Calibration and Collaboration: Important Tools to Design High-Performance Affordable Housing Buildings

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ABSTRACT

Maverick Gardens Mid-Rise A is a six-story apartment building located in East Boston, Massachusetts. The building was designed and constructed to meet the ENERGY STAR Homes Program rating and the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED®) certification. During the design phase, the development team developed the energy models for both baseline building design and proposed high-performance building design, using DOE-2.1E computer simulation software. The purpose of the whole building energy simulation is to demonstrate energy savings potential from various energy-efficient technologies installed in this high-performance building. When comparing the energy use predicted by the proposed design energy model with utility bills, the development team observed that this building's actual electricity use was about one-third of that estimated by the proposed design model, and therefore, requested technical support from the authors through the U.S. Department of Energy's Rebuild America Program to calibrate the proposed design energy model.

This paper describes the energy simulation calibration methodology used for this study. Details of calibration results and the actual building energy performance are presented. Upon the completion of calibration, the DOE-2 model predicted monthly electricity use difference with actual use was reduced from 70% to 3% for apartments, and from 40% to 12% for building common areas. This study also discusses lessons learned during the simulation calibration process and demonstrates the importance of collaboration among the various disciplines, as a way to ensure that high-performance building goals are met.

Introduction

When new technologies are installed in a building, it is difficult to know if the building will perform as well as expected. Do the systems operate as designed? Are high-performance buildings actually saving building owners energy and, ultimately, money? These are some questions often overlooked when designing, constructing, and investing in new buildings. These questions are especially important when designing buildings for low-income residents. Calibrated energy simulation is a widely used technique to verify and quantify the actual energy savings realized from the various features in high performance buildings. A calibrated energy simulation typically aims to represent building performance with the best available as-constructed, as-operated information available at the time. In most cases, this information consists of as-built drawings, construction inspection notes, visual inspection, utility bills, trendlog data, weather data, and construction management, building management, and occupant interviews. Analysis of actual energy use and metering data from the building in operation allows the proposed design model to be calibrated to more accurately represent actual performance. Furthermore, many of the proposed design model inputs modified by the calibration would also be applicable to a baseline model (i.e. a building in compliance with ANSI/ASHRAE/IESNA Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ANSI/ASHRAE/IESNA, 2004)) thus yielding a more appropriate baseline model for comparison.

Calibrated energy simulation has been used widely in a lot of areas such as building design, operation and commissioning (Hasnain et al. 2000; Deru et al. 2006; Pan et al. 2007; Xu et al. 2007). It allows more reliable identification of energy savings and demand-reduction measures (involving equipment, operation, and/or control changes) in an existing building and increased confidence in the monitoring and verification process once these measures are implemented (Reddy, 2006). Calibration of simulation models is necessary and crucial for the accuracy and use of energy simulation. A previous study by Ahmad and Culp (2006) shows that uncalibrated simulations can have very low accuracy in predicting the energy use in a building. Still the goal of calibration is challenged by many factors including difficulties in properly metering energy end uses, availability of analysis expertise and limited capability of simulation tools.

Building Description

Maverick Gardens Mid-Rise A is a six-story, 119-unit affordable housing building located in East Boston, Massachusetts and is owned by the Boston Housing Authority. Figure 1 is a picture of the building under construction. This new apartment building was occupied in December 2004.

Figure 1. Maverick Gardens under Construction (Snell and Neuhauser, 2005)

The building was designed and constructed to meet the ENERGY STAR Homes Program standards and the U.S. Green Building Council's LEED® (Leadership in Energy and Environmental Design) certification. The building is conditioned through a two-pipe fan-coil unit system, with manual switching between the heating season and the cooling season. In addition to a high-performance thermal envelope, the building was equipped with a gas-fired absorption chiller/boiler to reduce summer electric demand, thus lower electricity costs. A 75-kW internal combustion natural gas combined heat and power generator and 37-kW photovoltaic (PV) panels were installed to generate electricity on site. The electric generated by the generator and the PV system supplies the electricity for the building common areas (i.e., interior lighting, plug load, elevator, etc.), and the heating, ventilating and air-conditioning (HVAC) equipment in the mechanical room. Waste heat from cogeneration is recovered to provide domestic hot water and space heating, supplemented by the absorption chiller/boiler. Table 1 summarizes major design features of this high performance building. Additional building information has been reported previously (Henriquez et al., 2006).

Table 1. Summary of Building Energy Components and Features (Snell and Neuhauser, 2005)

Building Component or Feature	Specification or Description
Building Enclosure	
Roof assembly	U-factor: 0.026 Btu/h-ft^2-°F, High albedo rolled roof membrane, 6 in. Polyisoncyanurate on metal deck
Wall system	U-factor: 0.0624 Btu/h-ft^2-°F, brick veneer or metal panel, air space, 1in. extruded polystyrene, denseglass sheathing, metal framing w/ R19 fiberglass batt insulation
Wall system air barrier	Roll (liquid) applied two-coat air barrier
Windows	U factor: 0.32 Btu/h-ft^2-°F, solar heat gain coefficient (SHGC) 0.33, double-glazed, low-e, fiberglass frame, all orientations
Floor over semi-heated garage ceiling plenum	2 to 3 in. low-density urethane foam
Semi-heated garage ceiling plenum	R-19 fiberglass, sidewalls and underside.
Central HVAC – Plant	
Primary heating and domestic hot water (DHW) plant	Internal Combustion natural gas combined heat and power generator, 0.49 MBtuh at 54% thermal efficeincy
Secondary heating and DHW plant	Direct-fired natural gas absorption chiller/boiler, 2.4 MBtuh boiler with full modulation at 85% efficiency
Back-up heating and DHW plant	Sealed combustion, condensing 5:1 modulation turn down ratio, natural gas boiler 1.4 MBtuh at 85% to 98% EFF
Cooling plant	Gas-fired absorption chiller/boiler, 170 ton, 1.2 COP Two-speed fan cooling tower, no water-side economizer
HVAC – Distribution	
Corridor make-up air units (20 to 50% outdoor air)	Heat and cooling coils from primary loop, no economizer
Apartment-level terminal equipment with outdoor air intake (one per apartment)	Vertical fan-coil units, direct outside air intake ~10% of rated flow, face-bypass damper, no intake damper, thermostat operates face-bypass damper
Apartment-level terminal equipment without fresh air intake	Vertical fan-coil unit, thermostat cycles fan
Apartment exhaust ventilation	Exhaust – continuous background exhaust in bathrooms with fixed dampers set to exhaust 50 cfm per apartment
DHW	
Storage tanks	Two 575-gallon DHW tanks with internal heat exchangers
Lighting/Appliances	
Lighting-common areas	Compact fluorescent, non-dimming, no occupancy sensors
Lighting-apartments	Compact fluorescent for all hard-wired fixtures
Appliances	ENERGY STAR® where provided
On Site Generation	
Cogeneration plant – service to house meter	Internal combustion natural gas 75 kW, electrical generator efficiency 28%, thermal efficiency 54%
Photovoltaic array – net meter to grid with disconnect	37 kWdc, fixed panels, angled 42 degrees from horizontal

Energy Simulation Calibration Approach

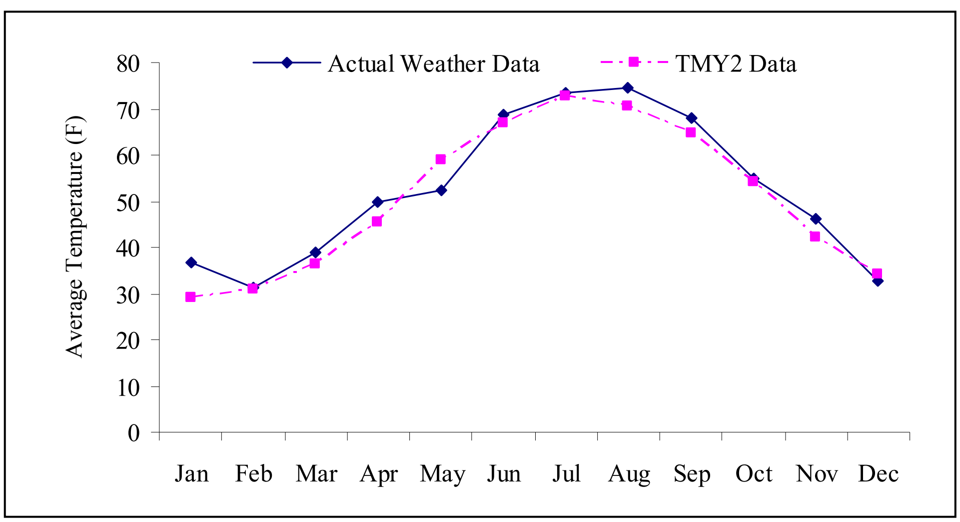
The energy simulation calibration methodology used in this study involves five steps: (a) gathering as-built drawings, utility bills, weather data and as well as some other related building data such as building inspection notes, building management, and occupants interview; (b) short-term metering of certain key end-uses; (c) calibrate the energy model based on the energy consumption data for the key end-use components such as lighting, plug load, and fan-coil system; (d) calibrate the energy model based on the whole building energy consumption data; (e) evaluate accuracy of calibration by calculating statistical indices and fine tune the energy model to reach acceptable calibration uncertainty limits.

Weather Data

Building simulation software is driven by weather conditions, which in turn drive the building heating and cooling loads. Weather data used in the simulation provides the hour-by-hour changes in weather conditions that correspond, in principle, to the governing relationships that drive heat transfer through the building envelope, ventilation and infiltration loads. For the model calibration process, it is important that the weather conditions used for simulation represent the actual environmental conditions that result in the measured energy performance. Preferably, weather data should be measured on site, but a nearby reliable weather station with the required weather data can also be used.

For a proper comparison, typical meteorological year (TMY2) data (National Renewable Energy Laboratory, 1995) for Boston, Massachusetts, used in the original simulation was compared to the actual weather data for the period that the monthly energy use data was provided. The actual weather data was obtained from a national weather service station located at Boston Logan International Airport (National Climatic Data Center, 2006). The airport is located approximately 2 miles east of the Maverick Gardens. A typical comparison of monthly average dry-bulb temperature is shown in Figure 2. It is observed that the differences of the monthly average temperatures between the actual data and the TMY data range from -6°F to 7°F; for most of the months the actual monthly average temperatures are higher than the TMY data.

Figure 2. Actual Weather Data and TMY2 Data Comparison (Apr 2005 - Mar 2006)



The relatively large differences for the monthly average dry-bulb temperature between the TMY2 and the actual measured data justified creating a new weather file. This original TMY2 weather file for Boston, Massachusetts, was modified to match weather conditions from April 2005 to March 2006. The modified weather data included dry-bulb temperature, wet-bulb temperature, wind speed and direction. Solar radiation data was not modified because the hourly weather data of the weather station does not provide solar radiation information. The modified weather file was then repacked into TMY2 format and used in the calibration process for comparison with actual building energy performance.

Building Short-Term Metering Data

Because there are many input parameters that need to be specified (and, hence, be tunable) in a detailed simulation program (i.e. DOE-2, EnergyPlus), the use of short-term measured data from certain key end-uses can improve the accuracy and reliability of model calibration process. Conducting short-term field measurement of key internal loads, such as lighting and plug load, and then extrapolating this data over the course of one full year can significantly improve the accuracy of simulation results by reducing the uncertainty typically associated with determining the variability of internal loads (Lunneberg, 1999). A short-term metering plan was formulated to get some insights on how building components actually operate. Several data loggers were installed in selected locations in the building to monitor the lighting use pattern and space temperature and relative humidity (RH) for several months. The fan-coil unit operation was also monitored by installing a data logger in the management office, and the data was collected for several months. These short-term metering data allowed adjustments for some of the simulation input parameters to closely represent the actual building performance. Table 2 summarizes all the available metering data used for the model calibration.

Table 2. Summary of Maverick Gardens Mid-Rise A Short-Term Metering Data

Metered Data	Description	Metering Period
HOBO Lighting Loggers	Sample apartment units	Dec 7, 2005 to Dec 21, 2005 5-min interval
HOBO Temperature and Relative Humidity (RH) Loggers	Space temperature and RH in the sample apartments and hallways Fan-coil unit supply and return air temperature and RH at management office	Oct 21, 2005 to Dec 7, 2005 15-min interval
HOBO Current Loggers	One fan-coil unit current amps at the management office	Dec 2, 2005 to Dec 7, 2005 1-min interval
Cogeneration Trend Log	Trend log data for the 75-kW cogeneration	Intermittent periods from Jan 2005 to Mar 2006 30-min interval

Observing the actual measured lighting data for four monitored locations (apartment numbers were not able to be identified), we found that each measured schedule has a different pattern. Thus, it is difficult to extrapolate these limited data to the lighting schedules for the other apartments. The lighting data shows that the maximum lighting intensity in the sample apartments is about 15 lumen/ft^2, which is approximately 0.44 W/ft^2 for spaces using compact fluorescent for all hard-wired fixtures (assuming 75% of the lamps are hard-wired). Figure 3 is a plot of a daily profile of the lighting intensity for one of these four locations. Daylighting was not modeled because daylighting technologies are not implemented in this building. Figure 4 shows the actual fan-coil operating schedule for the management office, from which we can see that the fan-coil unit is cycled on and off periodically to maintain the space temperature set point. This information was used to adjust the fan operating schedule for the management office fan-coil unit model. Based on the space temperature measurements in the sample apartments, the average room temperature varies from 72°F to 80°F during winter (based on the metering data from Nov 3, 2005 to Dec 7, 2005). The space temperature and humidity measurements for summer and swing seasons were not available. These metering data provided information for setting lighting power density and apartment heating set point for the model.

Figure 3. Sample Lighting Schedule and Intensity in an Apartment on Dec 16 and Dec 17, 2005 (Friday and Saturday)

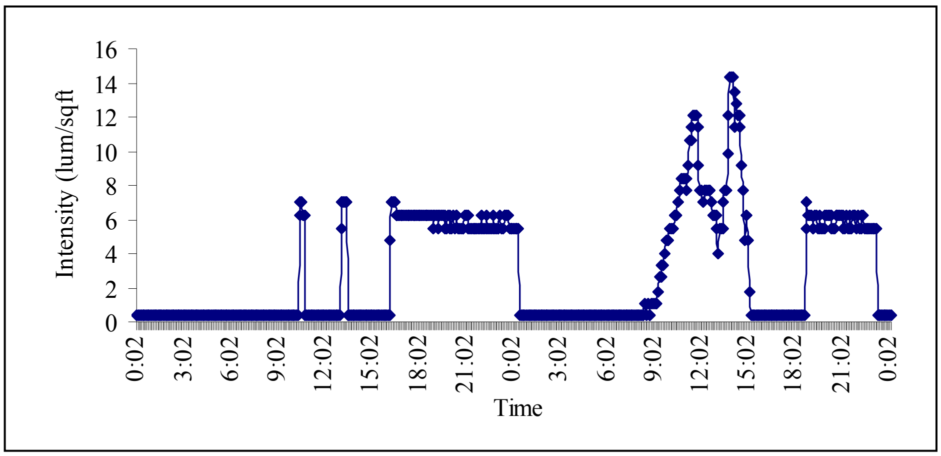
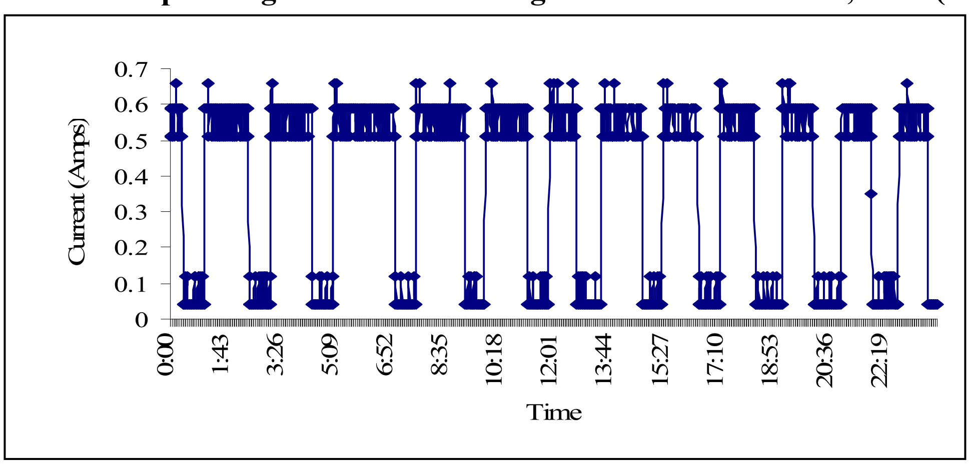


Figure 4. Fan Coil Operating Schedule in Management Office on Dec 5, 2005 (Monday)



Calibration Approach

Individual apartment electricity use data electricity data from April 2005 to March 2006 were provided by the development team. Apartment electricity use is metered individually and the development team read each apartment meter monthly. For those apartments with missing data for a certain period, the electricity use was estimated based the other apartments that have complete data. For instance, if the electricity use data for an apartment was missing, the average electricity uses of the other apartments belonging to the same thermal zone were used for this apartment. Furthermore, it was assumed that the energy performances for all the apartments are similar. During calibration, the total electricity use for all the apartments rather than individual apartment electricity use was used for comparison because DOE-2.1E can not report electricity use in individual thermal zone, and assumptions such as lighting and plug load schedules were adjusted to match the measured energy performance. The air flow rate and fan power consumption of the fan-coil unit for each apartment was provided by the development team, therefore representing the actual energy performance of the fan-coil unit.

Electricity use for the common areas was also calibrated, which includes energy use for pumps and ventilation fans, common areas lights, and the elevators. The common areas are served by three electric sources, including the power grid, the cogeneration system and the PV system. The master electric meter records electricity use supplied by the grid and monthly electricity demand. However, it is very difficult to know the actual electricity use of the common areas because the amount of electricity fed to the common areas by cogeneration and PV systems was not recorded[1]. Therefore, the electricity utility bills in another building (Mid-Rise B) were used to calibrate the common areas electricity use in Mid-Rise A. Mid-Rise B is located next to Mid-Rise A and was constructed at the same period with the same building features. The only difference between these two buildings is that Mid-Rise B does not have the cogeneration and PV systems. The energy performance of the common areas and the interaction between the apartments and the common areas are very similar for these two buildings.

Performance data from the natural gas-fired electric generator were recorded at 30-min intervals during intermittent periods from Jan 2005 to Mar 2006. However, gas consumption data is not available in the trend log. Therefore, calibration of the electric generator is limited to calibrating the amount of electricity generated. Because of the unavailability of the absorption chiller/boiler gas use data and the missing data for the whole building gas use for many months, the calibration of natural gas use was not conducted. Furthermore, PV system calibration was excluded from this study because DOE-2.1E does not have the capability for modeling PV systems.

Calibration Results and Discussions

Table 3 summarizes the major changes made to the original pre-construction DOE-2.1E model to reduce the difference between measured energy use and model projected energy use. Some other parameters such as plug load schedule and domestic hot water schedule were slightly adjusted to reduce calibration error.

[1] kW trend log equipment was installed as part of the original Solar PV design, however, the equipment was sized to meet the electrical engineer's electrical panel capacity design. Actual electricity consumption fell below the measurable accuracy of the oversized current transducers that were installed. Confounding the DOE-2 calibration, the gas-fired generator and PV system may have fed electricity back into the grid during periods of low building electricity consumption. The electric meter installed at Maverick Gardens only records electricity flowing into the building.

Results and Discussions

Table 3. Summary of Major Changes to the Original DOE-2.1E Model

Parameters	Changes Made to the Original Pre-Construction DOE-2 Model	Justification
Apartment plug load power density	Reduced from 1.50 w/sf to 0.56 w/sf	Calculated based on Building America Research Benchmark Definition (Hendron, 2008)
Apartment interior peak lighting power density	Reduced from 1.50 w/sf to 0.44 w/sf	Metering data
Elevator	Added an elevator electrical power and associated elevator schedule	Elevator contributes to building common areas electricity use
Fan-coil units fan operation schedule	Changed from always on mode to seasonal adjusted schedule	Fan-coil short-term metering data and professional judgment
Space heating thermostat set point	Changed from 70°F to 74°F	Metering data
Heating, cooling availability schedules	Heating is available from Sep 15 through Jun 15	Based on State Code requirements
Oven electricity use	Removed from building common areas and included in individual apartment	Oven electricity use is included in individual apartment
Natural gas-fired electric generator size	Changed from 0.256 MBtu to 0.15 MBtu	Generator is operated at 60% of output
Domestic hot water heater	Delete domestic hot water heater	No domestic hot water heater is used based on as-built plant operation schedule
Heat recovery	Recovered waste heat provides both domestic hot water and space heating	Based on the as-built plant operation schedule

The ASHRAE Guideline 14-2002 *Measurement of Energy and Demand Savings* (ASHRAE, 2002) document sets uncertainty or tolerance limits for calibrated simulation. Section 6.3.3.4.2.2 of the document states: "models are declared to be calibrated if they produce NMBEs within ± 10% and CV-RMSEs within ± 30% when using hourly data, or 5 % - 15% with monthly data". These two statistical metrics, Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CV-RMSE), are used to compare the model projected energy use with the actual energy use in this study. NMBE and CV-RMSE are defined in Equation (1) and (2).

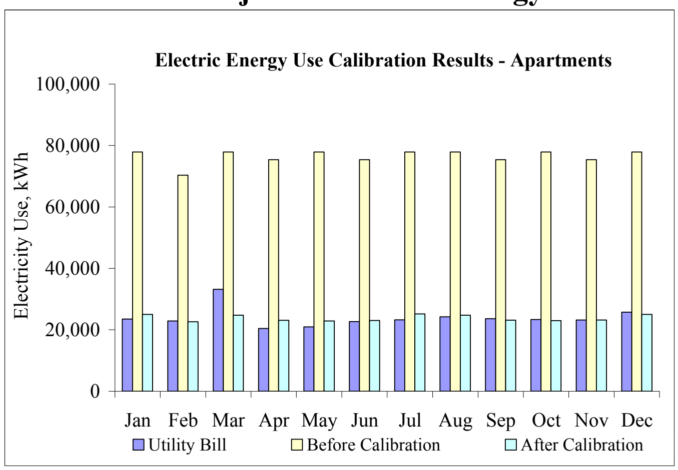
$$NMBE = \frac{\dfrac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}}{\bar{y}} \times 100 \tag{1}$$

$$CV - RMSE = \frac{\left(\dfrac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-1}\right)^{1/2}}{\bar{y}} \times 100 \tag{2}$$

where y is the measured actual data, $\hat{y}$ is the simulation predicted data, $\bar{y}$ is the mean measured value, and n the number of data points.

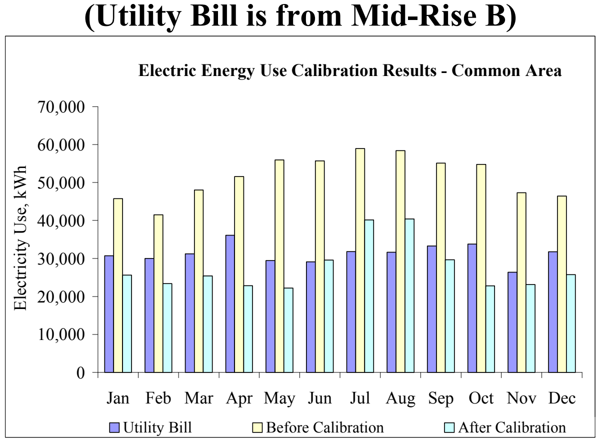
We observe that monthly utility bills span over periods that have different lengths from months. The utility bills were adjusted to represent monthly use over the same length of time as that in the simulation. Figure 5 shows the calibration results of the total electricity use for all the apartments. By lowering apartment interior lighting power density and plug loads in the original DOE-2 model, apartment electric use is reduced significantly. The NMBE and CV-RMSE are 3% and 6%, respectively. Also as expected, apartment electric load is fairly constant throughout the year, with electric energy use in winter and summer slightly higher than the other months. This is because the total combined electricity use for lighting and appliances in all apartments is fairly constant, while fan-coil unit fans usually run more often during the summer and winter season.

Figure 5. Actual versus Projected Electric Energy Use for Apartments



Calibration results for the building common areas electric energy use are plotted in Figure 6. The NMBE and CV-RMSE are 12% and 25%. Heating and cooling availability schedules have great impact on the energy use in the common areas. Because a two-pipe fan-coil system is used to provide space cooling and heating and the State Sanitary Code in Massachusetts requires that heating must be available from September 15 to June 15 to maintain apartment space temperature between 68°F during the day and 64 at night but no higher than 78°F, the building is set for heating mode during that time. The State Sanitary Code does not include

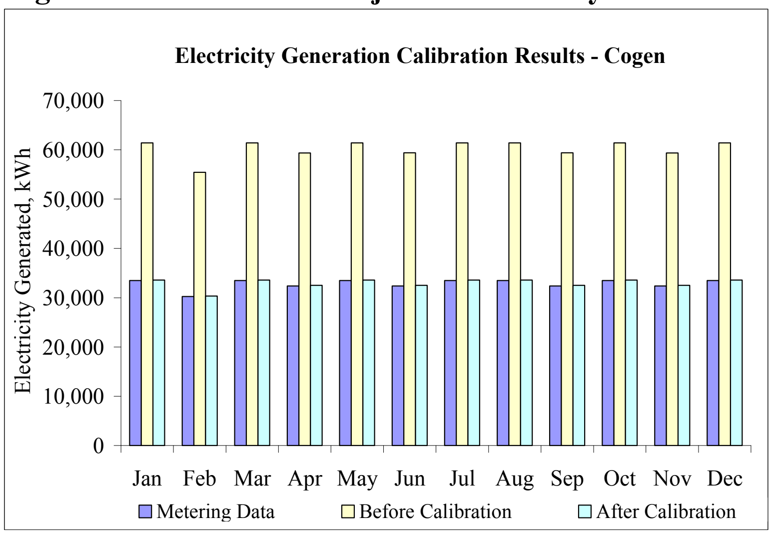
Figure 6. Actual versus Projected Electric Energy Use for Common Areas (Utility Bill is from Mid-Rise B)



cooling requirements. Because two-pipe systems can not provide simultaneous heating and cooling, space temperature can be out of throttle, as defined by the heating and cooling set point schedules. This was verified by the metered data in the sample apartments. The model predicted whole building electricity use, including the electricity use for both apartments and common areas, was also compared with the actual data. The NMBE and CV-RMSE are 6% and 15%.

The equipment size of the natural gas-fired electric generator in the DOE-2 model was adjusted to reflect the fact that the generator is operated at 60% of its electrical output capacity. The model's projected electricity generation was very close to the actual metered data recorded at the generator, as shown in Figure 7.

Figure 7 Actual versus Projected Electricity Generation



The calibrated DOE-2 model simulation outputs were reviewed to gain insights into how mechanical systems in this particular building interacted and were operated. The simulation outputs show that waste heat recovered from the electric generator meets approximately 76% of domestic hot water demand and 15% of space heating load. The absorption chiller/boiler provided the rest of the domestic hot water load and space heating load. A breakdown of the projected natural gas energy use is given in Table 4. From Table 4, we observe that the absorption chiller/boiler was operating in cooling mode from June to September and in heating mode from October to May. The absorption chiller/boiler also supplied partial domestic hot water use, which consumed more gas during winter and less gas during summer, although the domestic hot water demand was fairly constant throughout year. This may be explained by the fact that the DOE-2 model uses the ground temperature as the domestic make-up water inlet temperature, which fluctuates widely in Boston from winter to summer.

Summary

This study used a five-step methodology to calibrate the proposed design model. As-built drawings, actual weather data, utility bills, short-term metering data, trendlog data and development team interview were gathered for the model calibration. This study also shows that uncalibrated energy models could have very low accuracy in predicting actual building energy use. Upon the completion of calibration, the DOE-2 model predicted monthly electric use

Table 4. DOE-2 Model Predicted Natural Gas Energy Use Breakdown

Month	Cooling (therm)	Heating (therm)	Domestic Hot Water (therm)	Electricity (therm)	Total (therm)
Jan	0	2,818	421	4,092	7,331
Feb	0	4,410	456	3,696	8,562
Mar	0	2,189	511	4,092	6,792
Apr	0	114	447	3,960	4,521
May	0	5	357	4,092	4,454
Jun	2,770	3	255	3,960	6,988
Jul	6,708	0	181	4,092	10,981
Aug	6,772	0	131	4,092	10,995
Sep	2,841	0	122	3,960	6,923
Oct	0	19	168	4,092	4,279
Nov	0	642	239	3,960	4,841
Dec	0	3,578	338	4,092	8,008

difference with actual use was reduced from 70% to 3% for apartments, and from 40% to 12% for building common areas. The calibrated DOE-2 model simulation outputs were also reviewed to gain insights into how various mechanical systems in this particular building interacted and were operated.

This study is a good example of energy simulation calibration under real-world situations with practical constraints such as limited performance data and barriers of collaboration among the various disciplines. This paper also shows that even with limited data, the accuracy of energy simulation can be greatly improved. Throughout this study, it is learned that the strong outreach to the design community about advancing the concept of measured building performance is critical. More importantly, building energy metering for key end-uses should be planned and implemented during the building design and construction processes. On one hand, the design professionals usually have limited capabilities of metering and energy simulation. On the other hand, the energy simulation professionals usually do not have enough knowledge of how buildings are designed and operated. The delivery of high-performance buildings calls for significantly increased collaboration among the various disciplines throughout the design, construction, commissioning, and post-occupancy evaluation process.

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References

Ahmad, M. and C.H. Culp. 2006. Uncalibrated Building Energy Simulation Modeling Results. *International Journal of HVAC&R Research*, Vol. 12, No. 4.

ANSI/ASHRAE/IESNA. 2004. *ASHRAE Standard 90.1-2004*, *Energy Standard for Buildings Except Low-Rise Residential Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

ASHRAE. 2002. *ASHRAE Guideline 14-2002: Measurement of Energy and Demand Savings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

Deru,M., S.D. Pless and P.A. Torcellini. 2006. BigHorn Home Improvement Center Energy Performance. *ASHRAE Transactions*, Vol. 112, Pt 2.

Hasnain, S.M., M. S. Smiai, Al-Ibrahim, A. M. and S.H. Al-Awaji. 2000. Analysis of Electric Energy Consumption in an Office Building in Saudi Arabia. *ASHRAE Transactions*, Vol.106, Pt. 2.

Hendron, R. 2008. Building America Research Benchmark Definition, NREL/TP-550-42662, January 2008.

Henriquez, S., S. Barnat and N. Ludwig. 2006. Maverick Landing Sustainable, Affordable Housing. http://web.mit.edu/dusp/mhg/ppts/ludwig.pdf

Lunneberg, T.A. 1999. Improving Simulation Accuracy Through The Use Of Short-Term Electrical End-Use Monitoring. *Sixth International IBPSA Conference*, Building Simulation '99, Kyoto, Japan, 13-15 September 1999, September 1999.

National Renewable Energy Laboratory, 1995. TMY2 Typical Meteorological Years Derived from the 1961-1990 National Solar Radiation Database. Golden, Colorado.

National Climatic Data Center, 2006. http://www.ncdc.noaa.gov/oa/climate/stationlocator.html.

Pan, Y., Z. Huang and G. Wu. 2007. Calibrated Building Energy Simulation and Its Application in a High-Rise Commercial Building in Shanghai. *Energy and Buildings* 39 (2007) 651–657.

Reddy, T.A. 2006. Literature Review on Calibration of Building Energy Simulation Programs: Uses, Problems, Procedures, Uncertainty, and Tools. *ASHRAE Transactions*, Vol. 112, Part 1.

Snell, J. and K. Neuhauser. 2005. Dynamic Interactions and Competing Objectives in Multifamily Green Building Design. *10th Canadian Conference on Building Science & Technology*, Ottawa, Canada, May 12-13, 2005.

Xu, P., J. Huang, R. Jin and G. Yang. 2007. Measured Energy Performance of a US-China Demonstration Energy-Efficient Office Building. *ASHRAE Transactions*, Vol. 113, Part 1.