LBNL-60978

To be presented at the 2007 ASHRAE Winter Meeting, January 27-31, 2007, Dallas, TX.

Measured energy performance a US-China demonstration energy-efficient office building

Peng Xu
Joe Huang
Ruidong Jin
Guoxiong Yang

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Measured energy performance of a US-China demonstration energy-efficient office building

ABSTRACT

In July 1998, the U.S. Department of Energy (USDOE) and China's Ministry of Science of Technology (MOST) signed a Statement of Work (SOW) to collaborate on the design and construction of an energy-efficient demonstration office building and design center to be located in Beijing. The proposed 13,000 m^2 (140,000 ft^2) nine-story office building would use U.S. energy-efficient materials, space-conditioning systems, controls, and design principles that were judged to be widely replicable throughout China. The SOW stated that China would contribute the land and provide for the costs of the base building, while the U.S. would be responsible for the additional (or marginal) costs associated with the package of energy efficiency andrenewable energy improvements to the building. The project was finished and the building occupied in 2004.

Using DOE-2 to analyze the energy performance of the as-built building, the building obtained 44 out of 69 possible points according to the Leadership in Energy and Environmental Design (LEED) rating, including the full maximum of 10 points in the energy performance section. The building achieved a LEED Gold rating, the first such LEED-rated office building in China, and is 60% more efficient than ASHRAE 90.1-1999. The utility data from the first year's operation match well the analysis results, providing that adjustments are made for unexpected changes in occupancy and operations. Compared with similarly equipped office buildings in Beijing, this demonstration building uses 60% less energy per floor area. However, compared to conventional office buildings with less equipment and window air-conditioners, the building uses slightly more energy per floor area.

INTRODUCTION

In July 1998, the U.S. Department of Energy (USDOE) and China's Ministry of Science of Technology (MOST) signed a historic Statement of Work (SOW) to collaborate on the design and construction of an energy-efficient demonstration building and design center to be located in Beijing. The proposed 13,000 m^2 (140,000 ft^2) nine-story office building would use U.S. energy-efficient materials, space-conditioning systems, controls, and design principles that were judged to be widely replicable throughout China. The SOW stated that China would contribute the land and provide for the costs of the base building, while the U.S. would be responsible for the additional (or marginal) costs associated with the package of energy efficiency and renewable energy improvements to the building.

One of the authors (Huang) completed in 1999 a feasibility study of energy-efficiency options based on the preliminary drawings provided by the project architect in China (Huang et al. 1999). The study contained detailed energy and economic analysis of a broad range of energy efficiency and renewable energy measures that might prove suitable to this building. The study explored two types of energy savings: those achievable through the building's geometry and orientation, and those achievable through inclusion of energy saving measures or components in the building itself. The exploration of building geometry led to the selection of a cross-shaped building design to maximize daylighting potential, but with windows located predominantly on the north and south facades for better solar control. Computer analysis using DOE-2 indicated that lighting, air-conditioning, and air-handling or ventilation would make up from 69-74% of the total energy cost for the building.

Further energy analysis of this base design produced a list of eight additional cost-effective energy saving measures with predicted total energy cost savings of 40% to 42%, depending on the level of building operations assumed. The eight measures are:

- Light colored wall/roof surfaces
- Recessed windows
- High-efficiency lighting
- Low-E window glazing
- Bi-level light switches as a simplified daylighting strategy
- Reduced window height
- Staged chillers
- Improved chiller efficiency
- Economizer

The identified measures appear to be very cost-effective and therefore likely to be attractive in the commercial building market in China (Huang et al. 1999). Using U.S. mature market costs and current Chinese energy costs, the recommended strategies have a combined payback period ranging from 2.2 to 10.2 years, depending on how the costs are considered and the building is operated.

Ground-breaking for the demonstration energy-efficient office building occurred in February 2002. The building was completed at the end of 2003, and became fully operational in early 2004. It has an excellent location in the western part of downtown Beijing overlooking Yuyuantan Park, the second largest green space in the metropolitan area. The building has a total floor area of 13,000 m^2 (139,500 ft^2), located on a site area of 2,200 m^2 (23,680 ft^2). It is a nine-story building, with two levels below grade, eight stories above the ground level, and a small penthouse on the ninth floor. The building height is 34.1 m (111.2 ft). Figure 1 shows the final building design and the typical floor plan.

The Beijing City Planning Institute Design Bureau was responsible for the design and construction of the building. The design team adopted almost all of the energy-related strategies recommended in the feasibility study. The final design of the building is a cross-shape structure, with light-colored well-insulated exterior walls having a U-value of 0.62 $W/(m^2{\cdot}K)$ (0.11 $Btu/h{\cdot}ft^2{\cdot}{}^oF$). The windows are double-pane with low-E glass and thermally-broken vinyl-clad aluminum frames, having a U-factor of 1.67 $W/(m^2{\cdot}K)$ (0.29 $Btu/h{\cdot}ft^2{\cdot}{}^oF$) and a SHGC of 0.68. Both the roof and the exposed floor are insulated with polyurethane foam, and have the same overall U-value of 0.57 $W/(m^2{\cdot}K)$ (0.10 $Btu/h{\cdot}ft^2{\cdot}{}^oF$).

The cooling plant consists of two high-efficiency screw chillers, each with an estimated COP of 4.4. The secondary system is a two-pipe fan-coil with a dedicated constant-volume outside air system. This dedicated air system brings the outside fresh air to the design room air conditions, thus eliminating the outside air load from the fan-coil units. Since internally-driven latent loads are relative small in an office building, the fan-coils are dry most of the time and provide only sensible cooling. Using a two-pipe rather than a four-pipe fan-coil system forces the mechanical engineer to zone the building carefully, since such a system cannot provide simultaneous heating and cooling to different parts of a building.

Two-pipe fan-coil systems with dedicated outside air are very common in Chinese commercial buildings. Such systems are inexpensive and flexible in allowing occupants to control heating and cooling locally. They also take up less space and use less energy compared to the all-air systems typically found in U.S. buildings, because water is a much more efficient medium than air for transporting or removing heat. The main disadvantage of a two-pipe fan-coil system is its inability to provide “free cooling”, such as with an economizer cycle, during the swing season. During these conditions, the occupants need to open their windows to provide natural ventilation. For this reason, almost all Chinese commercial buildings have operable windows, as is the case for this building.

The dedicated outside air system has a roof-mounted air-to-air heat exchanger with an average effectiveness of 0.78. In addition, the building has a photovoltaic (PV) system on the roof, as well as an ice thermal energy storage (TES) system in the basement. The PV system consists of 168 modules, 120 of which are horizontal and 48 inclined at 45^o, with a total collector area of 108.6 m^2 (1170 ft^2). The system has a total capacity of 15 kW, and is expected to generate about 15,000 kWh of electricity annually. The electricity is used to meet some of the building’s electrical loads, but not fed back to the grid, since China does not have such a PURPA-type buyback policy. The TES system stores cooling in the ice tanks during off-peak hours when the electricity price is low and then discharges it during the peak hours when the electricity price is high.[1] The building is also equipped with a small flat-plate solar hot water system with a collector area of 20 m^2 (215 ft^2) to provide hot water for use in the bathrooms and lavatories. Space heating is provided by district heating. The building is also equipped with a full DDC control system.

The building has a very efficient lighting system with efficient fixtures, daylighting, automated occupancy controls, and light shelves on the southern façade. 80% of the lighting fixtures are T-8's, while the rest of them are T-12's. The estimated lighting power density used in energy simulation was 6.7 W/m^2 (0.62 W/ft^2). The actual installed lighting power density is less than 4W/m^2 (0.37 W/ft^2), because of the use of high-efficiency lamps and lower lighting lumen level which still meet Chinese design requirements for office buildings. The lighting system also has digital dimming ballasts and occupancy sensors.

There are very few windows on the west and east facades of the building. These, as well as those on the south facade, are recessed into the walls. The south-facing windows, in addition, also have combination light shelf/exterior shading devices located two-thirds of the way up on the windows (see Figure 2). The exterior shades extend outwards about 0.4 m (1.3 ft) to guard against direct solar radiation during the cooling season, while the light-colored light shelves extend inwards 0.2 m (0.8 ft) to allow daylight to penetrate deeper into the perimeter offices.

The building houses the offices of the Administrative Centre for China's Agenda 21 (ACCA21), a semi-governmental organization responsible for managing China's climate change mitigation program, and other branches of the Ministry of Science and Technology (MOST). Under the US-China MOU, the second floor will house a Sustainable Energy Technology Demonstration Center to provide educational outreach, display U.S. energy-efficient and renewable building technologies, and explain the design principles of the demonstration office building. As of summer 2006, this demonstration center is under design by a US consultant, while the spaces have been temporarily converted to regular offices.

LEED OPTIMAL ENERGY ANALYSIS

A US team led by the Natural Resources Defense Council (NRDC) conducted a LEED (Leadership in Energy and Environmental Design) analysis of the building to verify that the building is environmentally friendly and energy-efficient. LEED is a voluntary, consensus-based rating system developed by the U.S. Green Building Council (USGBC) to provide a complete framework for assessing building's environmental performance and ability to meet sustainability goals. LEED emphasizes strategies for sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality.

The authors were responsible for the energy analysis of the building in accordance with LEED for New Construction and Major Renovation, Version 2.1. The LEED rating system has a maximum total credit of 69 points. Buildings with 52-69 points are rated as platinum, 39-51 as gold, 33-38 as silver, and 26-32 as certified. The energy efficiency section has a maximum of 10 points, or roughly 15% of all the credits. The number of energy credit points is determined by comparing the energy cost of the candidate building against the energy budget in ASHRAE 1999-90.1. Table 1 shows a list of the points a building can earn depending on its energy savings compared to ASHRAE 90.1.

The energy analysis was done using DOE-2.1E. Two DOE-2 simulation models were created following standard ASHRAE 90.1 calculational procedures; the first for the *Candidate Building*, and the second for the *Reference Building* used to calculate the target energy budget. This *Reference Building* was created by modifying the *Candidate Building* to the prescriptive requirements and default conditions specified in ASHRAE 90.1. The two models have the same geometry and similar HVAC systems. Table 2 lists the differences between the two models.

For example, the *Candidate Building* has Low-E windows, while the *Reference Building* has standard double-pane windows. The U-values for the walls and roof in the *Candidate Building* are smaller than the U-values in the *Reference Building*. In addition, the *Candidate Building* has both daylighting controls and a TES system.

---

[1] Electricity prices in Beijing in 2004 are 0.7555 RMB/kWh from 8 – 11 am and from 6 – 11 pm, 0.463 RMB/kWh from 7-8 am and 11 am – 6 pm, and 0.190 RMB/kWh from 11 pm to 7 am; the conversion of RMB to USD is 8.21 in 2004, and now 7.94 in 2006

The results of the two simulations are summarized in Table 3. The percent savings of the *Candidate Building* compared with the *Reference Building* is 58%, which translates into 9 LEED points. Most of these savings are from the lighting and cooling systems. The lighting system in the *Candidate Building* uses significantly less energy, while the energy cost for space cooling was about 30% less than that in the *Reference Building*. The savings in space heating and ventilation are small. Since DOE-2 is not able to model onsite generation, a separate calculation was done for the PV system that showed an annual saving of $3,000 US dollars. In the final document submitted to the USGBC, the net savings for the *Candidate Building* compared to the *Reference Building* was more than 60%, giving the demonstration building the full 10 credit points for energy efficiency.

MEASURED PERFORMANCE

As described earlier, the building was designed to be a highly efficient office building. Since the building was fully occupied in late 2004, there is now more than a year's utility data that can be used to determine the actual energy performance of the building and verify the predicted energy savings. Two major difficulties in evaluating relative building energy performance in China are (1) the shortage of good benchmark energy consumption data for buildings, and (2) the wide disparity in building services and operating conditions among Chinese buildings. The available building energy use data are for very small sample sizes, of unknown statistical representation, and often anecdotal in nature. Thus, it has been easier to determine the actual energy use of this building, but more difficult to assess its energy performance compared to other Chinese office buildings.

Measured electricity consumption

Figure 3 shows the measured total electricity consumption of the building for the first eight months of 2005. The electricity consumption per floor area is calculated and then compared with data from other buildings and other available energy-use benchmarks. The general shape of the electricity consumption is as expected, being relatively high in the summer and winter, and low in the spring. The electricity consumption was low in February because of Chinese New Year, during which most people take at least a week off and the building was probably unoccupied. For a similar reason, the electricity consumption in May was also low, since Labor Day (May 1st) is another major holiday in China during which most workers take the entire week off.

The measured electricity consumption of the Agenda 21 building over the first eight months of operation was 43 kWh/m^2. For comparison, one report gave the average annual electricity usage for ten typical office buildings in Beijing to be only 40 kWh/m^2 [Zhou, 2003], which would be significantly lower than the measured electricity use for this building. Such a comparison, however, is not valid for the following reasons:

1) The typical office buildings mentioned in Zhou 2003 differ substantially from the Agenda 21 demonstration building in their services and equipment. Typical office buildings in Beijing have only central heating, and limited cooling provided by window air conditioners during the summer. They thus provide a lower level of thermal comfort and service than the Agenda 21 building.

2) The real occupancy density of the Agenda 21 building was almost twice as high as the design occupancy. The building was designed to accommodate 825 people, or about 15 m^2 per person. However, after the building was completed, nearly double that number of occupants moved into the building. The added occupancy not only increased the latent and sensible cooling loads, but also the equipment (mostly computers) and lighting loads. The dedicated air system is a VAV, with the outside air amount regulated by CO_2 sensors. Despite the unexpected increase in occupancy, the building owner felt that the indoor air quality was not significantly affected, because the engineer had increased the fresh air supply during construction in the aftermath of the SARS epidemic in summer 2003. As a result, the CO_2 concentration is set at 450 PPM, while the worst case found in the building was 600 PPM in one zone. In comparison, the average outdoor CO_2 concentration is 380 PPM.

A better benchmark would be data from new office buildings constructed in recent years with central air conditioning. A survey of the annual electrical consumption of 16 department stores and hotels in Beijing showed that the electricity consumption for cooling alone was roughly 160-220 kWh/m^2 per year (IBES 2000). Even recognizing that cooling loads in hotels and stores are normally higher than in offices, the numbers still indicate that the Agenda 21 building is very energy-efficient.

Measured heating energy consumption

The Agenda 21 building is heated from a district heating system that provides hot water during the heating season from November to March. A heat exchanger converts the heat from district heating system to the hot water used in the building's two-pipe fan coil system. Throughout China, the heating bill from such district heating systems is charged by the building floor area instead of being metered. However, for this building, the owner was able to obtain the amount of heating used by installing heat flow meters on the hot water pipes after the heat exchanger.

Figure 8 shows the averaged daily heating consumption of the building throughout the entire 2005-2006 heating season. The blank data between the columns are for the weekends and holidays when the heating to turned off. The measured peak hourly heating consumption is 30.5 W/m^2 (9.7 Btu/h·ft^2). The measured peak daily averaged heating consumption is 28.2 W/m^2 (8.9 Btu/h·ft^2), which occurred on February 8th during the coldest period in Beijing. The seasonally averaged heating consumption is 15.4 W/m^2 (4.9 Btu/h·ft^2).

Figure 9 compares the annual measured heating consumption to the simulated heating consumption during design, and the simulated ASHRAE 90.1 energy budget. The annual heating consumption is 46.25 MJ/m^2 (4.09 kBtu/ft^2), or 599 GJ (571 MBtu) for the entire building. This measured annual heating consumption is slightly lower than the ASHRAE 90.1 energy budget, as well as the simulated heating energy consumption during design.

Estimated total energy consumption

Although the measured data are incomplete (8 months of electricity in 2005, heating for winter 2005), the total energy consumption of the Agenda 21 building is estimated at 65 kWh/m^2 (6.0 kWh/ft^2) for electricity and 13 kWh/m^2 (1.20 kWh/ft^2) for heating, or a total of 78 kWh/m^2 (7.25 kWh/ft^2). For comparison, a study of 9 offices and department stores in Shanghai found their average energy consumption to be 1.8 GJ/m^2 (159.3 kBtu/ft^2) or 500 kWh/m^2 (46.4 kWh/ft^2), many times higher than that of the Agenda 21 building (Long et al. 1998). The same study also noted that the average energy consumption reported for office buildings in Japanese cities with similar climate conditions, the annual energy consumption was 1.256 GJ/m^2 (111.1 kBtu/ft^2) or 348 kWh/m^2 (32.3 kWh/ft^2), also several times the energy usage of this building. In the U.S. study by one of the authors (Huang), the annual energy use of a prototypical office building in Chicago, which has similar climate condition to Beijing during the summer, is estimated as 252 kWh/m^2 (23.4 kWh/ft^2) for the whole building and 60 kWh/m^2 (5.57 kWh/ft^2) for cooling (Huang et al. 1991). Both of these numbers are higher than for the Agenda 21 building.

The low energy consumption of the Agenda 21 was not obtained at the expense of lowered indoor environmental quality (IEQ). According to the building owner, the average indoor temperatures during the summer are between 23-25 C, and satisfactory indoor air quality (IAQ). However, when the building was first opened, some of the occupants thought the building IAQ was poor, with not enough fresh air. The building owner then contracted with Tsinghua University to retro-commission the building, at which time it was found that a number of fire dampers had been installed backwards, so that they could not be fully opened. After this problem was fixed, all of these complaints stopped.

Parenthetically, when the authors visited the building in August 2006, they found it in the throes of a large change-over in occupancy, with the first unplanned tenants leaving to be replaced by the originally planned staff. Since the building was almost completely empty, the building owner decided to shut off the air-conditioning system. During this period, despite the hot summer weather in Beijing frequently reaching 38 ºC (100ºF), the maximum indoor temperature reached in the building was 30ºC (86ºF), indicating the high thermal integrity and basic thermal stability of the building.

The facility management team in the building also provided anecdotal evidence why they thought this building was much more efficient than a typical office building in Beijing. They compared the utility bills of the Agenda 21 building with those from two other similar fully-equipped buildings in Beijing with central space conditioning. Since the utility rates for all these buildings are the same, the utility bill will be proportional to the energy use. The two examples are:

Example 1: A recent completed office building in the ZhangGaiChun district of Beijing has a total floor area of 11,000 m^2 (102,000 ft^2), and a utility bill for heating and cooling of roughly 1.2 million RMB. This translates to a per area utility cost of 109 RMB/m^2, of which an estimated 30 RMB/m^2 is for heating, and the remaining 79 RMB/ m^2 for electricity.

Example 2: A 10,000 m^2 (92,900 ft^2) commercial building built in 90s has an electrical bill of 1.18 million RMB per year, which translates to a per area electricity cost of 118 RMB/m^2.

In contrast, the electricity bill for the Agenda 21 building is roughly 660,000 RMB, which translates to a per area electricity cost of 50.8 RMB/m^2, which is 40% less than that for Example 1 and roughly half that for Example 2. In addition, the Agenda 21 building also uses much less heating in the winter, although those savings are not reflected in the heating bill from the district heating system that is charged at a standard rate of 24.7 RMB/m^2. The facility manager knows the heating usage is very small during the winter because the number of days when the building was in heating mode was very small.

The facility manager also claims that the Agenda 21 building uses less energy than do traditional office buildings with window air conditioners. Although the Agenda 21 building may have higher cooling electricity use due to the central air-conditioning system, this is balanced by the much higher heating energy use in traditional office buildings due to their poor insulation. A rough calculation indicates that the heating energy used in the Agenda 21 building is roughly 1/5 of that in traditional buildings. Thus, even though the Agenda 21 building provides a much better level of services, its combined energy consumption for heating and electricity should be no more than that of a traditional building.

Beijing now has time-of-day electricity charges to encourage consumers to use more energy in off peak hours and less in on peak hours. The schedule of the utility rate for different time periods is shown in Figure 4. The utility rate of peak hours could be five times higher than that during the night.

The solar hot water system worked well in the first year of operation. The hot water system has a capacity of 4 m^3 (1060 gallons) and supplies water at 75°C (167°F). The hot water system has been designed large enough to provide domestic hot water for lavatory and bathing. However, in operation, the facility manager noticed a shortage of hot water. The reason was that workmen in the building were bringing other people to the building to use the hot water showers, because very few offices nearby have any bath facility. The facility managers have to limit the usage of the bath facility to the people working in the building only in order to solve the problem. This is another example why sometimes engineers in China tend to oversize the mechanical equipment. The usage and functions of the building and its equipment are hard to predict in the design phase.

Comparison of utility data with simulation results

Figure 5 compares the measured electricity consumption to the simulated electricity consumption done during the design phase. The measured electricity consumption was available for only the first eight months of 2005, with the projected electricity consumptions for the remaining four months shown as dashed line boxes. The actual measured electricity consumption was much higher than the simulation results.

Figure 6 provides further evidence that the actual cooling load was much higher than the simulated cooling load. A standard assumption is made that there is little cooling in April, so that all the increase in electricity usage in July and August can be attributed to cooling. This leads to an estimated cooling electricity use in August that is about five times higher than that in the original simulations. It is also possible to estimate the peak cooling demand. Considering the energy loss through the ice storage system, the average cooling electricity demand from 9 am to 12 pm can be estimated as 9.89 W/m^2 (0.92 W/ft^2), which implies a cooling load of about 45 W/m^2 (4.18 W/ft^2), or 885 MW for the entire building, compared to 300 MW peak cooling capacity estimated in the original simulations.

Two prime reasons for the large discrepancy between the measured and simulated energy usage are: (1) the actual occupancy was found to be nearly double the design occupancy used in the simulations, and (2) the occupants were found to leave some windows open for fresh air or when there is smoking, even though the building was in mechanical cooling or economizer modes. For example, the authors observed a total of 50 windows opened during a visit in June 2005 when the building was running in the mechanical cooling mode.

The simulation model was revised to the actual number of occupants and the amount of air infiltration increased to two air-changes per hour in the 10% of the rooms that have operable windows. Figure 7 is a new plot comparing the measured and revised electricity consumption. The results of the revised simulation are very close to the measured results.

Ice storage system

The two Carrier 30HXC100 screw chillers has a total nominal capacity of 348 kW, with a nominal power input of 72 kW. The nominal pump power is 5.5 kW. In a typical day operation, the ice storage system makes ice from 11 pm to 7 am. The ice storage has a capacity of 2010 kWh. The electricity price difference of daytime to nighttime is 3.37:1.

As of spring 2006, measured data on ice storage power and cooling load was not available. However, the savings due to the ice storage system can be estimated from the whole building power data. Figure 4 shows that the baseline load for non-peak hours from 11pm to 6 am is roughly 1.0 kWh/m^2 (0.09 kWh/ft^2) per month. However, during the summer, this load was increased to 1.8 in July and more than 2.0 in August, mostly due to the running of the ice storage system at night. Therefore, this load difference is used to estimate the amount of cooling stored by the system as shown in Table 4. Assuming that the chiller runs during the ice making period at the same COP of 4 as during peak cooling hours, and an overall ice storage store system efficiency of 80%, the estimated cost saving comes to roughly 16,600 RMB total or 1.27 RMB/m^2 (0.18 RMB/ft^2) per year. However, this calculation is just a rough estimation from the limited data in the first year of operation, and a more accurate economic calculation will be possible later when better data become available.

SUMMARY AND DISCUSSION

The following conclusions can be made from this study:

1. A highly energy-efficient US-China demonstration building has been built in Beijing. The building has a number of energy conservation features, including both building envelope and mechanical system measures. In the feasibility study, the building design was estimated to be 40% more efficient than the original design. In the LEED analysis, it was found to be 60% more efficient than the ASHRAE 90.1 energy budget benchmark and earned the full 10 points in the optimal energy performance section of LEED. Most of the energy features in this building are very attractive in the Chinese building market.

2. Although the building uses more energy than traditional office buildings that provide much fewer services, measured performance data indicated that the building is much more energy efficient than similarly equipped “full service” office buildings in East Asia and the US. In the first year of operation, we were not able to obtain end-use electricity data that can distinguish between cooling and lighting loads, for example. More measured data is required to quantify the savings from cooling and lighting.

3. An initial estimate from the whole building consumption data indicated significant cost savings from the ice thermal energy storage system. More data on the direct measurement of the system is required to further calculate the savings.

There are still many uncertainties about the energy performance of this building due to the limited amount of data available in the first year. The authors have been working in 2006 with the building owner and two subcontractors to install a monitoring system with submeters on different end uses, as well as with the facility managers to set up the control system to collect performance data on the HVAC system. These will enable better understanding of the building's energy performance and help to determine the cost-effectiveness of the various energy efficient measures that have been installed in the building.

Another problem is the lack of comparable benchmarks for quantifying the savings. There are very limited data available for building energy consumption in Beijing, especially monthly separated data. A benchmark tool designed specifically for buildings in China will not only be helpful for research purposes, but also help raise the energy-efficiency awareness of building owners and operators in China.

ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

Huang, Y.J., Akbari, H., Rainer, L., and Ritschard, R.L. 1990. "481 prototypical commercial buildings for twenty urban market areas (Technical documentation of building loads data base developed for the GRI Cogeneration Market Assessment Model)", LBL Report 29798, Lawrence Berkeley National Laboratory, Berkeley CA USA.

Huang, Y.J., Judkoff, R., and Sherman, M. 1999. "Feasibility study of a US-China demonstration energy-efficient commercial building", LBNL Report 44306, Lawrence Berkeley National Laboratory, Berkeley CA USA.

Institute of Building Environment and Services 2000. *Report on the investigation and analysis of building energy efficiency in China.* Tsinghua University, Beijing, CHINA.

Kashiwagi, Takao 2002. *Natural Gas Cogeneration Plan/Design Manual 2002*, Japan Industrial Publishing Co.,Ltd., Tokyo JAPAN, pp. 35.

Long, Weiding 1998. "The analysis of energy consumption and energy efficiency potential in public buildings in Shanghai". *China National HVAC Conference 1998.*

Zhou, Dadi 2003. *China's Sustainable Rnergy Scenarios in 2020*, China Environmental Science Publishing Company, Beijing, pp. 596-598.

Table 1. LEED credits in optimize energy performance

Task	% Savings	LEED Points
Reduce Energy Costs –	15%	1
Reduce Energy Costs –	20%	2
Reduce Energy Costs –	25%	3
Reduce Energy Costs –	30%	4
Reduce Energy Costs –	35%	5
Reduce Energy Costs –	40%	6
Reduce Energy Costs –	45%	7
Reduce Energy Costs –	50%	8
Reduce Energy Costs –	55%	9
Reduce Energy Costs –	60%	10

Table 2. Building features in design and ASHRAE 90.1 energy budget simulations

	Design building	**ASHRAE 90.1 budget building**
North windows	Double Low-E (e3=.20) IG, U-value 0.29 Btu/h·ft^2·^{o}F (1.67 W/ (m^2·K)), SHGC 0.68 (2615)*	Double Green IG, U-value 0.56 Btu/h·ft^2·^{o}F (3.16 W/ (m^2·K)), SHGC 0.50 (2209)*
East/west windows	Double Low-E (e2=.04) CLR IG, U-value 0.24 Btu/h·ft^2·^{o}F (1.34 W/ (m^2·K)), SHGC 0.43 (2662)*	Double Ref D Tint IG, U-value 0.48 Btu/h·ft^2·^{o}F (2.72 W/ (m^2·K)), SHGC 0.35 (2471)*
South windows	Triple Low-E Film (55) CLR IG, U-value 0.22 Btu/h·ft^2·^{o}F (1.22 W/ (m^2·K)), SHGC 0.25 (3672)*	Double Ref D Tint IG (same as above)
Wall	U-value 0.071 Btu/h·ft^2·^{o}F (0.403 W/ (m^2·K))	U-value 0.102 Btu/h·ft^2·^{o}F (0.579 W/(m^2·K))
Fan	All AHU fans are VFD controlled	Inlet vane controlled fan
Lighting	Day lighting control, Lighting power density 0.38 W/ft^2 (4.1 W/m^2)	No day lighting control, Lighting power density 1.3 W/ft^2 (14 W/m^2)
Thermal storage	The building is equipped with a cooling ice storage system	No ice storage system
Utility rate	Peak hours 8am-11am, 6pm-11pm, RMB 1.057/kWh; Flat hours 7-8am, 11am – 6pm, RMB 0.673/kWh; Night 11pm-7am, RMB 0.311/kWh.	Same as in design building

* Window5 library ID

Table 3. LEED analysis summary

		Design Energy Cost (DEC)			Energy cost budget (ECB)		
	Energy Source	Source Energy MBtu	(GJ)	Cost (Regulated)	Source Energy MBtu	(GJ)	Cost (Regulated)
Space cooling	Electricity	447.65	(470.03)	$21,976	410.29	(430.80)	$29,868
Heat rejection	Electricity	55.16	(57.92)	$2,708	171.16	(179.72)	$12,460
Space heating	Electricity	57.45	(60.32)	$4,604	68.73	(72.17)	$5,509
Space heating	Gas	613.60	(644.28)	$19,267	741.50	(778.58)	$23,283
Hot water	Gas/solar	0.00	(0.00)		48.00	(50.40)	$1,508
Vent. fans	Electricity	69.89	(73.38)	$5,228	84.99	(89.24)	$6,360
Pumps & aux	Electricity	125.01	(131.26)	$6,137	125.33	(131.60)	$9,124
Lighting	Electricity	999.92	(1049.92)	$66,352	3021.60	(3172.68)	$214,416
Total		2368.68	(2487.11)	$126,272	4623.60	(4854.78)	$302,528
% Saving		(ECB-DEC)/ECB		58%			

Table 4. Ice storage savings calculation

	Whole building power consumption in low price period	Ice storage system power consumption[2]	Stored cooling [3]	Peak cooling load reduction[4]	Peak electricity load reduction[5]	Net saving[6]
	kWh	kWh	kWh	kWh	kWh	RMB
Apr-05	12,000	0	0	0	0	0.00
May-05	12,000	0	0	0	0	0.00
Jun-05	13,500	1,500	4,500	4,050	1,012	687.50
Jul-05	24,000	12,000	36,000	32,400	8,100	5,500.02
Aug-05	28,500	16,500	49,500	44,550	1,1138	7,562.52
Sep-05[1]	18,278	6,278	18,834	16,951	4,238	2,877.42
Total		36,278	108,834	97,951	24,488	16,627.48

1. Based on projected whole building power consumption.
2. Using April and May operation as baselines with no ice storage operation.
3. Assume night time chiller COP in ice making is 4.
4. Assume the ice storage efficiency is 80%.
5. Assume day time chiller COP is 4.
6. Electricity rate is 1.043 RMB/kWh at peak hours and 0.249 RMB/kWh at night.

Table 5. Ice storage system operation cost analysis[1]

	Ice storage/chillers			Conventional chiller plant		
	Operation	kWh	RMB	Operation	kWh	RMB
23:00-7:00	Making ice, Cooling storage is 1846.8kWh[2]	620[3]	153	None	0	0
12:00-15:00	Ice storage discharge, pump operation only	16.5	13.7	Normal operation for three hours, cooling load is 554 kW	343.9	286.5
Total		636.5	166.7		343.9	286.5
Daily Electrical Cost Saving	RMB 119.8					

assumptions:

1. peak cooling demand is 554 kW, and the net cooling energy shifted by the ice storage system is 1662 kWh.
2. ice storage efficiency is 90%, so that 1846 kWh of cooling storage will compensate for exactly 1662 kWh of cooling during peak hours; nominal ice storage capacity is 2010 kWh.
3. electrical consumption for both chillers and glycol pumps.

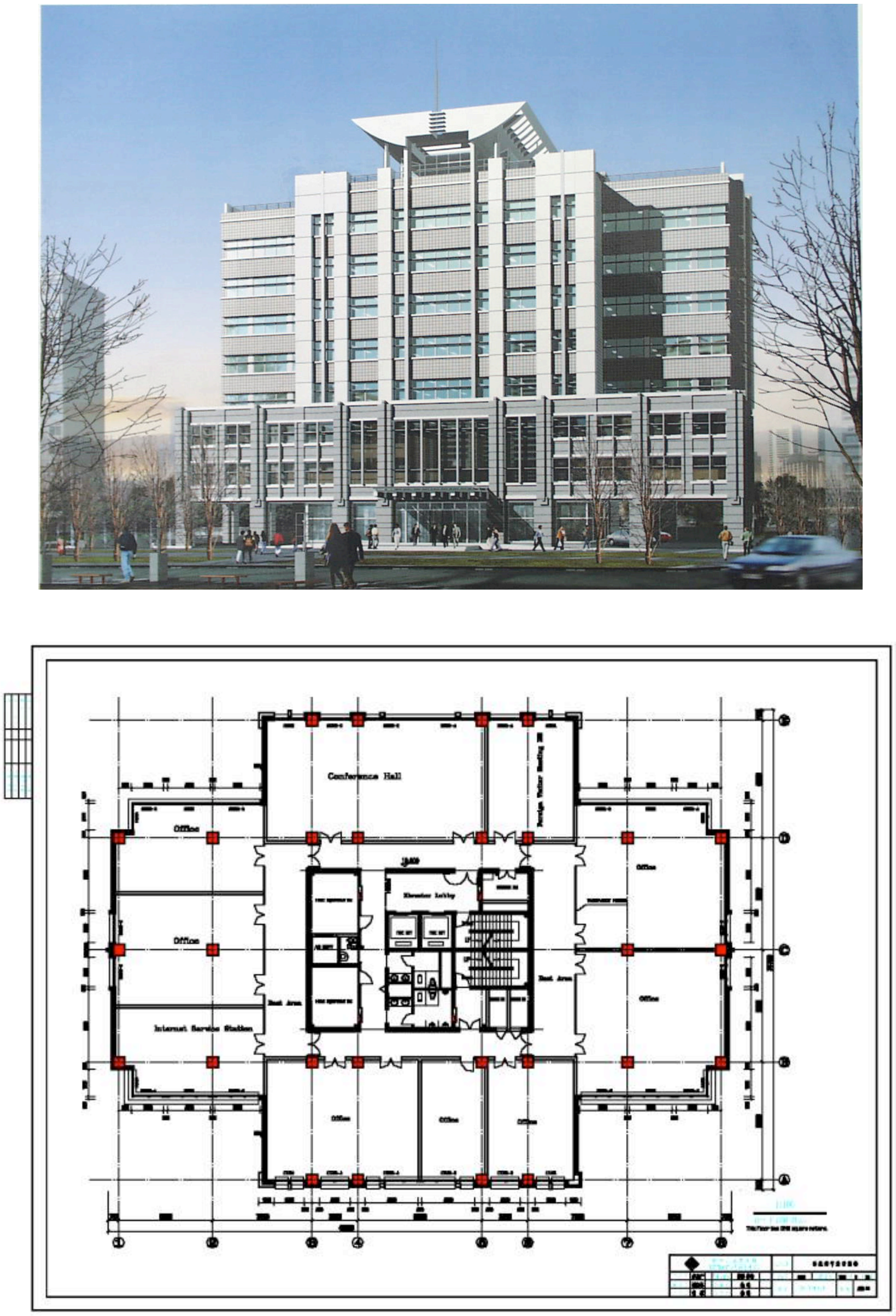

Figure 1. Artist's drawing and standard floor plan of US-China Demonstration Energy Efficient Office Building

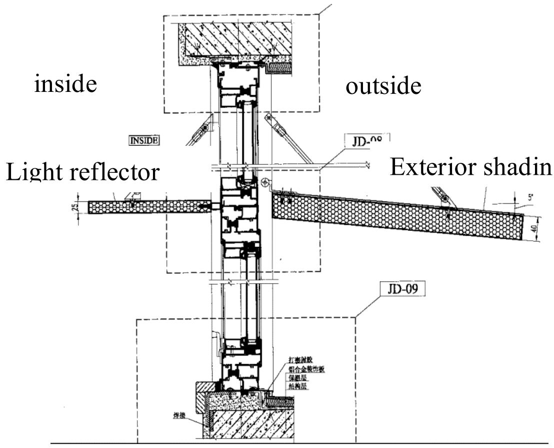

Figure 2. Lighting shelf and exterior shading device

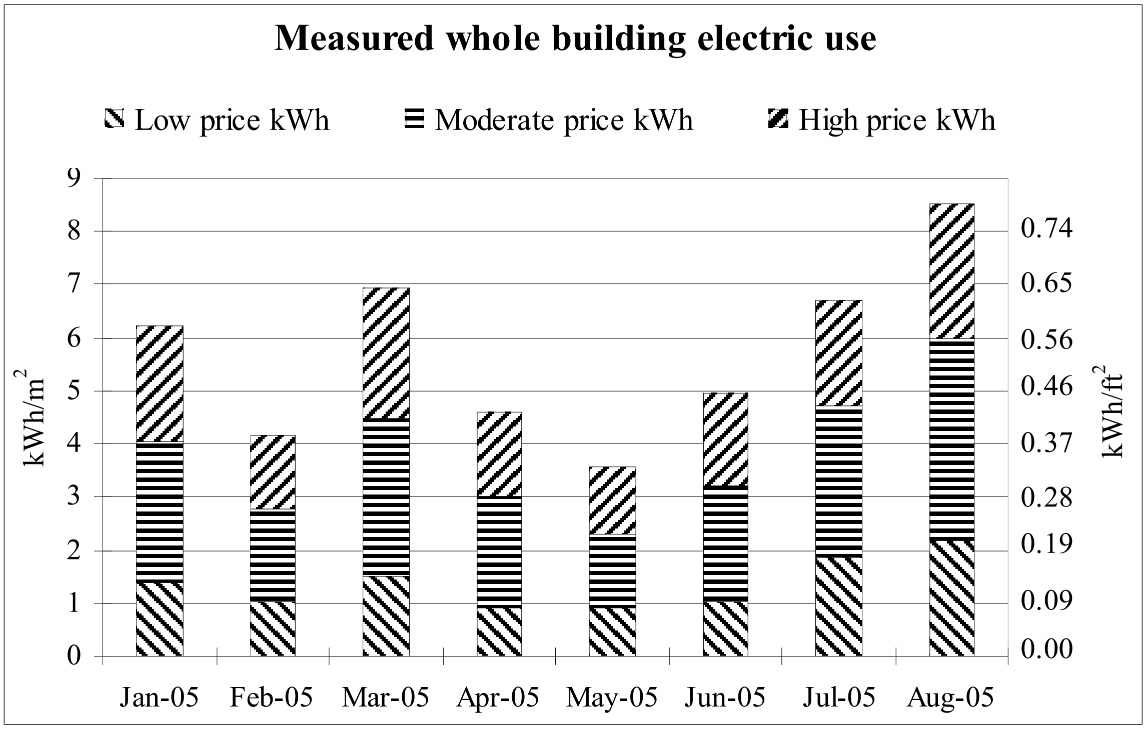

Figure 3. Whole building electricity consumption for the first eight months of 2005

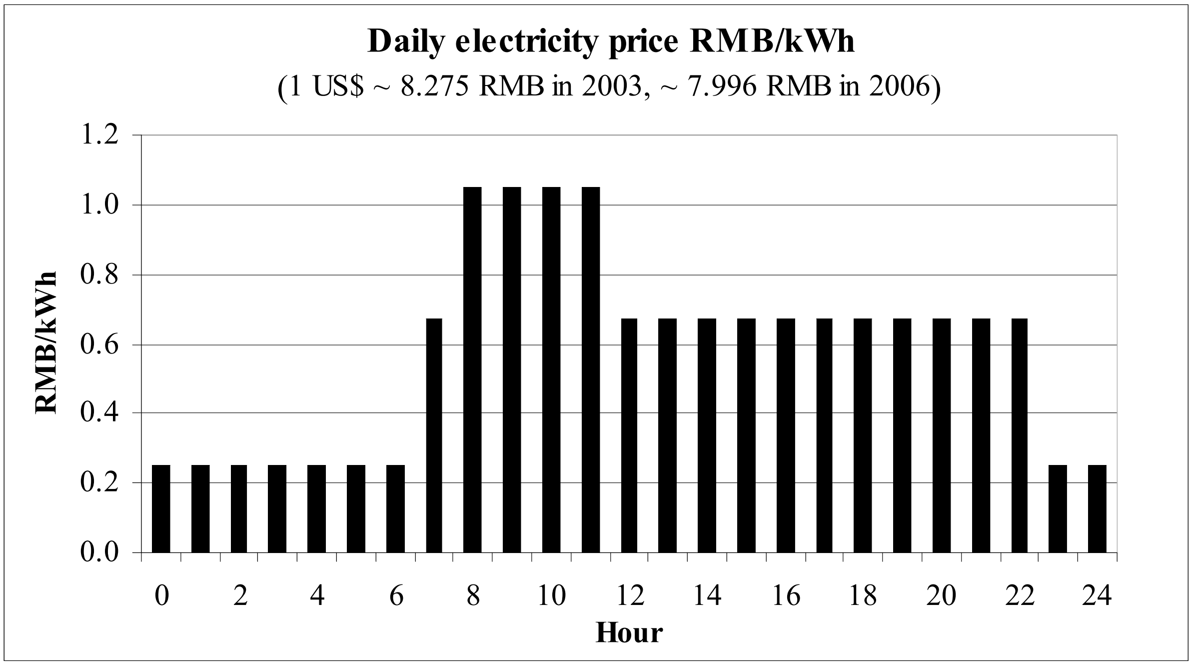

Figure 4. Summer utility rates of different hours in Beijing

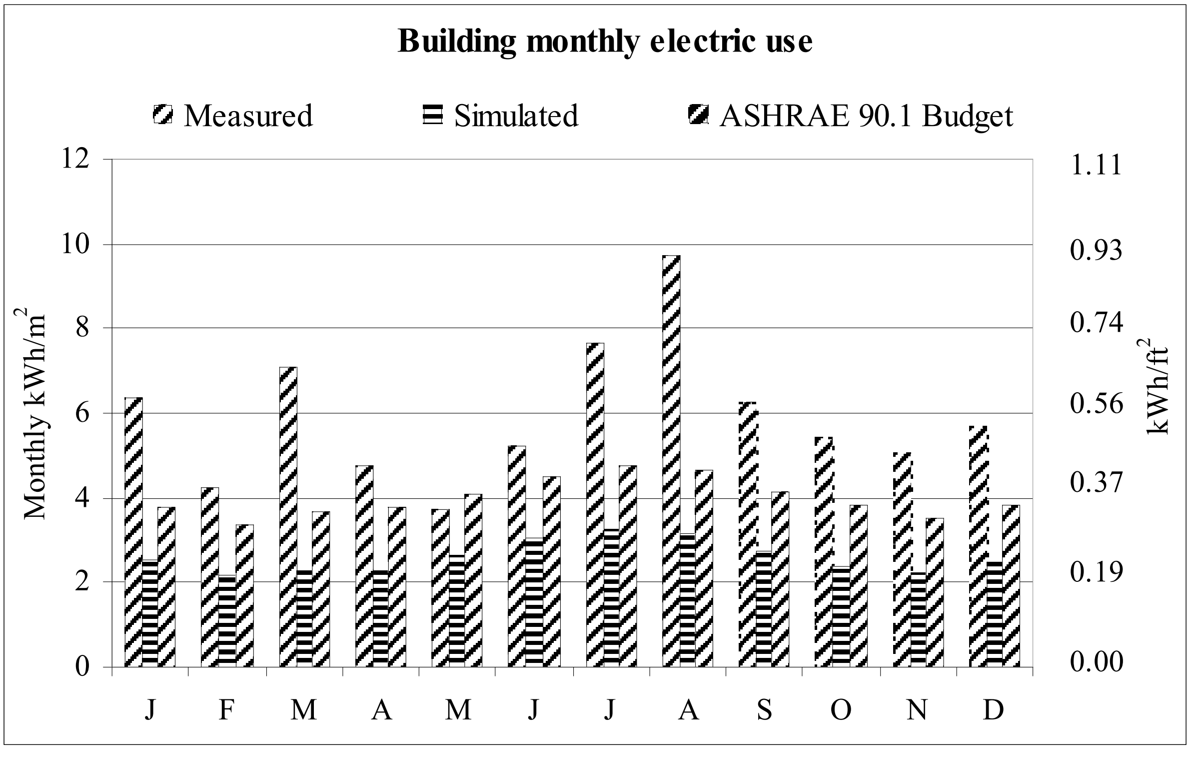

Figure 5. Comparison of measured to simulated monthly whole building electricity use

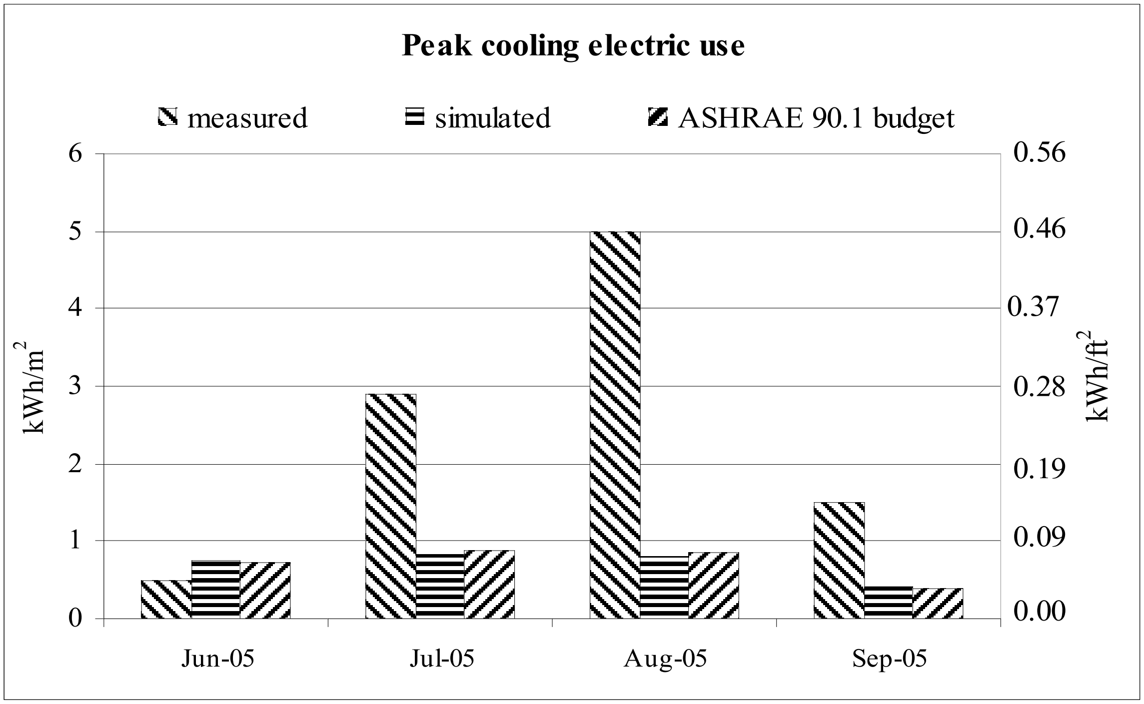

Figure 6. Comparison of measured to simulated peak cooling electricity use

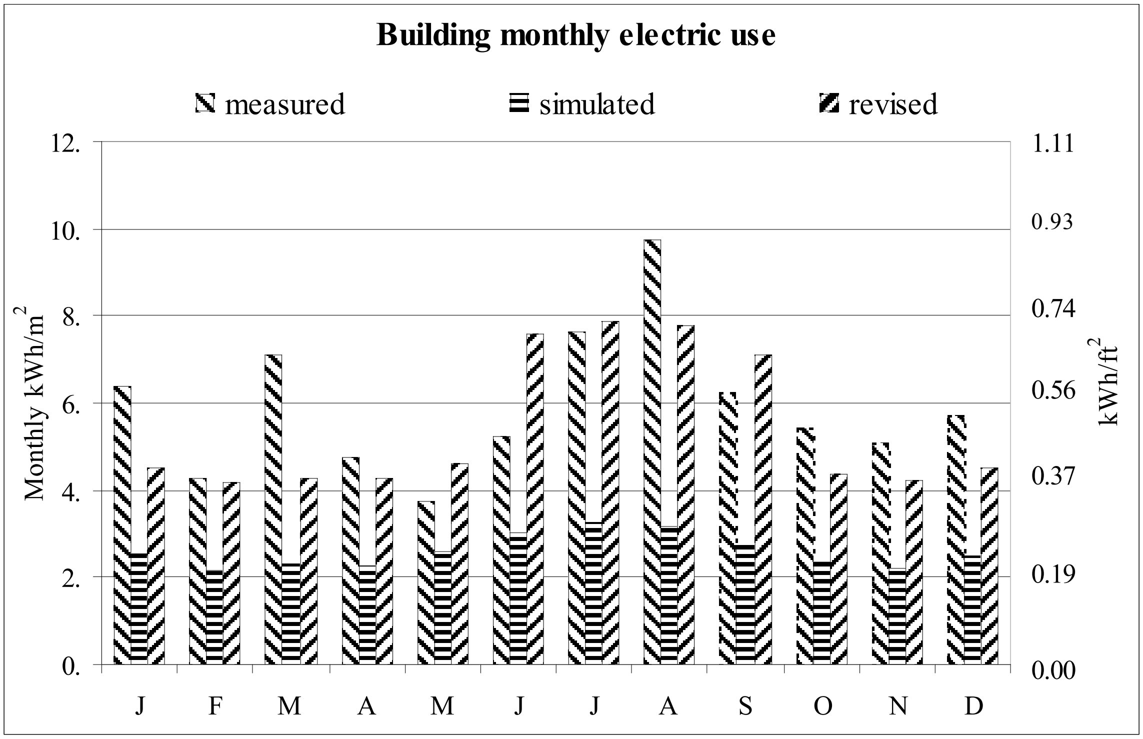

Figure 7. Comparison of measured monthly whole building electricity use to revised simulation results

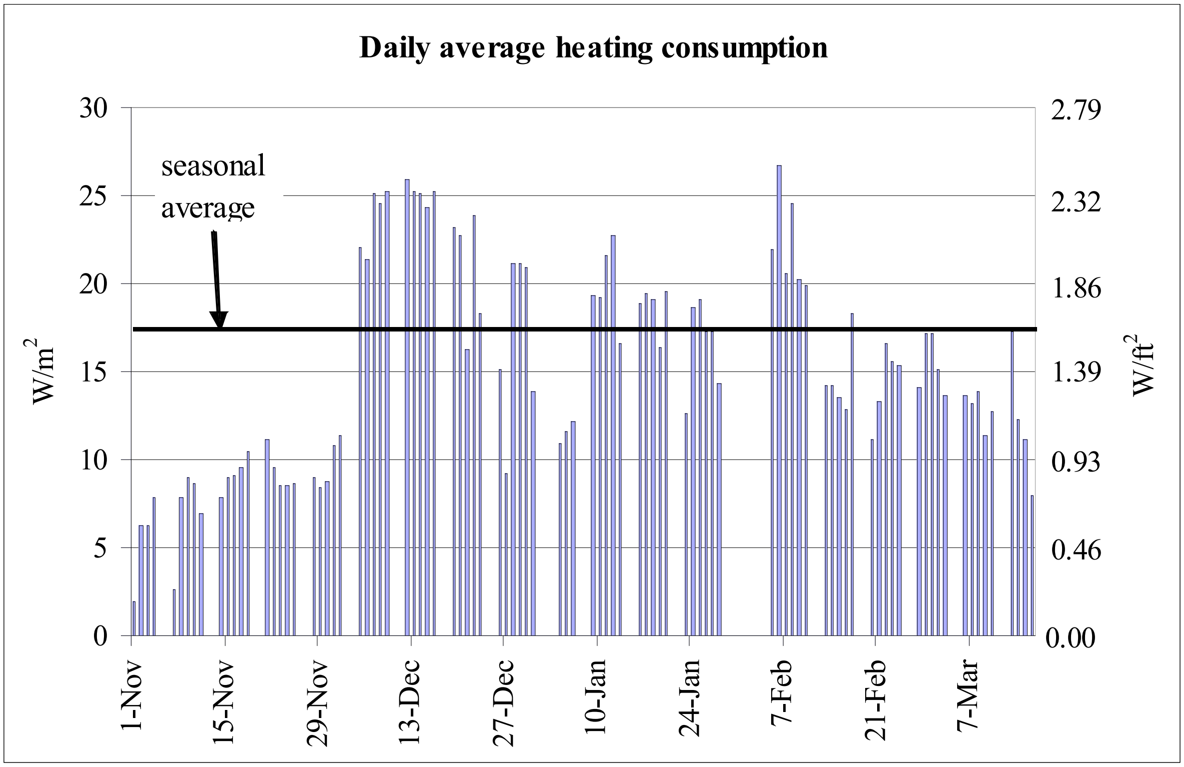

Figure 8. Average daily heating consumption in winter 2005

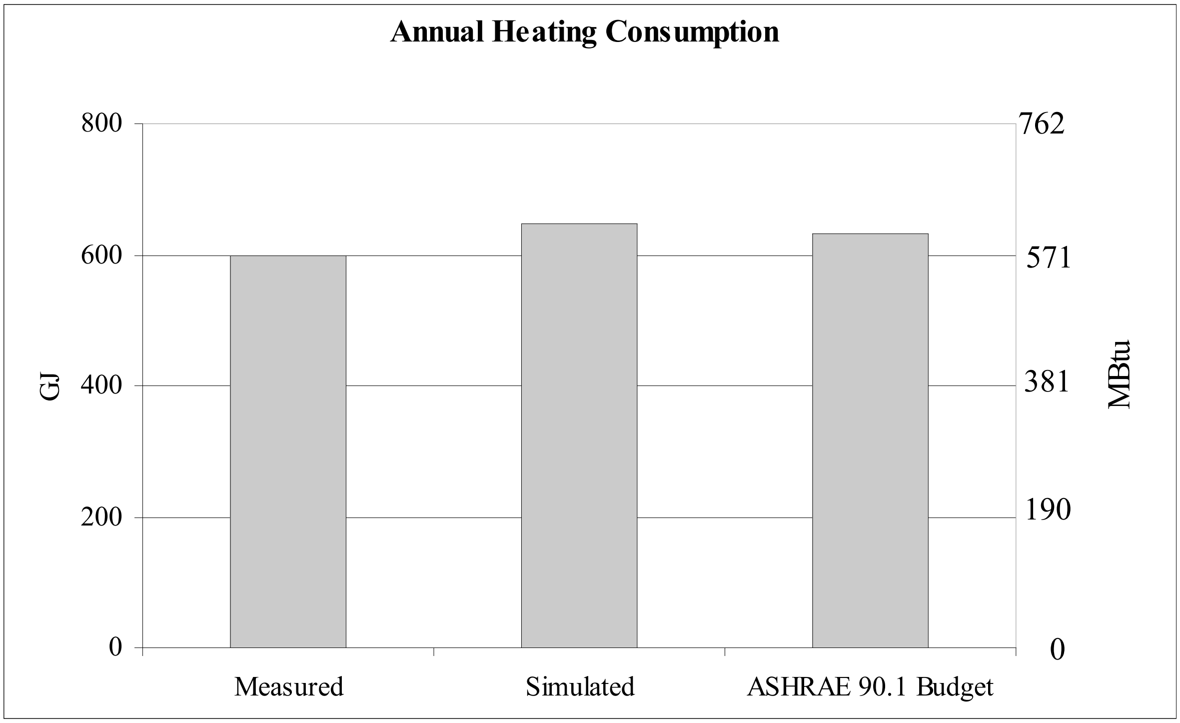

Figure 9. Comparison of measured to simulated annual heating use