lighting, office appliances, etc., which are used to function the buildings. The main energy source is electricity, except for centralized heating in North China [6]. The area average energy consumptions of different types of commercial buildings in China are shown in Fig. 11.

In this subsection, three types of commercial buildings, including office buildings, hotels, and shopping malls, are selected for discussion.

## Energy Consumption of Buildings and Each Part of the Building Energy System

Figure 12 shows the total energy consumptions ($E_{tot}$, in the unit of equivalent electricity consumption kWhe) and annual area average energy consumption ($e_{area}$, in the unit of kWhe/(m$^2$·a)) of the three types of commercial buildings in Shanghai in 2010. Figure 12a–c shows the percentages of buildings in different $E_{tot}$ ranges for office buildings, hotels, and shopping malls, respectively. There were 45% office buildings whose $E_{tot}$ are in the range of 3.5 and 7 million kWhe. Besides, 33% and 38% hotels had $E_{tot}$ in the ranges of 3.5–7 million kWhe and 10–20 million kWhe, respectively. Moreover, 30% and 30% hotels had $E_{tot}$ in the ranges of 7–10 million kWhe and 10–20 million kWhe, respectively. "$e_{area}$" eliminates the influences of building area and makes comparison of energy consumption fairer among buildings. Figure 12d shows that office buildings and hotels had similar $e_{area}$, which was around 120 kWhe/(m$^2$·a), which was close to 180 kWhe/(m$^2$·a) for shopping malls.

Figure 13 shows the distribution of building numbers with $e_{area}$ of three types of commercial buildings in Shanghai. It can be seen that $e_{area}$s of office buildings and hotels are in a normal distribution in the range of 94–117.6 kWhe/(m$^2$·a) and

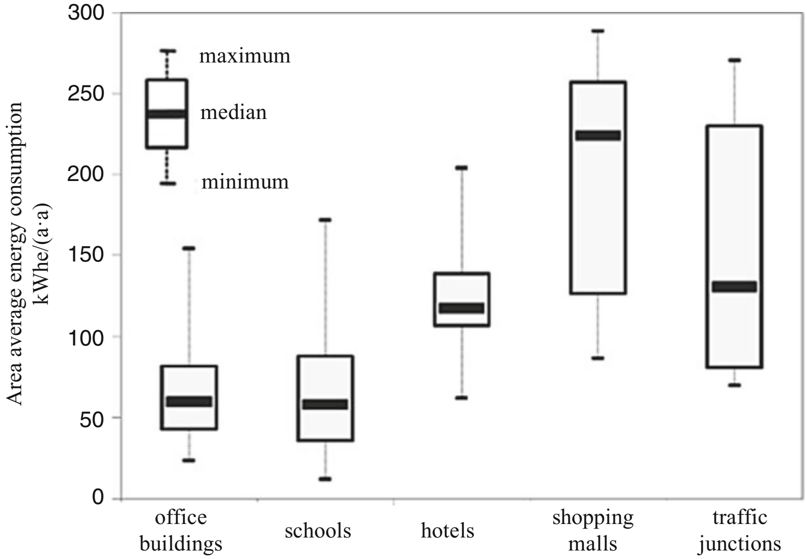



**Fig. 11** The area average energy consumptions of different types of commercial buildings in China [6]

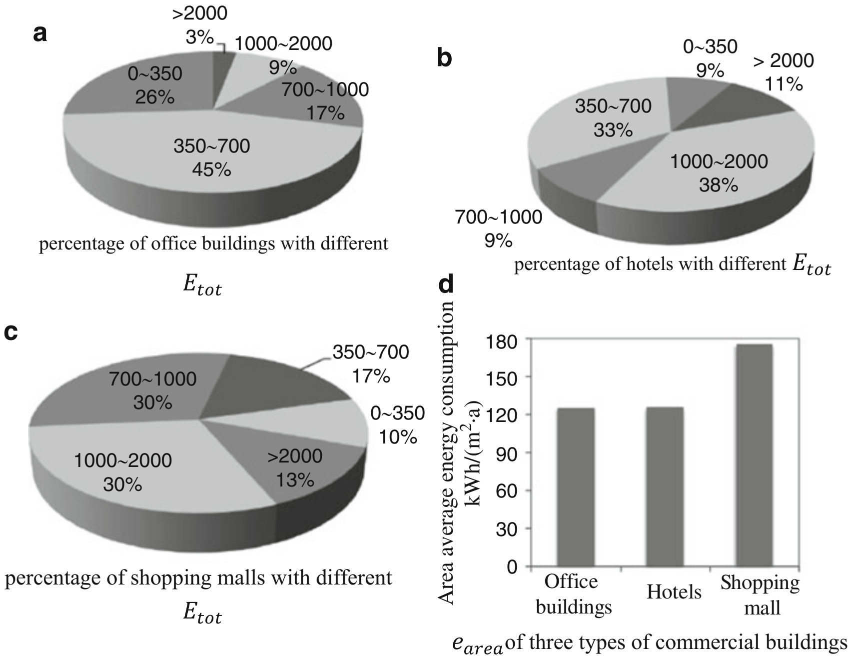



**Fig. 12** Total energy consumption (10,000 kWhe) and energy consumption densities and distribution of three types of commercial buildings in Shanghai in 2010 [6]

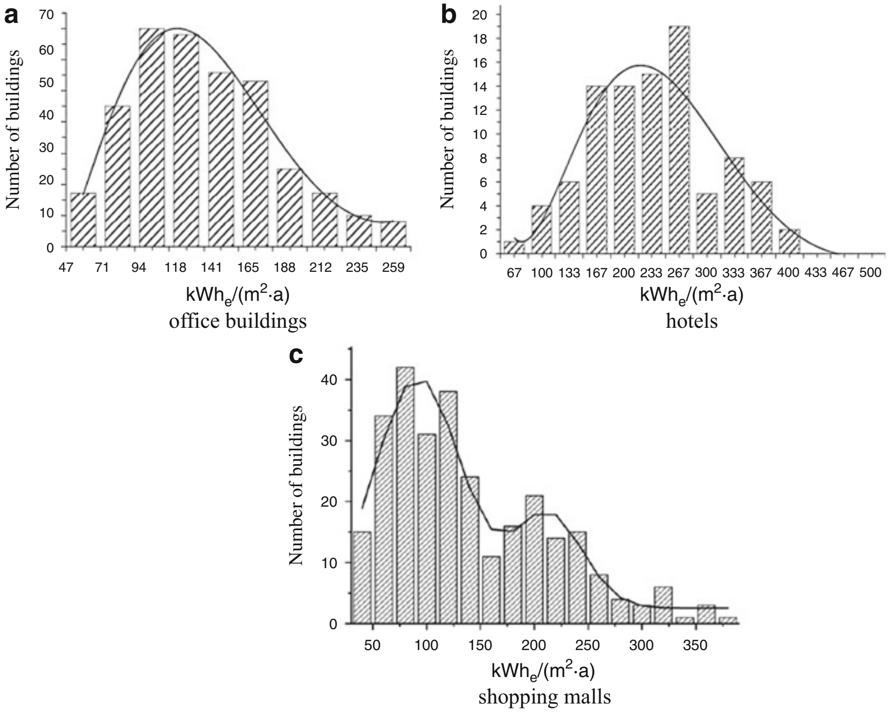



**Fig. 13** Energy density distribution of the three commercial building samples in Shanghai 2010 [6]

66.7–433.3 kWhe/($m^2$·a), respectively. There were 292 out of 367 office buildings falling in the range of 71–165 kWhe/($m^2$·a). Besides, there were 62 out of 94 hotels which were in the range of 167–267 kWhe/($m^2$·a). However, it is shown that bimodal distribution was in the range of 35.4–489.6 kWhe/($m^2$·a) for shopping malls. There were 144 out of 285 shopping malls being in the range of 50–125 kWhe/($m^2$·a), and 65 out of 285 shopping malls was in the range of 175–250 kWhe/($m^2$·a) [6].

Figures 12 and 13 illustrate the energy consumption of the whole building energy system. The building energy system serves for several different purposes, such as air conditioning system (HVAC), lighting, plugs, water heating, etc, with the assistance of one kind or several kinds of end users. Therefore, the building energy systems can be classified into different categories based on the functions of end users. Through calculating the energy consumption of each end user or category, the energy consumption situation of each category can be obtained and hence to be compared with other categories in the same building or with the same category in other similar buildings. This is beneficial for energy consumption analysis and energy system retrofitting.

Basically, the functions of building energy system are space cooling and heating, lighting, office appliance electricity supply, water heating, etc. Fig. 14 shows the classification model which was proposed based on these functions (ISO 12655:2013 Energy performance of buildings – Presentation of measured energy use of buildings).

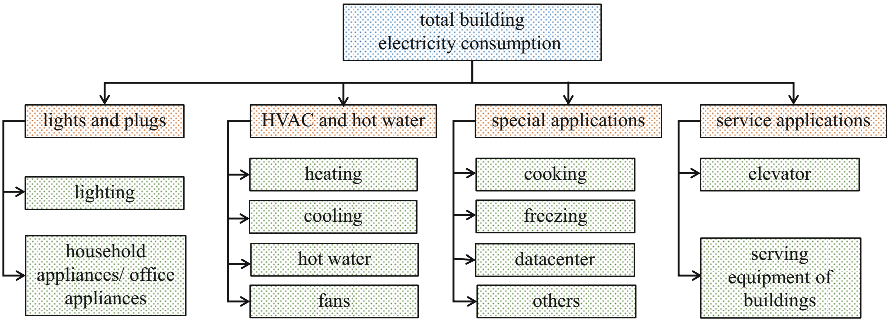



**Fig. 14** Classification model based on functions of end users [6]

Total building electricity consumption in this model is divided into four primary classifications, including electricity consumption of artificial lights and plugs, electricity consumption of air conditioning system (HVAC), electricity consumption of power supply, and electricity consumption of special applications. Each end user is categorized into only one of the four primary classifications.

The index of energy consumption intensity (*ECI*) is usually adopted to evaluate the energy efficiency of the building energy system, which can be calculated through Eq. 1 [7].

$$ECI = E_{tot}/GFA \tag{1}$$

where

*ECI* [kWhe/(m$^2$·a)] = energy consumption intensity
*GFA* [m$^2$] = gross floor area

*GFA* is the gross floor area, namely the area of all enclosed space of the building measured. $E_{tot}$ of the commercial building was divided into five parts [7], including: electricity consumption of the air conditioning system ($E_{ACS}$), electricity consumption of lighting system ($E_{LS}$), electricity consumption of indoor equipment system ($E_{IES}$) like water heaters and plugs, electricity consumption of integrated service system ($E_{ISS}$) such as average power appliances, and electricity consumption of special service region ($E_{SSR}$). The corresponding formulas are Eqs. 2, 3, 4, 5, and 6.

$$ECI_{ACS} = E_{ACS}/ACA \tag{2}$$

$$ECI_{LS} = E_{LS}/GFA \tag{3}$$

$$ECI_{IES} = E_{IES}/GFA \tag{4}$$

$$ECI_{ISS} = E_{ISS}/GFA \tag{5}$$

$$ECI_{SSR} = E_{SSR}/SSR \tag{6}$$

where

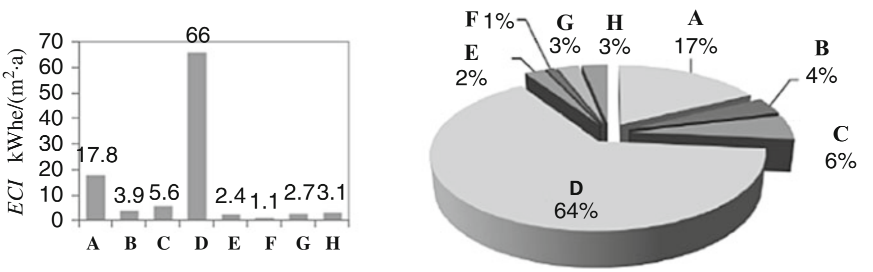
$ACA$ [$m^2$] = air conditioning area
$SSR$ [$m^2$] = special service region

It should be noted from Eqs. 1, 2, 3, 4, 5, and 6 that the floor areas used to calculate *ECI* vary a lot depending on energy consumptions. For ACS or HVAC, which only serves the air conditioning area, $ECI_{ACS}$ should be calculated by dividing $E_{ACS}$ with *ACA* for fair comparison between different buildings. Special regions, like kitchens and data centers, have different energy consumption features, namely heat dissipate density and running period. Taking data centers as an example, the computers or servers run 24/7 with large heat dissipation rate around 100–500 kW/$m^2$, which is much larger than the heat load of offices. The data centers must be cooled 24/7 using ACS, which is specifically designed for them. Therefore, $ECI_{SSR}$ should be calculated separately from other ACS systems by dividing $E_{SSR}$ with *SSR*. Other energy consumption categories like lighting, plugs, and power appliances are normally designed for the whole building while the corresponding *ECIs* are calculated based on *GFA*.

The tested *ECI* and percentages of each end users in a typical office building, a hotel and a shopping mall in Shenzhen China are shown in Figs. 15, 16, and 17, respectively.

## Energy Consumption of HVAC Systems in Commercial Buildings

Figures 15, 16, and 17 show that energy consumption of air conditioning system takes around 27–34% of the total energy consumption of the commercial buildings in Shenzhen. Figure 18 shows the annual energy consumption as well as the percentage of different classifications of shopping malls located at different climate regions in China. It is noted that energy consumptions of air conditioning systems take 27–67% of the total building energy consumption, especially for all-air systems in hot and




A: chiller plant; B: AHU and cooling tower; C: FAU and FCU;
D: office lighting and plugs; E: public lighting; F: domestic water pumps; G: elevators; H: others

**Fig. 15** Actual *ECI* and percentages of each end users in a typical office building in Shenzhen [6]

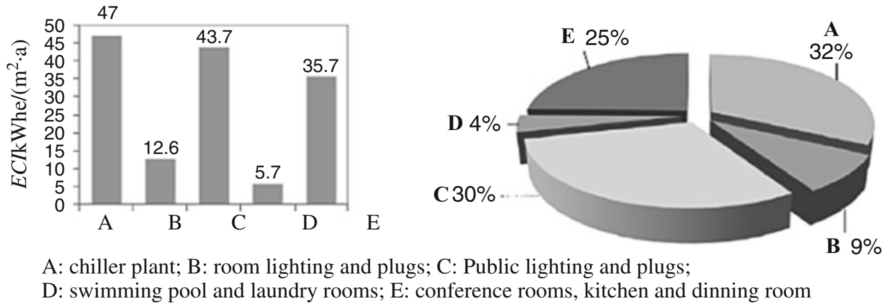



**Fig. 16** Actual *ECI* and percentages of each end users in a typical hotel in Shenzhen [6]

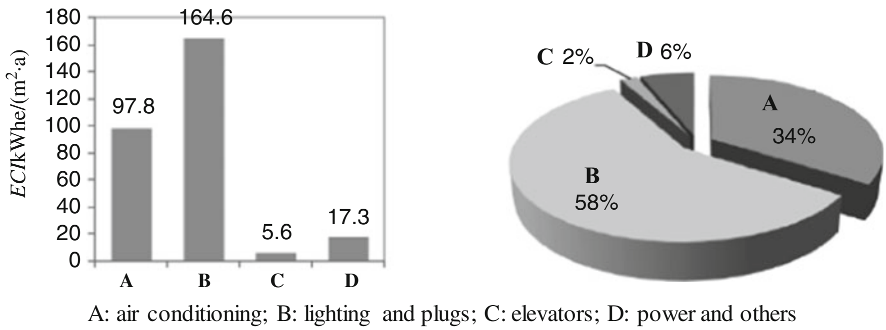



**Fig. 17** Actual energy consumption densities and percentages of each end users in a typical shopping mall in Shenzhen [6]

humid climate regions. It is important to dig into the air conditioning systems to improve its efficiency.

This subsection is mainly focused on energy consumptions of centralized air conditioning systems. The centralized air conditioning system includes two parts, namely chiller plants and indoor terminals, shown in Fig. 19. For commercial buildings, the energy consumption of HVAC is 30–60% of the total energy consumption [6]. *EER* is used to evaluate the annual overall energy efficiency of the chiller plant, which can be calculated through Eq. 7 [6].

$$EER_{\mathrm{plant}} = W_{\mathrm{plant}}/Q_e \tag{7}$$

where

$EER_{\mathrm{plant}}$ [−] = Energy Efficiency Ratio of the chiller plant
$W_{\mathrm{plant}}$ [kWh] = Energy consumption of the chiller plant, including vapor compressors, pumps, and outdoor fans
$Q_e$ [kWh] = Cooling capacity of the chiller plant

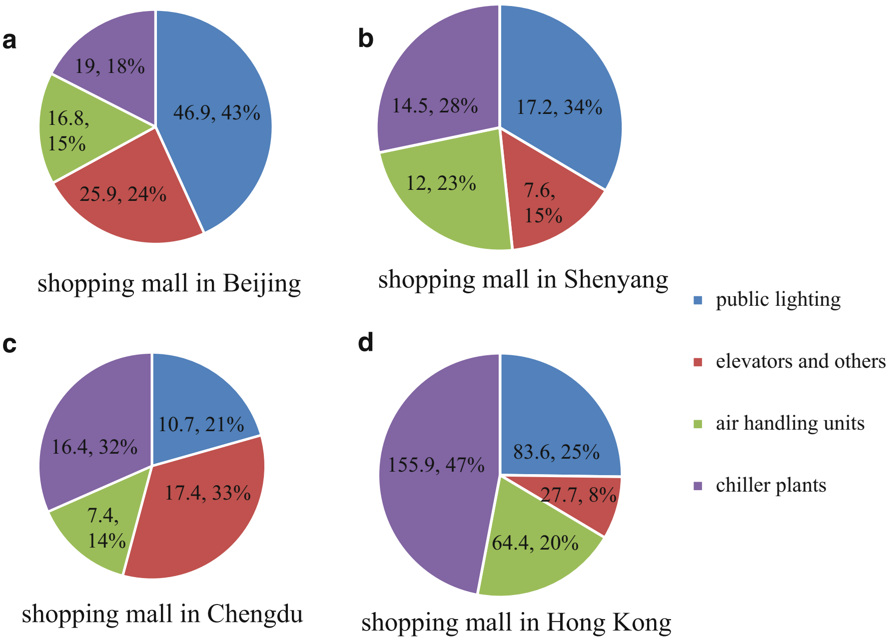



**Fig. 18** Annual area average energy consumption (kWh/(m$^2$·a)) of shopping malls with all-air air conditioning system located in different climate regions [6]

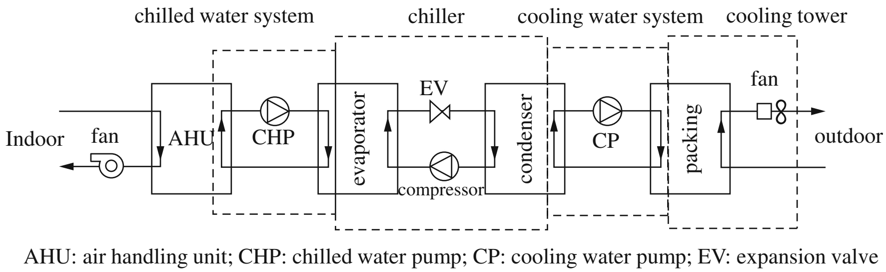



**Fig. 19** Schematic of typical centralized air conditioning system [6]

Lower $EER_{plant}$ means less energy is consumed to produce or transfer the same cooling capacity. Performance of the chiller plant can be evaluated as excellent, good, average, which can be improved based on $EER_{plant}$. Tsinghua University proposed a scale (based on the ASHRAE standard) which displays the tested *EER* of several centralized chiller plants of commercial buildings, which is shown in Fig. 20 [6].

This scale is drawn based on ASHRAE standards. These samples are shopping malls, office buildings or hotels with centralized chiller plants. Buildings R, S, and P

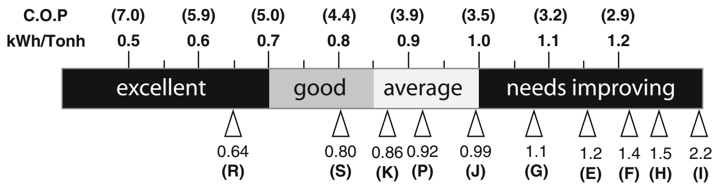
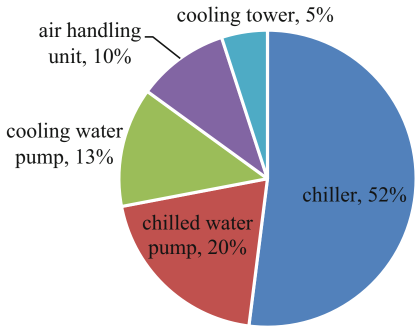



**Fig. 20** Annual energy efficiency of tested chiller plants shown on the scales [6]

**Fig. 21** Energy consumption percentage of each subsystem of the centralized air conditioning system in a five-star hotel in Beijing [6]




are located at Hong Kong while others are located at mainland China. It can be seen that $EER_{\text{plant}}$ differs greatly among different buildings.

Figure 21 shows that typical chiller plants include four parts, which are chillers, chilled water system, cooling water system, and cooling towers. Vapor compressors of chillers, chilled water pumps, cooling water pumps, and fans of cooling towers are the energy consumption end users.

Among all the equipment of chiller plants, the chiller has the highest energy consumption, which takes 40–50% of the energy consumption of the air conditioning system [6], which is followed by the chilled water pumps and cooling water pumps. They totally take 30% of the energy consumption of the air conditioning system [6]. Figure 21 shows the energy consumption percentage of each subsystem of the centralized air conditioning system in a five-star hotel in Beijing. It shows that chillers, chilled water pumps, and cooling water pumps take about 50%, 20%, and 20%, respectively, of the energy consumption of the centralized air conditioning system.

Similar with $EER_{\text{plant}}$, performance of each part of the chiller plant can be evaluated by dividing the corresponding energy consumption based on the cooling capacity, which is shown in Fig. 22. For example, *EER* of the chilled water system, $EER_{CHWP}$, is the power consumption of chilled water pumps, $W_{CHWP}$, divided by the cooling capacity, $Q_e$. *EER* of the chiller, the cooling water system and the cooling tower can be defined in the same way.

The operation of each part of the chiller plant can not only directly influence the *EER* of itself, but also influences *EER* of the neighbor part. Taking the cooling tower

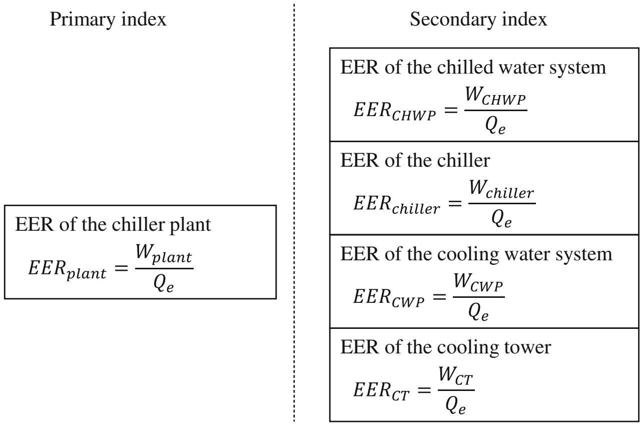



**Fig. 22** Performance indexes of the chiller plant [6]

system as an example, the cooling water temperature can be reduced by improving the cooling tower efficiency. Lower cooling water temperature is beneficial to the increase of the efficiency of chillers. Therefore, the following two aspects should be kept to improve the overall performances of chiller plants: (a) Increasing the efficiency of each equipment, such as increasing *COP* of chillers, increasing pump efficiency, etc; (b) Operation of the equipment should be matched properly, such as the controlling strategies among chillers, matching operation between the cooling tower and the chillers, etc.

For energy conservation operation, the priority is to increase chiller *COP*. After this, efficiencies of chilled water system and cooling water system should be improved. Figure 23 shows the $EER_{\mathrm{plant}}$ of six commercial buildings before and after retrofitting. It shows that after retrofitting, part of the chiller plants went into the "good" region while some jump into the "excellent" region. This illustrates that efficiency of centralized chiller plants can be greatly improved by increasing equipment efficiencies and improving operation modes, etc.

## Building Energy Consumption of Residential Buildings

Energy consumption of residential buildings refers to the energy used by the household appliances to support living, studying, and resting. The energy sources are mainly electricity and natural gas [5]. The energy consumption can be divided into six subsections, including summer air conditioning, decentralized winter heating, hot water, cooking, lighting, and household appliances [5]. It should be noted that this part only focuses on downtown residential buildings. The energy consumption of centralized heating in the downtown residential buildings is excluded from the total energy consumption. However, the decentralized heating, such as split heat pumps, is included in the total building energy consumption.

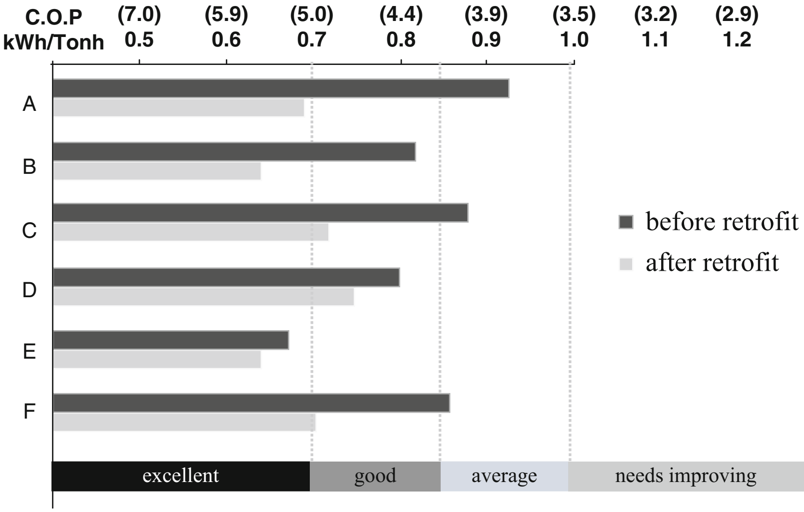



**Fig. 23** Performances of chiller plants before and after retrofitting [6]

## Energy Consumption of Residential Buildings in China

The energy consumption from 2001 to 2015 and the corresponding portions of the above mentioned six subsections are shown in Fig. 24. It shows that cooking (29%), household appliances (20%), and lighting (16%) serve as the top three energy consumption subsections, which are right followed by hot water, which started from 7% in 2001 and increased to 14% in 2015. Air conditioning and decentralized heating were the lowest energy consumption subsections, with the portions of 12% and 9%, respectively. However, during 2001–2015, the total energy consumptions of these two subsections were increasing and therefore their portions were becoming larger.

Generally, energy consumption in residential buildings can be classified as heat consumption and electrical consumption. The heat consumption is obtained from the burning of fossil fuels. By converting the consumptions of each fossil fuel into standard coal, the heating consumption can be obtained as the weight of standard coal. Similarly, the electricity consumption can be converted into the weight of standard coal as per the coal consumption for power generation. (1 kWh electricity equals to 326 gce as per the coal consumption for power generation in 2008 in China.) This makes the electricity consumption comparable with the heat consumption.

Figure 25 shows the field test results of residential heat and electricity consumption per household in seven cities located at different climate regions in China. Figures 25a–g show the heat consumption and electricity consumption of each family in different cities. Figure 25h shows the annual area average heat and electricity

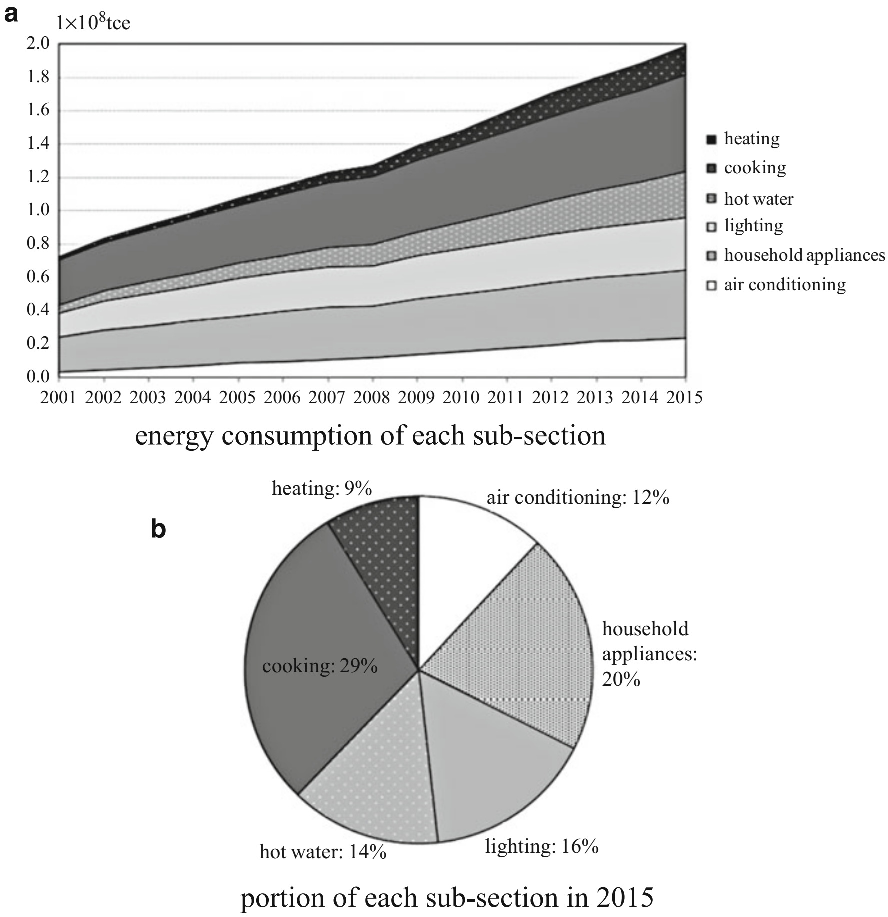



**Fig. 24** Annual energy consumption of each subsection from 2001 to 2015 and the corresponding portion of each subsection [5]

consumption of the seven cities. It can be seen from Fig. 25h that $e_{area}$ of the seven cities were higher than 10 kgce/(m$^2$·a) and lower than 20 kgce/(m$^2$·a), which were 19 kgce/(m$^2$·a) and 18 kgce/(m$^2$·a) for Beijing and Shanghai, respectively.

$e_{area}$ and the portion of heat consumption increased with city scales, which can be approved by Beijing and Shanghai. Electricity consumption of cities in South China, like Shanghai, Wuhan, Wenzhou and Suzhou, was 3 kgce/(m$^2$·a) on average, which was higher than that of other cities in North China, like Beijing, Shenyang and Yinchuan. This is because centralized heating is not included in the energy consumption while energy consumption of decentralized heating, which were usually vapor compression heat pumps that were adopted by cities in South China, was included. According to previous investigations, the energy consumption of

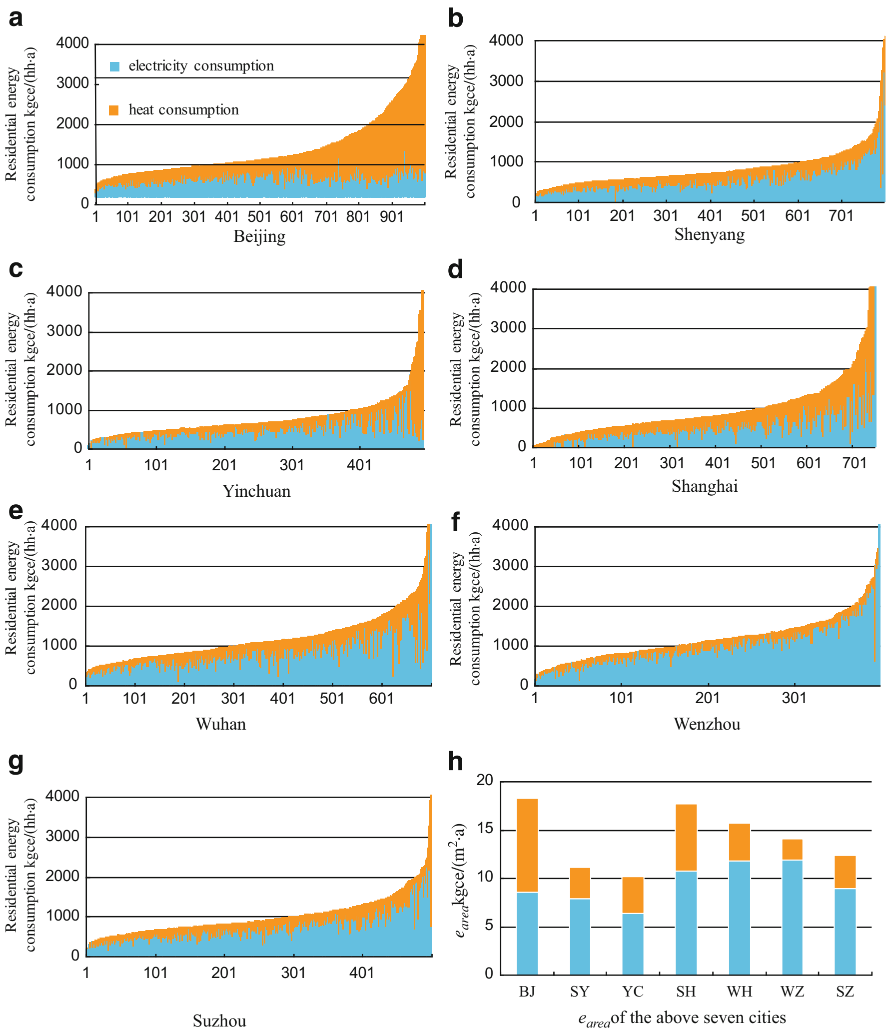



**Fig. 25** Field test results of heating and electricity consumption of seven typical cities in China [8]

decentralized heating was around 0.5–3 kgce/(m$^2$·a), which corresponded well with this result.

## Energy Consumption of Residential Buildings in Foreign Countries

Energy structure differs greatly in different counties. Natural gas, liquid petroleum gas, biomass and solar energy are popular energy sources in residential buildings apart from electricity. It is difficult to acquire the energy consumption data of every energy source. However, as the main energy source, the electricity consumption data is easy to obtain. It can be used as an important index to evaluate the energy consumption of residential buildings. Figure 26 shows the annual household average electricity consumption of selected cities in the world [8].

It can be seen from Fig. 26 that Canada and USA, which belong to the North America, have the highest annual household average energy consumption, which are 11,879 and 11,698 kWh/(hh·a) correspondingly. They are followed by countries located in Pacific area and North Europe, which exceeds 6000 kWh/(hh·a).

| | | | | | |
|---|---|---|---|---|---|
| **World average** | **3471** | | | | |
| **Europe** | **4464** | **North America** | **11718** | **Africa** | **2083** |
| **EU** | **4155** | Canada | 11879 | Gabon | 6273 |
| Sweden | 9697 | U.S.A. | 11698 | South Africa | 4389 |
| Finland | 9385 | **Middle East** | **11527** | Egypt | 2421 |
| Iceland | 7756 | Israel | 7495 | Algeria | 1987 |
| Macedonia | 7332 | Syria | 4943 | Congo | 1834 |
| France | 6343 | Jordan | 4541 | Senegal | 1473 |
| Cyprus | 5689 | Iran | 3580 | Tanzania | 1381 |
| Irland | 5287 | **Pacific** | **5518** | Tunisia | 1371 |
| Switzerland | 5278 | New Zealand | 7918 | Morocco | 1305 |
| Austria | 4896 | Australia | 7227 | Kenya | 1156 |
| Belgium | 4688 | **Asia** | **1625** | Niger | 1093 |
| England | 4648 | Taiwan China | 8475 | Chad | 917 |
| Luxembourg | 4599 | Japan | 5513 | Ghana | 691 |
| Slovenia | 4562 | Hong Kong China | 4745 | Ivory Coast | 672 |
| Greece | 4490 | Korea | 4215 | Nigeria | 570 |
| Spain | 4131 | Thailand | 2112 | Ethiopia | 502 |
| Croatia | 4059 | Pakistan | 1949 | Cameroon | 470 |
| Denmark | 4043 | Indonesia | 1475 | **Commonwealth of Independent States** | **2357** |
| Bulgaria | 4002 | China | 1349 | | |
| Albania | 3676 | Philippines | 973 | | |
| Portugal | 3650 | India | 900 | Russia | 2419 |
| Estonia | 3512 | Nepal | 443 | Kazakhstan | 2104 |
| Germany | 3512 | | | **Latin America** | **2046** |
| Czech | 3257 | | | Paraguay | 3235 |
| Holland | 3172 | | | Argentina | 3160 |
| Hungary | 2967 | | | Colombia | 2250 |
| Turkey | 2777 | | | Brazil | 1834 |
| Italy | 2777 | | | Mexico | 1809 |
| Slovakia | 2641 | | | Peru | 1414 |
| Poland | 2134 | | | Bolivia | 1079 |
| Latvia | 2123 | | | | |
| Lithuania | 1959 | | | | |
| Romania | 1618 | | | | |

**Fig. 26** Annual household average electricity consumption of selected cities in the world [8]

Countries in Middle East, which export petroleum like Saudi Arabia, also have high annual household average energy consumption, which is 11,527 kWh/(hh·a). The annual household average energy consumption in Africa and Latin America is around 2000 kWh/(hh·a). Asian countries have the lowest annual household average energy consumption, which is only 1625 kWh/(hh·a). However, there are exceptions like Taiwai China and Japan, which are 8475 kWh/(hh·a) and 5513 kWh/(hh·a), respectively. Generally, the annual household average energy consumption of China is relatively low, which is 1349 kWh/(hh·a).

Residential building energy consumption of USA, Japan and Italy are selected for detailed analysis. Data of USA comes from Building Energy Data Book (http://buildingsdatabook.eren.doe.gov/) provided by U.S. Department of Energy. Data of Italy comes from Italian National Agency for New Technologies (http://www.enea.it/it), Energy and Sustainable Economic Development. Data of Japan comes from The Statistics Bureau of Japan (http://www.stat.go.jp/english/data/index.htm) and Energy Conservation Center of Japan. To make this comparable between different countries, the consumption of different energy sources like electricity, natural, petroleum, etc., are converted into standard coal. The primary energy power generation efficiencies of Japan are 40.88% as per EDMC, and that of Italy is 40.93% as per Enerdata (http://www.enerdata.net/). The data of USA comes from Building Energy Data Book directly, which is recorded as primary energy consumption.

Figure 27 shows the energy consumption of different energy sources of residential buildings in USA, Italy and Japan. Figures 27a, b show the results for USA in 2010. It is shown that energy was mainly consumed by heating and air conditioning, which were 1937 kgce/(hh·a) and 1053 kgce/(hh·a), taking 28% and 15% of the total consumption, respectively. This is followed by residential hot water and lighting, which were 901 kgce/(hh·a) and 673 kgce/(hh·a), occupying 13% and 10%, respectively. Figures 27c, d show the results for Italy. It is shown that heating, which took 52% of the total energy consumption, was the main energy consumption end user. This is followed by household appliances and lighting, which together took 34%. Portions of residential hot water and cooking were 9% and 5%, respectively. Figures 27e, f show the results for Japan. It can be seen that household appliances and lighting was 1239.7 kgce/(hh·a) with the portion being 52%. This is followed by heating and residential hot water, which were 431.5 kgce/(hh·a) and 484.4 kgce/(hh·a), occupying 18% and 20% respectively. Air conditioning consumed the least energy, which was 60.6 kgce/(hh·a), with the portion being 3%.

Table 1 presents a comparison of the residential buildings in downtown China, USA, Japan, and Italy in the names of different energy consumption. It should be noted that the energy consumptions generated by cooking, hot water, lighting, air conditioning, household appliances were included. The energy consumption of heating was excluded.

Table 1 shows that the energy consumption of downtown residential building in China was left far behind the developed counties. This can be explained with lower household average area and lower household average energy consumption, as shown in Figs. 28 and 29 and Table 2. The statistics in Fig. 28 and Table 2 are the same with

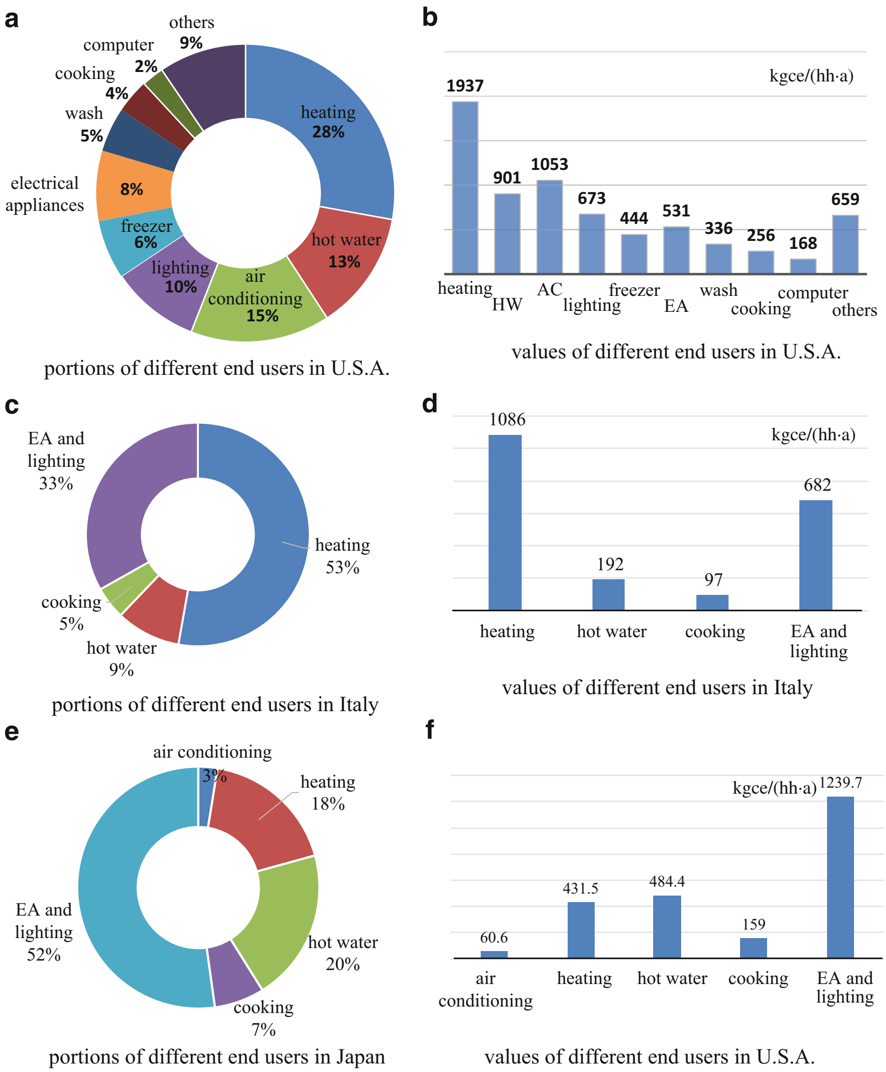



**Fig. 27** Energy consumption of different end users [8]

Table 1. The energy consumption of heating is excluded from the total energy consumption.

## Energy Consumption of Air Conditioning in Residential Buildings

Table 2 shows that, the energy consumption of air conditioning systems in residential building only takes 3–20% of the total energy consumption. It is interesting to find

**Table 1** Energy consumption among four typical countries [8]

| Year | Country | Person average (kgce/(cap·a)) | Household average (kgce/(hh·a)) | Area average (kgce/($m^2$·a)) |
|---|---|---|---|---|
| 2011 | Downtown China | 222 | 585 | 10.2 |
| 2010 | USA | 1849 | 5024 | 20 |
| 2009 | Japan | 936 | 2375 | 24.0 |
| 2007 | Italy | 390 | 972 | / |

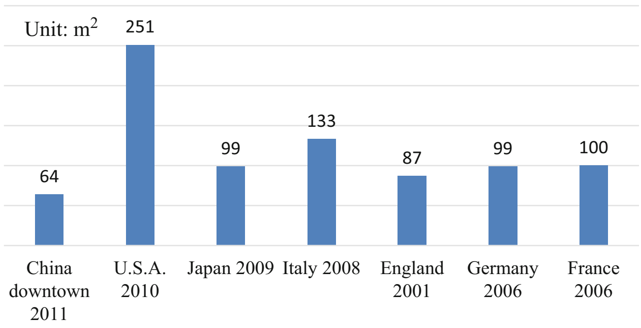



**Fig. 28** Household average area of some countries (Data resources: USA: EIA-Building Energy Data Book 2011; Japan: EDMC-Handbook of Energy & Economic Statistics in Japan; Italy: field investigation of Italy; others: Ministry of Housing and Urban-Rural Development of the People's Republic of China, Report of Foreign Residential Buildings No.1, 2010)

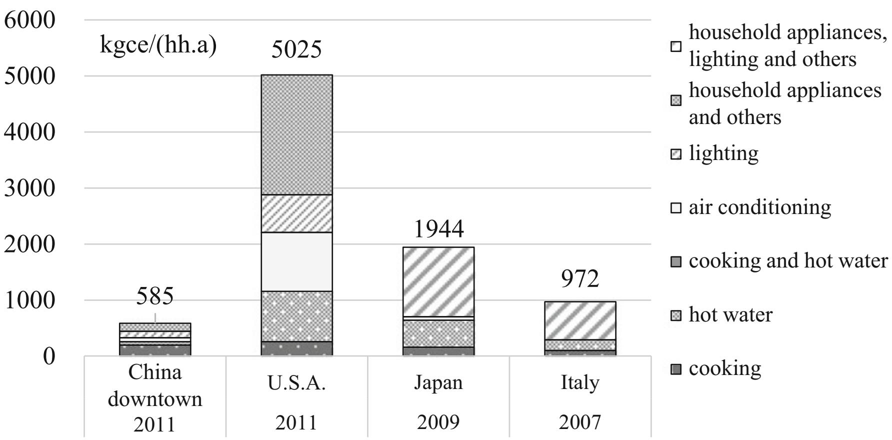



**Fig. 29** Household average energy consumption of some countries (Data resources: USA: The United State Department of Energy. 2007 Buildings Energy Data Book. USA: D&R International, Ltd., 2011; Japan: The Energy Data and Modeling Center. Handbook of Energy & Economic Statistics in Japan, 2009; Italy: ENEA-Italian National Agency for New Technologies, Energy, and Sustainable Economic Development, 2004)

**Table 2** Household average energy consumption comparisons among China, USA, Japan, and Italy (kgce/(hh·a)) [8]

| Country | Total | Cooking | Hot water | Air conditioning | Lighting | Household appliances and others |
|---|---|---|---|---|---|---|
| China | 585 | 198 | 60 | 67 | 118 | 142 |
| USA | 5025 | 258 | 898 | 1051 | 675 | 2137 |
| Japan | 1944 | 159 | 484 | 61 | 1240 | |
| Italy | 972 | 97 | 192 | 682 | | |

**Table 3** Residential buildings with different air conditioning systems [9]

| No. | Total area/m$^2$ | Floor number | Year of construction | Household number | Air conditioning system | $e_{area}$/(kWh/m$^2$) |
|---|---|---|---|---|---|---|
| A | 11,146 | 18 | 1996 | 108 | Separate air conditioner | 1.36 |
| B | 27,220 | 26 | 2003 | 192 | Separate air conditioner | 2.98 |
| C | 29,120 | 26 | 2005 | 104 | Centralized air conditioning | 19.83 |

that the energy consumption differs greatly among different countries, and among different air conditioning systems, namely centralized air conditioning system and separate air conditioners. For the States, where centralized air conditioning is popular, air conditioning systems take 20% of the total household average energy consumption. For China and Japan, where split air conditioning is popular, household average energy consumptions generated by air conditioning systems for both countries are similar, which are both around 6%. The portions are 10% and 3%, respectively. The reasons for these differences will be discussed.

Taking China and USA as an example, the residential buildings in downtown China are mainly high rise apartments. Split air conditioners are the dominate air conditioning method. The household centralized air conditioning system is less than 5% even for the newly built top grade residential buildings [8]. However, centralized air conditioning systems are popular in the States. There are 85% of single houses, which occupy 65% the total residential buildings, are equipped with air conditioning systems, within which 80% is centralized air conditioning systems [8]. Seventy-seven percent of apartments are equipped with air conditioning systems, within which 59% is centralized air conditioning systems [8].

Table 3 shows the investigation results of residential buildings with different air conditioning systems. The investigating results show that the $e_{area}s$ of residential buildings with the centralized air conditioning system are much larger than those buildings with the separate air conditioning system.

There are several reasons that lead to the larger $e_{area}$ of residential buildings with centralized air conditioning systems. First, there is energy consumption of auxiliary units like chilled/cooling water pumps, cooling towers, etc. Second, cooling capacity of centralized air conditioning systems is higher because of the whole-time and whole-space operating mode. Third, the average *COP* of chillers in the centralized air conditioning system during summer cooling period is lower than the separate air conditioners because of the low part load efficiency of chillers, even though the chillers are of higher rated *COP*.

## Conclusion

The overall energy consumption situation in China shows that, total energy consumption of commercial buildings has grown into the largest energy consumption part with the increase of building scales and area average building energy consumption. The energy consumption of residential buildings took one third of the rest of total building energy consumption. This chapter mainly focuses on the current energy consumption of commercial buildings and residential buildings in China and some foreign countries based on field measurement.

For commercial buildings, the area average energy consumptions of three building types, namely office buildings, hotels, and shopping malls, are compared. The energy consumptions of different categories of the energy system for the three building types are discussed, showing that the air conditioning systems take around 27–67% of the total building energy consumption. The detailed discussions of air conditioning systems proposed ways to increase the system efficiency, which can obviously improve the system performances after retrofitting.

For residential buildings, the energy consumption situations as well as portions of each energy classification of China downtown, USA, Japan, and Italy are discussed and compared based on different energy consumption indexes. It shows that energy consumption of the downtown area in China was lower than that of the developed counties. This is due to lower household average area and lower household average energy consumption of China downtown compared with the other countries. The differences of air conditioning energy consumptions among these countries are explained from the prospect of types of air conditioning systems, namely centralized and split air conditioning systems. The results show that centralized air conditioning consumes more energy due to energy consumptions of auxiliary units, larger cooling capacity, and low part load efficiency.

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