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Comparison of building energy use data between the United States and China

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Abstract

Buildings in the United States and China consumed 41% and 28% of the total primary energy in 2011, respectively. Good energy data are the cornerstone to understanding building energy performance and supporting research, design, operation, and policy making for low energy buildings. This paper presents initial outcomes from a joint research project under the U.S.-China Clean Energy Research Center for Building Energy Efficiency. The goal is to decode the driving forces behind the discrepancy of building energy use between the two countries; identify gaps and deficiencies of current building energy monitoring, data collection, and analysis; and create knowledge and tools to collect and analyze good building energy data to provide valuable and actionable information for key stakeholders. This paper first reviews and compares several popular existing building energy monitoring systems in both countries. Next a standard energy data model is presented. A detailed, measured building energy data comparison was conducted for a few office buildings in both countries. Finally issues of data collection, quality, sharing, and analysis methods are discussed. It was found that buildings in both countries performed very differently, had potential for deep energy retrofit, but that different efficiency measures should apply.

Keywords: Buildings, comparison, data analysis, data model, energy benchmarking, energy monitoring system, energy use, retrofit

1. Introduction

Worldwide, the building sector is the largest emitter of carbon dioxide (CO_2) and the main contributor to climate change [1]. Buildings account for 72% of U.S. electricity use and 36% of natural gas use, and U.S. buildings currently contribute 9% of the world's CO_2 emissions [2]. In 2007, China's building sector consumed 31% of China's total primary energy [3]. China is also the second largest building energy user in the world, ranking first in residential energy consumption and third in commercial energy consumption [4]. In both developed and developing countries, buildings are responsible for more than 40% of global energy use and one-third of global greenhouse gas emissions [5]. In 2011, buildings in the U.S. and China consumed 41% and 28% of total primary energy in both countries, respectively. Furthermore, China's percentage is on the rise.

Better understanding of and improvements to building energy performance and operation are critical steps toward sustainable development and mitigation of global climate change. In the building sector, two distinct scenarios apply: Buildings in China have lower design efficiency levels [6] but also lower needs in terms of energy use; buildings in the United States have higher design efficiency levels but also higher needs for energy use. As a result, U.S. buildings use much more energy than those in China. This is mainly driven by essential differences between building operation and occupant behavior in both countries: Chinese buildings typically operate in a part-time, part-space mode – only occupied spaces during occupied time are conditioned, while U.S. buildings typically operate in a full-time, full-space mode – the whole building is conditioned most of the time including unoccupied hours with thermostat setback [7]. Therefore while buildings in the world's two largest economies have large energy savings potential, different energy savings measures will be needed.

Good building energy data are the foundation for research and building energy efficiency policy making. Energy monitoring, data collection, and analysis play crucial roles to support the design and operation of low energy buildings. Several studies, including a National Institute of Standards and Technology (NIST) report, show that energy feedback devices can provide real energy savings by motivating building occupants to modify behavior, and while the level of savings varies, typical energy reductions on the order of 10% can be expected [8]. Moreover, a commissioning study shows that problems of building energy performance are pervasive and well known [9].

Keeping in mind the importance of monitoring and building energy performance management and to further the understanding of building operations, an Energy Information Handbook, published by Lawrence Berkeley National Laboratory (LBNL), is part of a DOE sponsored project to educate commercial building owners, facility managers, and operators [10]. The importance of this field is also emphasized by the fact that International Standards Organization (ISO) is developing a Standard 12655, *Energy Performance of Buildings — Presentation of Real Energy Use of Buildings* [11], to standardize the data model used to represent measurement and performance data across all buildings and participating nations. DOE is also working on a building performance database to provide engineering and financial practitioners with a decision-support platform that enables them to evaluate energy efficiency products and services in commercial and residential buildings. The IEA's Energy Conservation in Buildings and Community Systems (ECBCS) Annex 53, *Total Energy Use in Buildings: Analysis and Evaluation Methods*, also aims to develop new methods and tools to better understand and predict energy use of buildings [12].

Several cities in both countries are actively installing online measurement and monitoring platforms, which mostly measure electricity consumption, cooling loads, indoor air temperature, etc. Electricity consumption measurements include not only total use, but also each major end use, subcircuit branch use, and large power equipment use. However, most of these building energy monitoring platforms are relatively isolated and lack a common data structure. This makes communication and exchange of building energy performance data difficult. One of the challenges in comparing the performance of a set of buildings that have different data acquisition systems, data output formats, and energy analysis platforms is the lack of a common platform for data analysis. To make the communication and exchange of building energy consumption information seamless across all monitoring platforms and building automation systems (BAS), a standard and uniform building energy use description and a definition of minimum measured data requirements are urgently needed. Furthermore, most monitoring systems are separated from existing BAS, which leads to incomplete data collection and places extra burden on building owners and operators to run and manage both systems. Data analysis capability is also limited in providing actionable information for key stakeholders and decision makers to achieve energy savings.

To better understand building energy performance and improve building operations to reduce energy waste and increase efficiency, and more importantly to investigate the discrepancy in building energy use between the U.S. and China, a study of buildings in both countries with different climatic conditions and occupant cultural differences can play an important role. This paper presents outcomes from a joint research project under the U.S.-China Clean Energy Research Center for Building Energy Efficiency. The project aims to create knowledge, tools, and guidance to support the development of a standard methodology for building energy data definition, collection, presentation, and analysis; apply the developed methods to a standardized energy monitoring platform, including hardware and software to collect and analyze building energy use data; and compile offline statistical data and online real-time data in both countries to fully understand the current status of building energy use. A dozen buildings with online measurement and monitoring platforms were selected across the several climatic conditions in both countries. To gain a detailed understanding of building performance, measurements included three types of data at one-hour or 15-minute intervals: (1) building energy use, including building totals and a breakdown into major end uses for various fuel types; (2) operating conditions of HVAC systems and equipment; and (3) indoor and outdoor environmental conditions. The collected data were analyzed for three main purposes: (1) energy profiling — annual and monthly end uses, weekly and daily use patterns; (2) energy benchmarking — comparison of annual and monthly energy end uses among selected buildings to identify and understand driving factors of high performance buildings and demonstrate good design and operation practices; and (3) energy diagnostics — analyzing the performance of HVAC systems and the central plant to identify potential energy and operating issues and recommend retrofit measures.

This paper first reviews and compares several popular existing building energy monitoring systems in the U.S. and China. System structure, function, and performance are compared for each monitoring system, and the common field and basic functions of these monitoring systems are discussed. Next a standard energy data model for building energy monitoring is presented. Then a detailed building energy data comparison was done for a few selected office buildings in both countries. Finally, issues of data collection, quality, sharing, and analysis methods are discussed.

2. Building energy monitoring systems

Granderson et al. [10] reviewed and summarized the characteristics of more than 20 building energy information systems (EIS), as well as their differences with building management systems (BMS) and energy management and control systems (EMCS). The study covered key EIS characteristics: data collection, transmission, storage and security, displays and visualization, energy analysis, advanced analysis, financial analysis, demand response, remote control and management, and other general management issues.

In general, building information tracking can be categorized as system tracking and energy tracking, as shown in Fig. 1. System tracking focuses on building systems (such as lighting and HVAC) performance, including basic building automation control, fault detection and diagnostics (FDD), and continuous system optimization. Energy tracking focuses on building energy consumption. Based on customer needs and metering strategies, energy tracking can further be divided into utility tracking and benchmarking, meter visualization, and EIS. Utility tracking and benchmarking takes a whole building's portfolio and looks at its energy performance. Meter visualization is used to analyze more detailed building submetering information and calculate building end-use energy.

Some systems offer comprehensive solutions and a generic application programming interface (API) for both energy and system tracking. These systems require secondary programming to meet each user's needs. This offers great flexibility to energy and system tracking, allowing users to build a system topology and embed different algorithms for data processing and analysis.

Fig. 1. Building performance tracking systems (Granderson [13]).

Various monitoring systems were used in the selected buildings. All the systems share some characteristics, such as a centralized database, data acquisition module, and a data visualization GUI. Most systems can provide good support on technical features, data analysis, and fault detection, but each has different capacities in terms of data analysis and fault detection. Some in-house-developed systems have relatively simple GUI and user-customized functions, while some commercialized platforms often offer better GUI and more comprehensive data processing capability. 3. A standard building energy data model

3.1. Necessity of a data model

As a platform of building energy conservation management and auxiliary diagnosis, the building energy monitoring system is designed on a national or even global building energy database. The monitoring system is multi-user and object oriented, which differs from traditional building information and management systems like BAS, EMCS, and BMS. Analyzing the differences by comparing the data among a large portfolio of buildings is the main advantage of such a standard monitoring system.

Common building energy diagnosis methods focus on some details of subsystem models, analyzing operational performance using various types of data, such as air-flow rate, water-valve opening, and supply and return air temperature and humidity. However, in the monitoring system, these common diagnosis methods are not well implemented. Common methods of energy conservation analysis rely on the in-depth study of a detailed building load model or detailed mechanical and control models. The methods, based on monitoring systems, employ an empirical building model derived from detailed statistical analysis. Furthermore, some operational problems can be found more easily by making comparisons between buildings rather doing than a longitudinal analysis of a single building.

As cross-sectional comparison is the basic analysis method in monitoring systems, building energy data models should be uniform to assure that energy data and system structure are comparable. Building data and information, especially time-series energy use, can then be compared between different buildings, and even different monitoring systems. The monitoring system would produce more knowledge on building energy performance with a database of a large number of buildings.

Most existing monitoring systems focus on energy data analysis in a single building and do not fully consider the use of a building data model. For example, Brown, et al. [14] diagnosed the operational schedule problem of lighting using hourly electricity data, but the monitoring structure and energy model were not mentioned. Dong, et al. [15] tried to find the linear relationship between energy consumption and climate parameters. With this linear building energy model, the monthly building energy data can be made uniform and comparable, but only total accumulated data were considered. For benchmarking studies, researchers [16-18] compared monthly or annual total energy use, but ignored detailed operational information and correlation in the hourly time-series data, and therefore lacked a comprehensive data comparison. Thus, it is necessary to discuss and unify the functions of the system, and define the types of data for collection. A standard building energy data model should be developed to make monitoring systems comparable and valuable.

3.2. Basic functions

Data storage, automatic correction, data analysis, visualization, and reporting are basic functions of a monitoring system [19-21]. In particular, visualization and reporting are extensively discussed in subtask B2 of IEA Annex 53. However, these functions are used for final analysis and presentation purposes while this paper introduces the fundamental background function: data processing.

Many studies have looked at operational fault diagnosis and benchmarking, even if they are independent topics. The energy monitoring system is just a bridge connecting them. Energy monitoring and comparison are the core of the system; meanwhile this system also offers auxiliary information and analysis for benchmarking and detailed diagnosis. Thus, there are three levels of monitoring system function on data processing: (1) audit and benchmarking, (2) monitoring and management, and (3) energy conservation and operational performance diagnostics.

The first level is usually available in most existing monitoring systems or benchmarking databases. The whole building's annual or monthly data are compared or ordered according to its climate zone and building type. Statistical methods can be used to analyze the profile of energy consumption and its correlation with climate parameters. For short- and medium-term management, the second level mainly includes monthly or weekly energy auditing, analysis of daily energy consumption by various end uses, characteristics comparison, and the analysis of a 24-hour curve of various end uses. Comparison approaches can use common references, be between buildings, or use historical records of the same building. Comparison at various intervals is a brief but efficient approach to managing the building's operational performance. The third level is for preliminary diagnosis in a microcosmic view. Hourly time-series analysis, correlation analysis, and efficiency calculation provide more assistance to on-site investigation and diagnosis.

3.3. Standard data model

To realize all three basic functions, the collected information and energy data should cover various types of end uses with a short time interval. During this project, contributions were made to develop a uniform data model, certified in the ISO Standard 12655 [11], shown in Fig. 2.

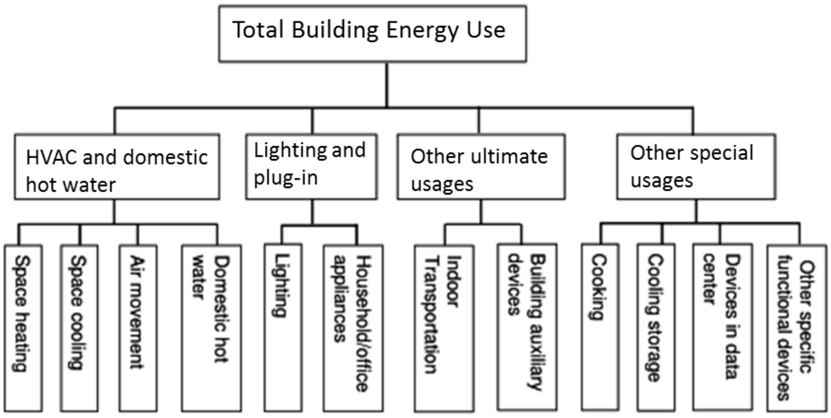

Fig. 2. Building energy use data model.

This model follows a tree structure, from total energy use down to each major end-use. End-uses in both the first and second tiers are described clearly in this standard. The model has a clear structure and logical relation between each sub-item. Ideally, it can be applied in most buildings, and benchmarking can be performed across buildings based on these detailed end-uses.

3. Building energy data comparison

4.1. Introduction of case study buildings

To deeply understand the discrepancies of building energy use between the U. S. and China, as well as the drivers to different performances, the buildings selected from both countries, for analysis and comparison, should meet the basic selection criteria as follows:

1) Medium- to large-size office buildings are preferred, as they are the most common types of commercial buildings (referred to as "public buildings" in China). The end uses of such buildings can be more easily clarified as there are not so many special devices or complicated systems as in other building types, such as hospitals.
2) Detailed building information is available: floor area, number of stories, vintage, location, climate, operating hours, number of occupants, description of building energy service systems.
3) Detailed energy data for major end uses are available, including lighting, plug-loads, data center if any, elevators, service water heating, and HVAC (chiller, boiler, cooling tower, fan, pump, any direct expansion [DX] unit and radiators).

4) At least one complete year's valid measured energy use data are available, with one-hour or shorter time intervals.
5) Overview of the monitoring system is available, showing the hierarchy of sub-metering.
6) High-level description of BMS is available, including key data points.
7) Optional but necessary for HVAC analysis and diagnostics: typical HVAC system and central plant operating conditions. For example, chiller power consumption, cooling loads, chilled water flow rate, inlet and outlet water temperature; AHU supply airflow rate, fan power, supply air temperature, etc.
8) Optional but good to have: indoor conditions, including typical space air temperature and humidity; outdoor conditions, including outdoor air temperature and humidity, wind speed and direction, solar radiation.

A dozen office buildings, five in the U.S. and seven in China, were selected based on the above criteria. Four of the buildings, for which the data collection and initial analysis has been completed, were used in this study for detailed analysis and comparison. Table 1 summarizes key information of the four buildings.

Table 1 Basic information of the case study buildings.

Name	Building A	Building B	Building C	Building D
Location	Beijing, China	Beijing, China	Merced, California, U.S.	Berkeley, California, U.S.
Climate zone	Zone 4B,	Zone 4B,	Zone 3B,	Zone 3C,
HDD18ºC	2,918,	2,918,	1,495,	1,612,
CDD10ºC	2,286	2,286	2,657	1,614
Year Built	1989	1987	2005	1960
Floor area (m²)	54,490	39,211	16,000 (7,000 for the office wing)	8,316
Operation hours	M-F 7 a.m.-6 p.m.	M-F 6 a.m.-6 p.m.	M-F 7 a.m.-6 p.m.	M-F 7 a.m.- 6 p.m.
HVAC	Water-cooled chiller, district heating, VAV + CAV systems	Decentralized AC for cooling, district heating	District cooling, district heating, VAV systems	DX cooling and gas-boiler heating, VAV + CAV systems
Monitoring Platform	iSagy	iSagy	EPP	Pulse Energy
Data-interval	1 hour	1 hour	15 min	15 min
Photo				

Building A is a large, mixed-use commercial office building with some restaurants, stores, and a bank. It consists of a tall main building with large glass curtain walls and an annex. Building B is a government administrative office building, served by decentralized cooling systems and district heating with radiators, without any other air-side equipment. Building C is a mixed-use building with a library wing (9,000 m^2) and an office wing (7,000 m^2), and is served by the campus' district cooling and heating systems. Only the office wing is used in this study. This building was newly built with a design energy goal of 38% greater energy efficiency than the 2001 California Title 24 standards [22]. Building D is the oldest among these four buildings, with metal-panel walls without insulation; and leaky, single-pane, clear-glass windows. It is served by various DX HVAC systems.

4.1. Energy data comparison

A whole year of energy use data for each building were selected and compared based on annual, monthly, weekly, and daily analysis. Since there is no gas consumption data for space heating in the selected Chinese buildings, which are served by the city-wide district heating system, only electricity consumption was compared in this study. The electricity consumption was normalized by using the gross floor area (not the conditioned floor area) of each building to obtain the energy use intensity (EUI) for comparison.

When calculating the EUI for Building C, the total area of 16,000 m^2 was used for sub-items that involve the whole building, just like the other buildings, while 7,000 m^2 was used for sub-items that only involve the office wing. As an exception, while the elevator is an electricity end-use shared by both wings, the library wing, with more floating people and a longer operation time, has much higher elevator use rate than the office wing. Therefore to split the elevator electricity use, the office wing is roughly considered to account for only 25% of the total. In addition, a ratio based on cooling tonnage consumed by all campus buildings to cooling tonnage of Building C was used to roughly estimate the percentage of plant equipment (chillers, pumps, and cooling towers) energy consumed by Building C.

4.1.1. Annual data analysis

Figures 3 to 6 show a breakdown of annual total electricity use for the four buildings. Since the submetering systems in these buildings differ significantly in terms of detailed subcategories, the end-use structure shown in these figures is not exactly the same as the proposed standard energy data model.

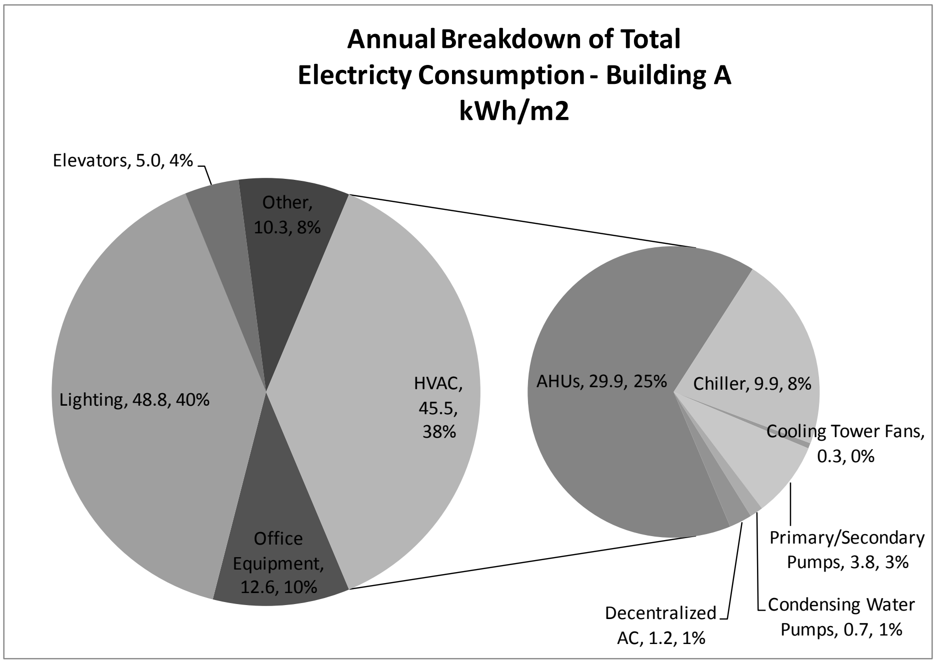

Fig. 3. Building A total annual electricity usage breakdown.

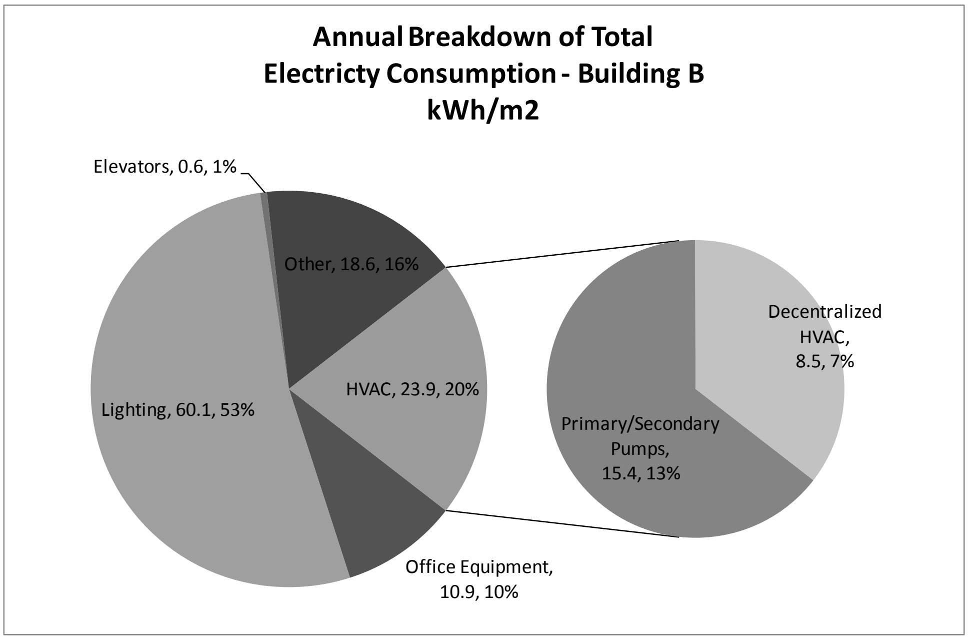

Fig. 4. Building B total annual electricity usage breakdown.

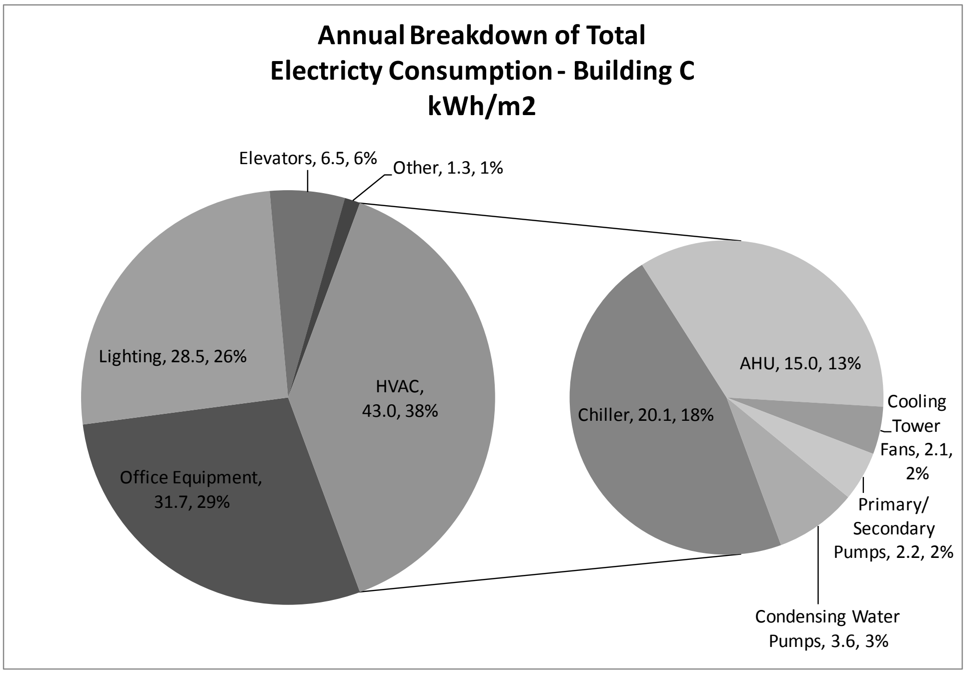

Fig. 5. Building C total annual electricity usage breakdown.

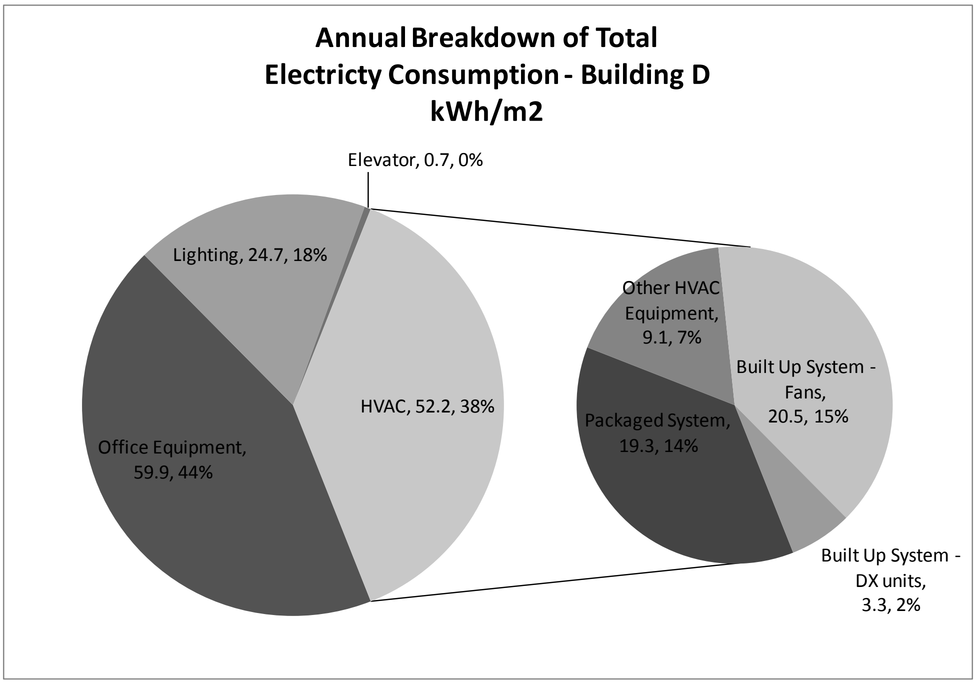

Fig. 6. Building D total annual electricity usage breakdown

As a consequence of the relatively rough submetering system of Building D, the breakdown for this building is not as specific as that of the other buildings. The sub-item "Other" shown in the Buildings A, B, and C is included in the "Office Equipment" in Building D. In terms of HVAC, the packaged systems include rooftop units and ductless split units, while the built-up system consists of fans and DX units. The DX units consume a very small amount of electricity mainly because they are usually off when fans can operate alone with cool outside air due to the airside economizer. Besides, there is a mixed sub-item containing some other HVAC equipment like a small AHU, service hot-water pumps, and a fan that can't be separated.

To compare these buildings and typical office buildings in both countries, the annual total electricity consumption of each building was broken down into four major subcategories, as shown in Fig. 7. The data source of the typical Chinese office building is the 2007 Beijing Municipal Government Office Buildings and Large Public Building Energy Consumption Statistical Summary [23], which is the average of 513 office buildings in Beijing, including 102 Class 1 large administrative office buildings, 379 Class 2 large commercial office buildings, and 32 Class 3 common office buildings. The data source of the typical U.S. office building is the California Commercial End-Use Survey, available from the EnergyIQ website [24]. It is the average of 112 office buildings in California, built after 1940, and with a total floor area of 25,001~150,000 ft^2 (about 2,323~13,935 m^2).

Data for HVAC in these buildings may include energy consumption on equipment related to space heating (primary/secondary pumps, AHUs, etc.), though excluding space heating source energy. The subcategory "other" in the figures can be a mix of things, such as elevators, data centers, kitchen equipment, sewage drainage pipes, etc.

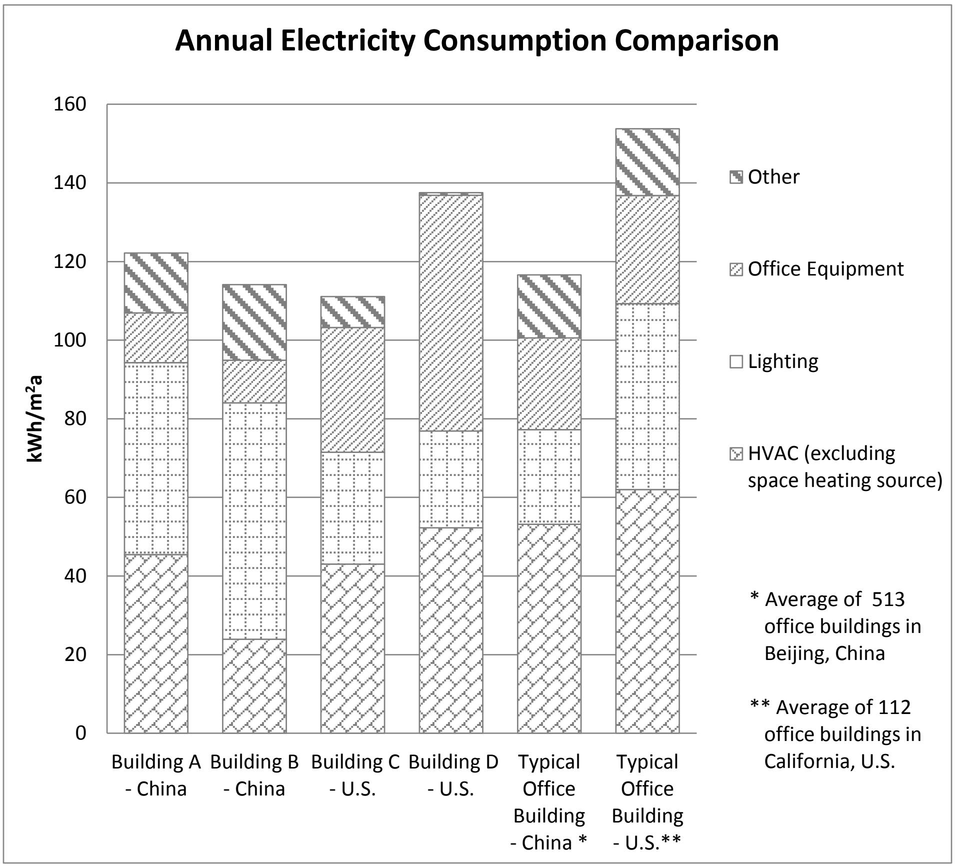

Fig. 7. Annual electricity consumption comparison of case-study buildings against typical office buildings in China and the U.S.

For the total annual electricity consumption, Buildings A and B performed similarly to the typical Chinese office building. However the two U.S. buildings, especially Building C, consumed much less energy than the typical U.S. office building. The more efficient lighting and HVAC systems contributed to the lower energy use of Building C.

In terms of HVAC, Building B, which uses decentralized HVAC for cooling, consumed the least electricity, which indicates that a decentralized HVAC may perform more efficiently than a centralized HVAC. Building D, though located in a warmer zone, consumed more HVAC energy than the Chinese buildings. This may be caused by several factors. First, Building D’s indoor space temperature setpoint for cooling is 21~22℃, while Building A’s is 24~26℃. Second, Building D’s old and poor envelope results in much higher cooling and heating loads. Finally, in general, more outdoor air is provided in the U.S. buildings, and related U.S. ventilation standards are more stringent than those in China, leading to more electricity use to condition outdoor air.

As for lighting, the Chinese buildings consume much more energy than do the U.S. buildings. This may be a combination of design and operation: lighting power, occupant density, operation mode of lights, and different use of natural light. What’s more, according to the sub-metered data, Building B’s lighting system not only consumes more electricity during the daytime, but also stays high at night, contributing to the greatest lighting energy use among the buildings. On the other hand, Building D’s single-pane windows introduce more natural light, and its lighting system has gone through some retrofit. In addition, occupancy sensors in Buildings C and D turn off lights when occupants leave the office for longer than five minutes. More information is needed to decide whether the lighting systems in Buildings A and B need retrofit. However, the typical office building in the U.S. consumes more lighting energy than that in China. This may be caused by large variations of lighting electricity use in the survey buildings. In general, lights in most U.S. office buildings are on during the day and most of the night and without occupancy sensor control, which lead to more energy use than typical Chinese office buildings.

Meanwhile, the two U.S. buildings, especially Building D, consume much more electricity in office equipment than do the two Chinese buildings. Though the office equipment of Building D is mixed with some other equipment, excluding the elevator, it’s still much higher than the sum of “Office Equipment” and “Other” of other buildings. Many computers in Building D are left on or in standby mode at night for various reasons, including remote access by staff, data backup, and operating system and security software updates. This building also has more personal fans, heaters, and desktop task lights, which lead to higher electricity use in this sub-item.

4.1.2. Monthly data analysis

After an overview of annual total electricity consumption, it’s imperative to go further, into monthly data analysis. The data of these buildings were selected from different time periods. To make comparison easier, the time series on the horizontal axis is set uniform, from January to December, but actual data can cross two calendar years.

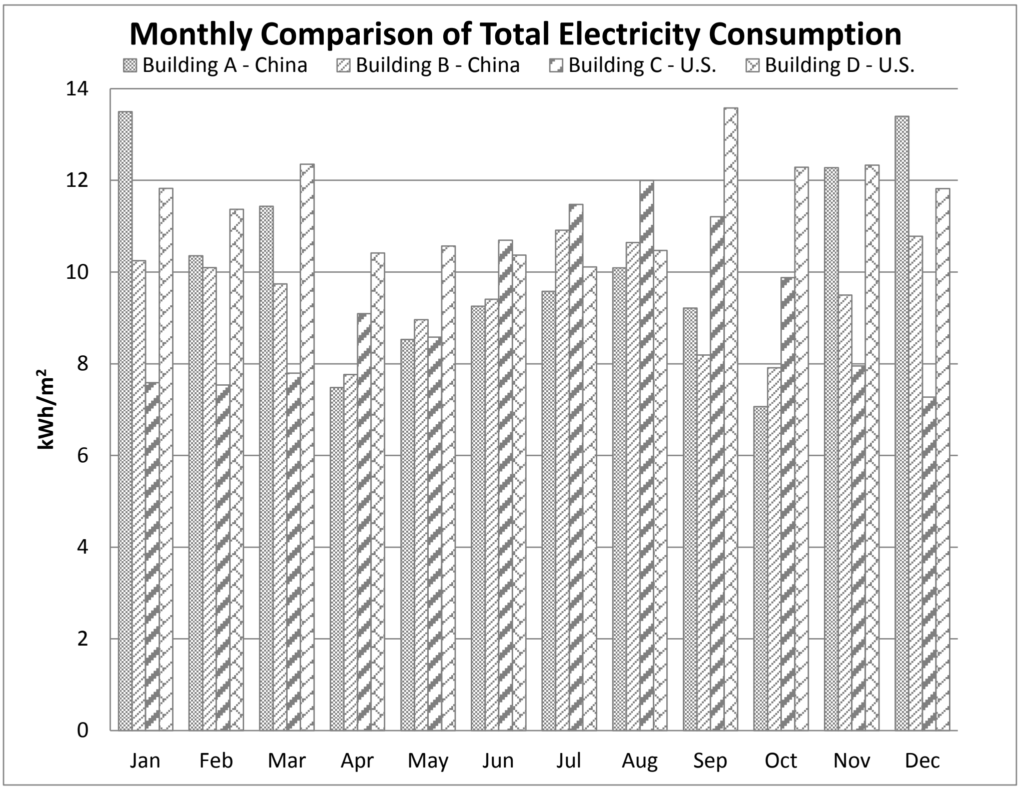

Fig. 8. Monthly comparison of total electricity consumption.

It’s clear that the four buildings differ widely in total electricity consumption from month to month. The discrepancy is much larger in winter than in summer. Buildings A and B consume more energy than Building C in winter but less in summer, while electricity use of Building D is always at a relatively high level. To determine the reason for the differences, a monthly breakdown of total electricity use for each building is shown in Figures 9 to 12.

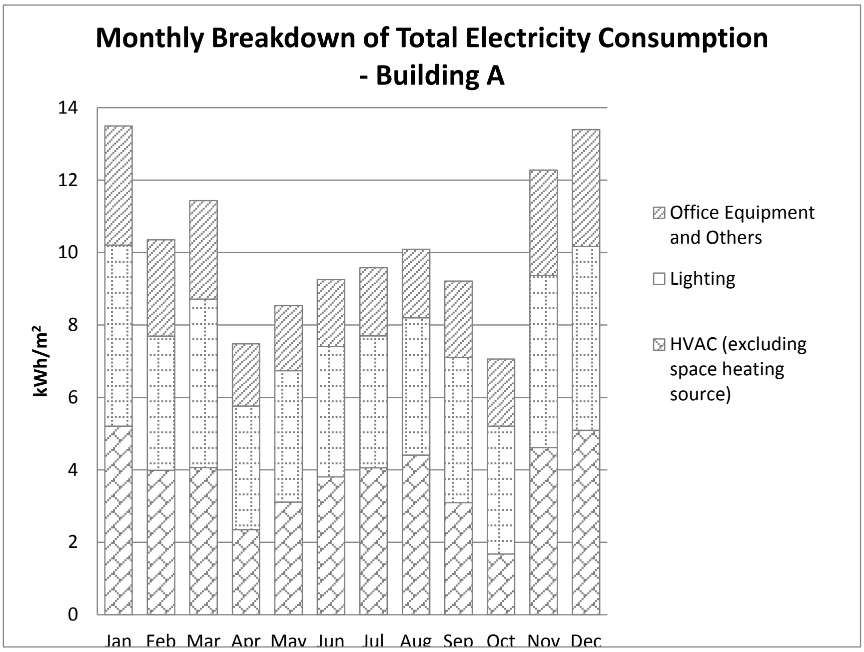

Fig. 9. Building A monthly electricity consumption.

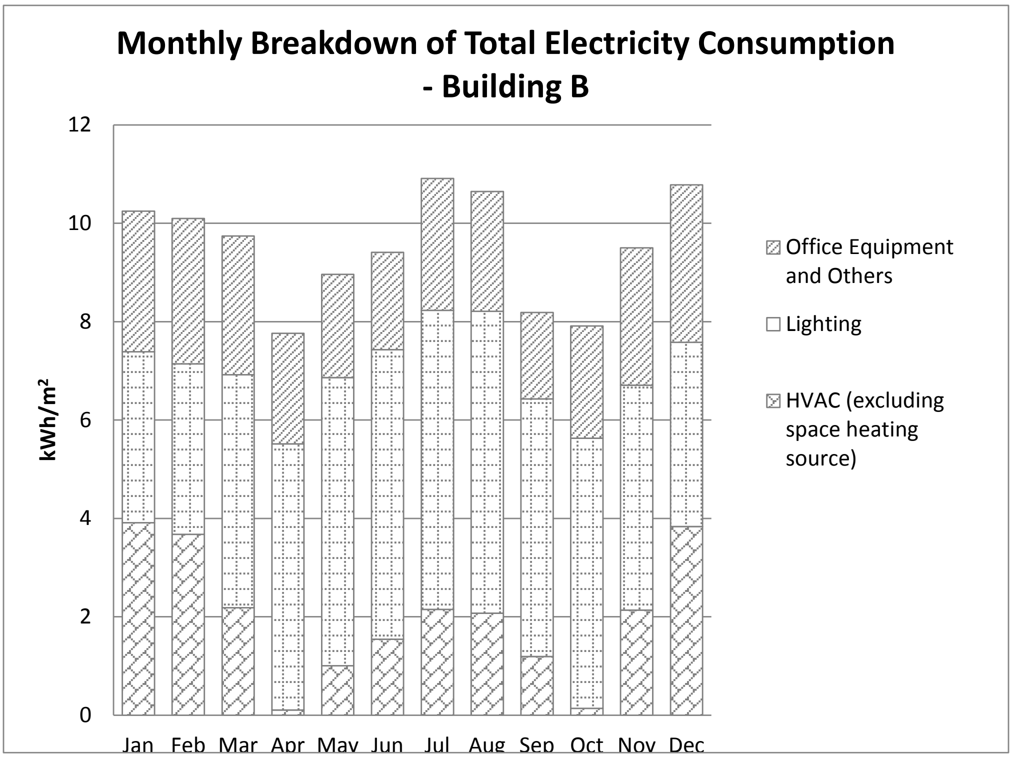

Fig. 10. Building B monthly electricity consumption.

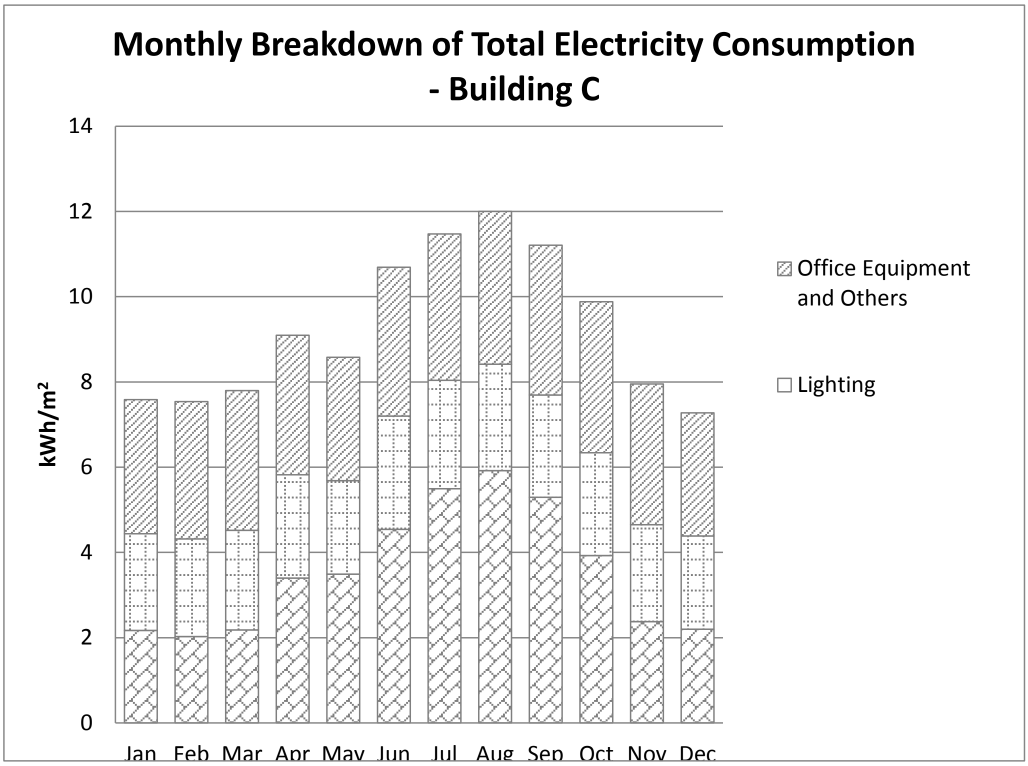

Fig. 11. Building C monthly electricity consumption.

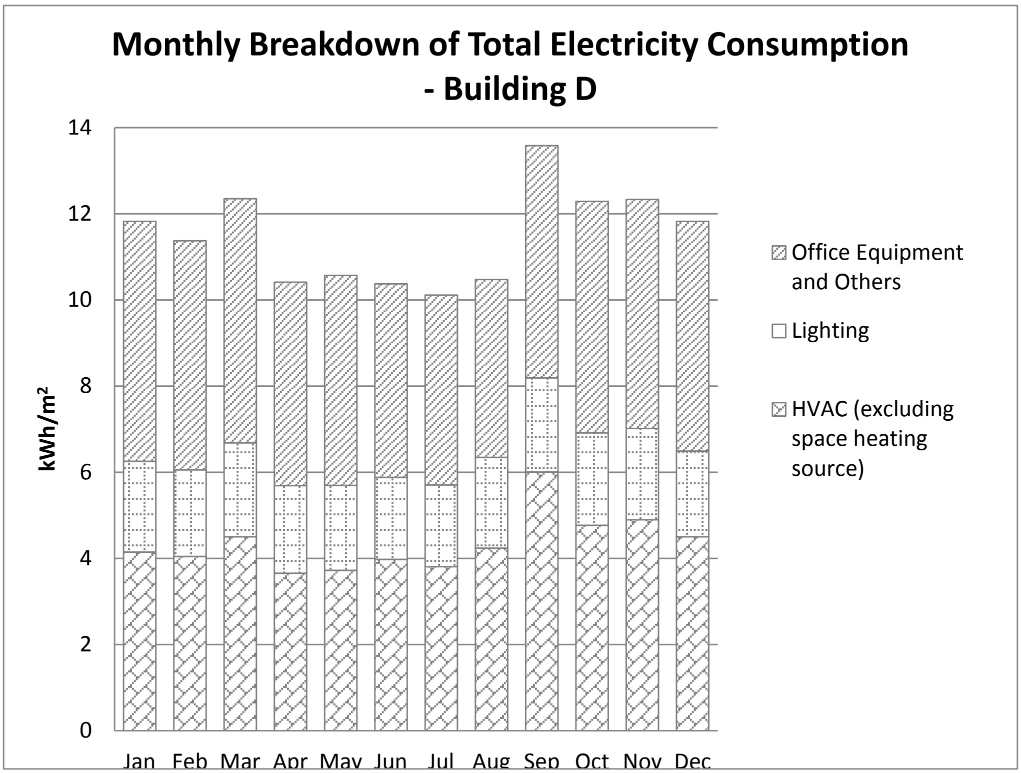

Fig. 12. Building D monthly electricity consumption.

As can be seen, the month-to-month changes in total electricity consumption of these buildings are mainly due to the changes of electricity consumed by HVAC, while the other subcategories, which are not weather related, stay relatively constant throughout the year. For the two Chinese buildings, A and B, district heating is provided from November 15 to March 15 of the following year. As shown in the figures 9 and 10, electricity consumed by HVAC has a large increase during this period, due to the equipment related to space heating, such as AHU and pumps. Further investigation of occupant comfort or measurement of indoor air temperature would help to determine whether the building is overheated or the heating systems need retrofit. It can also be seen that less electricity is consumed during the transition season in April and October when heating is shut-down and little cooling is needed.

For the two U.S. buildings, Building C consumes more electricity in summer and less in winter, while Building D consumes the most in September, the hottest month of the year at this location, mainly caused by changes of HVAC energy. Unlike the Chinese buildings, Buildings C and D have no obvious HVAC increase in winter. In addition, it is curious that Building D's electricity use is higher in March than in the previous and following few months, while electricity use in July and August is much less than in September. This may be because the fourth floor was under retrofit and unoccupied from April to August in this year.

4.1.3. Weekly data analysis

Fig. 13 is a comparison of total electricity consumption of the four buildings in a typical summer week. Since the hottest month for Building D is September, different from the usual summer months of July and August, a typical week was selected from September for Building D.

Though the data were collected at 15-minute time intervals for Buildings C and D, instead of the one-hour intervals for Buildings A and B, the latter interval is adopted for uniform comparison.

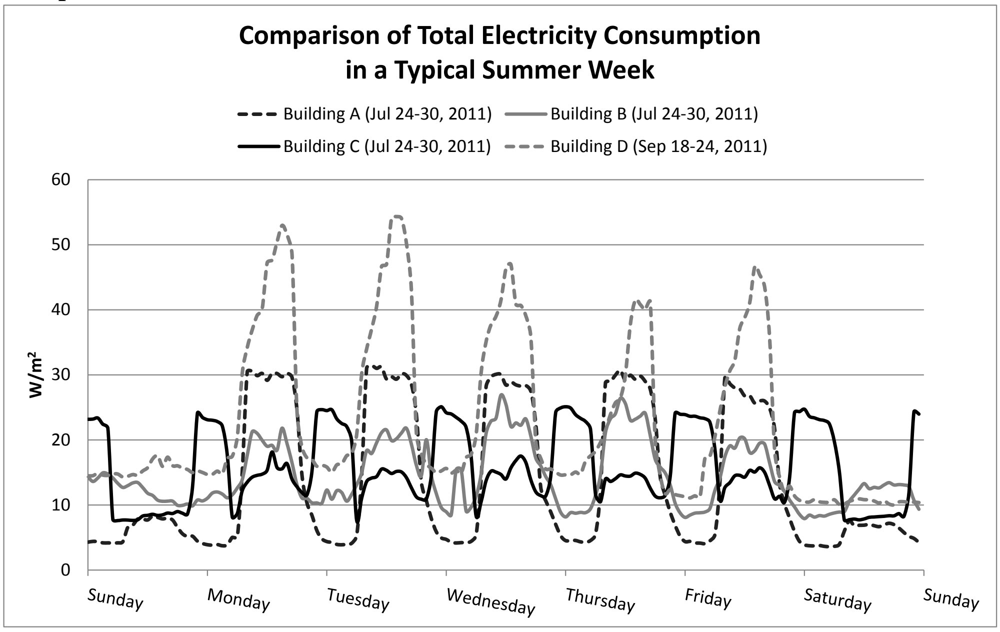

Fig. 13. Typical summer weekly comparison of total electricity consumption.

In terms of total electricity consumption in a typical week of the hottest period for each building, Building D is much higher than the other buildings in the daytime on weekdays, and also has a higher base load at night. Unlike the others, Building C consumes more at night and less during the day. This is a result of its district cooling system, in which the chillers and cooling towers work at night when electricity is cheaper, and supply chilled water during daytime on weekdays. The lower peak in daytime is caused by other normal electricity end uses.

To compare the difference between energy use on weekdays and weekends, it is important to calculate the ratio of average weekday energy use to the average weekend in the selected summer week for each building. In such calculations, each weekday or weekend consists of 24 hours of a whole day. The results are listed in Table 2.

Table 2 Average weekday-weekend energy use ratio in a typical summer week.

Building	**A**	**B**	**C**	**D**
Average weekday-weekend energy use ratio	2.94	1.36	1.24	2.06

According to these ratios, Buildings A and D consume less electricity on weekends, and perform more efficiently throughout the whole week, though they may consume more on weekdays. However, the low ratio of Building C is mainly due to the district cooling equipment, which operates every night, including on weekends.

4.1.4. Daily data analysis

Further in depth, a typical weekday from each season was selected respectively for each building, to compare total electricity consumption. Typical weekdays in a same season were close to each other except for the special summer for Building D.

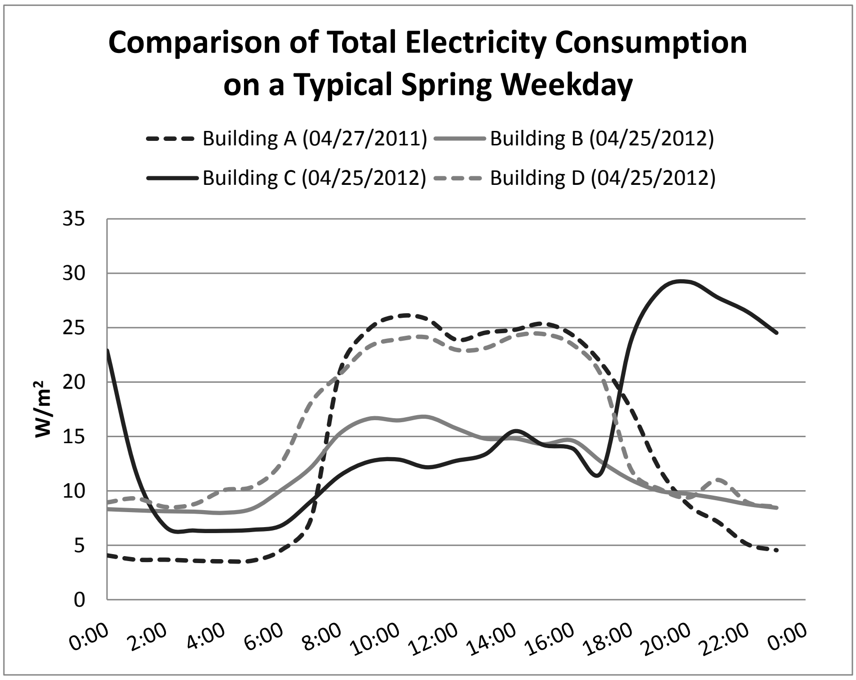

Fig. 14. Comparison of total electricity consumption on a typical spring weekday.

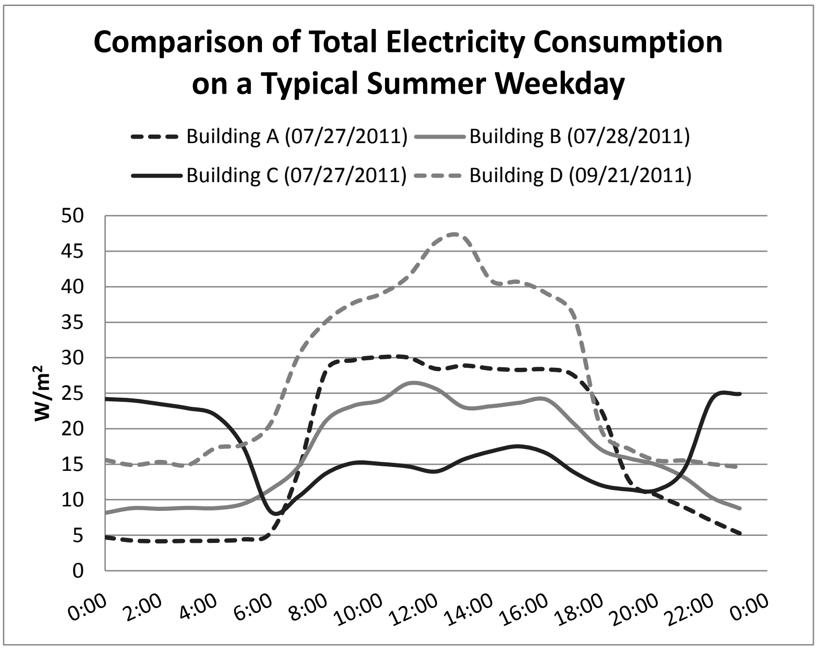

Fig. 15. Comparison of total electricity consumption on a typical summer weekday.

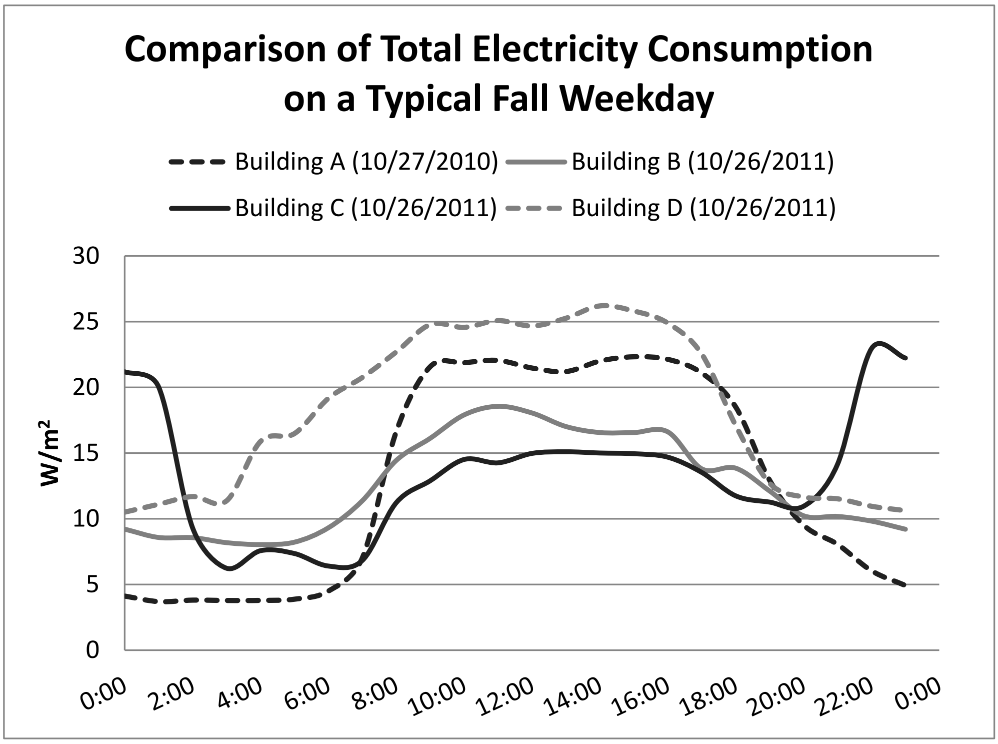

Fig. 16. Comparison of total electricity consumption on a typical fall weekday.

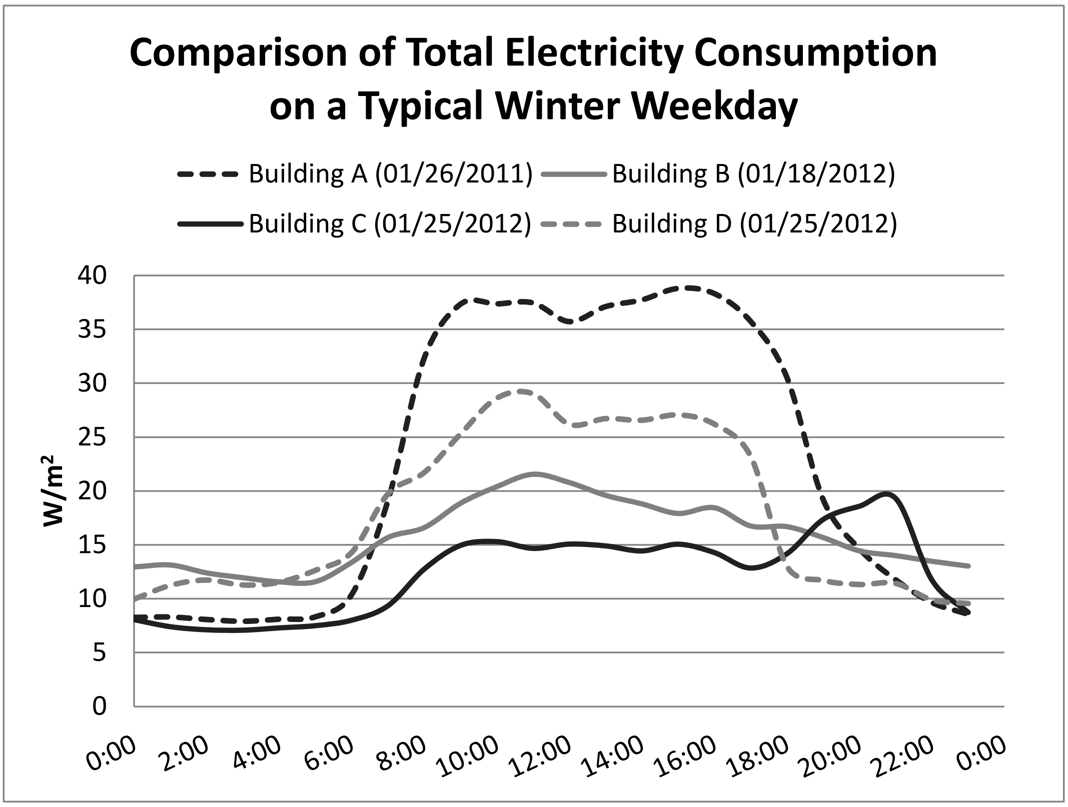

Fig. 17. Comparison of total electricity consumption on a typical winter weekday.

There are many important observations from these charts:

- Buildings A and D are always the top two in terms of peak electricity consumption in different seasons, but Building A has the lowest base power.

- Building A experiences a small decline in total electricity use during lunchtime on each typical weekday, which indicates Building A's occupants are more conscious about turning off unnecessary appliances.
- According to the trends of the Building C's curves, the district cooling system works longer on summer nights and is nearly out of use on winter nights.
- In terms of operation hours, regardless of the rough information provided by building managers, there appears to be no big difference among these buildings, except Building C, in any season, though it is not totally consistent every day.

According to Figures 14 to 17, 7:00~19:00 is taken as the operation period for Buildings A, B, and D for calculating peak demand of a day, and the remaining hours are used for base load calculation. The ratio of average peak load to average base load of these buildings on typical weekdays in each season was calculated and is shown in Table 3. The typical days selected here are the same as those in the above figures. Since Building C has a quite different pattern, it is not included into this comparison.

Table 3 Peak-base energy use ratio on typical weekdays in four seasons.

	Spring	Summer	Fall	Winter
Building A	5.35	5.33	4.47	4.20
Building B	1.94	2.22	2.04	1.68
Building D	2.54	2.65	2.11	2.44

Building A clearly has a much higher peak-base energy-use ratio, especially in spring and summer, which indicates it consumes little electricity when there is no need, and thus it is more efficient and reasonable in electricity use throughout a whole day. Building B has the lowest ratio in every season, partly due to the large load of lighting at night. This may be a good reason for Building A's lower total electricity consumption than Building B in some months, although it always consumes much more than Building B during the daytime.

4.2. Summary

From the above analysis and comparison, buildings may differ a lot in specific sub-items, yet at times seem similar on total electricity consumption. As for the four case-study buildings, the Chinese buildings consumed more electricity in lighting than did the U.S. buildings, contrary to the comparison between typical office buildings in both countries. More information is needed to determine whether the lighting systems in the Chinese buildings need retrofit.

For HVAC, the Chinese buildings experience a large increase in electricity use in winter due to heating-related equipment, while there is no such increase in the U.S. buildings. This may be a result of different climates, but there is still some need to determine whether the buildings are overheated or need retrofit. Decentralized HVAC systems appear to consume less energy than centralized systems. The lower temperature setpoint for cooling and more outdoor air required in most U.S. buildings may be a cause of their higher HVAC electricity use. Besides, old buildings with poor envelopes, like Building D, are more likely to consume more electricity in HVAC in general.

The two U.S. buildings, especially Building D, consume much more electricity in office equipment than the two Chinese buildings, due to more equipment and longer operation hours.

The peak-base energy use ratios of the buildings are quite different, probably due to different operation modes, manual management, and occupants' energy saving consciousness. It is clear that Building A performs much better in this aspect, and even has a small decline during lunchtime, which should be a good model for other buildings.

5. Discussion

Energy benchmarking for commercial buildings has always been difficult. Limiting the scope and normalizing discrepancies while taking into account case-specific circumstances are barriers to useful and proper analysis. However, this task can be made easier with correct data and necessary preparation before data analysis begins.
Some common challenges associated with benchmarking are discussed based on the real experiences from this study. In addition, some primary suggestions to try to overcome these challenges in the future are listed and discussed.

5.1. Data collection

A large number of commercial buildings in the U.S. have some kind of monitoring system installed. The newer buildings with Leadership in Energy and Environmental Design (LEED) certification require building monitoring as a part of the commissioning process. End-use-level detailed hourly or sub hourly building energy monitoring, however, is rare and generally is provided only in buildings used for research. The authors investigated a large number of buildings that claimed to have building energy monitoring systems installed, and found that most of the buildings lacked component level detailed measurement; for example, plug-loads and lighting power were not metered separately. Hourly or subhourly data were unavailable in most of the buildings. Some buildings were installed with an EMCS that can monitor and/or control the lighting and equipment energy, heating and cooling energy, and other end uses as well as indoor temperature and humidity in real time. Unfortunately, some of those systems were not connected to a monitoring system to store the data for a longer period of time.

Another challenge was estimating the building's cooling and heating energy from district cooling and heating systems. Some buildings in this study are located on a large campus and connected to a district cooling and heating system. For a consistent comparison with all other buildings, the cooling and heating energy for the selected buildings had to be separated from the total plant's energy, but this could only provide a rough estimate of the building's cooling and heating energy.

5.2. Data sharing

Once a few buildings with a reasonable amount of detailed measurement data were selected, a major challenge was data sharing. None of the building owners or facility managers was willing to share their measured building energy data. This challenge was overcome by personal discussions with facility managers, site visits, nondisclosure agreements, and by the promise to share analysis results and identify retrofit measures. The research team also provided the funding for additional metering, where lacking. It is vitally important to communicate with building managers before such a project actually starts, to gain deeper information and let building managers know their responsibilities throughout the monitoring process.

5.3. Data retrieval

When database access is allowed, it is still a labor-intensive procedure to download and export data to researchers' computers. Some systems need certain computer language to retrieve and export the data of every useful data point, which can take a long time. The difficulty level of such work depends on the technical features of the energy-monitoring system. Improvements to data retrieval, downloading, and exporting features would ease data acquisition and result in fewer manual errors.

Although raw data are sampled at short intervals by the monitoring systems, such as five-minute or even less, the time intervals of the data available for downloads can be different, depending on what time intervals are used in the post-processing of the raw data. In this study, the post-processed 15-minute interval data were downloaded for the two U.S. buildings, while the one-hour interval data for the two Chinese buildings.

5.4. Naming of data points

The benefits of consistent and useful data point names in BAS are becoming more apparent as computerized systems containing hundreds or thousands of points are deployed in commercial buildings. Well-chosen point names can provide useful information about installed systems and make it easier to monitor, retrieve and download, analyze, maintain, modify, and interconnect data of various building systems. Software that performs automated analysis of HVAC system performance may benefit from consistent application of a point-naming standard [25].

5.5. Missing data

Generally, obtaining complete sets of data are by far the largest barrier for benchmarking and analysis of energy use of commercial buildings. Most of the selected buildings have some missing data, and there seems no pattern to which meters might lose data during what time periods. The causes of missing data vary. U.S. buildings have a high frequency of missing energy data around weekends and missing condition data at night, suggesting the monitoring system is sometimes out of use when no one is in charge.

Chinese buildings' biggest problems lie in the connectivity between meters, database, and online system. When connection is lost, all data are lost for all equipment.

Meter instability may cause occasional individual missing data, while large sets of missing data may be caused by the retrofit of either the monitoring system itself or energy service system (like HVAC or lighting), or even by power failure in the buildings, during which the meters don't measure, the connection is lost, and even the computer is out of power, leaving missing data in the database. To avoid these problems requires higher quality meters, sensors, nonstop operation of the monitoring system, and better emergency measures when power is out and connection is lost.

5.6. Data quality

Even if the data obtained are complete, data quality may suffer, mainly due to the uncalibrated or broken meters or sensors. Some invalid data — such as negative values and abnormally mutational findings — can easily be detected, while some seemingly normal data may actually be inaccurate, considering the error of measurement. Higher quality meters and sensors, along with more frequent maintenance, would avoid these problems.

Moreover, it is possible for invalid data to appear during the downloading and exporting process, especially when exporting a large set of data at one time. A higher quality data transmission system may avoid this possibility.

5.7. Data correction

To get the data in workable order for calculation, analysis, and benchmarking, the missing or invalid (mainly negative) data should be replaced with data during time periods or days that were similar to the invalid points, taking weather condition into account as well. For example, a few missing data would be replaced by the previous or following few proper data, or their average. Several hours' missing data would be replaced by data of the same time periods on the previous or following day, taking into account weekdays and weekends. The same goes for missing or invalid data of an even longer period.

5.8. Data analysis

Analyzing and comparing more than a year's complete and corrected submetered energy data are a big challenge. Although the importance of data analysis is well acknowledged, there is still no standard for it. Some methods are used and some charts are presented in this paper for better and deeper analysis and benchmarking, through which we have achieved some basic understanding of the difference of energy use between buildings in the U.S. and China. However, more research is needed to develop a standard and widespread methodology for building energy data analysis and benchmarking.

6. Conclusions

Existing energy monitoring platforms lack an industry standard in the whole process of data collection and analysis. Especially, a standard data model is needed to describe the hierarchy of energy end uses in buildings to support energy profiling, benchmarking, and diagnostics. Good data are the foundation of building energy research. It requires better and uniform methods to deal with all the issues involved in data collection, sharing and retrieval, naming of data points, and handling of missing and poor quality data.
The detailed data analysis and benchmarking of the four office buildings demonstrated that buildings in the U.S. and China performed very differently, had deep potential for energy savings, but different efficiency measures should apply.

Ongoing research focuses on: (1) developing new data analytics, especially for energy diagnostics; (2) benchmarking more office buildings with detailed end uses, and HVAC operating and environmental conditions data; and (3) proposing retrofit measures to building owners and energy efficiency guidance to building designers and operators.

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References

[1] Architecture 2030, http://architecture2030.org/, 2012.
[2] U.S. Department of Energy, Energy efficiency trends in residential and commercial buildings, 2008.
[3] IEA, Energy balances of OECD/non-OECD countries, 2007.
[4] J. Eom, L.E. Clark, S.H. Kim, China's building energy use: A long-term perspective based on a detailed assessment, PNNL Report PNNL-21073, 2012.
[5] UNEP, Buildings and climate change, summary for decision-makers, 2009.
[6] T. Hong, A close look at the China Design Standard for Energy Efficiency of Public Buildings, Energy and Buildings 41 (2009) 426–435.
[7] Y. Jiang, China gives green light to building energy reductions combining energy conversation technologies with green lifestyle. IEA ECBCS News 55 (2012).
[8] W.M. Healey, Measurement challenges in achieving energy monitoring systems in buildings, NIST Technical Note, TN-1656, 2010.
[9] E. Mills, N. Bourassa, M.A. Piette, H. Friedman, T. Haasl, T. Powell, D. Claridge, The cost effectiveness of commissioning new and existing commercial buildings: Lessons from 224 buildings, Proceedings of the National Conference on Building Commissioning, 2005.
[10] J. Granderson, M.A. Piette, B. Rosenblum, L. Hu, et al., Energy information

handbook applications for energy efficient building operations, Lawrence Berkeley National Laboratory, Technical Report, LBNL-5272E, 2011.
[11] ISO, Standard 12655: Energy performance of buildings — presentation of real energy use of buildings, 2012.
[12] IEA, ECBCS Annex 53: Total energy use in buildings – analysis and evaluation methods, 2009-2012.
[13] J. Granderson, Monitoring-based commissioning: Continuous performance investigation and evaluation, Presented at Lawrence Berkeley National Laboratory, Berkeley, CA, 2012.
[14] N. Brown, A.J. Wright, A. Shukla, G. Stuart, Longitudinal analysis of energy metering data from non-domestic buildings, Building Research & Information 38 (1)(2009) 80-91.
[15] B. Dong, S.E. Lee, M.H. Sapar, A holistic utility bill analysis method for baselining whole commercial building energy consumption in Singapore, Energy and Buildings 37 (2005) 167-174.
[16] E. Mlecnik, A. Bossaer, J. Coolen, et al., Benchmarking of energy use in Belgium, Energy and the Environment 7 (2003) 113-122.
[17] D. Sartor, M.A. Piette, W. Tschudi, et al., Strategies for energy benchmarking in cleanrooms and laboratory-type facilities, Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings, 2000.
[18] S. Kinney, M.A. Piette, Development of a California commercial building energy benchmarking database, Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, 2002.
[19] H. Akihiro, K. Mitsuhiro, Smart buildings (BEMS) to optimize the energy supply and demand control of buildings, NEC Technical Journal *7* (1)(2012) 82-86.
[20] A. Noreacuten, The first step to cost savings: Smart building power management automation, Building Services & Environmental Engineer, 28 (70) (2010).
[21] M.A. Piette, S. Kinney, P. Haves, Analysis of an information monitoring and diagnostic system to improve building operations, Energy and Buildings 33 (2001) 783–791.
[22] Green Building Research Center, UC Berkeley, Best Practices Case Study, 2008.
[23] BECSS, Beijing municipal government office buildings and large public building energy consumption statistical summary, In Chinese, 2007.
[24] Lawrence Berkeley National Laboratory, EnergyIQ, http://energyiq.lbl.gov/, 2012.
[25] J.F. Butler, R. Veelenturf, Point naming standards, ASHRAE Journal, November issue, 2010.