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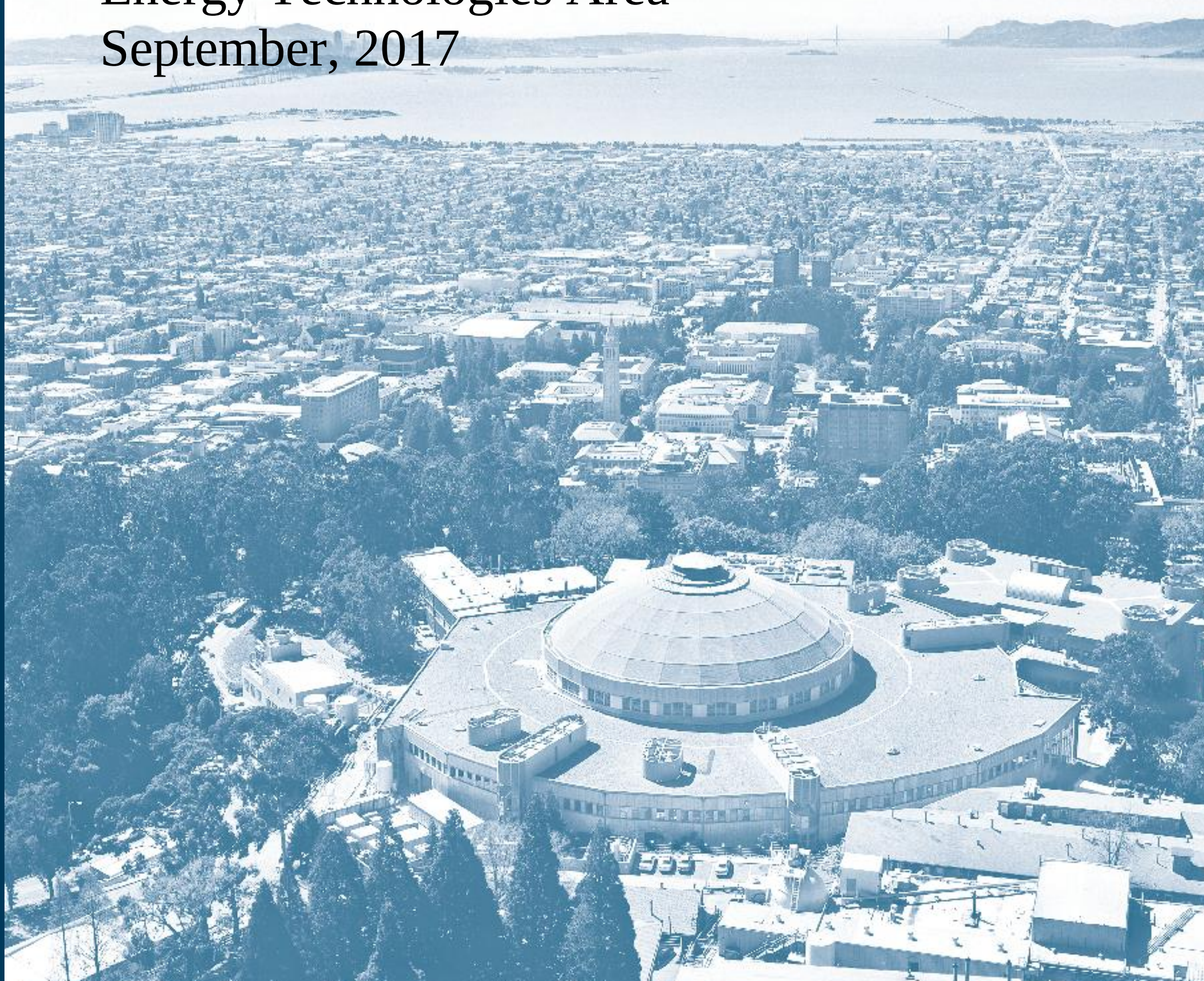

# A Thorough Assessment of China's Standard for Energy Consumption of Buildings

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## Abstract

China's Design Standard for Energy Efficiency of Public Buildings (the Design Standard) is widely used in the design phase to regulate the energy efficiency of physical assets (envelope, lighting, HVAC) in buildings. However, the standard does not consider many important factors that influence the actual energy use in buildings, and this can lead to gaps between the design estimates and actual energy consumption. To achieve the national energy savings targets defined in the strategic 12th Five-Year Plan, China developed the first standard for energy consumption of buildings GB/T51161-2016 (the Consumption Standard). This study provides an overview of the Consumption Standard, identifies its strengths and weaknesses, and recommends future improvements. The analysis and discussion of the constraint value and the leading value, two key indicators of the energy use intensity, provide insight into the intent and effectiveness of the Consumption Standard. The results indicated that consistency between China's Design Standard GB 50189-2015 and the Consumption Standard GB/T51161-2016 could be achieved if the Design Standard used the actual building operations and occupant behavior in calculating the energy use in Chinese buildings. The development of an outcome-based code in the U.S. was discussed in comparison with China's Consumption Standard, and this revealed the strengths and challenges associated with implementing a new compliance method based on actual energy use in buildings in the U.S. Overall, this study provides important insights into the latest developments of actual consumption-based building energy

standards, and this information should be valuable to building designers and energy policy makers in China and the U.S.

**Keywords**: code and standard, energy efficiency, energy consumption, outcome-based code, energy use intensity, China

# 1 Introduction

The Chinese economy has been growing at a rate of 10% per year for more than two decades (Morrison, 2014). In association with this growth, the total annual primary energy consumption soared to 3.25 billion tons of coal equivalent (TCE, 1 TCE = 29.39 GJ) in 2010. To sustain the economic growth in the future and control energy consumption, energy savings programs have emerged as an important strategic approach at the national level (MoLR, 2011; NBS, 2011). In addition, as the second largest economy in the world, China promised at the 2015 COP21 meeting in Paris to control its $CO_2$ emissions so that the emissions reach a peak no later than 2030 (UNFCCC, 2015). This too will require reductions in energy consumption.

About 40 billion $m^2$ of new floor space will be built in China by 2025 (Woetzel et al., 2009). So far, nearly 25% of the total primary energy in China is consumed by buildings (BERC, 2012; Fridley, 2008; Price et al., 2011). Under the strategic 12$^{th}$ Five-Year Plan, the total energy use in China will have to be controlled to less than four billion TCE per year by 2020. Therefore, in the China Roadmap for Building Energy Conservation (Peng et al., 2013), it was determined, via analyses of current and potential future technology and policy developments, that the building sector energy use should be not more than one billion TCE per year. More concretely, targets have been set for building energy use intensity (EUI, site energy); overall, building energy use intensity will need to be less than 65.0 kWh/$m^2$, with specific EUI criteria of 70 kWh/$m^2$ for office buildings, 40 kWh/$m^2$ for schools, and 80 kWh/$m^2$ for hotels (Peng et al., 2013; Xiao, 2011; Yang, 2009).

With the aim of achieving sustainable economic growth, the Chinese government and associated administrative entities have strived to stimulate building energy savings through the passage of relevant legislation. Keystones of this legislation include the 2007 milestone for China's law on energy conservation and the following two significant regulations enacted in 2013: (1) China's 12th Five-Year Plan for the development of energy conservation and (2) the new national standard for the energy consumption of buildings.

Setting energy standards for the design and construction of buildings is a common way to achieve building energy savings all around the world. According to studies by Iwaro and Mwasha (2010) and Janda (2009), design standards have been proposed in most developed countries and around 60% of developing countries. Along with macro-level laws, China's Ministry of Housing and Urban-Rural Development (MoHURD) developed the Design Standard, which defines the efficiency requirements for building envelopes, e.g., minimal insulation of walls, roofs, and floors, thermal performance of windows, and minimal efficiencies of HVAC equipment and systems (MoC, 1993; MoC, 2005; MoHURD, 2015). A separate regulation provides details for the lighting system design (MoC, 2001; MoC, 2004; MoHURD, 2013; Shui et al., 2009). The target of these standards is to provide a prescriptive compliance path so that the design of building components will meet specific efficiency requirements. In regard to the building envelope, lighting, and HVAC systems, the prescriptive requirements detailed in the Chinese standards are slightly less stringent than those in the United States (Evans et al., 2010; Feng et al., 2014; Hong 2009; Hong et al., 2015; Mo et al., 2010). However, similar to the United States (with federal and state code adoption pathways), the Chinese codes are mandatory at the national level, but local governments are allowed to adopt more stringent standards.

Despite energy conservation efforts, building energy standards are not necessarily effective in all situations (Iwaro and Mwasha, 2010). In general, the design standards of most countries do not consider some important factors (e.g., building operations and occupant behavior) that can influence the actual building energy use, and this can lead to a potentially large gap between the design estimates and actual energy consumption of the building (Li et al., 2014; Newsham et al., 2009; Peng et al., 2013; Scofield, 2009). Overall performance-based standards, which prescribe only an annual energy consumption level, usually provide more flexibility and incentives for innovation (Gann et al., 1998; Rosenberg and Hart, 2014). To address such issues and achieve the national energy savings goal defined in the 12th Five-Year Plan, China recently developed the first standard for energy consumption of buildings, titled the "Standard for Energy

Consumption of Buildings, GB/T51161-2016" (denoted as the Consumption Standard hereafter; it is also referred to as the energy quota standard). This standard is, based on the actual energy use in buildings. The main components of this standard include prescriptive indicators of the actual energy use for various types of buildings. MoHURD expects that the Consumption Standard, which went into effect on December 1, 2016, will provide guidance to control the actual energy use of buildings so as to achieve the national energy savings targets in the building sector.

This study aims to provide insights into China's Consumption Standard for building designers and energy policy makers, as well as provide an overview of the Consumption Standard for researchers outside China. First, a comprehensive review was conducted to understand what metrics were used and how energy quotas were developed based on the building type, location, and operation conditions. Then, the relation of the Consumption Standard with China's Design Standard for Energy Efficiency in Public Buildings (GB 50189-2015) was discussed, and quantitative comparisons between the energy use intensities calculated from energy models of prototype buildings compliant with the Design Standard and the corresponding energy use intensities specified in the Consumption Standard were conducted. Finally, the Consumption Standard was compared with the proposed outcome-based code in the United States, and areas of improvement for China's Consumption Standard in future revisions were recommended and discussed.

# 2 Overview of the Standard for Energy Consumption of Buildings

In northern China, all regions north of the Qinling Mountains–Huaihe River use building space heating that is traditionally supplied by centralized city scale district heating networks. This differs from other regions of China, and the energy used in the northern urban regions for space heating is closely related to the heating source and network. Hence, the heating energy is monitored in units consisting of one heating system instead of individual buildings or households. This leads to different energy use characteristics and unique technologies and policy roadmaps to fulfill energy conservation goals compared with other energy end uses in buildings. Consequently, this part of the building energy use is considered as one sub-sector of the national building energy consumption in China. In China, because of the varying economic levels in urban areas and rural areas, the life styles, building forms, and energy consumption behaviors are totally different between urban residential buildings and rural residential buildings. Rural residents tend to make a living through agricultural activities, and their household and energy consuming behaviors are closely related to agriculture production, unlike the urban residents. Similar to developed countries, the building forms and energy consuming behaviors of urban residential buildings in China are also totally different from the public and commercial buildings. For these reasons, China reports its national building energy consumption in four major categories (Table 1), which include (1) energy consumption for space heating in northern China, (2) energy consumption of urban residential buildings, (3) energy consumption of non-residential buildings, and (4) energy consumption of rural residential buildings.

In 2013, the Chinese building sector consumed 750 million TCE of primary energy, with each of the four categories accounting for about 25%. The energy use for space heating in northern China is specific to the energy consumed for space heating during the winter months, and for such buildings located in the provinces or regions where space heating is regulated by building codes. These codes are partly carried over from legacy standards developed as part of comprehensive building environmental regulations enacted in the 1980s. The space heating in northern China is normally supplied by district heating systems, which use combined heat and power (CHP) generation, district scale coal or gas boilers, region scale boilers, and heat pumps for central heating, and these systems are often supplemented with different kinds of decentralized heating systems (e.g., gas stoves, furnaces). Because of the special characteristics of the heat energy sources (coal, gas) as well as the fixed operation and maintenance schedules (continuous operation during the cold season), the energy use for space heating is always monitored and reported as a specific category (BERC, 2012). Thus, the energy use of urban residential buildings refers to the energy use in urban residential buildings excluding the space heating in northern China, and it includes energy use associated with household appliances, air conditioners, lighting, cooking, domestic hot water supplies, and individual space heating systems at the household level. The major energy source for residential buildings is electricity and gas. Energy use for non-residential buildings (i.e., commercial or public buildings) includes energy use associated with air conditioners, lighting, electrical appliances, information technology (IT) equipment, service water heating, and space heating (with the exception of northern China). Similar to residential buildings, the major energy source for commercial buildings is electricity and gas. The energy consumption of rural residential buildings refers to the consumption of biomass energy and the electricity use of appliances. As China's urbanization trends progress, the rural population will further decrease, and therefore, the rural residential energy use, as a portion of China's total energy consumption, will continue to decrease (NBS, 2015).

**Table 1 Definition of the four energy consumption categories**

| | Geographic Area | Buildings included | Types of Energy Use |
|---|---|---|---|
| **Energy consumption for space heating in northern China** | Urban area in northern China (excluding the rural area) | Residential buildings and non-residential buildings | Energy used by the heating source;<br>Energy used by the auxiliary equipment |
| **Energy consumption of urban residential buildings** | Urban area all over China (excluding the rural area) | Residential buildings only | Electricity used by all appliances;<br>Gas used for cooking, domestic hot water; |
| **Energy consumption of non-residential buildings** | Urban area all over China (excluding the rural area) | Non-residential buildings only | Electricity used by appliances & lighting;<br>Electricity used by air conditioning systems;<br>Electricity used by domestic hot water systems;<br>(space heating is not included for non-residential buildings in northern China) |
| **Energy consumption of rural residential buildings** | Rural area all over China (including the northern and southern China) | All residential buildings in rural area | All energy used in buildings in rural residential buildings (biomass, traditional energy use for space heating is included) |

The Consumption Standard covers both new and existing buildings, and it is a national standard designated as GB/T51161-2016 (GB means Guo Biao, which refers to a national standard in China). The Consumption Standard has gone through extensive public review and was adopted on December 1, 2016. Three of the four energy use categories, including energy consumption for space heating in northern China, energy consumption of urban residential buildings, and energy consumption of non-residential buildings, are the most critical to address in China's building energy conservation program. Therefore, they are dealt with separately in the Consumption Standard. The structure of the Consumption Standard is illustrated in Figure 1. It is worth mentioning that the residential buildings stand for urban residential buildings unless the category is specifically flagged as covering rural residential buildings as well.

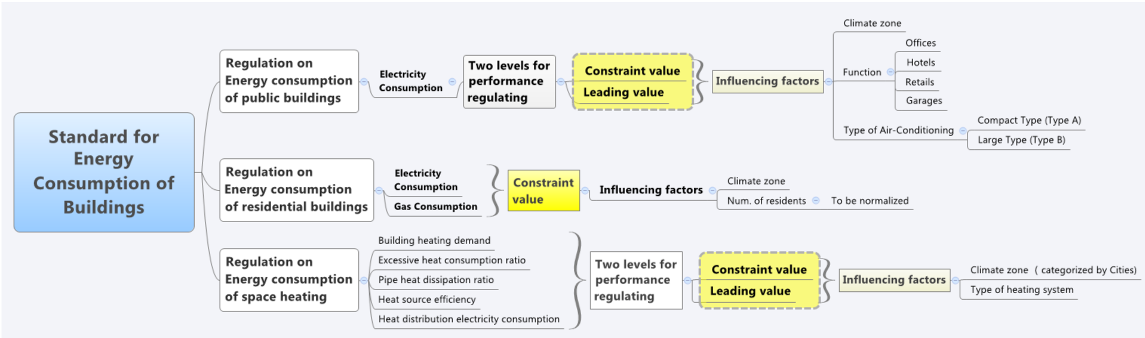


**Figure 1 Structure of China's Standard for Energy Consumption of Buildings**

The energy consumption of rural residential buildings is not included in the Consumption Standard for the following three reasons: (1) the major challenge facing China's rural residential buildings involves improvements in indoor comfort levels and not reductions in energy consumption; (2) the fuel structure of rural households is totally different from urban households, and rural households use large amounts of coal and biomass, which are difficult to measure and manage; and (3) the energy consumption level of rural residential buildings is currently much lower than that of urban residential buildings. Therefore, the control of energy consumption in rural residential buildings is not a top priority for China.

## 2.1 The indicators used in the Consumption Standard

The Consumption Standard adopts two indicators of the energy use intensity (EUI), namely, the constraint value (CV) and leading value (LV). These indicators represent the annual energy use in GJ per square meter of the building's total conditioned floor area ($GJ/m^2 \cdot a$) for the three categories of energy consumption detailed in the standard. The CV is designed for mandating actual energy use in buildings as the bottom line, while the intent of the LV is to represent the actual EUI of energy efficient buildings in China. The CV is drawn from nationwide, on-site surveys of the actual energy use taken from thousands of buildings located in large cities in China. The actual energy use for each of the three categories is then normalized by the climate (heating degree days and cooling degree days). Finally, the CV is determined by the top quintile of the EUIs of the surveyed buildings for each category, which means that only 20% of the buildings in each category have EUIs higher than the defined CV. The Consumption Standard requires that the actual EUI of buildings not exceed the prescribed CVs for their respective category. However, the Consumption Standard does not include any enforcement provisions. It is the duty of the local (province and city levels) building code agency to authorize, inspect, and enforce the actual energy use in buildings. China uses the CV as an important criterion to regulate the actual energy consumption of the existing building stock, and this approach is a significant component of China's efforts to achieve the overall energy savings targets defined in the Five-Year Plan.

While the CV is used to regulate inefficient buildings in terms of the EUI, the companion LV sets an EUI target for energy efficient buildings. The value of the LV is drawn from the same on-site energy consumption surveys used to determine the CVs. However, the LV is computed as the lower quartile of the EUIs taken from the surveyed buildings, such that in each category only 25% of the buildings consume less energy (in terms of the EUI) than the indicated LV value. The LV aims to promote energy efficient buildings in China, but it is a voluntary target. The Consumption Standard does not describe how LVs can be used in China's building energy code compliance or energy performance benchmarking, rating, and labeling programs. Thus, additional details about how the LVs can be adopted will have to be specified in China's future building energy regulations.

## 2.2 Regulations on energy consumption for space heating in northern China

The regulations on energy consumption for space heating in northern China include the space heating energy use of the buildings as well as the efficiency of key components of the heating system. These key components include the efficiency of the heat source, thermal performance of the building envelope, and efficiency of the piping distribution system. Figure 2 shows the structure and regulated efficiency items for space heating in northern China. All of these items apply to both residential and commercial buildings in the urban areas of northern China.

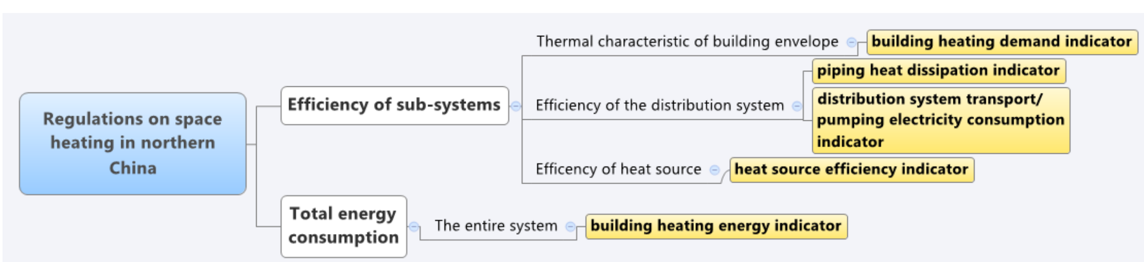

**Figure 2 Framework of the regulation on space heating in northern China**

The building heating demand indicator represents the space heating (EUI) from the demand side of a building for the entire heating season in northern China. Because of the differences in climate, the heating season varies from city to city in China. For example, the heating season in Beijing starts in mid-November and ends in mid-March of the following year, while that in Harbin, a colder city, ranges from mid-October to mid-April of the following year. The heating demand is driven by the outdoor air temperature and is also influenced by the envelope insulation level, window types, and air infiltration system of the building. The building heating EUI is determined by dividing the overall space heating energy with the building's total heated floor area. A building's overall heating energy is measured at the building boundary with heat energy meters located at the supply (inlet) and return (outlet) areas of the building. The Consumption Standard normalizes the building heating EUI by weather conditions (heating degree days) and the number of residents in the building. Figure 3 shows the CVs and LVs for 16 large cities in northern China. The findings show that, because of the climate differences, the values for the CV and LV are fairly similar for some cities like Jilin and Heilongjiang, thus indicating that these buildings consume consistent amounts of heating energy. In contrast, Tibetan buildings require variable amounts of heating energy, as indicated by the large difference between the CV and LV, and this is indicative of a diverse range in building efficiencies. For the 16 listed cities, the CV ranged from 0.2 to 0.39 $GJ/m^2 \cdot a$, while the LV ranged from 0.12 to 0.34 $GJ/m^2 \cdot a$.

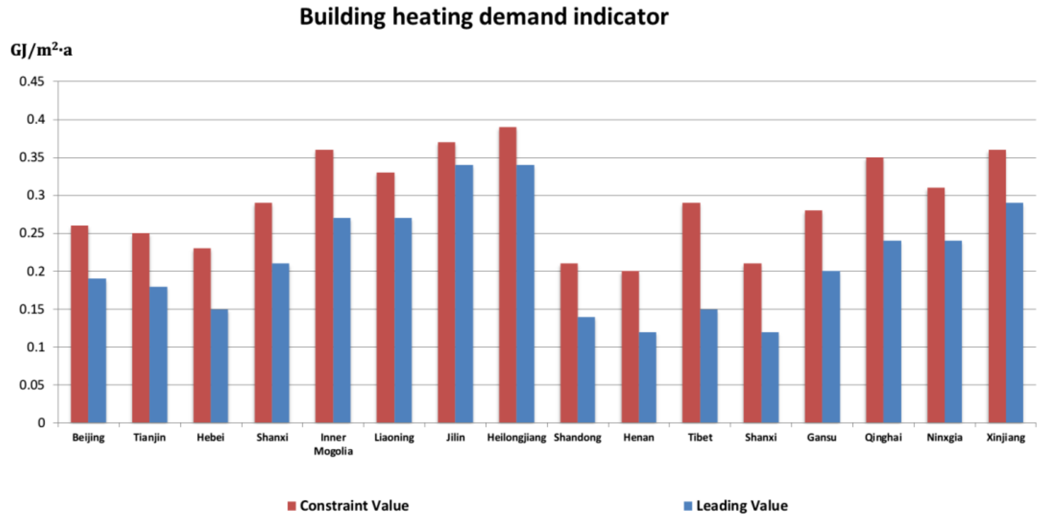


**Figure 3 Indicators of space heating energy use in northern China**

The piping heat loss indicator and the electricity consumption due to distribution pumping are vehicles to regulate the efficiency of the heat distribution system of a district heating system. The easiest way to reduce heat losses from water pipes would be to shorten the distribution length of the pipes and improve the pipe insulation. In addition, distribution system pumping energy can be reduced by increasing the water temperature difference between the supply and return pipes, thus reducing the water flow rate in the pipes, and by using bigger pipes to reduce the velocity of the hot water. The prescribed values of these two indicators are listed in Tables Table 2 and Table 3. In Table 2, the piping heat loss only applies to the central heating system at the district or city scale. The CV was 5% for the city scale heating systems and 2% for the district scale centralized heating systems. With larger systems, there is a greater surface area for heat loss to occur along the distribution line. This is the reason for the large magnitude losses occurring at the city scale, as highlighted in Table 2. The energy consumed by the pumps of the distribution system, as shown in Table 3, is another challenge for large heating systems. The CV and LV of the pumping energy depend on the duration of the heating season (the longer the heating season, the larger the CV and LV values), but not the heating system type.

**Table 2 Indicators of piping heat loss for space heating systems in northern China**

| Type of heating system | Piping heat loss indicators |
|---|---|

| | Constraint Value | Leading Value |
|---|---|---|
| Centralized heating system – city scale | 5% | 3% |
| Centralized heating system – district scale | 2% | 1% |

**Table 3 Indicators of pumping electricity use for heat distribution systems**

| Duration of heating season | Pumping electricity consumption (kWh/m$^2$·a) | |
|---|---|---|
| | Constraint Value | Leading Value |
| 4 months | 1.7 | 1.0 |
| 5 months | 2.1 | 1.3 |
| 6 months | 2.5 | 1.5 |
| 7 months | 2.9 | 1.8 |
| 8 months | 3.3 | 2 |

The efficiency of the heat source of the heating system is defined as the total fuel energy consumed by the heat source divided by the amount of heat produced for space heating. The prescribed heat source efficiency indicator depends on the heating system type as well as the fuel type, as shown in Table 4. According to conventional efficiency terms, 1 kgce = 0.02939 GJ, so 28 kgce/GJ is equivalent to 81% and with 1 Nm$^3$ for natural gas = 0.0383 GJ, then 25 Nm$^3$/GJ is equivalent to 94%. It can be observed that the requirements for larger systems are more stringent than those for smaller systems. The heat source efficiencies of the large scale systems are 30% higher than the centralized district systems in terms of the CV. The LVs of large systems are roughly 50% lower than those of the district systems. A similar phenomenon can be observed for the large and small systems using natural gas. This reflects one advantage of large heat source systems, in contrast to their disadvantages in regard to piping heat losses and pumping energy use. Besides, the efficiency of the heat source at the building or household level is very close to the district scale centralized system. This implies that the heat sources at the household scale may have been greatly improved. Such systems are very promising for the future of heating system design. At the household or building scale, heating systems that use coal are not covered by the standard because coal heating is no longer commonly employed in urban areas of China.

**Table 4 Indicators of the heat source efficiency**

| Type of heating system | Heat source efficiency (Coal: kgce/GJ) | | Heat source efficiency (Natural Gas: $Nm^3/GJ$) | |
|---|---|---|---|---|
| | Constraint value | Leading value | Constraint value | Leading value |
| District heating system – city scale | 30 | 20 | 27 | 20 |
| Centralized heating system – district scale | 43 | 38 | 32 | 29 |
| Building or household heating system | n.a. | n.a. | 32 | 30 |

Lastly, the Consumption Standard specifies a building heating energy indicator to regulate the overall energy consumption of the entire heating system. This indicator is defined as the aggregation of the energy used to produce heat for space heating and the energy used by auxiliary equipment (e.g., pumps). The building heating energy indicator depends on the heating system type and fuel type of the heat source. The CVs and LVs of two large cities (Beijing and Tianjin) and 14 provinces in northern China are listed in

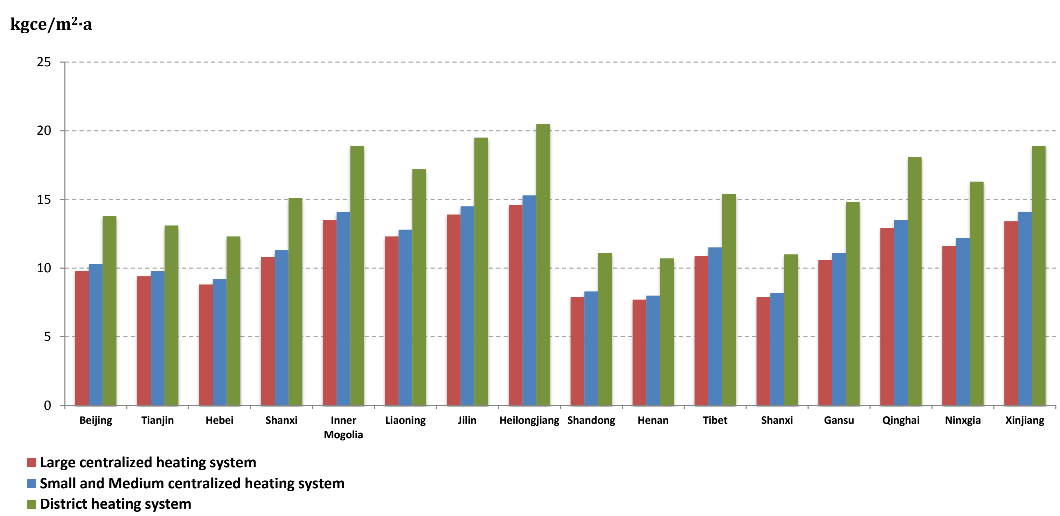

Figure 4 to

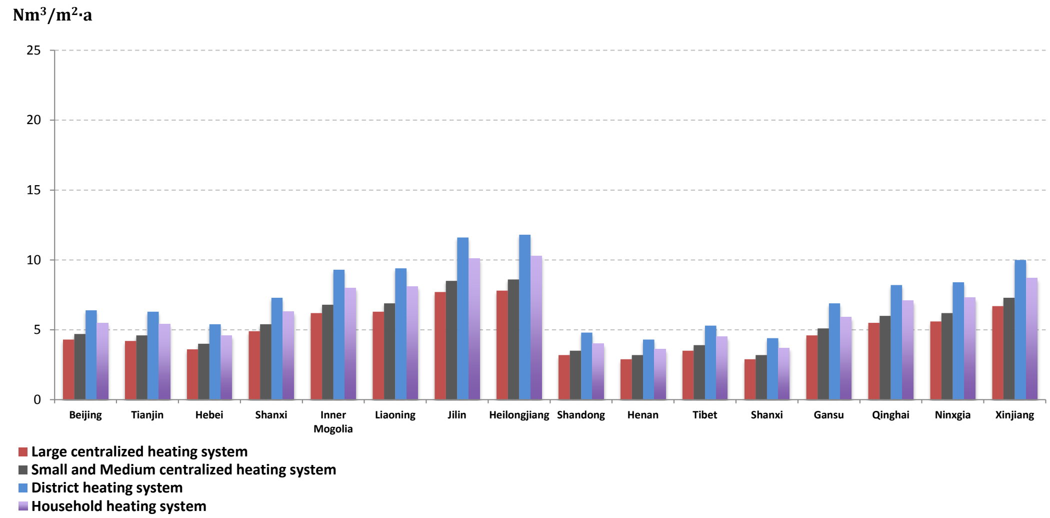


Figure 7.

The CVs of the district heating systems were found to be consistently higher than the small, medium, and large centralized heating systems (serving a single building or a small group of buildings) for all of the cities

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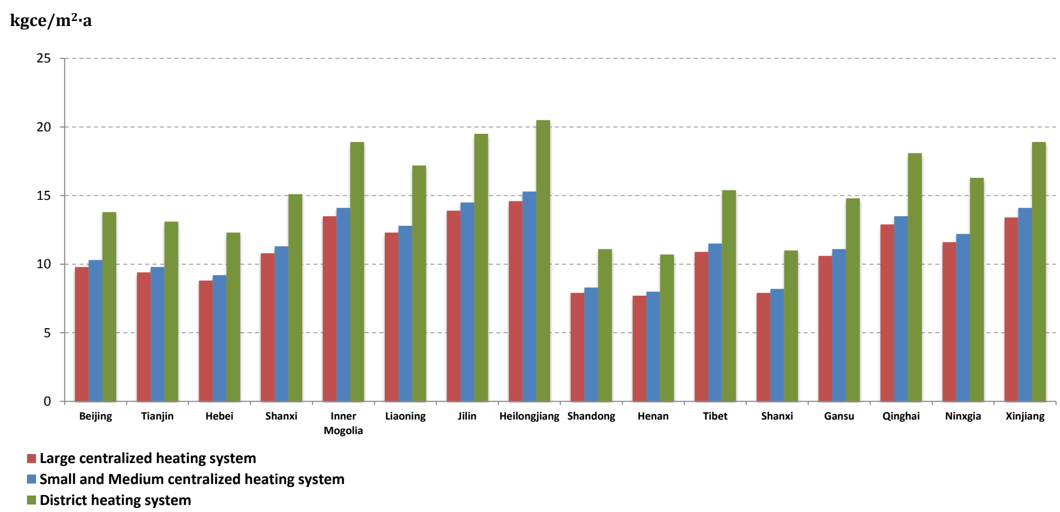


Figure 4). The CVs of the small and medium centralized systems are quite close to those of the large centralized systems. This suggests that the Consumption Standard encourages district heating systems despite their much higher pumping energy use and piping loss compared to centralized heating systems.

For district heating systems, it is much easier to control air pollution from their heat source than many coal-fired boilers used in centralized heating systems. However, the implementation of additional district heating may be hindered by the need to construct new infrastructure. For each of the three system types, the CVs demonstrated similar variation trends among the cities. In addition, Inner Mongolia, Liaoning, Jilin, and Heilongjiang displayed relatively higher quotas than the other cities and provinces, which was mostly due to their longer heating seasons and higher heating demands. Cities and provinces located within close proximity to each other, and thus sharing somewhat similar climates, expressed similar CVs. For example, CV similarities between (i) Qinghai, Ningxia, and Xinjiang, and (ii) Beijing, Tianjin, and Shandong may be explained by their geographic closeness

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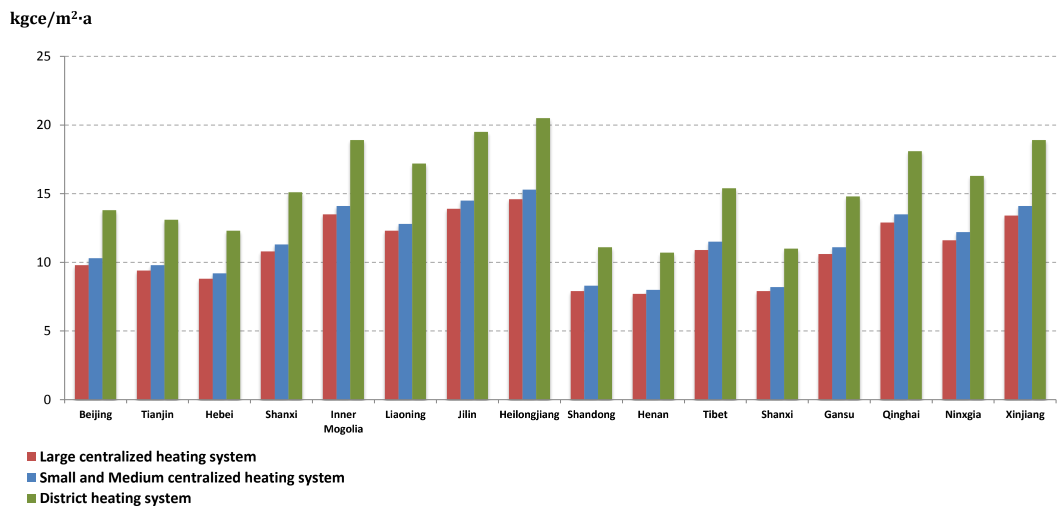
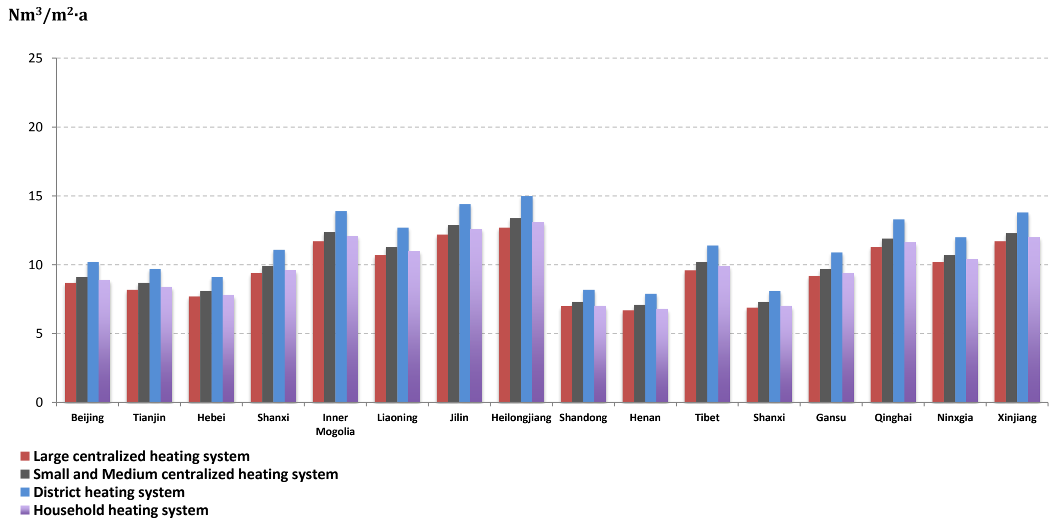



Figure 4).

For heating systems using natural gas, the CVs and LVs for the heating energy indicator (Figures

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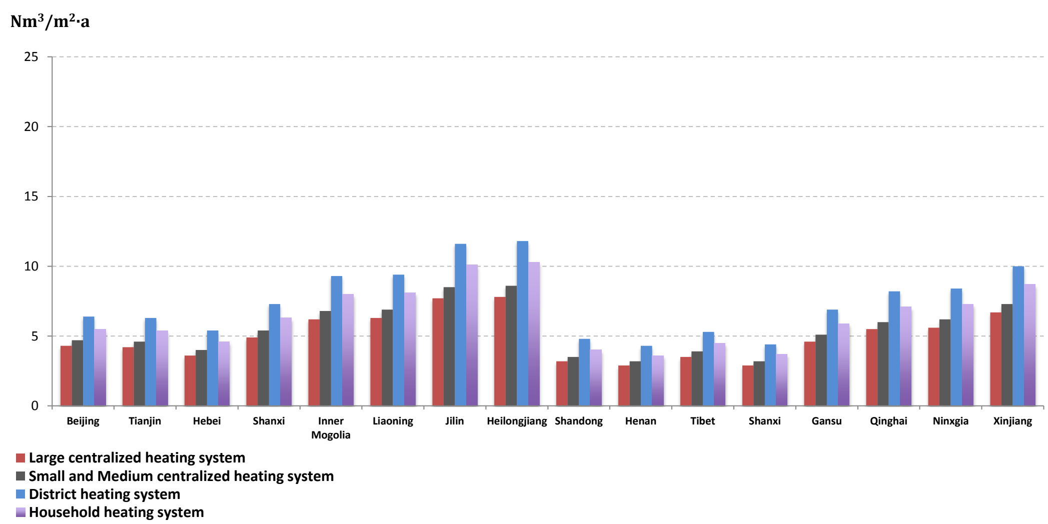
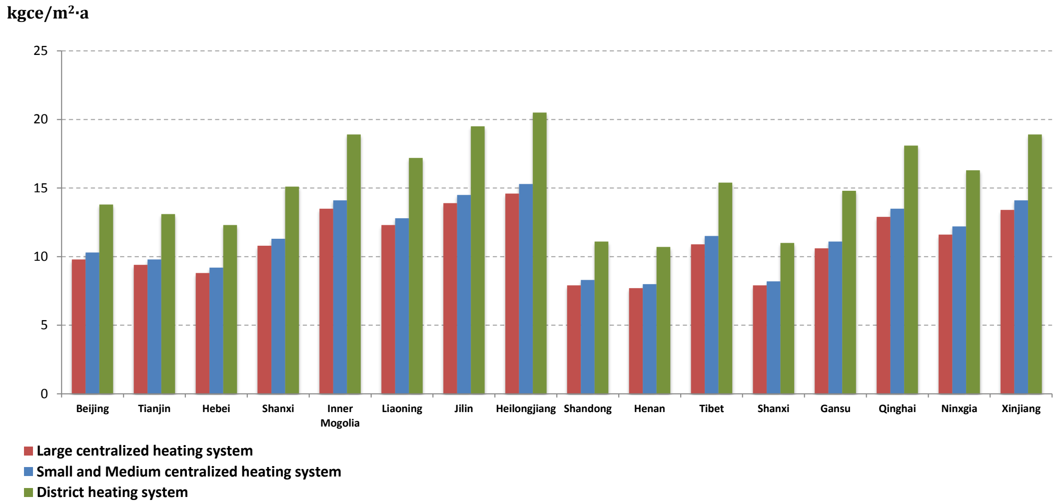



Figure 7) showed similar trends among different system types and different cities. In general, the LVs are on average 30% lower than the CVs. Moreover, the variations in the trends of the LVs for cities using the

natural gas system are within the same range as those for coal systems (Figures

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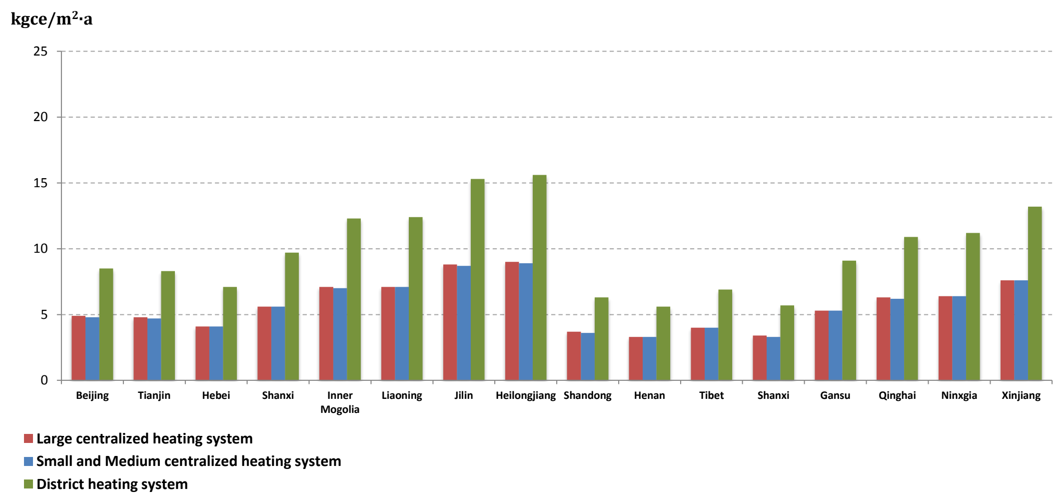



Figure 5). For example, Heilongjiang, Jilin, Liaoning, and Inner Mongolia had higher quotas than other cities/provinces, and Qinghai, Ningxia and Xinjiang showed similar trends.

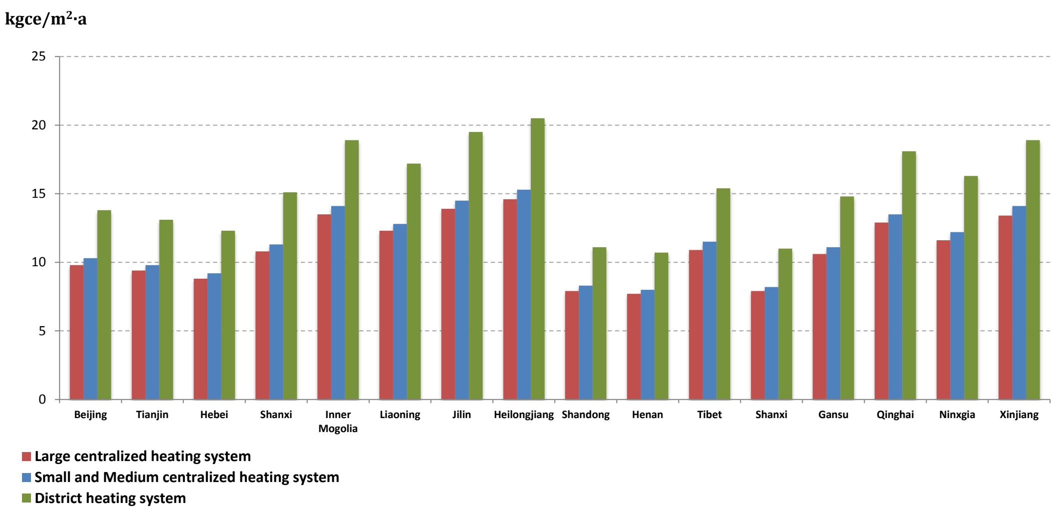



**Figure 4 Constraint values for heating energy indicators (using coal)**

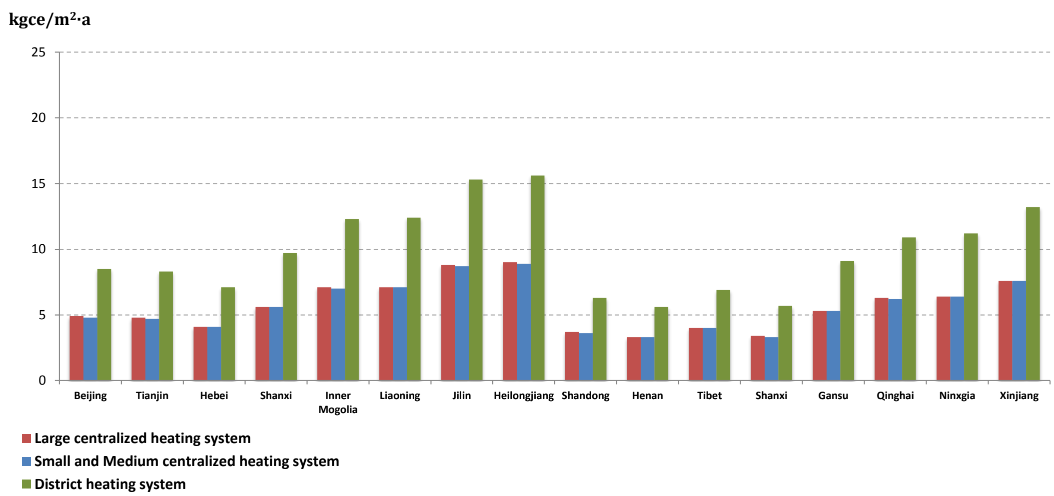



**Figure 5 Leading values for heating energy indicators (using coal)**

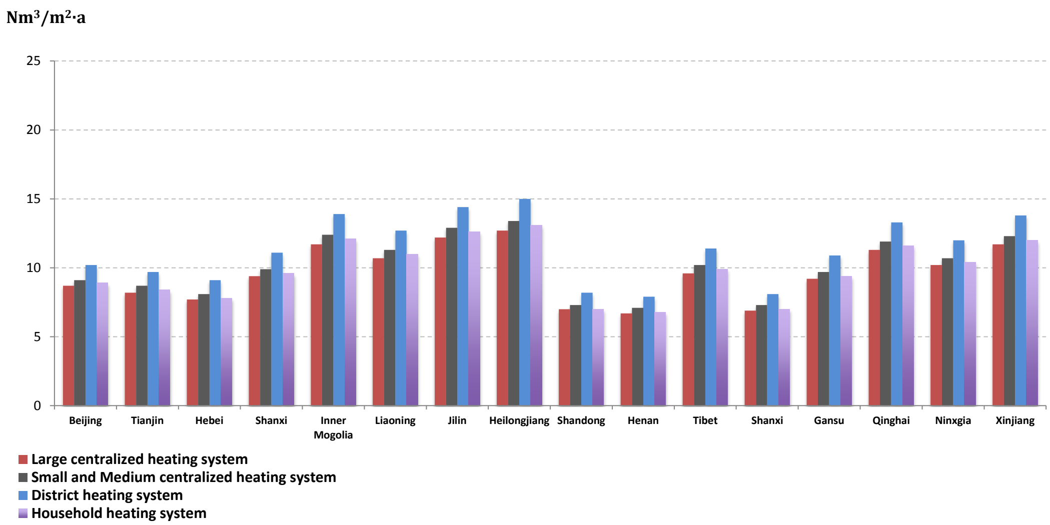



**Figure 6 Constraint values for heating energy indicators (using natural gas)**

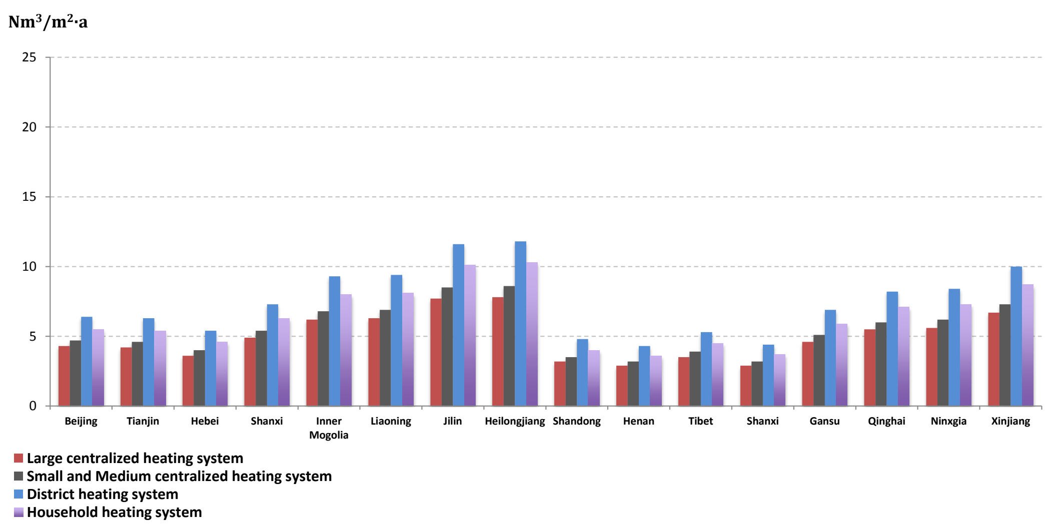



**Figure 7 Leading values for heating energy indicators (using natural gas)**

It should be noted that the CVs and LVs of the heating systems using coal are higher than those of the heating systems using natural gas. This can be mainly attributed to the very low energy efficiency levels of current coal heating systems in China.

## 2.3 Regulations on energy consumption for residential buildings

In China, the following five major climate zones (Figure 8) can be distinguished based on the average outdoor air temperatures of the coldest and hottest months: the severe cold zone (the average temperature of the coldest month is less than -10°C, and that of the highest month is less than 25°C), the cold zone (the average temperature of the coldest month ranges from -10 to 0°C, and that of the highest month ranges from 18 to 28°C), the hot summer and cold winter zone (the average temperature of the coldest month ranges from 0 to 10°C, and that of the highest month ranges from 25 to 30°C), the hot summer and warm winter zone (the average temperature of the coldest month is higher than 10°C, and that of the highest month ranges from 25 to 29°C), and the temperate zone (the average temperature of the coldest month ranges from 0 to 13°C, and that of the highest month ranges from 18 to 25°C).


**Figure 8 China's five climate zones**

Energy consumption regulations for residential buildings apply to dwellings where the electricity and gas consumption use are metered and a bill is charged. To consider the influence of the number of residents and weather conditions, the Consumption Standard provides prescriptive CVs for each climate zone, and it normalizes the CVs by the number of residents by assuming a typical family size of three people, two parents and one child. Table 5 shows the CVs for the electricity and gas use of each household. The CVs are determined according to the threshold of the energy consumption that 80% of the families would not exceed based on their actual utility bill. The Consumption Standard does not prescribe LVs for household energy use. The concept of a household LV is somewhat frivolous considering the fact that the energy use pattern of most Chinese families is culturally routine and there is a lack of enforcement mechanisms at the residential level.

The CV for the hot summer and cold winter climate zone (Table 5) is the highest as a result of the seasonal electricity (3100 kWh/household·a) used for cooling in summer and gas (240 $m^3$/household·a) used for heating in winter. This can be explained by the fact that in the severe cold and cold climates, space heating is usually provided by district heating systems and this energy use is excluded from the residential energy use category. For the hot summer and cold winter climate, space heating is either provided individually or at the building level.

**Table 5 Indicators for electricity and gas consumption in residential buildings**

| Climate Zone | Constraint value for electricity consumption (kWh/household·a) | Constraint value for gas consumption ($m^3$/household·a) |
|---|---|---|
| Severe Cold | 2200 | 160 |
| Cold | 2900 | 140 |
| Hot-Summer and Cold-Winter | 3100 | 240 |
| Hot-Summer and Warm-Winter | 2800 | 160 |
| Temperate | 2200 | 190 |

## 2.4 Regulations on energy consumption for non-residential buildings

Non-residential buildings are mostly public buildings in China and equivalent to commercial buildings in the U.S. The characteristics of energy use in the non-residential building are quite different from those in residential buildings mainly because of the different energy consuming equipment employed and the different operation schedules. The main energy source used in non-residential buildings is electricity for lighting, air conditioning, ventilation, and office equipment. The regulations pertaining to energy consumption for non-residential buildings will be discussed based on non-residential buildings categories defined by the building type, climate zone, and window-to-wall ratio. The energy use for space heating in non-residential buildings in northern China is not included as part of the energy use regulated by this part of the standard; it is regulated as part of the energy consumption for space heating in northern China as described in Section 2.2. For buildings in other areas of China, which use individual heat sources, the heating energy consumption is converted into electricity and added to the total energy use.

The energy consumption indicators for non-residential buildings are grouped into several categories based on the building function, location (climate zone), and area of operable windows (which drives natural ventilation). The regulations consider (i) three building types (office, retail, and hotel), (ii) four climate zones (the combined severe cold region and the cold region, the hot summer and cold -winter region, the hot -summer and warm winter region, and the temperate region), and (iii) two categories of operable windows (small and large dependent upon the operable window-to-wall ratio). Figure 9 lists the factors used for categorizing the non-residential buildings. The combinations of these factors result in 24 subcategories. In the Consumption Standard, the indicators, CVs and LVs, are developed separately for each subcategory.

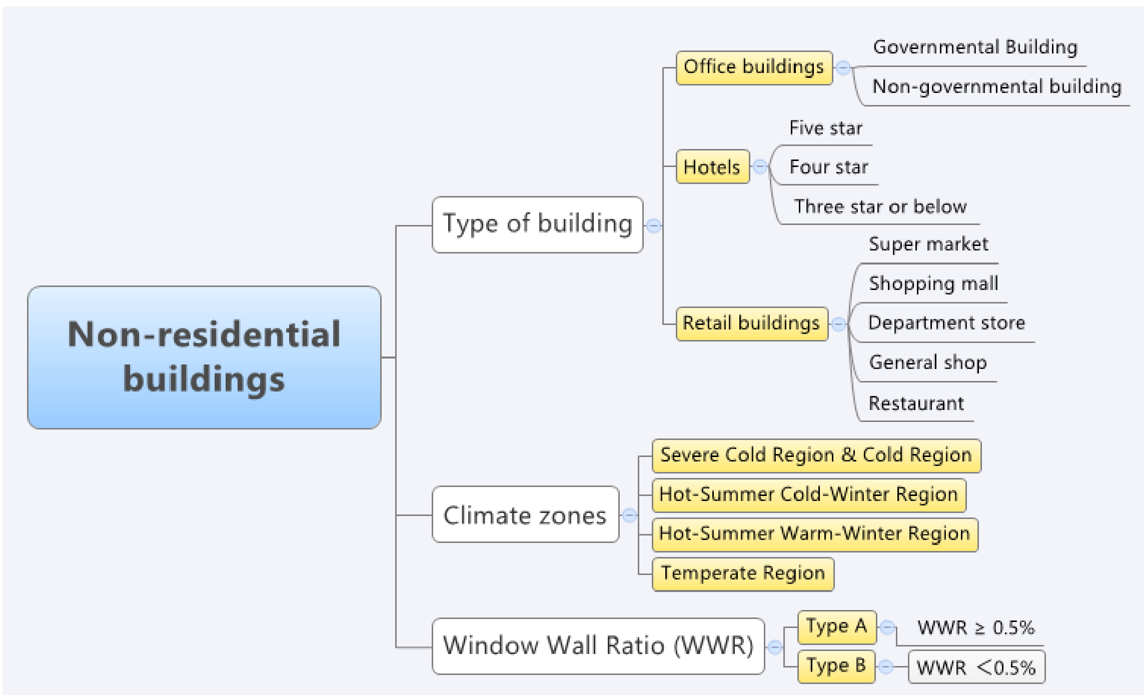



**Figure 9 Categorization of non-residential buildings by using the ontology of building type, climate zone, and window-to-wall ratio**

This operable window-to-wall ratio (WWR), which is defined as the ratio of total area of operable windows to the total area of exterior walls, reflects the significance of natural ventilation (NV) through operable windows in non-residential buildings. The application of natural ventilation is usually related to building type. Large building complexes (with total floor areas larger than 20,000 m$^2$), which are normally equipped with curtain walls, cannot use natural ventilation. Conversely, normal-sized buildings (with floor areas less than 20,000 m$^2$) that have more openable windows can better adopt natural ventilation. Both types of buildings are prevalent in China. The Consumption Standard designates Type A buildings for the normal-sized buildings and Type B buildings for the large building complexes. Indicators for Type A buildings are more stringent than those for Type B buildings (Figure 8). However, all new buildings are encouraged to comply with the indicators for Type A buildings. For Type B buildings, approval of a specific waiver is required before development because authorities are obligated to limit the construction of buildings that have limited operable windows for natural ventilation. By designating different energy indicator values based on the potential for natural ventilation in buildings, the Consumption Standard aims to promote the use of natural ventilation.

The Consumption Standard provides stringent requirements for government (central, provincial, and city) office buildings, as the government is leading the energy savings effort. Therefore, the category of office buildings is further divided into two types, namely, governmental and non-governmental office buildings. Figures Figure 10 to Figure 13 show the indicators for non-residential buildings according to the Type A and Type B categories.

For Type A buildings, the hot summer and cold winter zone exhibits the highest CV and LV indicators among all of the building categories (i.e., government offices, commercial offices, three star and below, four star, five star, stores, shopping centers, super markets, restaurants, general retail). The severe cold and cold climate zones have the lowest indicators, and the values range from 40 to 90 ($kWh/m^2 \cdot a$) for the CVs and 30 to 80 ($kWh/m^2 \cdot a$) for the LVs. The reason for this behavior is that buildings in the hot summer and cold winter zone consume electricity for both cooling and heating demands, while buildings in the hot summer and warm winter zone have less heating demands, and the heating demand in the severe cold and cold zone is normally served by district heating systems. In the comparison among the different building categories, the hotels and retail buildings (stores, shopping centers, and super markets) have higher quotas than the other building types. This pattern might be caused by their long operating hours and the high energy use associated with amenities. In general, the CVs (60 to 75 $kWh/m^2 \cdot a$) and LVs (42 to 60 $kWh/m^2 \cdot a$) of the commercial office buildings are slightly higher than the government offices (CVs: 42 to 60 $kWh/m^2 \cdot a$; LVs: 25 to 42 $kWh/m^2 \cdot a$). In the cross comparison between the CVs and LVs, LVs were generally found to be 20% lower than the CVs.

Type B buildings exhibit contrasting behavior from Type A buildings (

Figure 12). For example, the Type B large retail buildings located in the hot summer and warm winter zone consume much more energy than similar buildings in the other two climate zones. While for the Type B office buildings, whose quotas in the hot summer and warm winter zone are still lower than those in the hot summer and cold winter zones, the differences between the indicators in the two zones are not significant. The reason for this might be due to the fact that Type B buildings have larger interior zones that require more cooling than smaller buildings with mostly perimeter zones. The extremely high cooling demands drive the energy use in these buildings and eventually cause the total energy use to exceed that of the buildings in the other two climate zones with less cooling demands. The trends among different building types indicate that the relationships between the corresponding CVs and LVs for Type A and Type B buildings are similar. For example, hotels and retail buildings of both Type A and Type B display show LVs that are about 25% lower than the corresponding CVs.

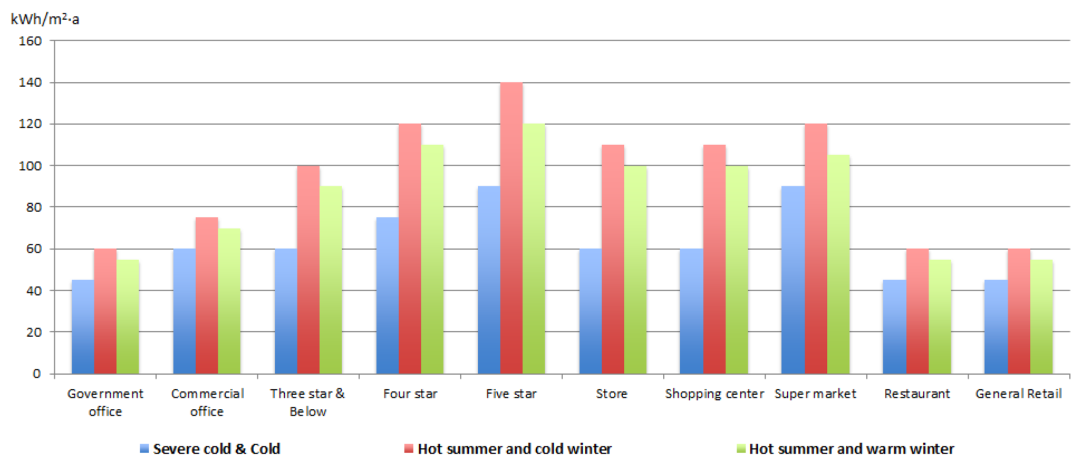



**Figure 10 Constraint values for energy use intensity of Type A buildings**

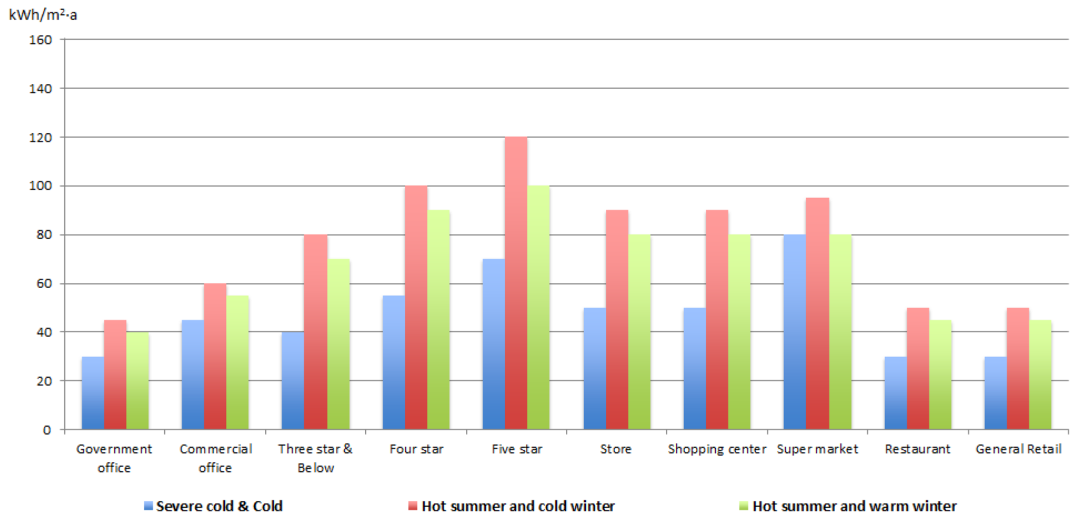



**Figure 11 Leading values for energy use intensity of Type A buildings**

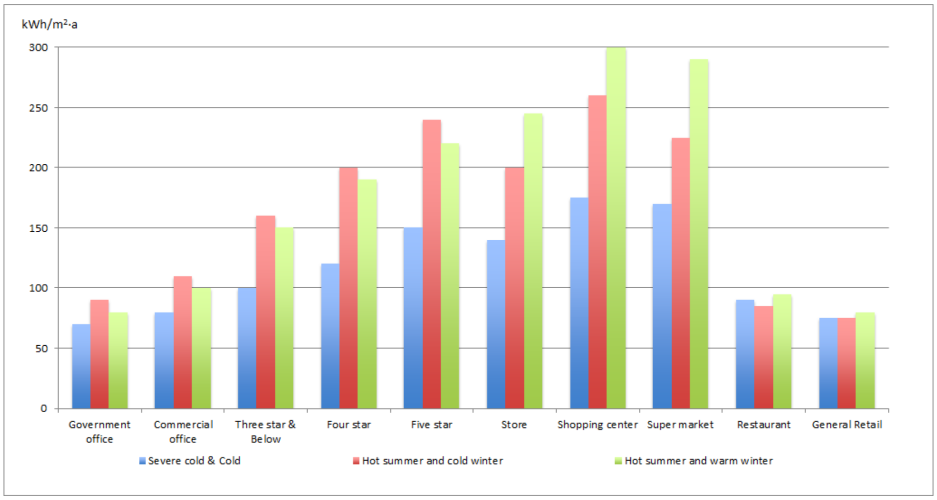



**Figure 12 Constraint values for energy use intensity of Type B buildings**

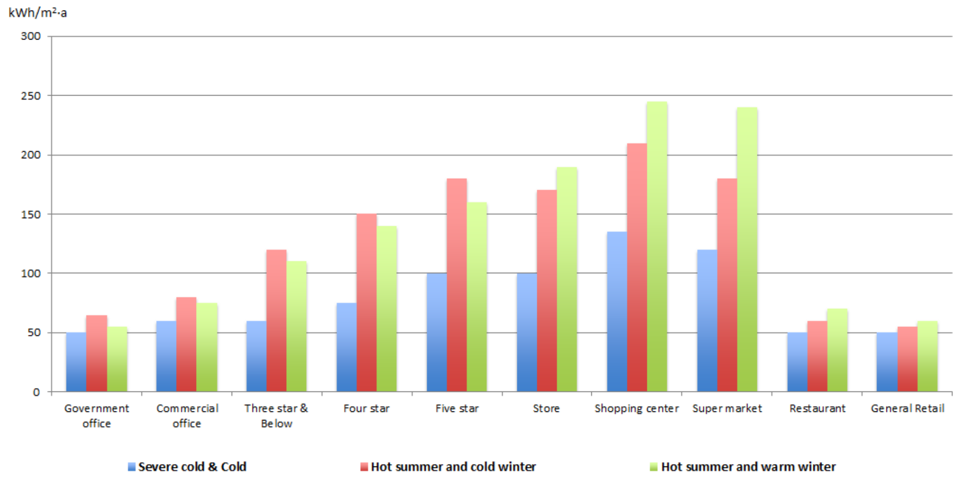
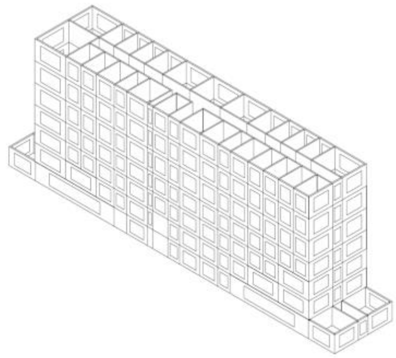



**Figure 13 Leading values for energy use intensity of Type B buildings**

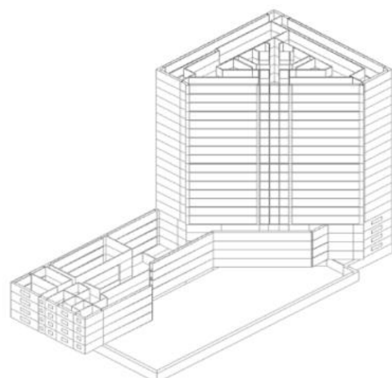
# 3 The Relationship between the Design Standard and the Consumption Standard for Buildings in China

China's Design Standard (GB 50189) and Consumption Standard (GB/T51161-2016) are the kernel vehicles carrying the most regulatory responsibility to control building energy consumption. The Design Standard aims to regulate energy efficiency of buildings during the design process, while the Consumption Standard aims to regulate the actual energy consumption of buildings after they are put to use. The main purpose of the Design Standard is to realize energy conservation in buildings by controlling building physical assets such as the building envelope, lighting, HVAC, and service water heating, but the standard does not address building operations or occupant behavior. However, high energy efficiency may not always lead to low energy consumption. Even under high levels of energy efficiency, the increase of energy demand in buildings may result in high energy consumption, which will sometimes lead to the unnecessary wasting of energy, such as that used for lighting and HAVC services in empty rooms, and that involved with the over-heating of rooms in winter or over-cooling of rooms in summer (Arens et al., 2015; Mendell and Mirer, 2009). The ultimate purpose of the building energy conservation work is to decrease the actual energy consumption so as to meet the requirements of mitigation programs aimed at climate change and improvement programs for the atmospheric environment. Thus, the Chinese government treats the control of the actual building energy consumption as one of its main missions, and improvements to energy efficiency are an important leveraging tool to keep the total energy consumption in buildings under control while providing high service levels and comfort for occupants. Based on this framework, the Consumption Standard was developed, and it focuses on the actual energy use of buildings. Specifically, this standard defines actual energy objective values instead of directly regulating the building assets, operations, or occupant behavior, and this approach can be realized by taking the detailed energy-saving measures from the Design Standard as technical references. Without the Design Standard, the Consumption Standard can be hard to reach for a building without reducing occupant comfort or requiring significant energy retrofits because of the building's potential low energy efficient design; on the other hand, without the Consumption Standard, the Design Standard may not achieve low energy consumption in reality because of the lack of consideration of actual building operations and occupant behaviors. Therefore, these two standards are necessary and together can support each other to realize the final energy savings as well as occupant comfort.

The easiest way to test the consistency between the two standards is to check if the actual energy performance of a building designed to comply with the Design Standard can meet the criteria defined in the Consumption Standard. This can be done by comparing the energy use calculated from energy models of prototype buildings compliant with the Design Standard to the corresponding energy use indicator specified in the Consumption Standard. To enhance this discussion, two building models were built to represent Type A (normal-sized buildings) and Type B (large buildings) offices in the Consumption Standard, as shown in Figure 14. The. Type A building is a seven-story building with a floor area of 6,000 $m^2$. It is a medium-sized building with operable windows for natural ventilation and perimeter zones for natural daylighting. The Type B building is a large-sized, high-rise building with a floor area of 53,000 $m^2$; thus, it is not capable of utilizing natural ventilation or daylighting effectively. The energy efficiency of the two building models was set to minimally comply with the requirements prescribed in the Design Standard. Building energy simulations were conducted by using the DeST program (Yan et al., 2008) for both building models, and the simulated EUIs based on the Design Standard were then compared to the two prescribed EUIs (CV and LV) in the Consumption Standard.



(a) Type A buildings



(b) Type B buildings

**Figure 14 Sketch of the two energy models for non-residential buildings**

**Table 6 The envelope performance of the two building energy models**

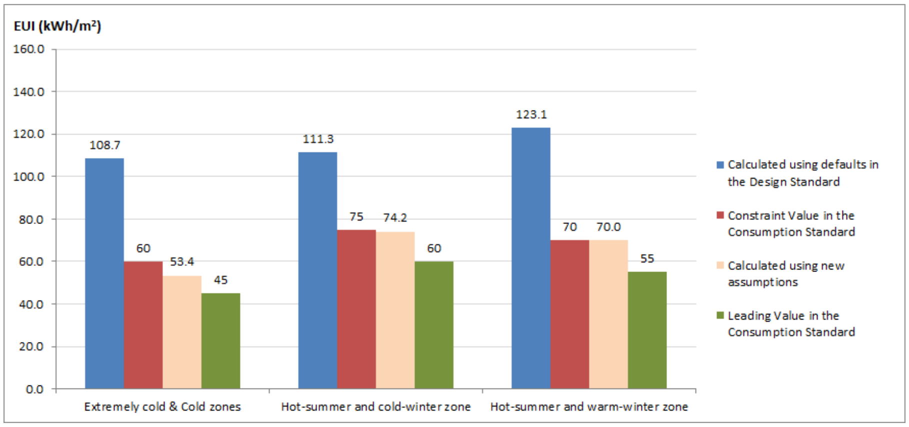
| Building Type | A | B | A | B | A | B |
|---|---|---|---|---|---|---|
| Climate zone | CZ | CZ | HSCWZ | HSCWZ | HSWWZ | HSWWZ |
| Heat transfer coefficient of external wall ($W/m^2/k$) | 0.6 | 0.6 | 1 | 1 | 1.5 | 1.5 |
| Heat transfer coefficient of external wall ($W/m^2/k$) | 0.55 | 0.55 | 0.7 | 0.7 | 0.9 | 0.9 |
| Window-wall-ratio | 0.4 | 0.7 | 0.4 | 0.7 | 0.4 | 0.7 |
| Heat transfer coefficient of external wall ($W/m^2/k$) | 2.7 | 2 | 3 | 2.5 | 3.5 | 3 |
| Shading coefficient of window | 0.7 | 0.5 | 0.5 | 0.4 | 0.45 | 0.35 |

It has been widely recognized that building operations and occupant behaviors are two primary drivers of actual energy use, in addition to the extent of compliance with the building design code. Therefore, the following two sets of assumptions were used in the energy modeling: (1) default values (operating schedules, comfort temperature settings, outdoor air ventilation rates, and HVAC controls) provided in the Design Standard, and (2) actual values compiled from a large scale (covering hundreds of buildings) building survey conducted in China.

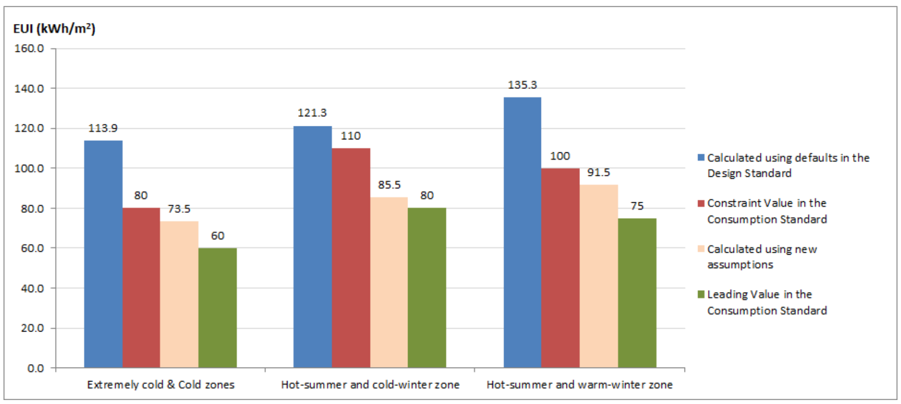
**Table 7 Input parameters for the two building energy models**

| Input parameter | Value |
|---|---|
| Lighting power density ($W/m^2$) | 11 |
| Plug-in power density ($W/m^2$) | 15 |
| Occupant density ($p/m^2$) | 0.125 |
| Occupant sensible heat gain (W/p) | 66 |
| Occupant latent heat gain (g/h/p) | 102 |
| Average outdoor air flowrate ($m^3/h/p$) | 30 |

Figure 15 shows the results of the comparisons among the calculated EUIs based on technical prescriptions in the Design Standard, the use of two different sets of modeling assumptions for the building operations and occupant behaviors, and the two prescribed EUIs from the Consumption Standard for both Type A and Type B buildings. It can be seen that for both building types, the simulated EUIs that used more realistic assumptions from surveys for the Design Standard fell within the two EUIs prescribed by the Consumption Standard (Figure 15). In contrast, for both building types, the simulated EUIs that used default assumptions from the Design Standard were much higher than the CVs, i.e., the constraint values of EUIs prescribed in the Consumption Standard. Such comparisons reveal that both standards will have good consistency if simulated EUIs of the Design Standard are based on actual building operations and occupant behaviors. A by-product of this comparison study is the confirmation that the default assumptions, which were mostly borrowed from the U.S. ASHRAE Standard 90.1, did not represent actual building operations or occupant behaviors in Chinese buildings.




(a) Type A buildings




(b) Type B buildings

**Figure 15Comparison of EUI indicators in the Design Standard and Consumption Standard**

In conclusion, the findings show that the Consumption Standard and Design Standard can support each other and promote progress in building energy conservation programs in a complementary manner. The release of the Consumption Standard should thus enrich the standard system used for building energy conservation and allow it to become a complete system that addresses issues ranging from technical guidance to energy consumption tests.

# 4 The Outcome-based Code in the U.S. and Comparison with China's Energy Consumption Standard

China's Design Standards for commercial buildings and other design standards for residential buildings adopted similar methodology as the ASHRAE Standards 90.1 and 90.2 in the U.S. Additionally. China's variety of climates are similar to those of the U.S. This study compared China's Consumption Standard with the related standards in the U.S. as part of a joint research program under the U.S.–.-China Clean Energy Research Center for Building Energy Efficiency sponsored by both governments.

As China developed and implemented its Consumption Standard, new discussions of the building performance requirements (i.e., EUIs) for building energy standards and code compliance in the U.S. have occurred. The U.S. has recently announced an aggressive target for building energy performance for the next 20 years (NBI, 2012). However, with the ultimate target of constructing nearly zero-net energy buildings, the U.S. building sector will need more stringent energy codes to be able to realize its goals (Cohan et al., 2010).

The current energy standard system primarily addresses the physical characteristics of buildings. Some end uses, such as plug loads that account for up to 40% of energy use in office buildings, are currently outside of the regulatory scope (Denniston et al., 2011). The energy savings potential of the current standard system has been exploited for three decades. Therefore, simply increasing the stringency in the present codes may not lead to expected energy savings targets. A revamping of the existing codes may represent a potential solution.

It has been widely recognized that building energy use is driven by two factors beyond the building's physical characteristics, that is, the operational characteristics and occupant/tenant behaviors (Li et al., 2014). The energy standards should address the operational characteristics such as commissioning, control system function, maintenance practices, and system operations including those affected by tenant behaviors, working schedules, occupant density, and habits, as well as tenant-provided equipment power densities and use (Denniston et al., 2011). Nevertheless, physical building characteristics are the easiest to regulate and are therefore a common target of regulations. Activities related to operational and behavior characteristics tend to go beyond the traditional design process, and these occur at multiple stages in the building's operation Therefore, simply adding some relevant provisions into the current model-based code will not solve the problem. Under such circumstances, an outcome-based code has been proposed to complement the code systems in the U.S. (Denniston et al., 2011).

In view of this, the U.S. is now developing the outcome-based code by using performance metrics of the actual energy consumption of buildings (Conover et al., 2011; Rosenberg et al., 2015). This approach is quite similar to China's Consumption Standard, as the outcome-based code also uses EUIs of the buildings for code compliance. However, the role and underlying philosophy of the outcome-based code is quite different from China's Consumption Standard.

Generally, the current energy code systems in the U.S. have three pathways for code compliance: (1) code-defined prescriptive measures, (2) model-based whole building performance measures derived with building simulations, and (3) model-based envelope performance measures derived with building simulations. For residential buildings, there is one more pathway, namely, the HERS (Home Energy Rating System) Index. While prescriptive options are easier for code compliance enforcement, such options lack flexibility for designers. For example, the WWR cannot exceed certain limits. The model-based options provide design flexibility and consider the integrative effect of measures, but they require detailed inputs for building the energy models; hence, more effort is required. Such model-based options also have the drawback that there can be higher uncertainty in the results compared to other techniques. Neither the prescriptive nor the model-based options consider the impact of building operations or occupant behaviors, and thus, these approaches can lead to large gaps between the designed energy targets and the actual energy performance of buildings.

A potential new option involves an outcome-based code compliance path that works in parallel with the other three paths. In opting for the outcome-based code compliance pathway, the design team and the building owner commit to meet a specific energy target and need to provide data on the actual energy use over a 12-month period during the post-occupancy stage. The design team has to assure that the design and construction of buildings comply with baseline building requirements. Following several years of initial occupancy, the owner is required to provide the administrative entity with a certain time span, usually 12 months, of energy use data to demonstrate the achievement of the energy target (Colker, 2014). Upon confirmation of target achievement, the building will be issued a certification of building performance and final occupancy. This outcome-based compliance option was officially implemented in the International Green Construction Code (IgCC) in November of 2014 (Colker, 2014), and it is perceived as a potential complement to the code system because of its coverage of complete energy uses and the flexibility afforded to design work, operations, and code compliance activities. It should be noted that an outcome-based code can also provide a basis for energy benchmarking. However, an outcome-based code has not been adopted yet by U.S. federal or state governments because of implementation challenges and political obstacles.

The research focused on building performance has benefited from the accumulation of data and information on building energy consumption. From this body of work, some publically available databases such as the EIA CBECS (Energy Information Administration's Commercial Buildings Energy Consumption Survey) (U.S. EIA, 2003) and DOE BPD (Department of Energy's Building Performance Database) (U.S. DOE, 2013) have been created. On the basis of the creation of such databases, some voluntary benchmarking programs on real building performance have been developed, including the ENERGY STAR Portfolio Manager (U.S. EPA, 2013), which is based on CBECS, and the EnergyIQ (LBNL, 2014), which is based on both CBECS and California CEUS (Commercial End-Use Survey) (CEC, 2013) data. Despite the success of benchmarking toolkits, some efforts are still needed with respect to implementation and adoption. Because various factors affect building energy performance, obligations need to be clarified and responsibilities need to be assigned to all stakeholders. Meanwhile, ordinances for monitoring and punishment should also be clearly defined. Despite these regulatory needs, outcome-based codes can provide maximum design flexibility, consider building operations and occupant behaviors, and regulate the actual energy use in buildings effectively.

As for the Consumption Standard in China, its application is distinctly different from the outcome-based code in the U.S. The Consumption Standard has been proposed as a sequential control mechanism, along with the Design Standard, for the energy use throughout the building design and operation processes. Conversely, outcome-based code work in the absence of a Design Standard aims to maximize the flexibility for the building design and operation processes. However, for China, some valuable lessons can be learned from the outcome-based approach. It is highly recommended that China build up a national database of building energy use, similar to the U.S. CBECS and BPD databases. Such a database would help to extend the coverage of the Consumption Standard; it is also the most important prerequisite for developing a sound building energy benchmarking system.

# 5 Discussion

As countries target deeper energy savings in the building sector, regulations such as China's Consumption Standard and the U.S. outcome-based code will face common challenges in terms of further development and enforcement.

## 5.1 Data collection and disclosure ordinance

Undoubtedly, data on the actual building energy consumption will form the foundation of many standards or codes based on actual performance. Generally, the development team relies on the collected data to determine the design criteria, and the owner uses recorded energy data to prove compliance and acquire the certification; meanwhile, the responsible administrative entity leverages the data for code enforcement and benchmarking programs. As the core of the entire code system, data collection and disclosures need to be enhanced through efforts addressing multiple issues.

For future enhancements, a disclosure ordinance would be an ideal first target. In China's Consumption Standard, both the CVs and LVs are generated from a database of actual building performance. As more and more buildings are included in the database, the indicators will become more meaningful and representative. Instead of voluntary disclosures, a well-organized data disclosure program regulated by authorities is more reliable, especially in respect to data completeness, consistency, and end use coverage. Moreover, a data disclosure ordinance is a prerequisite for regulating the actual building performance. The metering approach, metrics system, and reporting schedule also need to be prescribed for a complete data reporting program. Given that it plays such a critical role in actual performance based codes, the enactment and enforcement of a data disclosure ordinance should be the top priority for any country or region that envisions the application of an outcome-based code.

## 5.2 Scope of inspection for the actual performance

It is widely acknowledged that energy use is inherently affected by factors like building function, occupant density and behaviors, operation schedules, and building use patterns. Some of these factors are determinants for categorizing buildings, while others are the major variables for the optimization of energy performance. Given the significance of these factors, expanding the scope of inspections so that they adopt more variables into monitoring and measurements would be constructive for the buildup of databases and the development of standards. The development team and responsible administrative entity of the standard should thus take into account tracking and scheduling designs for reporting data, which could help with refining the outcome-based code.

## 5.3 Commitment and enforcement mechanisms

Normally, the regulating process under the current code system is only valid through the time of construction completion, or at the point of occupancy. However, for an outcome-based code, where the metric is real energy use during post occupancy, the regulations need to be extended into the operational life of the building. In order to do so, new incentives and administrative initiatives associated with the standard are needed. The coordination of related standards should be well designed in regards to the regulatory scope and consistency. In China, the Consumption Standard takes over the regulations subsequent to the Design Standard in the administrative chain. The Consumption Standard itself cannot achieve energy conservation in buildings directly. However, when it is adopted and enforced by the central or local governments as building codes, it will trigger energy retrofits or efficiency and operational improvements to those buildings with actual energy use higher than the constraint values, so as to reduce energy use.

Although not yet formalized, an ordinance about the enforcement of the Consumption Standard, which will pertain to administrative entities and offer details on verification, certification, rewards, and punishment, is expected to be proposed as a cornerstone of the code system. Similarly, in any context of outcome-based regulations, such an arrangement regarding enforcement will always be the top priority associated with the development of the standard.

## 5.4 Guidelines on commissioning and operations

The actual energy performance is highly affected by post-construction activities including commissioning at different stages and daily operations. However, unlike mature guidelines in terms of the building design, the guiding principles for these activities are still very rudimentary in China, where the concept of commissioning has just been introduced to the building industry. Commissioning and operations are activities that strongly depend on the practitioners' understanding of the energy services systems in buildings, and particularly, those experiences gained from practice. Thus, the administrative entities bear the responsibility of developing such guidelines for the ultimate energy savings target.

## 5.5 Limitations of this study

This study provides a thorough assessment of China's newly released Energy Consumption Standard for Buildings, and it includes a comparison with the U.S. outcome-based code under development. This study did not discuss similar efforts undertaken by other countries, which may be the focus of a future study. This study also did not address the actual energy distribution of buildings that forms the basis of the two EUI indicators because China did not publish those data. Only quantitative comparisons between the Consumption Standard and the Design Standard were summarized because of the limited scope of the article.

# 6 Conclusions

This study reviews China's newly released Energy Consumption Standard for Buildings. Key findings that provide insights into the Consumption Standard for building designers and energy policy makers are summarized below:

1) Compared with developed countries, which tend to focus more on achieving building energy savings through the use of high efficiency equipment and advanced systems and controls, China's building energy savings efforts have paid more attention to both building energy efficiency improvements and building energy conservation via the placement of caps (i.e., the building sector energy consumption should not be more than one billion TCE) on the total amount of energy consumption in the building sector as well as controls on the energy use intensity of individual building sub-sectors.
2) The Standard for Energy Consumption of Buildings is China's first standard to regulate the actual energy consumption of buildings. It was developed in response to the long-term energy savings goal set for the entire building sector in China. Using the prescriptive energy consumption of buildings, China has shifted its traditional focus from building technical measures outlined in the Design Standard GB 50189 to the holistic control of energy use in buildings by considering building

operations and occupant behaviors in the Consumption Standard. The release of the Building Energy Consumption Standard is a new milestone for China's building energy conservation work, and local standards and industry standards based on this national standard have been developed gradually. This triggered a new trend of outcome-oriented building energy conservation work in China.

3) Occupant behavior is a significant factor that affects building energy consumption. There are significant differences in occupant behavior in buildings between China and the U.S. The predominant Chinese life style and behavior involves part-time, part-space use and the application of natural resources first (e.g., natural ventilation, daylighting), while in the U.S., the typical behavior involves full-time, full-space use and the application of mechanical cooling and heating first (Xia et al.,, 2014). This leads to different technical optimization solutions for building and system designs. Because of the widespread adoption of distinct energy systems, China's Building Energy Consumption Standard provides different energy use indicators and directions for technical improvements.
4) The consistency of the energy use intensity in buildings between China's Consumption Standard and the Design Standard GB 50189 can only be achieved by using actual building operations and occupant behaviors in Chinese buildings, rather than by using default assumptions based on the current Design Standard. The development of an outcome-based code in the U.S. was discussed in parallel to China's Consumption Standard, and strengths of this method were revealed.

For future revisions of China's Consumption Standard, several areas of improvement were identified, and these included building energy use data collection efforts and a disclosure ordinance, expanded scope of actual performance monitoring and tracking, commitment and enforcement mechanisms, guidelines on commissioning and operations, and coverage of rural residential building energy use.

## Acknowledgments

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