METHODOLOGY FOR THE PRELIMINARY DESIGN OF HIGH PERFORMANCE SCHOOLS IN HOT AND HUMID CLIMATES

A Dissertation

by

PILJAE IM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2009

Major Subject: Architecture

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Approved by:

Chair of Committee,	Jeff Haberl
Committee Members,	Dan Turner
	Charles Culp
	Liliana Beltran
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ABSTRACT

Methodology for the Preliminary Design of High Performance Schools in Hot and Humid Climates. (December 2009)

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Chair of Advisory Committee: Dr. Jeff Haberl

A methodology to develop an easy-to-use toolkit for the preliminary design of high performance schools in hot and humid climates was presented. The toolkit proposed in this research will allow decision makers without simulation knowledge easily to evaluate accurately energy efficient measures for K-5 schools, which would contribute to the accelerated dissemination of energy efficient design.

For the development of the toolkit, first, a survey was performed to identify high performance measures available today being implemented in new K-5 school buildings. Then an existing case-study school building in a hot and humid climate was selected and analyzed to understand the energy use pattern in a school building and to be used in developing a calibrated simulation. Based on the information from the previous step, an as-built and calibrated simulation was then developed. To accomplish this, five calibration steps were performed to match the simulation results with the measured energy use. The five steps include: 1) Using an actual 2006 weather file with measured solar radiation, 2) Modifying lighting & equipment schedule using ASHRAE's RP-1093

methods, 3) Using actual equipment performance curves (i.e., scroll chiller), 4) Using the Winkelmann's method for the underground floor heat transfer, and 5) Modifying the HVAC and room setpoint temperature based on the measured field data. Next, the calibrated simulation of the case-study K-5 school was compared to an ASHRAE Standard 90.1-1999 code-compliant school.

In the next step, the energy savings potentials from the application of several high performance measures to an equivalent ASHRAE Standard 90.1-1999 code-compliant school. The high performance measures applied included the recommendations from the ASHRAE Advanced Energy Design Guides (AEDG) for K-12 and other high performance measures from the literature review as well as a daylighting strategy and solar PV and thermal systems. The results show that the net energy consumption of the final high performance school with the solar thermal and a solar PV system would be 1,162.1 MMBtu, which corresponds to the 14.9 kBtu/sqft-yr of EUI. The calculated final energy and cost savings over the code compliant school are 68.2% and 69.9%, respectively.

As a final step of the research, specifications for a simplified easy-to-use toolkit were then developed, and a prototype screenshot of the toolkit was developed. The toolkit is expected to be used by non-technical decision-maker to select and evaluate high performance measures for a new school building in terms of energy and cost savings in a quick and easy way.

DEDICATION

To my loving wife

ACKNOWLEDGEMENTS

This dissertation would not have been possible without all those who have helped me in the pursuit of my degree. Therefore, I would like to express my gratitude toward all those people. First of all, I would like to express the deepest gratitude toward Dr. Jeff S. Haberl for his leadership as committee chair. His patience on this research is deeply appreciated. During the thesis study, he provided necessary guidance whenever it was needed. Thanks to Dr. Dan Turner for his careful review and comments on my dissertation while serving on my committee. Thanks to Dr. Charles Culp for his valuable advice for the dissertation study and thoughtful review of my research as committee member. Thanks to Dr. Liliana Beltran especially for her guidance for daylighting simulation and other related advice as a committee member.

I also wish to extend my thanks and appreciation to the following people: Thanks to Mr. Jerome Gonzales and Mr. Royce Thomas, the HVAC maintenance personnel for the College Station I.S.D. for the case-study school, who provided me with HVAC information, tours of the school, and several interviews. Thanks to the College Station I.S.D. for letting me have access to the case-study school to continue my research.

Finally, I should say this long journey could not be completed without the support from my loving wife, Heeyoen Jo. Although there were so many hard times during this Ph.D. program, she always showed sincere trust in me and encouraged me to continue and finish this long journey.

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CHAPTER I

INTRODUCTION

1.1. Background

Today, with the growing concerns about increasing energy costs and the demand for healthy places to live and work, a high performance building (or green building) attracts attention because of its energy savings potential and environmentally friendly spaces. High performance buildings are buildings designed to maximize operational energy savings, improve the comfort, health, and safety of the occupants and visitors, and to limit the detrimental effects on the environment (DDC 1999).

In general, high performance buildings can be categorized by several features: energy and water efficiency, indoor environmental quality (i.e., indoor air quality, thermal comfort, acoustics and lighting), material and environmental impact (i.e., waste management and emissions reduction). When these features are successfully incorporated into the building design, the building can be called a high performance building. The benefits of a high performance building can be listed below (EERE 2006a):

- Energy use reduction of 50% or more compared to conventional buildings.
- Reduced maintenance and capital costs.
- Reduced environmental impact.

This dissertation follows the style of *ASHRAE Transactions*.

- Increased occupant comfort and health.
- Increased employee productivity.

Not surprisingly, schools are one of the popular target buildings for high performance applications. In particular, in a school, the energy efficiency and the IAQ (Indoor Air Quality) are considered the most important aspects when designing high performance schools.

According to the National Center for Education Statistics (NCES), U.S. Schools spent nearly $8 billion on energy costs in 2001, which is more than the cost of textbooks and supplies combined (Smith et al. 2003). In addition, about sixty-one percent of public school districts reported a shortfall in funding to pay their energy bills. As a result, most school districts need to reduce their energy expenditures just to make ends meet. Therefore, the application of high performance strategies to new and existing schools can be an effective solution for this problem. Furthermore, the average age of America's public schools is 42 years (Rowand 1999), which means the vast majority of existing schools could greatly benefit from the application of high performance retrofit strategies.

Along with the energy efficiency, the IAQ issue has always been a big concern in school buildings. According to the U.S. government's General Accounting Office (GAO), one in five schools in the United States has problems with IAQ (GAO 1995, 1996). Several studies have reported how IAQ affects the health and performance of students in schools. Many of them concluded that it is critical to provide an adequate amount of outdoor air and to maintain proper relative humidity levels to provide a healthy and productive learning environment for students (Bayer et al. 2000).

1.2. Problem Statement

In difference to the conventional school design process, a high performance school building design requires a “whole-building” or “integrated design” approach (U.S.DOE 2002). From the beginning of the design process, a design team that is composed of an architect, a project manager, an engineer, and a commissioning agent works together for the integration of the building components and systems and decides which option would be the best to save energy and reduce the impact on the environment. In general, there are six phases in the high performance school building design and construction process: 1) Program and goal setting, 2) Schematic/conceptual design, 3) Design development, 4) Construction documents, 5) Construction, and 6) Occupancy (Collaborative for High Performance Schools (CHPS) 2006). Not surprisingly, the opportunities to achieve a high performance school are decreased over time. Therefore, the high performance measures for the target school should be considered in early stage of the design procedure (i.e., preliminary design phase), in general, no later than programming phase. However, it is often too complicated and time consuming to determine which building components and systems would be the best in terms of energy savings in preliminary design phase. Although there are several high performance school design guidelines available today such as the Energy Design Guidelines for High Performance Schools (U.S.DOE 2002), the CHPS Best Practices Manual (CHPS 2006), and ASHRAE’s Advanced Energy Design Guide (AEDG) for K-12 School Buildings (ASHRAE 2008), all these guidelines only introduce different types of high performance features without verifying how much energy could be saved through the selection of high performance features for a specific school building. In addition, although there have been various studies investigating energy and cost savings from energy efficient measures, those studies usually explored the individual aspect of these issues, not the comprehensive approach for high performance features applied to a school. Since individual energy efficient measures can interact when several measures are applied together in a building, studies that only show the energy saving result from an individual measure may not be representative of a group of measures. Therefore, a comprehensive methodology, which includes the savings assessment from multiple measures, would be needed in the preliminary design phase for a high performance school building

1.3. Objectives and Scope

Therefore, this study proposes to develop a methodology for the preliminary design of high performance schools in hot and humid climates. To achieve this objective, several tasks are defined.

1) Review previous studies to select the appropriate high performance measures for schools in hot and humid climates.
2) Evaluate an existing case-study elementary school in a hot and humid climate in terms of energy performance and Indoor Air Quality (IAQ).
3) Propose multiple changes to the existing case-study school and simulate the improved energy performance and IAQ of both the individual and combined measures.

4) Generalize the procedure for the preliminary design of high performance schools in hot and humid climates and propose a simplified simulation tool for high performance schools that can be used in preliminary design phase as a web-based tool for non-technical decision makers

Although high performance school features include water conservation, sustainable materials, safety, etc., this study will focus primarily on the energy efficiency while maintaining acceptable IAQ conditions.

1.4. Organization of the Dissertation

This dissertation is divided into 10 chapters. Chapter I is the introduction. This chapter provides the background of the research, the problem statement, objectives and the scope of the study. Chapter II contains the literature review, which reviews the previous studies that are important to this research, including: energy efficiency and IAQ studies in schools, studies of high performance schools, studies that included calibrated simulation, a review of easy-to-use simulation tools, and a review of daylighting simulation studies that used the DOE-2 building energy simulation program. Chapter III describes the significance of the study as well as the limitations of the study. Chapter IV presents the research methodology, and discusses the procedures used in this study, which include: 1) A survey of high performance measures for schools, 2) An analysis of a case-study school, 3) The development of the calibrated simulation, 4) A study of daylighting simulation analysis, 5) The application of the selected high performance measures to the case-study school, and 6) The development of a simplified simulation tool for schools. In Chapter V through Chapter IX, the results of the study are presented. Chapter X summarizes the results and draws conclusions based on the results. Finally, an appendix is provided that contains supporting material.

CHAPTER II

LITERATURE REVIEW

The relevant literature for this study includes energy efficiency studies in schools, studies of IAQ in schools, studies of existing high performance schools, calibrated simulation, easy-to-use simulation tools, and studies of daylighting simulation that uses the DOE-2 program. Various sources were used to cover these topics. These include ASHRAE abstract archives & ASHRAE Publications, Energy and Buildings, and the high performance buildings database of USDOE's Energy Efficiency and Renewable Energy (EERE) program. Interestingly, the buildings database of EERE (EERE 2006b) provided most of the case studies for existing high performance schools.

2.1. Energy Efficiency Studies of Schools

In this section, the previous energy efficiency studies of schools were reviewed. As mentioned earlier, even though many of the schools analyzed are not defined as high performance schools, this review yielded relevant references about what types of energy efficiency measures have been previously applied and studied in school buildings. Many papers on energy efficiency in school buildings have been written over the years. For this research, over fifty papers were reviewed (Im and Haberl 2006), of these papers, sixteen studies were selected for a closer review. Table A.1 in Appendix A provides a summary of the selected papers. This table presents the author of paper, the classification of energy efficiency measures, the application of energy efficiency measures, the climate zones where the schools are located, the number of schools analyzed in each study, the total floor area of the school, the method of energy use analysis if any, and finally, the energy savings compared to other conventional schools.

In general, the energy efficiency measures analyzed in the previous studies can be classified into two types: building envelope measures and building systems measures. Of the sixteen papers reviewed, three papers showed the energy savings from the application of energy efficient building envelope measures such as tight windows, high insulation levels, shading devices, etc (Pletzer and Hunn 1988, Hunn et al. 1993, and Akbari et al. 1997). Eleven papers described energy efficient HVAC systems for schools such as ground source heat pumps, an ice-making thermal storage system, and a dual-path air distribution system (Cane and Clemes 1995, Dinse 1998, Goss 1992, Rafferty 1996, Shonder et al. 2000, and Khattar et al. 2003).

The total annual energy savings from these studies varies from 1% to 49%. However, most of the total annual energy savings are in the range of 20 to 40%. The energy savings were most often calculated by measured energy use, which was mostly from the utility bills or data loggers installed on-site. The baseline energy use for the estimation of energy savings are either the energy use from nearby similar schools or the previous energy consumption of the same school if the school was retrofitted. Some of the papers used building energy simulation programs such as DOE-2 to calculate the savings (Hunn et al. 1993, Cane and Clemes. 1995, Akbari et al 1997, and Shonder et al. 2000). In the following section, a detailed review is provided for studies that covered energy efficient envelope and HVAC systems.

2.1.1. Energy Efficient Envelope Measures

For the energy efficient envelope measures, shading devices and high-albedo roofs were the most noteworthy, which are reviewed in this section. One study (Pletzer and Hunn 1988) shows that the application of shading devices on residential buildings in Austin, Texas reduced annual energy use by 14%. Although this study targeted residential buildings, this study was worth mentioning because it showed the energy savings potential from shading devices in hot and humid climates, which may have similar effects on other building types. Hunn et al. (1993) also presented the results of a study of the effect of shading devices on annual heating, cooling, and total energy use, peak electric demand, and energy cost savings in a school as well as residences, a small office, and a high-rise office in Minneapolis, Minnesota. To estimate energy savings, the DOE-2 building energy simulation program was used. Surprisingly, the results showed that the annual energy savings for the school were less than 1%. This value is much less than the annual savings for the residence (4%), the small office building (5%), and the high-rise office building (5%) in the same climate. Even though the annual energy savings for the school were marginal, the savings would be expected to increase in cooling-dominated climates as indicated in Pletzer et al. (1988).

Akbari et al. (1997) reported on the effects of high-albedo roofs in Sacramento, California. They monitored peak power and cooling energy savings from high-albedo coatings from one house and two school buildings. The measured and simulated cooling energy saving in the two schools was 3.1 kWh/day (35% of base-case cooling energy use), and the peak demand reduction was 0.6 kW (41% of base-case cooling energy use). In summary, high-albedo roofs and shading devices appear to have a potential for significant savings in schools, which should also extend to the hot and humid climate considered for this study.

2.1.2. Energy Efficient HVAC Systems

For energy efficient HVAC systems in hot and humid climates, ground source heat pump systems and dual-path systems were found to be the most important and are reviewed in this section. In school buildings, ground source heat pumps have been one of the most popular choices for energy saving strategies particularly given the large land area that surrounds schools. Five papers (Cane and Clemes 1995, Dinse 1998, Goss 1992, Rafferty 1996, and Shonder et al. 2000) present results of analysis of ground source heat pumps in schools. Dinse (1998) described the energy and cost effectiveness of the geothermal systems installed in an existing school. The original school system which had a two-pipe chilled water system for cooling and electric resistance heating, was replaced with the geothermal heat pump (i.e., a water loop heat pump with a closed-loop geothermal heat exchanger). The measured energy consumption indicated that the total annual energy consumption was reduced from 3,481 MWh to 2,298 MWh (i.e., a 34% savings), which corresponds to a six year simple payback. This study is particularly noteworthy because it provided results from measured data from a retrofit to an existing school.

Another detailed study about geothermal heat pumps (GHP) in schools was conducted by the Oak Ridge National Laboratory (Shonder et al. 2000). This study verified the energy efficiency and life-cycle cost savings of the GHP systems installed in four identical schools in Lincoln, Nebraska. According the measured data and utility bills, on average, the GHP schools used 26% less source energy per square foot per year than the non-GHP new schools in the study.

Another interesting study about school HVAC systems is the dual-path system for school buildings (Khattar et al. 2003). "A dual-path system is one in which the ventilation air and recirculation airstreams are conditioned separately, each with its own set of heating, cooling and dehumidification coils." (Khattar et al. 2002, p.39). One of the benefits of dual-path systems is that this system can achieve improved air quality by providing the needed ventilation to the space while maintaining desired temperature and good indoor humidity control at all part-load conditions. Khattar et al.'s study was the first to show the potential benefit of using dual-path systems for schools, specifically, in hot and humid climates. In this study, the energy use of two schools (i.e., one with dual-path systems integrated with thermal storage vs. a conventional system without thermal storage) in Florida were compared. The measured indoor air temperatures and humidity levels indicated that the dual-path system maintained lower and more comfortable humidity levels (i.e., 40%-50% relative humidity, which is 10% less than comparable schools in the same area with a conventional system) as well as improved air qualities even in humid locations. With respect to energy, the school with the dual-path HVAC system and the TES system used about the same amount of total annual energy as the school with the conventional system. However, the authors did not mention that more energy would be required for the school with the conventional system to maintain the lower range of humidity levels maintained by the school with the dual-path HVAC system. Therefore, the savings from the dual-path system are expected to be larger than those reported by Khattar et al.

In summary, various energy efficient strategies for schools have been reported in the literature. Of the sixteen papers reviewed, three papers showed energy savings from the application of energy efficient building envelopes, and eleven papers presented energy efficient HVAC systems for schools. It was found that a proper selection of energy efficient HVAC system according to climate area and effective design of building envelope can reduce annual energy consumption in a school building as well as peak demand in the summer. Also, in the study of the dual-path systems, it was shown that thermal comfort can be significantly improved because lower relative humidity levels can be maintained, which is important for hot and humid climates where mold and mildew can be problematic.

2.1.3. Daylighting Strategy

It is well known that using daylighting strategies in school buildings can save energy as well as enhance the learning environment (Plympton et al. 2004). Most of the building energy savings from this strategy can be achieved by reducing the electrical lighting energy. In addition, by turning off or dimming the electric lighting when it is not needed, the cooling energy for the building can be saved because of the reduced heat generated from the electrical lighting. Although the energy savings by using daylighting strategies have been shown in school buildings, it was relatively difficult to find literature that presented measured or simulated energy savings specifically from daylit school buildings. In most cases these savings were combined with other measures.

One study (Nicklas and Bailey 2003) analyzed the energy performance and cost of daylit schools in North Carolina. In this study, three daylit schools (i.e., two middle schools and one elementary school) were compared to the similar schools in the same area. In this study, the construction cost comparison showed that the daylit schools cost little more in first-costs (i.e., less than 1% of the total construction budget) for the addition of the daylighting components. In addition, the study showed that the increased construction cost would be returned in less than three years because of reduced operating energy costs. The operating energy cost comparisons in the study showed that the total energy savings in the daylit schools were between 22% to 64% over typical schools. This study is important since it is one of the few studies that showed daylit schools can reduce operating energy costs compared to typical schools based on the actual total energy bills. However, there are several limitations in this study, including: 1) the new school building's energy costs were compared to existing schools' energy bills without daylighting, which overestimates the savings from daylighting alone, 2) the study did not consider the energy cost differences by the type of HVAC systems, building envelope, etc.

2.2. IAQ in Schools

Previous studies regarding common IAQ problems and their causes are reviewed in this section. In addition, the evaluation of school IAQ and ventilation control with indoor CO_2 concentration levels is discussed. The importance of IAQ in schools has been emphasized often for several reasons. One reason is that school-age children are still developing physically and are therefore more affected by the consequences of being exposed to unnecessary indoor pollutants during their early school years than adults under similar condition (Bayer et al. 2000). This problem is compounded by the fact that children spend many hours in school facilities during a school year. Another reason is that poor IAQ aggravates asthma and other respiratory illnesses, which is one of the major reasons for absenteeism (Bayer et al. 2000). According to the American Lung Association, asthma is responsible for an estimated 14 million lost school days (AAAAI 2004). Finally, studies show that the good IAQ in schools can enhance the learning performance and academic achievement of students (Wargocki and Wyon 2006)

Several studies have been performed to verify the most common IAQ problems in schools and the causes of the problems. Daisey et al. (1999) reviewed the existing literature and reports on IAQ, ventilation, and building-related health problems in schools. They found most of the major building-related problems were due to inadequate outdoor air ventilation. Water damage to the building envelope, which lead to mold growth, was the second most frequently reported building-related problem. Henkel and Angell (1999) also identified the common causes of IAQ problems. They summarized 169 investigate reports about IAQ problems in Minnesota schools and also concluded the major reason for poor IAQ in schools was insufficient outdoor air supply, which is the same findings by Daisey et al. (1999).

Therefore, adequate outdoor air ventilation must be considered in the design of new school buildings to ensure acceptable and healthy IAQ. In general, increasing outdoor air supply for improving IAQ is known to increase energy costs due to the increased cooling or heating load of the ventilation air. Often, air-to-air energy recovery ventilation equipment (ERV) can be an effective means of reducing the additional heating or cooling load. An ERV recovers energy from exhaust air for preconditioning outdoor air before supplying the conditioned air to the space.

2.2.1. Ventilation Rate and CO_2 Concentrations

As discussed above, adequate ventilation rates are critical to maintain good IAQ in schools. Often, the ventilation rate for new schools has been designed according to ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality. There have been several versions of ASHRAE Standard 62 (e.g., ASHRAE 62-1989, ASHRAE 62-1999, ASHRAE 62-2001, and ASHRAE 62-2004), and the ventilation requirements have been changed accordingly. Table 2.1 shows the changes of ventilation requirement by different versions of the standard. The minimum ventilation rate for classrooms recommended in ASHRAE Standard 62- 1989, 1999, and 2001 was 15 cfm/person. In 2004, the standard decreased the ‘per person’ ventilation and added a ‘per area’ component. This change results in a minimum ventilation rate of 10 CFM/person and 0.12 CFM/sq.ft. For example, in a typical classroom (i.e., 28ft x 28ft) with 20 students has a minimum ventilation rate of 300 CFM (i.e., = 15CFM/person x 20 students) with the ASHRAE Standard 62 – 2001, whereas the same classroom has a ventilation rate of 294 CFM (i.e., = (10 CFM/person x 20 students) + (0.12 CFM/sq.ft x (28 ft x 28ft))) with the new ASHRAE Standard 62 – 2004.

Table 2.1 - Ventilation Rate from ASHRAE Standard 62

ASHRAE Standard	Classroom Ventilation Rate (CFM/person)	Classroom Ventilation Rate (CFM/sqft)
62-1973	10	N/A
62-1981	5	N/A
62-1989, 1999, 2001	15	N/A
62.1-2004	10	0.12

CO_2 concentrations levels have been frequently used for the estimation of ventilation rates and the evaluation of IAQ. In general, 1,000 ppm of CO_2 concentration corresponds approximately to the 15 cfm/person of ventilation rate (ASHRAE 2001). However, rates below 1,000 ppm do not always guarantee that the ventilation rate is adequate for removal of air pollutants from other indoor sources (Seppanen et al., 1999; Apte et al., 2004). Some studies investigated the measured CO_2 concentrations in existing schools to evaluate the IAQ. Brennan et al. (1991) reported mid-afternoon CO_2

measurements in a non-random study of 9 U.S. schools. Concentrations ranged from about 400 to 5,000 ppm (mean = 1,480 ppm). CO_2 concentrations exceeded the recommended 1,000 ppm in 74% of the rooms.

Another study presented the measured CO_2 concentrations from 120 randomly selected classrooms in two school districts in Texas (Corsi et al., 2002). The median time-averaged and peak CO_2 concentrations were 1,286 ppm and 2,062 ppm, respectively. The time-averaged CO_2 concentration exceeded 1,000 ppm in 66% of the classrooms.

In summary, sufficient outdoor air ventilation is critical to maintain healthy IAQ in schools. However, several studies showed a significant proportion of existing school classrooms were not sufficiently ventilated as indication by CO_2 concentrations, which can cause potential IAQ problems. Therefore, an evaluation of IAQ for the case-study school should accompany any energy consumption recommendations in this dissertation research.

2.3. Studies of High Performance Schools

The relevant studies about high performance schools were reviewed. These studies include: Kats (2006), Turner Green Buidlings (2005), Eley et al. (2006), McCowan et al. (2006), Stanton-Hoyle and Brown (2006), Fischer et al. (2007), and as previously mentioned, the high performance buildings database (EERE 2006b) was reviewed for information about high performance schools around the world. The High Performance Buildings Database is a result of research sponsored by the U.S.

Department of Energy that seeks to improve building performance by collecting data on various factors that affect a building's performance, such as energy, materials, and land use (EERE 2006a). As of May 2008, there were six K-12 schools and seven higher education buildings in the database. Table A.2 in Appendix A presents the summary of these buildings. The table shows the Energy Use Index (EUI) for each school building, which is a measure of the total energy use normalized by conditioned floor area. Often, the EUI is used to compare the energy use of different buildings. As shown in the Table A.2, the EUI for high performance schools (K-12 only) in this database is about 23 to 60 kBtu/sq.ft. with an average of 29 kBtu/sq.ft. These values can be compared to the national average EUIs for K-12 school buildings, which are provided by several sources. These include 59 kBtu/sq.ft. from the California Commercial End-Use Survey (CEUS) database (PG&E 1999), 68 kBtu/sq.ft. from the Florida Solar Energy Center (FSEC) report (Callahan et al. 1997), and 75 kBtu/sq.ft. from 1999 CBECS report (EIA 2001). If one assumes the 29 kBtu/sq.ft is the average EUI for high performance schools, then the high performance schools use about 51% to 62% less energy annually compared to the national average for schools in U.S. However, since the national average EUI for schools was calculated not only from new schools but also from old schools that have inefficient systems and poor insulation, the energy savings benefit from high performance schools can easily be overstated. To compare the high performance schools to average new schools, those schools that were compliant with ASHRAE Standard 90.1-1999 (ASHRAE 1999) were assumed as the average new schools. Table A.2 shows the energy savings for the first three schools based on the school buildings compliant with

ASHRAE Standard 90.1-1999. From the table, high performance schools use about 20 to 40% less energy than the new schools compliant with 90.1-1999. In summary, it would appear that the EUI and the energy savings from a high performance school compared to the EUI from a code-compliant school (i.e., 90.1-1999) are more realistic comparison.

In contrast to the schools reviewed in the previous section, the high performance schools in this section considered various high performance (or green) strategies together in the design phase. Of the various green strategies, specific energy efficient aspects are shown in the right-hand column of the Table A.2. For the strategies listed, several common green strategies for school buildings were found. These include:

- High performance glazing (i.e., low SHGC and low U-value) for southern climates.
- High albedo roofs, or roofs with high solar reflectance for southern climates.
- High R-values for walls and roofs.
- T5 or T8 fluorescent lamps with electronic ballasts.
- Occupancy sensors to control interior lighting.
- Solar photovoltaic (PV) and solar thermal systems.
- Ground source heat pumps.
- High AFUE (e.g., over 90%) boilers.
- High efficient SWH.

From the EERE database, however, it is difficult to differentiate the energy efficient strategies according to climate area. In general, different strategies for different climate areas should be considered when a high performance school building is designed.

Plympton et al. (2004) analyzed affordable green designs for K-12 schools from each of the nine climate zones in U.S. Table 2.2 shows the green strategies used for each K-12 schools from Plympton et al. (2004). According to the table, high efficiency lighting (e.g., T5 and T8 fluorescent lighting) was the most common strategy regardless of climate zone. In addition, variable speed drives for HVAC systems were used for several climate areas. In one school, a 1-2 kW photovoltaic system was installed for the demonstration of the PV systems (i.e., Tucson Unified School District, in Arizona, which has excellent solar resources).

Detailed design guides for high performance schools by climate were also reviewed in the Energy Design Guidelines for High performance Schools (U.S.DOE 2002), ASHRAE's Advanced Energy Design Guide (ASHRAE 2008), and the CHPS Best Practice Manual (CHPS 2006). One well-documented design guideline is the "Energy Design Guidelines for High Performance Schools" by the U.S. Department of Energy (U.S.DOE 2002). In this document, there are nine design guidelines corresponding to the nine different climate zones in the U.S. (i.e., the same climate zone definition from Plymton et al. 2004). Each guideline presents a specific design strategy varied by climate zone. For example, according to the design guideline for hot and humid climates, the guideline recommends the use of desiccant dehumidification and cooling, and enthalpy heat exchangers, which can reduce the need for mechanical cooling. Also, natural gas and/or solar-driven absorption cooling were recommended as a method of reducing peak electricity consumption. Unfortunately, although this guideline recommends several types of high performance features, it does not provide

Table 2.2 - High Performance School Case Studies from Plympton et al. 2004

Climate Zone	Schools	Green Strategies
Temperate and Mixed Climates	Corvallis School District 509J, Corvallis, Oregon	* T-8 lighting * Digitally controlled heating, ventilating, and air-conditioning (HVAC) equipment * Energy-efficient boilers.
Hot and Dry Climates	Tucson Unified School District, Tucson, Arizona	* 1-2 kW photovoltaic system installations * Lighting upgrades * Vending machine controls * Energy management control systems.
Hot and Humid Climates	Marion County Public Schools, Ocala, Florida	* Lighting * Variable-speed drives for HVAC systems, * High-efficiency water fixtures, * Energy management system controls
Temperate and Humid Climates	Roanoke County Public Schools, Roanoke, Virginia	* T-8 lighting * Energy management system (EMS) * Monitor/controller unit for boilers.
Cool and Humid Climates:	Montour School District, McKees Rocks, Pennsylvania	* EMS * Energy efficient motors * Lighting controls
Cold and Humid Climates:	Elk River School District No. 728, Elk River,Minnesota	* Passive heating and cooling * Daylighting techniques
Cool and Dry Climates:	Council School District #13, Council, Idaho	* Biomass energy system fueled by wood chips * New T-8 lamps, new ballasts * Light reduction in areas tested for light intensity * Digital controls.
Arctic and Subarctic Climates:	Buckland K-12 School, Buckland, Alaska	* Aerodynamic form of the new structure (to reduce heat loss) * Better insulation (reducing fuel costs) and daylighting
Tropical Island Climates	Chiefess Kamakahelei Middle School, Lihue, Kauai, Hawaii	* Natural ventilation * VAV systems * High performance shell, with tinted, low-e windows and R-19 roof insulation * T-8 lamps

system details (e.g., savings, IEQ benefits, costs, etc.) which are needed to clarify the recommendations, nor did it provide specific savings amounts for the different recommendations.

Another detailed design guide for K-12 schools, the Advanced Design Guide for K-12 (AEDG K12) schools was developed by ASHRAE (ASHRAE 2008). The goal of this design guide is to achieve at least 30% more energy savings over ANSI/ASHRAE/IESNA Standard 90.1-1999 compliant school buildings. In order to set energy saving goals, the AEDG K-12 defines the code-compliant elementary school's baseline end uses (i.e., site energy use (kBtu/sq.ft.) across the 15 different climate zones. The end uses for each climate zone can then be used to identify the most energy consumptive category of end uses (e.g., heating, cooling, lighting, etc.) by climate zone, which then allows targeting for energy savings by end-use category. Chapter 3 of the AEDG for K-12 provides recommendation tables by climate zones. Using the table a 30% energy savings over ASHRAE Standard 90.1-1999 would be expected when all the building measures shown in the table are implemented together for a school building. The recommendation table for climate zone 2 and 3 will be considered for this dissertation when high performance features are selected for the proposed high performance school building. This would set a goal of 50 kBtu/sq.ft for a high performance school in Houston, Texas considering a baseline annual energy use of 72 kBtu/sq.ft in the same area for a 90.1-1999 code-compliant school.

2.4. Calibrated Simulation

During the past three decades, hourly building energy simulation programs have been used to predict the peak energy demand and energy consumption of new buildings, which includes the design and proper sizing of the heating, ventilating and air-conditioning (HVAC) systems. Simulation programs have also been used to evaluate energy savings from energy conservation retrofits to existing buildings. An important issue when evaluating energy savings in an existing building is how well the simulated model predictions fit measured data from a real building (Bronson et al. 1992, Bou-Saada 1994, Song 2006, Cho 2009). During the last ten years, numerous studies about calibrated simulations have been reported (Hsieh 1988, Subbarao et al. 1990, Kaplan et al. 1990, 1992, Bronson et al. 1992, Bou-Saada 1994, Soebarto 1996, Manke and Hittle. 1996, Haberl et al.1998a, Haberl and Bou-Saada1998, Abushakra et al. 2001, Sylvester et al. 2002, and Song 2006).

Of special interest are the studies by Hsieh (1988) who calibrated a DOE-2 model to two instrumented commercial buildings to track performance; Subbarao et al. (1990) who studied the problem of matching simulated data to measured data in buildings; Kaplan et al. (1990, 1992) who developed a general procedure for calibrated simulation; Bronson et al. (1992) who developed a procedure for calibrating DOE-2 to non-weather-dependent loads; Bou-Saada (1994) who showed an improved procedure for developing a calibrated hourly simulation model to weather-dependent loads; Soebarto (1996) who presented a calibration methodology using only two to four weeks of hourly monitored and monthly utility bills; Manke and Hittle (1996) who proposed short term building monitoring and calibration; Haberl et al. (1998a) who used calibrated simulation to analyze energy conservation measures in two identical Habitat for Humanity houses; Haberl and Bou-Saada (1998) who reviewed the previous literature about calibration techniques and presented several new calibration methods; and Abushakra et al. (2001) who presented a method to derive diversity factors and typical hourly load shapes of the lighting and receptacle loads in office buildings. In the study by Abushakra et al., the authors used a percentile analysis (i.e., the 50th percentile was used in their study) to derive the typical hourly load shapes.

In addition, Sylvester et al. (2002) presented a method for verifying the energy savings of a newly constructed commercial building using a baseline simulation model calibrated to the measured whole-building energy consumption; and Song (2006) who developed and demonstrated several new calibration methodologies for evaluating the energy performance of new commercial buildings. Of these, the following studies are the most relevant for the dissertation study.

Hsieh (1988) calibrated the DOE-2 model to two commercial buildings in New Jersey to track performance. This study was one of the first studies to show a general procedure for calibrating simulation. The results of Hsieh’s study showed that calibration at the hourly level to measured data provided the best alignment between the simulation and the measured data. The results also showed that a potential 18-20% difference in envelope heat loss could exist between the measured data and the design stage predictions, which showed the significance of calibration after design stage simulation. Hsieh's research provided this dissertation study with several procedures used for the calibration.

Kaplan et al. (1990) also calibrated a DOE-2 model to monitored data from a small office building. Their study was also one of the first studies to publish a general procedure for calibrated simulation. In this study, monitored data were used both to generate DOE-2 inputs and to verify DOE-2 outputs. Then, a series of iterations were made until the modeled output was within a certain tolerance band with the monitored data. The result showed that nine major changes were required to tune the DOE-2 model of the case-study building within the tolerance band. Although the target of the Kaplan et al. study was a small office building, the general calibration procedure is also helpful for this dissertation study.

Haberl and Bou-Saada (1998) reviewed the previous literature about calibration techniques and presented several new calibration methods including graphical procedures and statistical goodness-of-fit parameters for quantitatively comparing simulated data to measured data. Haberl and Bou-Saada's calibration methods were applied to a case-study building that was a four zone, single-story electrically heated and cooled building. The results showed that the new calibration procedures were able to produce an hourly mean bias error (NMBE) of -0.7% and an hourly coefficient of variation of the root mean squared error (CV(RMSE)) of 23.1 %, which is acceptable compared with the most accurate hourly neural network models (Kreider and Haberl, 1994; and Haberl et al. 1998b). Haberl and Bou-Sadda's research is useful for this dissertation study since it provides detailed calibration procedures including the required information for calibrating DOE-2, the graphical methods for improving a calibration, and statistical indices to gauge the goodness-of-fit of the calibration.

Song (2006) used several methodologies for evaluating the energy performance of new commercial buildings including several new calibration methods. Song's study also provided the detailed calibration procedures that could be useful to this dissertation. The detailed calibration procedures included: the importance of measured consistent solar radiation data, building thermal mass effects, and a new percentile analysis added to the previous signature method by Wei et al. (1998). The procedures by Song are also useful to the current study. In summary, the several previous studies about calibrated simulations provided useful procedures for calibrating a simulation that will be used in the current study.

2.5. Easy-to-use Simulation Tools

Currently, there are several web-based, easy-to-use building simulation tools, including COMCheck-Web (U.S. DOE 2006) and eCalc (ESL 2007). In general, such programs are designed for users to calculate the annual building energy use and peak energy use for equipment sizing. The programs are also used to calculate the energy savings by entering energy saving features and comparing the result to a base-case simulation. , and to check code-compliance of the building by entering selected information about the building such as building type, conditioned area, wall R-value, window U-value, and HVAC system specifications

COMCheck-Web, which was developed by the U.S. DOE, is an easy-to-use tool for code-compliance checking. In this tool, a knowledgeable user is asked to input basic building information in four categories (i.e., Project, Envelope, Lighting, and Mechanical). Compliance reports are then emailed or printed when a user completes the data entry. Although this tool was originally designed for the code-compliance checking by architects or engineers, it is worthwhile to review this tool since a school building can be simulated using COMCheck, and the inputs for this tool are simplified. However, this tool has several limitations including: 1) it only checks the code compliance based on the building envelope UA value and the electric lighting power density, and therefore, it does not provide detailed simulation results such as annual and hourly building energy consumptions without special intervention, 2) No HVAC systems can be simulated using this tool, and 3) it currently does not simulate many of the high performance measures and renewable energy systems that are being proposed in new buildings such as ground source heat pump systems, solar PV and thermal systems.

eCalc (ESL 2007) was developed by Energy Systems Laboratory at Texas A&M University. This tool can be used by the general public to design and evaluate various projects for energy savings and emissions reduction potential (i.e., NO_x, SO_x, and CO_2,). As of December 2008, 4 types of building projects (i.e., single family, multi-family, office and retail), 5 types of community projects (i.e., municipal, street lights, traffic lights, water supply and waste water), and 3 types of renewable projects (i.e., solar PV, solar thermal, and wind) can be evaluated using this tool for projects in Texas. In a similar fashion with COMCheck, a user will be asked to input information about the building in several categories (i.e., building, shade, construction, system, and plant). The simulation result, which contains the annual and average ozone season day energy use and the NO_x, SO_x and CO_2 emissions, are then emailed to the user. However, this tool does not support school building types, and the available energy from renewable energy systems cannot be directly integrated with a building project, which will be considered in this dissertation.

In summary, two easy-to-use simulation tools, COMCheck-Web and eCalc were reviewed. Although both tools are successful applications, they have limitations that prevented them from being used directly in this study. In order to overcome the limitations of these programs, a new easy-to-use simulation tool for K-12 school buildings in hot and humid climates will be developed in this dissertation.

2.6. Daylighting Simulations Using the DOE-2.1 Program

As described earlier, daylighting strategies have been used in school buildings to save energy and provide a better learning environment. In the design stage of a school building, building energy simulation programs are often used to estimate the energy impact by applying various daylighting options such as skylights, light shelves, roof monitors, etc. However, simulating all aspects of the thermal and visual environment in a daylit classroom requires specialized expertise that can exceed the resources of a design project.

The DOE-2.1e program (LBNL 2002), the main simulation program used for this study and the one of the most widely used for the building energy simulations, has daylighting simulation capabilities that can calculate the impact of a daylighting design on energy use, peak loads, and energy costs for simple daylighting systems. In DOE-2.1e, users define one or two reference points in a zone. Then, based on the illuminance level on the pre-defined reference points, stepped or continuously dimming control systems are simulated to determine the electrical lighting energy required by hour. However, the built-in daylight illuminance calculation in DOE-2 only works when daylighting reaches the reference points directly from the windows (i.e., without reflection from room surfaces) or just from one bounce from a wall or ceiling. Therefore, for the daylighting strategies that rely on many reflections (e.g., roof monitors, light shelves, light wells, etc.) the DOE-2.1e program is not be the most effective tool to predict the impact of the daylighting precisely (LBNL 2002).

Several previous studies have attempted to overcome this limitation in DOE-2. Rungchareonrat (2003) evaluated the lighting electricity cooling energy savings potential from the use of various shading devices applied to residential windows using DOE-2 proxy models in combination with a physical scale model and site measurements. Baker (1990) developed a DOE-2 FUNCTION for daylighting simulation. In Baker's study, a physical scale model was used to measure the actual daylighting factors under real or artificial skies. This daylighting FUNCTION that was created was based on determining the interior illumination levels from daylighting by interpolating values based on solar altitude and azimuth angles. Once a table of interior light levels was established, the solar altitude, and azimuth angles were input into the FUNCTION command that was developed, and the results that measured daylighting factors used to replace the built-in DOE-2 daylight factor calculations.

A recent study by Koti and Addison (2007) developed a new, more accurate daylighting DOE-2 FUNCTION to analyze their building's results. Instead of using the FUNCTION developed by Baker that uses a simple, empirical daylighting factor by solar altitude and azimuth angles, they develop a FUNCTION that enables all the DOE-2 calculated illuminance levels to be replaced with 8,760 lines of hourly simulated interior illuminance levels. To accomplish this, the daylighting simulations were first performed using the DAYSIM program (NRC 2009) and the same weather data (i.e., global horizontal and direct normal solar radiation) used for the follow-up DOE-2 simulation. The simulation results using the newly developed FUNCTION and DAYSIM simulations were then compared them against the DOE-2 calculated daylighting results. In their study, four types of daylighting strategies were evaluated that included: a simple window, a lightshelf, a simple skylight, and a roof monitor. They concluded that the DOE-2 results, which are based on a simplified daylighting method reported more energy savings than there might actually be for some of the cases. In the roof monitor case, they showed the most discrepancies (i.e., DOE-2's results over-estimated the simple payback time by 47%), while the simple diffusing skylight case showed close agreement with the DOE-2 calculated savings (i.e., DOE-2's results only over-estimated the simple payback time by 3.7%)

Although Baker (1990) and Koti and Addison (2007) developed and used special FUNCTION methods to overcome the DOE-2 daylighting simulation limitation, this study will use the original DOE-2 daylighting simulation. However, based on the Koti and Addision's findings, only a simple diffuse-type skylight will be applied to the school building as a daylighting strategy. In addition, the Desktop RADIANCE program will also be used to generate indoor classroom images to show the difference for classrooms with and without skylights.

2.7. Summary

The previous literature covering energy efficiency studies in schools, IAQ in schools, a survey of existing high performance schools, calibrated simulation, easy-to-use simulation tools, and daylighting simulations using the DOE-2 program were reviewed. The major findings from the reviews are summarized as follows:

- Various energy efficient strategies for schools were reviewed, including: high albedo roofs, effective shading devices, ground source heat pumps, and dual-path HVAC systems. It was found that a proper selection of energy efficient HVAC systems according to climate area, and an effective design of the building envelope can reduce annual energy consumption up to 20 to 40% in school buildings compared to conventional school buildings.
- In addition, it was found that sufficient outdoor air ventilation is critical to maintaining healthy IAQ in schools. The review showed that many existing school classrooms were not sufficiently ventilated, which caused potential IAQ problems. Therefore, any energy efficiency measure for a school must also consider proper IAQ and energy efficiency together.

- The average site EUI for the high performance schools in the USDOE's EERE database shows them to have 51% to 62% less consumption than the national average for existing schools in the U.S. The average site EUI for the high performance schools in the EERE database is also 20% to 40% less than schools compliant with the ASHRAE Standard 90.1-1999. Therefore, an average high performance school is about 20% to 40% less consumptive than an average new school that is compliant with ASHRAE Standard 90.1-1999
- The most popular choice of energy efficiency measures for high performance schools includes: high performance glazing (i.e., low U-value and low SHGC in hot climates), T5 or T8 fluorescent lamps with occupancy sensors, high R-values for walls and roofs, photovoltaic (PV) systems, ground source heat pumps, high efficiency chillers and air conditioners, and high efficiency (e.g., AFUE over 90%) boilers.
- ASHRAE's Advanced energy Design Guide for K-12 Schools (AEDG-K12) was developed to achieve at least 30% more energy savings over ANSI/ASHRAE/IESNA Standard 90.1-1999 compliant school buildings. In this design guide, available energy efficiency measures are recommended by climates zones. Based on the design guide, a high performance school in Houston, Texas is expected to use about 50 kBtu/sq.ft. of total annual energy, which is 30.5% less consumptive than the baseline annual energy use of 72 kBtu/sq.ft. in the same area for a code-compliant 90.1-1999 K-12 school.

- Several easy-to-use web-based building energy simulation tools are available such as COMCheck-Web and eCalc. However, none can simulate an integrated building energy savings with energy efficiency options and renewable energy systems for the special conditions found in K-12 schools.
- Specific procedures were found for calibrating simulations to evaluate the energy consumption in an existing building. Therefore, the current study will use several of these calibration methods in combination to calibrate the simulation results.
- Daylighting simulations in the DOE-2 program have limitations: the most important of which is that they cannot accurately simulate daylighting strategies that rely on interior or exterior surface reflections such as lighting shelves or roof monitors. Therefore, in order to overcome this limitation, several of the previous studies used coefficients derived from physical models or more accurate daylighting simulation models such as RADIANCE to calculate the interior illuminance levels in combination with DOE-2's FUNCTION commands to replace DOE-2's calculated illuminance levels with more accurate lluminance levels. These studies showed that the original DOE-2 daylighting simulations overestimated the energy savings from daylighting strategies specifically that utilize reflections from internal or external surface. One study showed a simple diffuse skylight strategy which uses few surface reflections can be simulated in reasonably well using the

original DOE-2 daylighting simulation, and therefore will be used in this study.

CHAPTER III

SIGNIFICANCE OF THE STUDY

3.1. Significance of the Study

A review of the previous literature showed that energy efficient measures can be applied to K-12 schools in hot and humid climates that realize energy savings as well as improved IAQ. However, there are few if any comprehensive methodologies to design and evaluate the benefits of new high performance school specifically in the preliminary design phase. Therefore, this study will develop a methodology for the preliminary design of high performance schools in hot and humid climates. As a final product of the study, functional specifications for a simplified easy-to-use, web-based tool is proposed. Such a tool will allow decision makers without specialized simulation knowledge to easily and accurately evaluate energy efficient measures, and IAQ in the preliminary design phase, which would contribute to the accelerated dissemination of high performance K-12 schools.

3.2. Limitations of the Study

Although this study purposes to develop a comprehensive methodology for preliminary design of high performance schools, the study has several limitations as follows:

1) The developed methodology is only for the new K-5 schools in hot and humid climates.

2) Several high performance measures available today (e.g., Under Floor Air Distribution (UFAD) system, advanced daylighting systems, heated/cooled slabs with Dedicated Outside Air System (DOAS), dual-path HVAC systems, and schools with natural ventilation) cannot be simulated with this tool due to the limitation of the DOE-2.1e simulation program.
3) The proposed tool has only one option for the building shape, which was defined as a dominant shape from a survey of 30 schools in central Texas
4) For this study, procedures for the automated generation of a K-5 school building geometry were developed for the prototype simplified tool. Other aspects of the tool such as selecting building HVAC systems would need to be developed in a future study.

CHAPTER IV

METHODOLOGY

This chapter describes the methodology used to develop a simplified simulation tool for the preliminary designs of new high performance K-5 schools in hot and humid climates. The chapter can be divided into 6 sections, including: 1) A survey of high performance measures for K-12 schools from the previous studies of high performance measures for hot and humid climates. 2) An analysis of a base-case school to understand the pattern of the school's energy consumption. 3) Performing as-built simulation for the case-study school. 4) An analysis using daylighting simulations. 5) Applying the selected high performance measures to the case-study school to estimate the energy saving potential, and finally 6) developing a methodology for a simplified simulation tool for schools. Figure 4.1 describes the overall procedure of this study including: 1) Calibrated simulation, 2) Calculation of energy savings from applying selected high performance measures, and finally 3) A discussion of the development of a toolkit for high performance schools. The detailed procedure for each step will be explained in the corresponding sections in this chapter.

4.1. Survey for High Performance Measures for K-12 Schools

As a first step of the study, high performance measures for K-12 schools available today were identified from the previous studies, several high performance design guidelines and high performance building database. From this survey, a group of high performance measures for this study was selected considering the climate zone and the

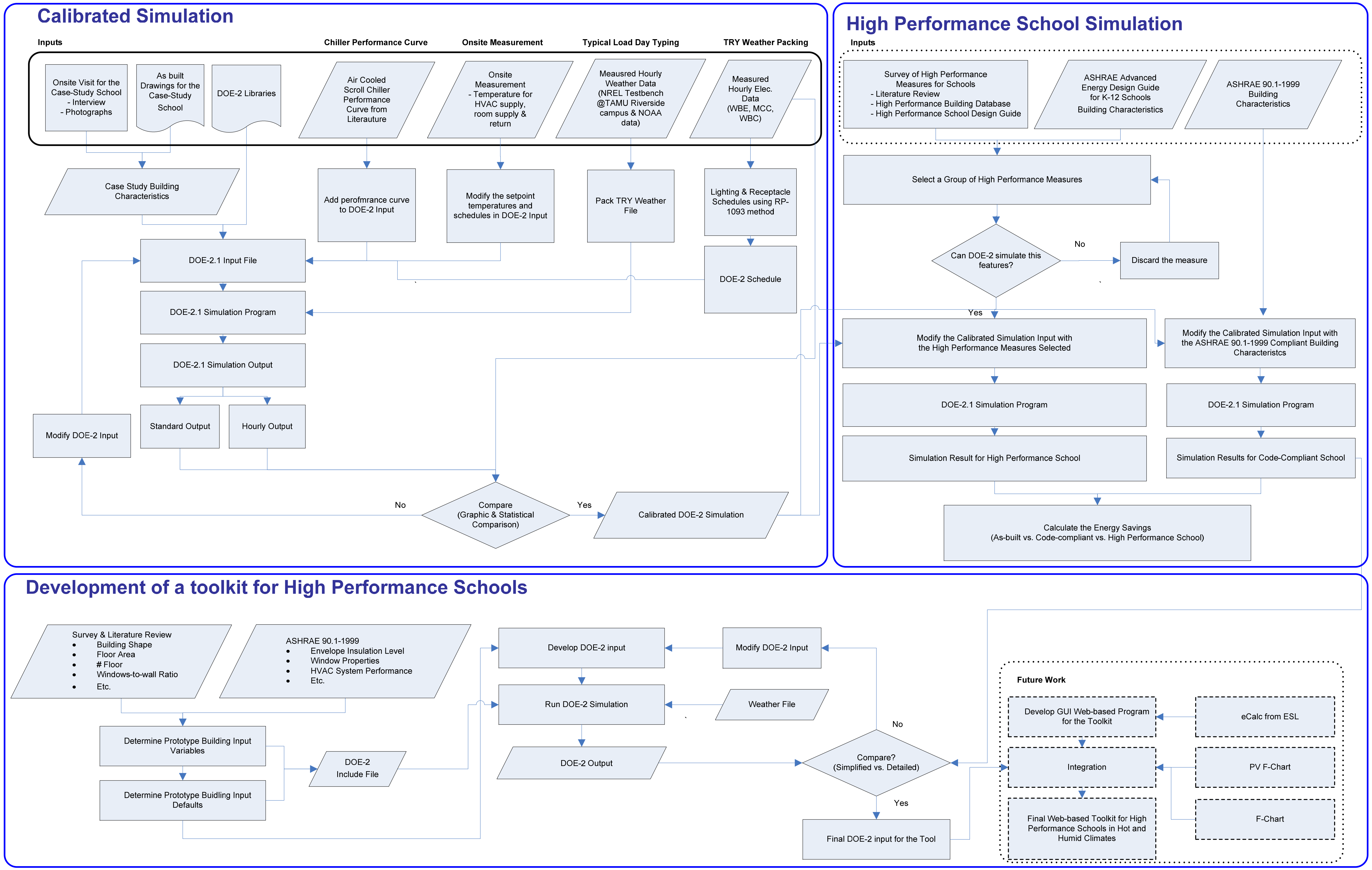


Figure 4.1 - Overall Procedure: Calibrated Simulation, High Performance Simulation, and Development of a Toolkit for High Performance Schools

simulation platform. The selected measures were applied to the existing case-study school in order to estimate the energy savings potentials. The methods to identify the high performance measures are described as followings.

4.1.1. Energy Savings Measures from Previous Studies

As described in Chapter II, previous studies of K-12 school buildings were reviewed to identify the energy saving measures available today specifically for K-5 school buildings in hot and humid climates. For this research, over fifty papers were reviewed using several sources such as the ASHRAE abstract archives & ASHRAE Publications, the proceedings of the ACEEE, the Journal of Energy and Buildings, the proceedings of the IBPSA, and the Google Scholar search engine. Then, the studies were summarized in the pre-developed summary table (See Table 4.1). The table contents include the followings: 1) The study number, 2) Author, 3) Classification of the methods (i.e., Envelope designs and/or HVAC systems), 4) Application, 5) Climate zone for the study, 6) Number of schools analyzed, 7) Floor area for the target schools, 8) the method of energy saving estimation (i.e., actually measured, simulated, or simple calculations), 9) Percent total annual energy savings, and 10) Remarks if any. In this summary table, the annual energy savings were color-coded by percentage (i.e., 10, 20,…, 70%) to make it easier to identify the percent cooling, heating and total energy use, and savings from the different measures. The details of the findings are presented in Section 2.1 of this dissertation.

Table 4.1 - Summary Table for Literature Review

No.	Authors	Classification	Application	Climate Zone	# Bldgs Analyzed	Size (ft2)	Energy Use Analysis*	Energy Savings (%)							Remarks
								10	20	30	40	50	60	70	
S1	Akbari et al. 1997	Envelope	High-albedo Roof	Hot and Dry	2	958	M,S		25 -	35					Cooling Energy Savings
S2	Becker 1990	HVAC System	Four Different Types of Heating and Cooling Systems	Temperate and Mixed Cool and Humid Temperature and Humid	16	62,200, 46,700, 31,293	M,S								
S3	Butala and Novak 1999	Envelope	Tight window, more insulation	Slovenia (Heating dominant)	24	3,422 ~ 287,278	C		20						Heating Energy Savings
S4	Cane and Clemes 1995	HVAC System	Closed-loop ground source heat pump (GSHP)	Ontario, Canada	1	185,000	M,S								Simulation of the performance of a GSHP(compare w/ measured data)
S5	Desideri and Proietti 2002	N/A	Survey existing schools find most efficient school	Central Italy	13		M			38					Heating Energy Savings
S6	Dinse 1998	HVAC System	Geothermal systems	Temperature and Humid	1	160,000	M			34					
S7	Fuller and Luther 2003	HVAC System	Small reverse cycle air conditioner	Australia	4	940	M		20 - 27						Heating Energy Savings
S8	Goss 1992	HVAC System	Direct and indirect use of groundwater	Cool and Dry	1		M			33					This school was an ASHRAE award winner in 1986
S9	Haughey 2003	HVAC System	Ice thermal storage	Cool and Dry	1		M								4.1 years of simple payback
S10	Hunn et al. 1993	Envelope	Shading device	Cold and Humid	1	54,746	S	1							
S11	Khattar et al. 2003	HVAC System	Dual-path, low temperature air -distribution system w/ thermal energy storage (TES)	Hot and Humid	2		M		22						
S12	Montgomery 1998	HVAC System	Ice thermal storage	Hot and Humid	1	103,114, 166,162									1.5 years of simple payback
S13	Rafferty 1996	HVAC System	Groundwater heat pump systems	Temperature and Mixed	2	55,000 56,000	M	1.7 (Cali			49 (Ore				
S14	Santamouris et al. 1994	N/A	Audit and estimate of the potential for energy savings	Greece	23				20						
S15	Shoner et al. 2000	HVAC System	Geothermal Heat Pump	Cool and Humid	1	69,000	M,S		26						Compared to 50 schools around
S16	Stotz and Hanson 1992	HVAC System	Using heat recovery and aquifer wells	Hot and Humid	1	210,000	M								

** Energy Use Analysis*
M: Actual measurement
S: Simulation
U: Utility Bills

4.1.2. High Performance Features for Schools

As another way of identifying the energy saving features for school buildings, existing high performance school buildings were reviewed. As previously mentioned, the high performance buildings database on the U.S. D.O.E.'s website EERE (EERE 2006b) was used to search existing high performance schools around the world. The database presents six K-12 schools and seven higher education buildings. These buildings were summarized in another summary table (See Table 4.2). In similar fashion as Table 4.1., this table also provides: 1) The study number, 2) Authors, 3) Building name, 4) Climate zone of the building, 5) Location of the building, 6) Building type (i.e., K-12 or higher education), 7) Number of Floors, 8) Total floor area, 8) Baseline used to calculate energy savings (e.g., ASHRAE 90.1-1999), 9) Method used for estimating energy savings (i.e., actually measured, simulated, or simple calculations), 10) EUI by percentage, 11) Annual energy savings by percentage, and 12) High performance strategies applied to the building. Of these, the EUIs of the schools gave a good idea about how much energy would be used in general high performance schools. In addition, the annual energy savings of the schools can be used to estimate how much energy could be saved by applying several high performance features. The last column of the table describes what strategies have been used for high performance schools. From this column, the commonly selected high performance features for the schools could be identified. The commonly found high performance features found from this table are summarized in Section 2.3 of this dissertation.

Table 4.2 - Summary Table Format for High Performance Schools

No.	Authors	Building Name	Climate Zone	Location	Bldg Type	Const. Year	Floor(s)	Size (ft2)	Baseline	Energy Use Analysis*	EUI (kBtu/sq-ft)							Energy Savings (%)							High Performance Strategies
											20	40	60	80	100	120	140	10	20	30	40	50	60	70	
SC1	EERE, 2006	Baca/Dlo'ay azhi Community School	Cool and Dry	Prewitt, NM	K-12	2003	1	78,900	ASHRAE 90.1-1999	**S (Using Trane Trace® 700 Software)**	**26.9**								**20**						* Low SHGC (0.52) * T8 fluorescent lamps * Occupancy sensors * Whole-roof R-value of 25 or greater * VAV systems
SC2	EERE, 2006	Clackamas High School	Temperate and Mixed	Clackamas, OR	K-12	2002	2	265,000	ASHRAE 90.1-2000	**S (Using Visual DOE)**	**28.1**										**39**				* Natural ventilation w/ fan coil back up unit * Thermal mass * 90% AFUE boiler * T8& T-5 fluorescent lamps
SC3	EERE, 2006	Clearview Elementary School	Cool and Humid	Hanover, PA	K-12	2002	2	43,600	ASHRAE 90.1-1999	**S (Using Power DOE v.1.17)**	**23.3**										**40**				* Ground source heat pump * Wall R-value of 25 or greater * Windows U-factor less than 0.32 * Heat-recovery ventilation * UFAD systems
SC4	EERE, 2006	Durant Road Middle School	Temperate and Humid	Raleigh, NC	K-12	1995	1	149,000	N/A	N/A	**25**														* Low SHGC (0.52) * T8 fluorescent lamps * Occupancy sensors * Whole-roof R-value of 25 or greater * VAV systems
SC5	EERE, 2006	Hidden Villa Youth Hostel & Summer Camp	Temperate and Mixed	Los Altos Hills, CA	K-12	2001	2	3,370	N/A	**S (Using Energy Scheming Software)**	**9.49**														* Ground-source heat pumps * High internal thermal mass * Evaporative cooling * Photovoltaic (PV) system * Replace incandescent lamps with CFLs
SC6	EERE, 2006	Third Creek Elementary School	Temperate and Humid	Statesville, NC	K-12	2002	1	92,000	N/A	**S (Using Trane Trace 600)**			**59.8**												* R-45 roof, R-22 walls, and low-emissivity windows * AC systems with a high efficiency rating * Windows U-factor less than 0.32 * Heat-recovery ventilation * Occupancy sensors * 97% Boiler efficiency
SC7	EERE, 2006	C. K. Choi Building for the Institute of Asian Research	N/A	Vancouver, Canada	Higher Education	1996		34,400	N/A	**U**		**41.6**													* Natural ventilation (no air conditioning) * Use light colors for surfaces and finishes * High-efficiency luminaires * Occupancy sensors * Achieve a whole-wall R-value of 15 or greater
SC8	EERE, 2006	Environmental Technology Center at Sonoma State University	Temperate and Humid	Rohnert Park, CA	Higher Education	2001		2,200	California's Title 24	**U**				**80**				**2.32**							* Photovoltaic (PV) system * High-efficacy T-5 fluorescent lamps * Direct-gain passive solar heating * Mass-wall passive solar heating
SC9	EERE, 2006	Management Building at Technology Square, Georgia Institute of Technology	Temperate and Humid	Atlanta, GA	Higher Education	2003		248,000	N/A	**S (Using DOE-2.1E Build 133)**			**59.5**												* Use light-colored exterior walls and roofs * Use high-efficacy T8 fluorescent lamps * VAV systems
SC10	EERE, 2006	Adam Joseph Lewis Center for Environmental Studies--Oberlin College	Cool and Humid	Oberlin, OH	Higher Education	2000		13,600	N/A			**30.1**													* Photovoltaic (PV) system * High internal thermal mass building * Windows U-factor less than 0.25 * Occupancy sensors * Roof R-value of 25 or greater * Closed-loop geothermal wells
SC11	EERE, 2006	Rinker Hall at the University of Florida	Hot and Humid	Gainesville, FL	Higher Education	2003		47,300	ASHRAE 90.1-1999	**S (Using DOE-2.1E)**		**30.1**										**57**			* High performance glazing * Occupancy sensor * Enthalpic heat-recovery ventilation * Reflective shade
SC12	EERE, 2006	Smithsonian Tropical Research Institute Research Station	N/A	Bocas del Toro, Panama	Higher Education	2003		7,530	N/A	**U**		**42.6**													* Building-integrated photovoltaics (PV) * High-efficacy T8 fluorescent lamps * Use light colors for surfaces and finishes
SC13	EERE, 2006	Vermont Law School James L. and Evelena S. Oakes Hall	Cold and Humid	South Royalton, VT	Higher Education	1998		23,500	N/A	N/A	**27.2**														* T-8 fluorescent lighting * Triple-glazed, argon-filled units with a single low-e coating (less than 0.25 U) * Enthalpic heat-recovery ventilation

** Energy Use Analysis*
M: Actual measurement
S: Simulation
U: Utilty Bills

4.2. Analysis of a Case-study School

As a second step of the research, an existing school building in a hot and humid climate was selected and analyzed to understand the pattern of energy consumption in school buildings to be used as a base-case simulation study.

4.2.1. Description of the Case-study School

The selected case-study elementary school is one of six elementary schools in the same school district in central Texas. The school, which was constructed in 1989, is a single-story building with 74,000 square feet of total gross floor area. As of 2006, about 600 students were enrolled. Figure 4.2 shows the satellite view of the school building. As commonly found in school buildings, the case-study building is composed of several main spaces, including: classrooms, library, administration office, gymnasium, cafeteria, and kitchen. Figure 4.3 illustrates the distribution of these main spaces and the AHUs serving each space of the building. As shown in Figure 4.3, the building is served by eight systems consisting of three different types of AHUs including: 1) four (4) variable air volume (VAV) systems for the classrooms and library, 2) three (3) constant volume (CV) systems for the gym, cafeteria, and kitchen, and 3) one (1) multi-zone unit (MZU) for administration offices. The building has two 100 ton, air-cooled, scroll chillers, one 2 MMBtu/hr boiler, and two 100 gallon service water heaters. More detailed information about the building will be described in Chapter V.

4.2.2. Data Measurement

In order to analyze the case-study building to be used for the simulation, several types of energy and environmental data were gathered, including:

- Hourly whole-building, chiller, and motor control center electricity use that was measured from a previously installed data logger.
- The temperatures (e.g., discharge temp, return air temp, mixed air temp, etc.) and RH at selected points were measured using portable data loggers.

Figure 4.2 - Satellite View of the Case-study School (Source: http://maps.google.com)

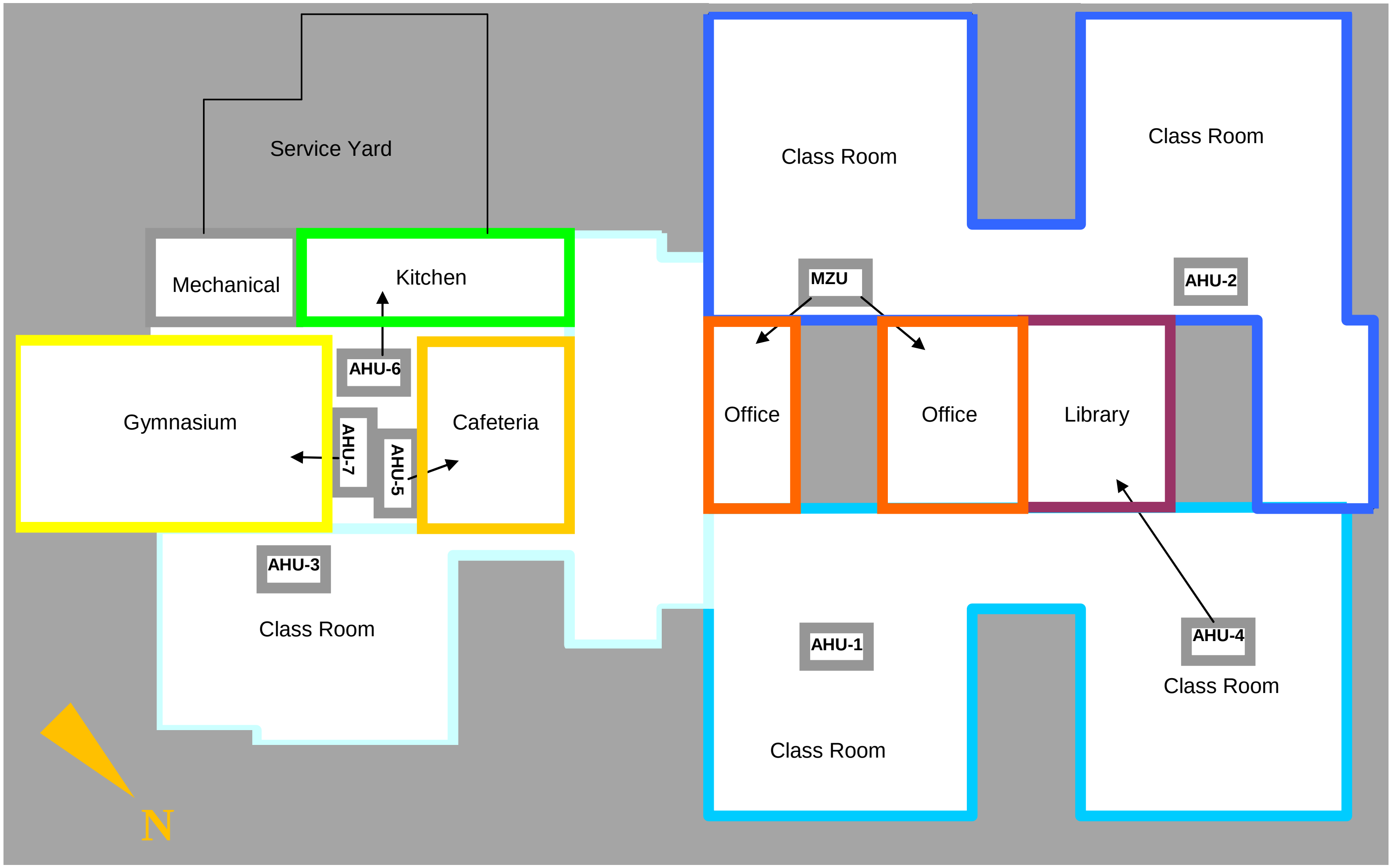


Figure 4.3 - Main Spaces and AHU Distribution of the Case-study School

- CO_2 concentrations from classrooms were measured in the return ducts for a selected period.
- Historical monthly utility bills were obtained from the school administration.

A detailed description of the data (e.g., the purpose of the measurements, measurement period, etc.) is presented in the following section.

4.2.2.1. Hourly Electrical Energy Use

The electricity data measured from the logger was used to better understand the patterns of energy use in the school and was used in the calibration procedure. The data logger was installed previously from a commissioning study by Energy Systems Laboratory. Since the logger measured several channels (i.e., whole-building electric, chiller electric, and MCC electric), the calibration of the simulation was more accurate than using only the monthly utility bills. The period of data measurement was from January 1, 2006 through December 31, 2006, which is the same period of the simulation. Table 4.3 presents the 10 channels used for the data measurement. The first six channels were assigned to chiller #1 and #2 electricity measurements, the next three channels were assigned to the MCC. The last channel was assigned to the whole-building electricity.

The data were downloaded weekly using a modem and plotted in a pre-configured inspection plot. In order to analyze the energy use versus weather conditions, weather data from NOAA were gathered and compared with a local weather station. Figure 4.4 shows an example of the weekly inspection plot. The first row of the plots shows four hourly plots for: 1) whole-building electric versus chiller electric, 2) Dry bulb temperature from NOAA and local weather station, 3) RH from NOAA and a local weather station, and 4) horizontal solar radiation from the local weather station, respectively. The second row of the plots shows two hourly plots for: 1) whole-building cooling electric, and 2) wind speed from the NOAA. The last row shows: 1) a scatter plot for the hourly whole-building cooling electric as a function of outdoor temperature, and 2) hourly MCC energy use.

4.2.2.2. Portable Data Logger Measurement

The purpose of these measurements was to verify the temperature and relative humidity from several points in the HVAC system. In addition, the measured data were used to examine the thermal comfort and the indoor air quality of the classrooms. To accomplish this, six (6) portable loggers (i.e., Onset Corporation's HOBO logger (Onset 2009)) were used to measure the temperature and the relative humidity in several points in the school. Figure 4.5 shows the picture of a portable logger. The portable loggers were calibrated with the standard calibration procedure (Wise and Soulen 1986; ASTM 1997; Greenspan 1976).

Table 4.3 - List of Current Transducers Used in the Case-study School

Channel #	Equipment Monitored	Phase
1	Chiller #1 (kW)	Chiller 1-A
2		Chiller 1-B
3		Chiller 1-C
4	Chiller #2 (kW)	Chiller 2-A
5		Chiller 2-B
6		Chiller 3-C
7	Motor Control Center (MCC) (kW)	MCC PH A
8		MCC PH B
9		MCC PH C
10	Whole Building Electric. (kW)	Whole Building Electric

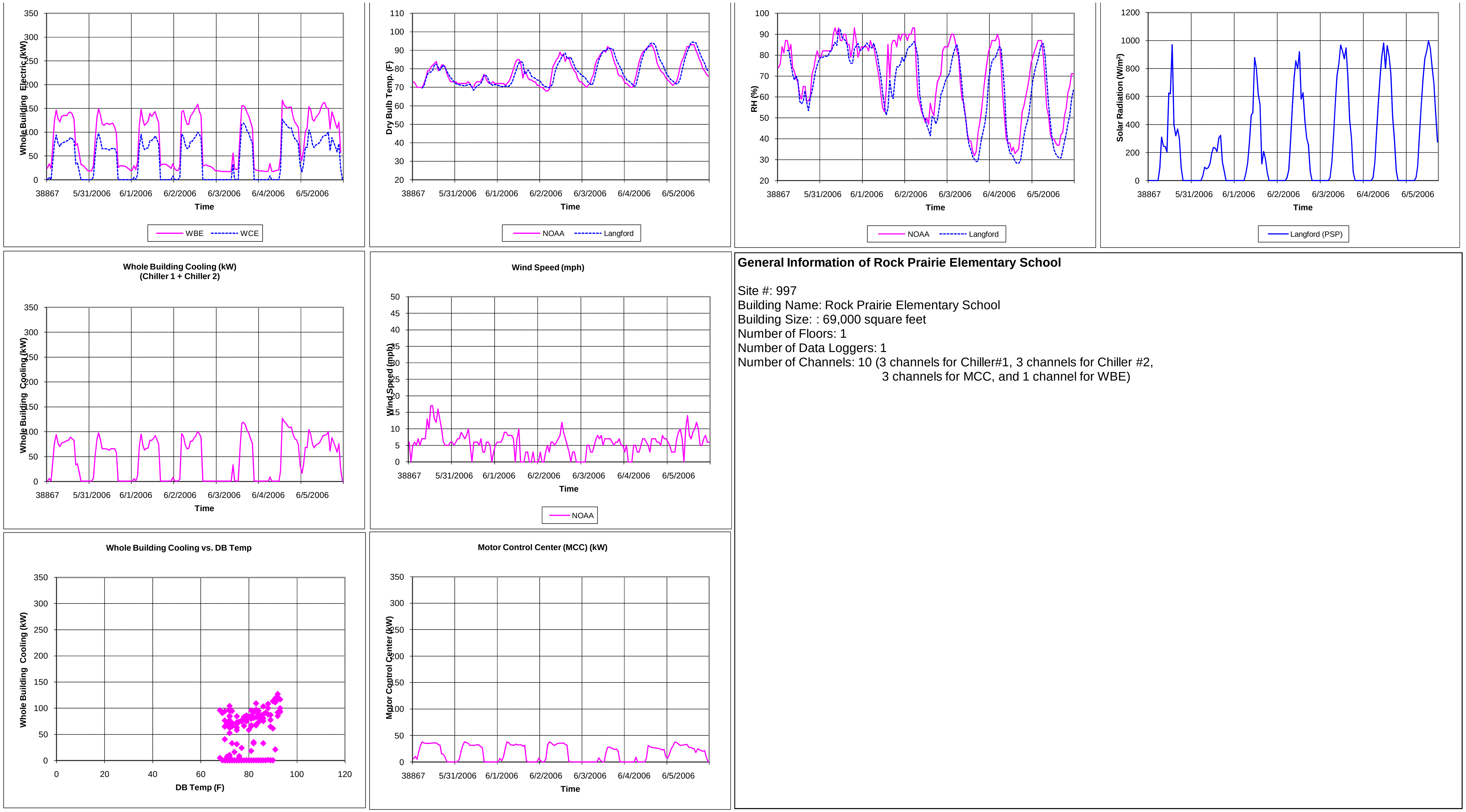


Figure 4.4 Example of Weekly Plot for the Case-study School

Figure 4.5 - HOBO Portable Logger (Onset Corporation 2009)

For these measurements, one of the eight (8) AHUs in the case-study school and one classroom served by the AHU were selected. The AHU #1 that was selected serves several classrooms. Of those classrooms, classroom #106 was selected to measure the indoor temperature and relative humidity conditions. Figure 4.6 shows the distribution of AHUs and the location of classroom #106. The pre-calibrated portable data loggers were installed in several points as followings:

- Logger #1 – Classroom Supply temperature and RH
- Logger #2 – Classroom Return temperature and RH
- Logger #3 – Mixed Air temperature and RH
- Logger #4 – Cold Deck temperature only (external channel)
- Logger #5 – Outdoor air temperature and RH

- Logger #6 – Return air temperature and RH

The detailed HVAC diagram from the DOE-2 program that was used in the simulation and photos of the installed loggers are shown in Figure 4.6. The installed loggers recorded the temperature and RH every hour. Along with the temperature and RH measurements, the CO_2 concentration from the classrooms served by AHU #1 was measured with a portable CO_2 meter. The CO_2 sensor used in this research is Ventostat 2001V manufactured by Telaire Systems, Inc. The sensor was installed in a data logger box and powered by an external power source. The outputs from this sensor were recorded using a HOBO volt which was installed in the same data logger box. Figure 4.7 shows the data logger box with the CO_2 sensor. This data logger box was installed in the return duct located in the mechanical room and logged the CO_2 concentration every 15 minutes. The results of the data measurements will be presented in Chapter VI.

4.2.2.3. Historical Monthly Utility Bills

Historical monthly utility bills for the years 2000 through 2006 were obtained from the school district office. These bills were used to verify the hourly electricity use measured from the data logger and to calibrate the simulated natural gas use since there were no hourly natural gas use data available. Appendix C shows the monthly electricity and natural gas use from 2000 through 2006.

AHU#1 & Classroom #106

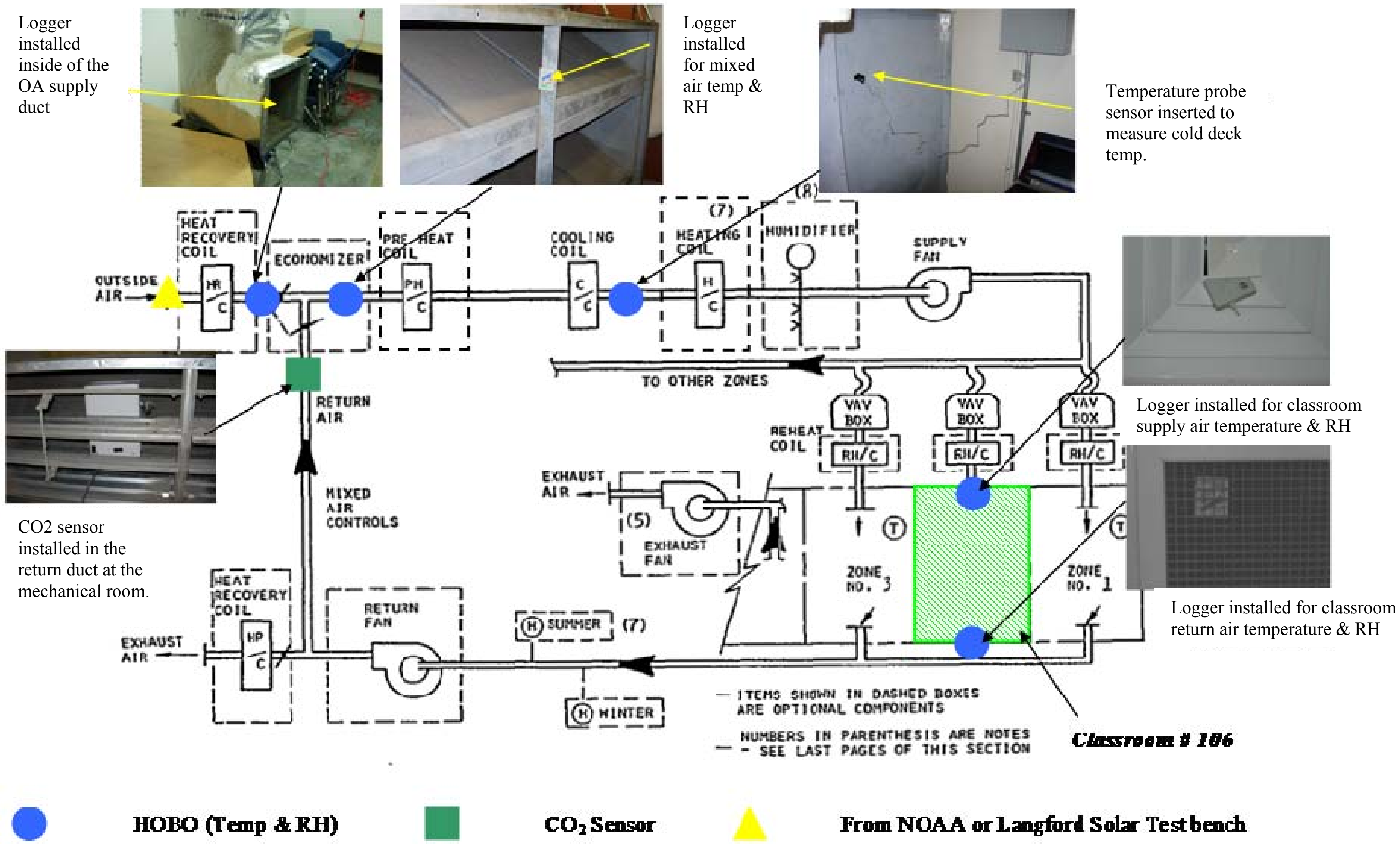


Figure 4.6 - Portable Data Logger Installations Shown Super-imposed on the DOE-2 VAV System Diagram

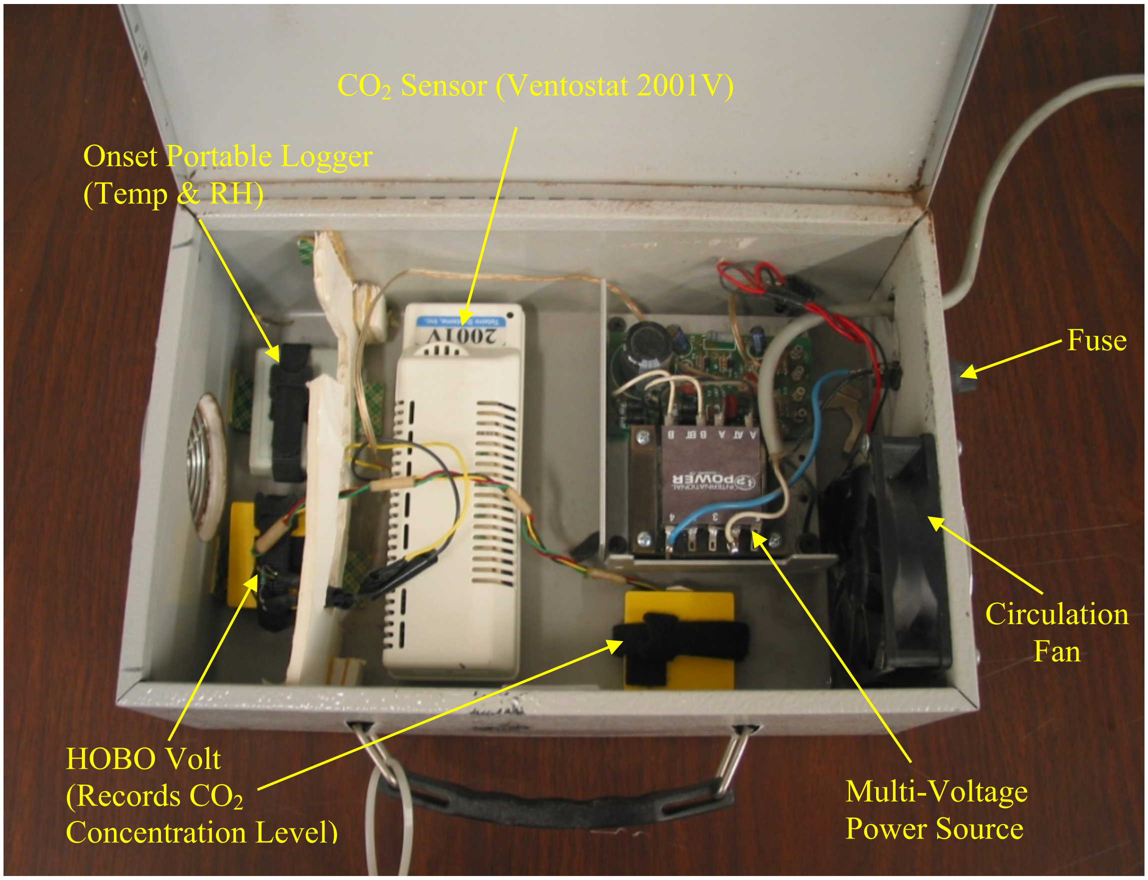


Figure 4.7 - Data Logger Box for CO_2 Concentration, Temp and RH Measurement

4.2.3. Building Characteristics

In order to develop an as-built school building simulation input file, the building characteristics and operational schedules were collected. The physical building characteristics were identified from the original architectural and mechanical drawings. The characteristics were then input into the pre-developed table (See Table 4.4). The table was developed based on the required information to develop a simulation input for DOE-2 program. The building operational schedules (i.e., occupancy schedule and HVAC operational schedules) were identified from the available information and a series of interviews with maintenance person. In addition, a series of onsite visits were

Table 4.4 - Building Information for Simulation Modeling

Description		Case Study School
General		
	Location (Logitude & Latitude)	Longitude: 96.30 Latitude: 30.57
	Floor Area, ft2	74,905
Architectural Features		
	Number of Floors	1
	Window-to-Wall Ratio	10%
	Floor-to-Ceiling Height	
	Classroom	9
	Gymnasium	23.5
	Admin. Office	9
	Cafeteria	23.5
	Exterior Wall	
	Structure	3” face brick + 1” air layer + 2” rigid insulation + 6” light weight concrete masonry + ½” gypsum board
	Calculated U-Factor (Btu/hr-ft2-F)	0.085
	Roof	
	Structure	¾” rigid insulation + 3 ½” batt insulation above the acoustic ceiling tiles
	Calculated U-Factor (Btu/hr-ft2-F)	0.054
	Slab-On-Grade Floor	
	Structure	light weight 4” concrete slab construction
	Calculated U-Factor (Btu/hr-ft2-F)	0.043
	Windows	
	Structure	Single Pane Glass
	Calculated U-Factor (Btu/hr-ft2-F)	1.09
	Shading Coefficient	0.59
Internal Loads		
	Number of Student	600
	Occupancy Schedule and Density (in separate table)	
	People Load (Sensible and Latent heat gain)	
	Lighting Fixture	T-8 with Electronic Ballas
	Lighting Density (W/sqft)	1.2
	Equipment Density (W/sqft)	0.6
	Lighting & Equipment Schedule (in separate table)	

conducted to check the models of the chillers, boilers, service water heaters, and pumps. After each visit, the specifications of the equipment from the manufacturer’s data were obtained and entered into the simulation.

4.2.4. Summary of Analysis of the Base-case Study School

The selected case-study elementary school is located in central Texas and was constructed in 1989. The total floor is about 74,900 sq.ft. The front of the building faces northeast. The building has eight (8) Air Handling Units that include three different types including: Variable Ari Volume (VAV), Constant Volume (CV) and Multi Zone Unit (MZU) (See Figure 4.6). In order to simulate the building, several types of data were collected and measured, including: 1) hourly electricity use from the data logger, which was previously installed in the building, 2) hourly temperature and RH at several points in the building measured using the portable loggers, 3) CO_2 concentration levels measured from a portable CO_2 sensor, 4) monthly utility bills for the school, and 5) building characteristics and operational schedules.

4.3. As-built and Calibrated Simulation

The overall procedure for developing the as-built simulation input and the calibration of the simulation input was presented in Figure 4.1. First, an initial as-built simulation input was developed based on the as-built drawings and onsite visits. The building's physical dimensions, including the building characteristics such as R-values for exterior wall, roof, and floor, glazing properties, and information about the HVAC system, chillers, and boiler were obtained from the as-built drawing and site visit. The occupancy schedule, room setpoint temperatures, and the HVAC operational schedules are obtained from interviews with the school district maintenance personnel (Personal communication 2006). An initial DOE-2 input was then run using the DOE-2.1e (ver 119) simulation program and the TMY2-Houston, Texas[1] weather file. The simulated hourly whole-building electricity use, hourly lighting & equipment electricity use, hourly whole-building cooling electricity use, and the monthly natural gas use were then compared against the measured electricity use from the data logger and the natural gas use from the utility bills to assess the goodness-of-fit of the simulation model. In this procedure, first, time series plots and the scatter plots (Figure 4.8) were generated as graphical method of calibration. As shown in Figure 4.8, there are four sets of time series and scatter plots. Those are for 1) Hourly Whole Building Electricity (WBE), 2) Hourly Lighting and Equipment, 3) Hourly Motor Control Center, and 4) Monthly Natural Gas. In each time series plot except for the natural gas, the blue, red and green lines represent the simulated use, measured use, and residual, respectively. Next to the time series plots, the scatter plot is shown. This plot presents the daily energy uses as a function of outside air temperature**.** In each plot, the solid and void dots represent the simulated and the measured energy use, respectively.

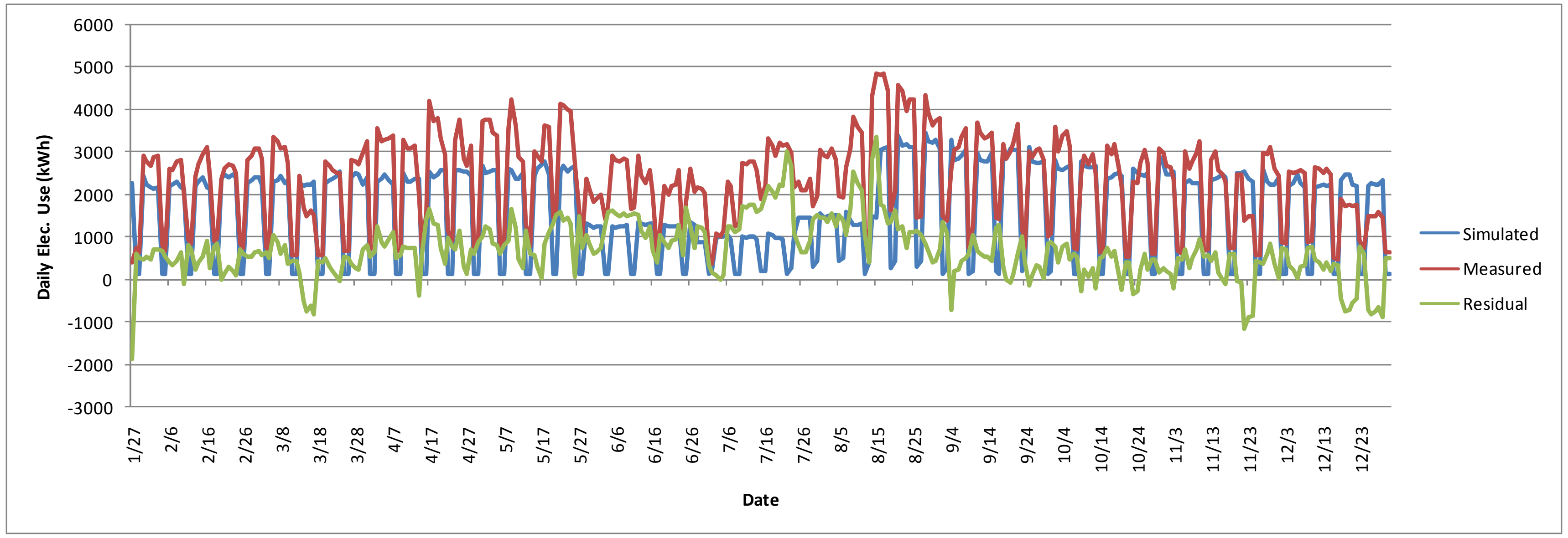
With the graphical method of calibration, the normalized mean bias error (NMBE), and the coefficient of variation of the root mean square error (CV(RMSE)) (Kreider and Haberl, 1994) were calculated using the hourly data to assess the goodness-of-fit of a simulation model. NMBE (%) and CV(RMSE) (%) can be calculated as followings:

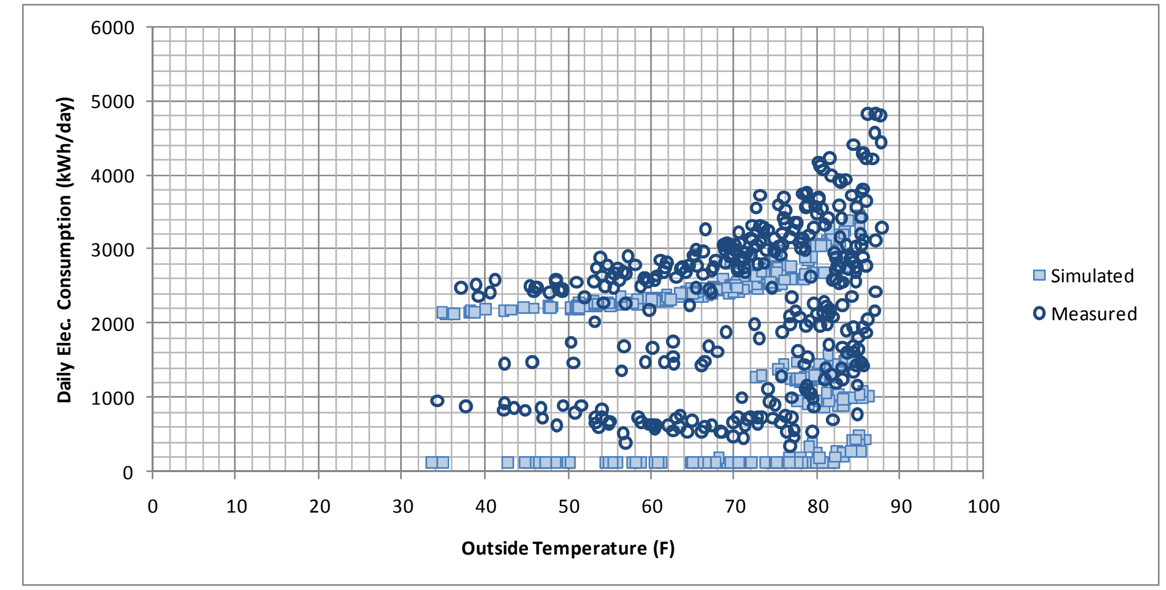
$$NMBE\,(\%) = \frac{\frac{\sum_{i=1}^{n} Residual_i}{n-p}}{M} \times 100 \qquad (4.1)$$

---

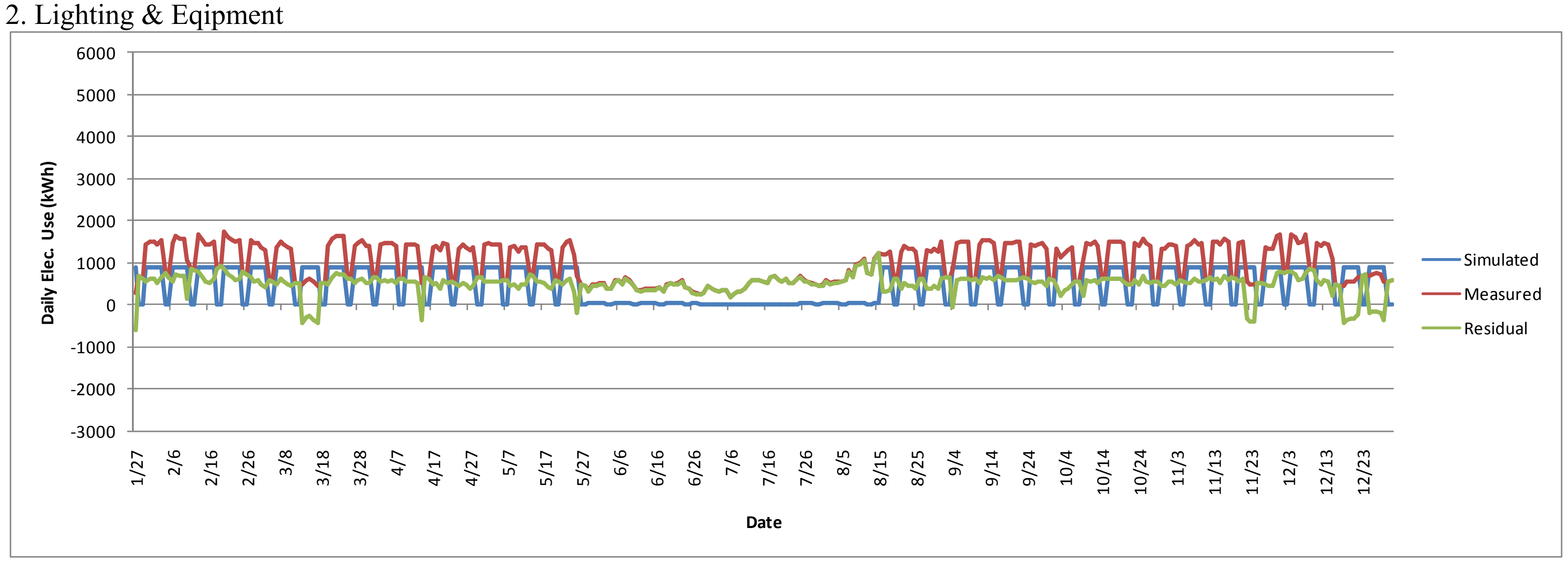
[1] Even though the building is located at another city located 100 miles to the north west, the Houston TMY2 weather file was used for the initial simulation since Houston is the nearest city with the target city.

1. WBE





2. Lighting & Eqipment



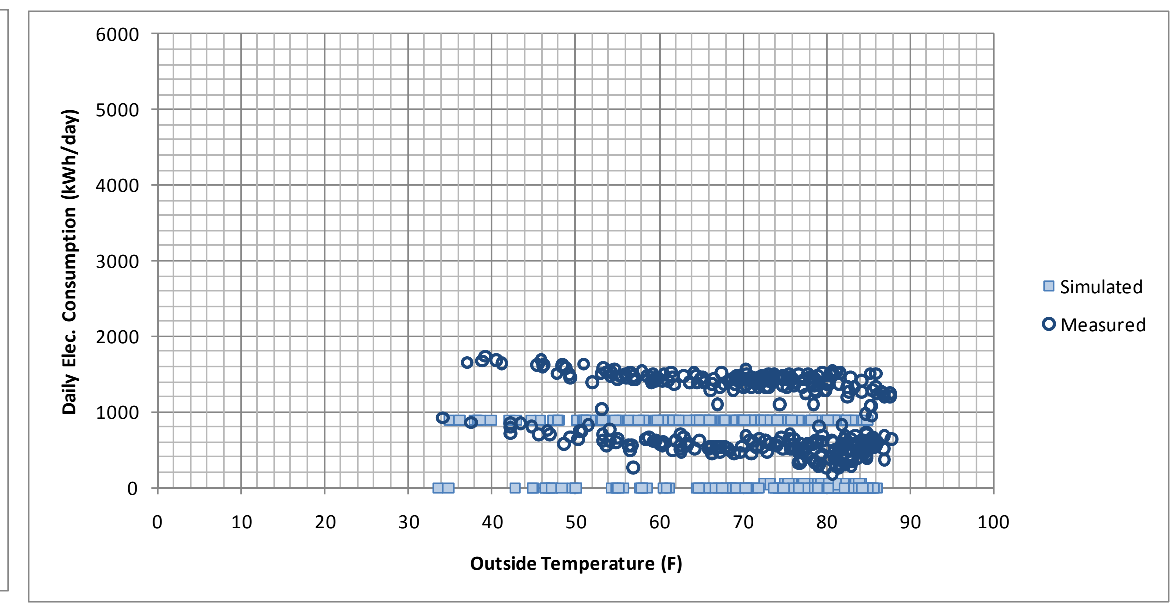
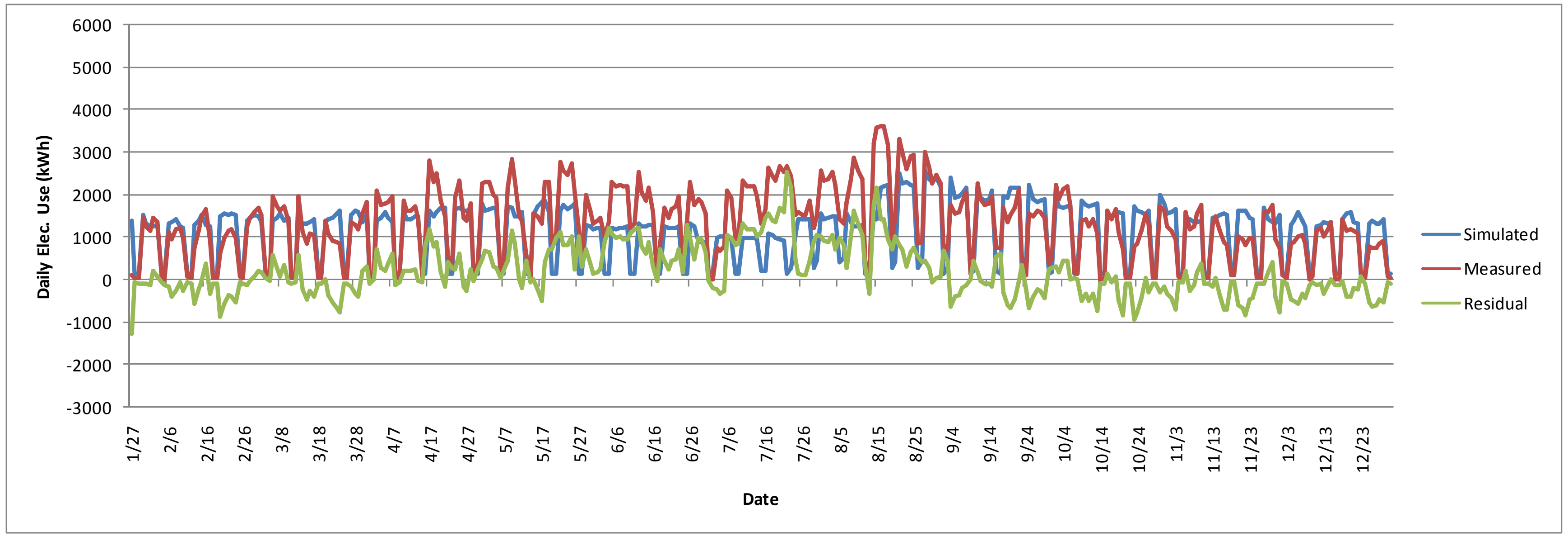
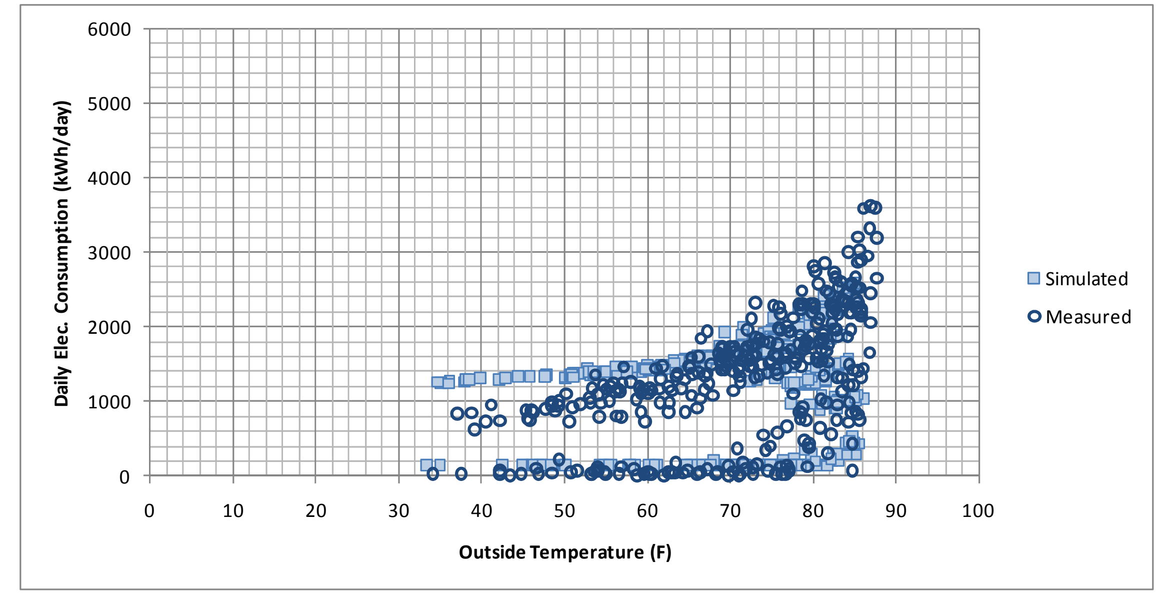


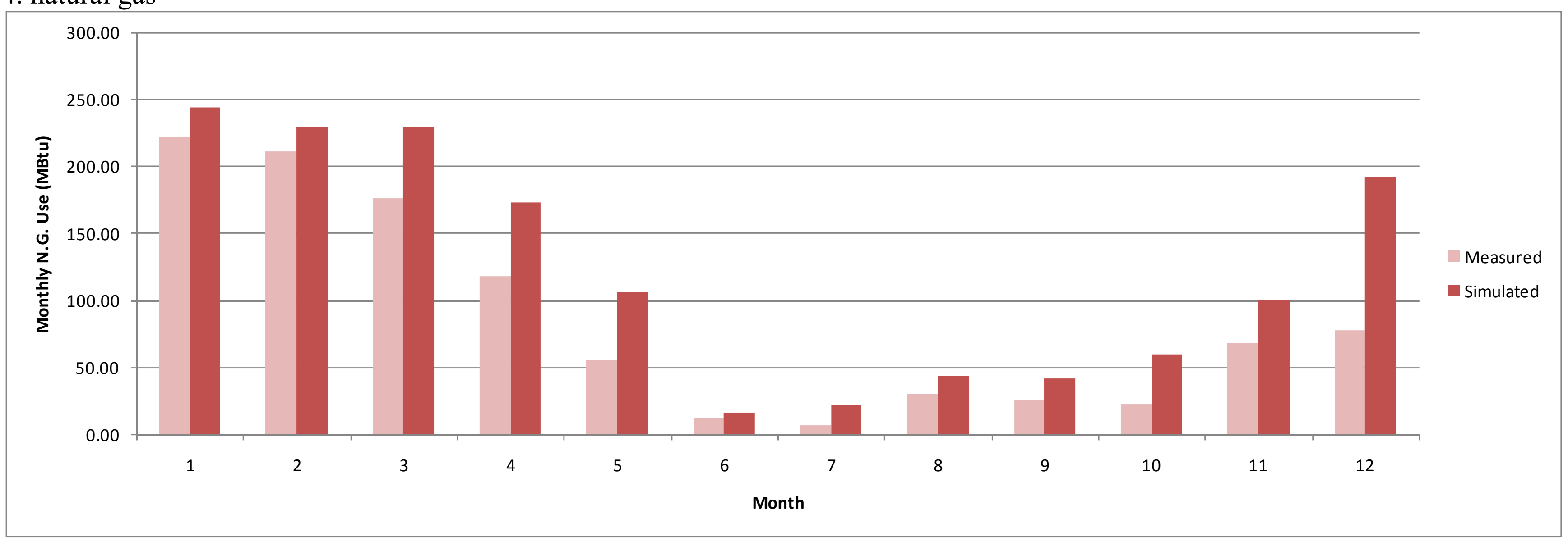
Figure 4.8 - Example of Time Series and Scatter Plots for Calibration Procedure

3. WBC + MCC





4. natural gas



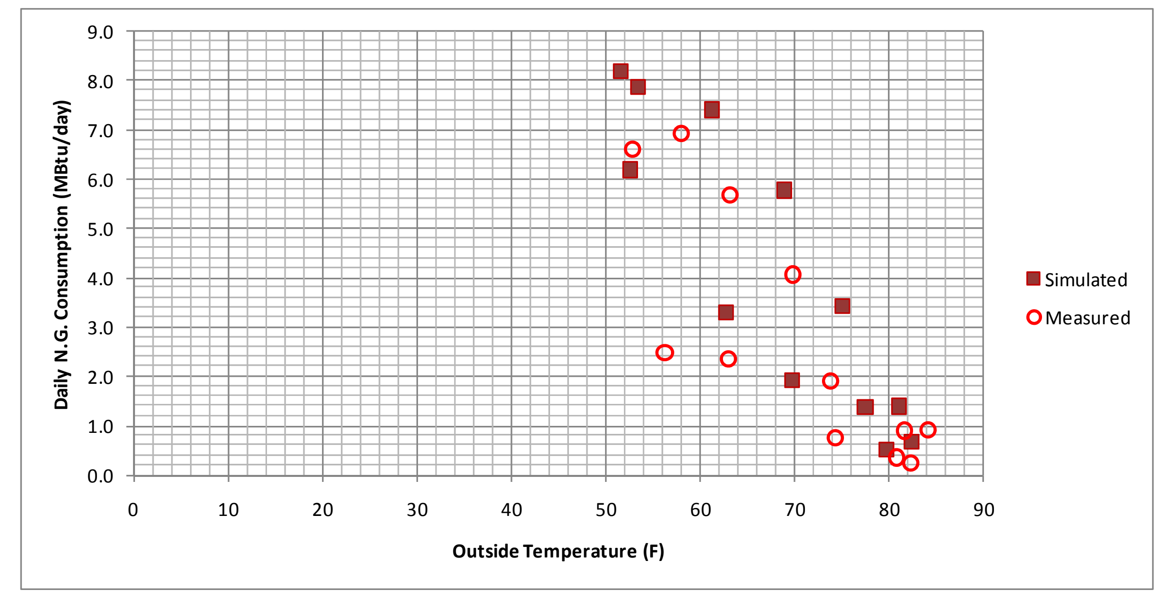


Figure 4.8 - Continued

$$CV(RMSE)\ (\%) = \frac{\sqrt{\frac{\sum_{i=1}^{n} Residual^2{}_i}{n-p}}}{M} \times 100 \qquad (4.2)$$

where,

n is the number of data points,
p is the total number of regression parameters in the model,
M is the mean value of the dependent variable of the set.

The NMBE and CV(RMSE) was calculated after each calibration step in order to assess the goodness-of-fit of a simulation model. According to the ASHRAE Guideline 14-2002 (2002) pp.41, "Models are declared to be calibrated if they produce a NMBE within ±10% and a CV(RMSE) within ±30% when using hourly data, or ±5% and ±15% with monthly data.".

The following sections describe the detailed calibration steps that were performed to achieve the final calibrated simulation.

4.3.1 Calibration Step 1: Using Actual Weather File

Several calibration steps were performed to match the simulation results with the measured energy use. First, instead of using the TMY2 average weather file for Houston, Texas, the actual weather file for 2006 for College Station, Texas was created or packed by using the measured weather data during 2006, which corresponds to the period of data collection for the energy use. The DOE-2 weather file contains weather-related hourly variables for one year (8,760 hours). The hourly data on the weather files are:

- Dry-bulb Temperature (F)
- Wet-bulb Temperature (F)

- Atmospheric Pressure (inches of Hg times 100)
- Wind Speed (knots)
- Wind Direction (compass points 0-15, with 0 being north, 1 NNE, etc.)
- Cloud Amount (0 to 10, with 0=clear and 10=totally overcast)
- Cloud Type (0, 1, or 2)
    - 0 is cirrus or cirrostratus, the least opaque;
    - 1 is stratus or stratus fractus, the most opaque; and
    - 2 is all other cloud types, of medium opacity
- Humidity Ratio (lb of water per lb of dry air)
- Density of the Air (lb/ft3)
- Specific Enthalpy of the Air (Btu/lb)
- Rain Flag (0 means it is not raining; 1 means it is)
- Snow Flag (0 means it is not snowing; 1 means it is)
- Total Horizontal Solar Radiation (Btu/hr-ft2)
- Direct Normal Solar Radiation (Btu/hr-ft2)

Table 4.5 presents the information required for the weather packing. Of these, the hourly data for dry bulb temperature, wet bulb temperature, relative humidity, wind speed have been obtained from the National Oceanic and Atmospheric Administration (NOAA) website. The solar related information (i.e., hourly global and direct normal solar radiations) was obtained and calculated from the local solar test bench located on the roof of the Langford Architecture building in College Station, Texas. Since the local solar test bench only provides hourly global solar radiations, the direct normal solar radiations were calculated using the Erbs correlation discussed in Duffie and Beckman (1991).

Table 4.5 - Information Required for TRY Weather File Packing

File Field Number	Columns	Element	Example
001	01 - 05	STATION NUMBER	44444
002	06 - 08	DRY-BULB TEMPERATURE	065
003	09 - 11	WET-BULB TEMPERATURE	063
004	12 - 14	DEW POINT TEMPERATURE	062
005	15 - 17	WIND DIRECTION	180
006	18 - 20	WIND SPEED	010
007	21 - 24	STATION PRESSURE	2970
008	25	WEATHER	0
009	26 - 27	TOTAL SKY COVER	00
010	28 - 29	AMOUNT OF LOWEST CLOUD LAYER	99
011	30	TYPE OF LOWEST CLOUD OR OBSCURING PHENOMENA	9
012	31 - 33	HEIGHT OF BASE OF LOWEST LAYER	999
013	34 - 35	AMOUNT OF SECOND CLOUD LAYER	99
014	36	TYPE OF CLOUD - SECOND LAYER	9
015	37 - 39	HEIGHT OF BASE OF SECOND LAYER	999
016	40 - 41	SUMMATION AMOUNT OF FIRST TWO LAYERS	99
017	42 - 43	AMOUNT OF THIRD CLOUD LAYER	99
018	44	TYPE OF CLOUD - THIRD LAYER	9
019	45 - 47	HEIGHT OF BASE OF THIRD LAYER	999
020	48 - 49	SUMMATION AMOUNT OF FIRST THREE LAYERS	99
021	50 - 51	AMOUNT OF FOURTH CLOUD LAYER	99
022	52	TYPE OF CLOUD - FOURTH LAYER	9
023	53 - 55	HEIGHT OF BASE OF FOURTH LAYER	999
024	56 - 59	SOLAR RADIATION	0000
025	60 - 69	BLANK	
026	70 - 73	YEAR	1999
027	74 - 75	MONTH	01
028	76 - 77	DAY	01
029	78 - 79	HOUR	00
030	80	BLANK	

DOE-2 weather processor recognizes the following solar data in TRY format:
Columns 57-59 Total horizontal radiation in Btu/ft2-hr
Columns 61-63 Direct normal radiation in Btu/ft2-hr

Based on the Erbs correlation, the diffuse radiation (Id) and the beam radiation (Ib) was calculated as followings:

$I_d / I = 1.0 – 0.09\, K_t$ For $K_t \leq 0.22$ (4.3)

$I_d / I = 0.9511\text{-}0.1604\, K_t + 4.388\times K_t^{\,2} –$

$16.638\times K_t^{\,3} + 12.336\times K_t^{\,4}$ For $0.22 < K_t \leq 0.8$ (4.4)

$I_d / I = 0.165$ For $K_t > 0.8$ (4.5)

where, K_t (Hourly clearness index) = I / I_o

where, I= Hourly measured solar radiation for College Station, TX

Io = Hourly extraterrestrial radiation

$$Io \ \cong Go = Gsc\left(1 + 0.033\mathrm{COS}\frac{360n}{365}\right) \times [\cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta] \tag{4.6}$$

where, Go = Hourly extraterrestrial radiation at any time between sunrise and sunset

Gsc = Solar constant (1367 W/m^2)

$\emptyset$ = Latitude (Degree)

δ = Solar declination (Degree)

ω = Hour angle at the midpoint of the hour (Degree)

Thus, $I_d = (I_d / I) \times I,\ I_b = (1\text{-}\ (I_d / I)) \times I$

After calculating the direct normal solar radiation, an unpacked TRY file was generated using Microsoft Excel to match with the format of a TRY unpacked file. Figure 4.9 shows an example of a TRY unpacked file. The unpacked TRY weather file was then packed then using the DOE-2 weather processor (i.e., DOE2WTH.EXE) which is included in DOE-2 program with the DOE-2 instruction file. An example of a DOE-2 instruction file can be found in Figure 4.10.

4.3.2 Calibration Step 2: RP-1093 Method

The next calibration step was performed to better match the lighting & equipment schedules with the measured data. For this procedure, the method developed for the ASHRAE 1093-RP project (Abushakra et al. 2001) was used with some modification.

```
444440650630621800102970000999999999999999999999999999900000000     1999010100
444440650630631800102970000999999999999999999999999999900000000     1999010101
444440660640631800082970000999999999999999999999999999900000000     1999010102
444440670640631800092970000999999999999999999999999999900000000     1999010103
444440670640631800072970000999999999999999999999999999900000000     1999010104
444440670650641800062970000999999999999999999999999999900000000     1999010105
444440670640631800092970000999999999999999999999999999900000000     1999010106
444440670650641800062970000999999999999999999999999999900000000     1999010107
444440680640631800082970000999999999999999999999999999900040031     1999010108
444440700650631800112970000999999999999999999999999999900070000     1999010109
444440730650611800142970000999999999999999999999999999900270001     1999010110
444440750650611800112970000999999999999999999999999999900750013     1999010111
444440770650601800162970000999999999999999999999999999901270074     1999010112
444440800660601800122970000999999999999999999999999999901820225     1999010113
444440810660591800152970000999999999999999999999999999901870269     1999010114
444440800660591800122970000999999999999999999999999999901700292     1999010115
444440790650591800092970000999999999999999999999999999901330310     1999010116
444440760650591800082970000999999999999999999999999999900520152     1999010117
444440740640591800102970000999999999999999999999999999900000000     1999010118
444440720640601800092970000999999999999999999999999999900000000     1999010119
444440690640621800082970000999999999999999999999999999900000000     1999010120
444440670640631800072970000999999999999999999999999999900000000     1999010121
444440630610601800052970000999999999999999999999999999900000000     1999010122
444440630610611800072970000999999999999999999999999999900000000     1999010123
444440630610601800052970000999999999999999999999999999900000000     1999010200
444440600580581800052970000999999999999999999999999999900000000     1999010201
444440550540541800052970000999999999999999999999999999900000000     1999010202
444440550530521800002970000999999999999999999999999999900000000     1999010203
```

Figure 4.9 - Example of TRY Unpacked File

The 1093-RP research project was developed to derive the diversity factors and typical load shapes of lighting and receptacle loads in office buildings. In general, this method divides the year into weekday and weekends, and generates lighting and receptacle schedules, or diversity factors for the DOE-2, BLAST or EnergyPlus simulation program based on the measured hourly data. The 1093-RP daytyping procedure is based on an analysis that uses percentiles, where the 10th, 25th, 50th, 75th, and 90th percentiles are reported for each hour of the day by daytype. The 1093 research project recommended that the 50th percentile values be used for the diversity factors of the lighting and receptacle loads, whereas the 90th percentile values were are used for peak load profiles. The detailed procedure that describes the use of the RP-1093 method for this study is described in Figure 4.11.

Since the original RP-1093 method was developed for office buildings that have relatively consistent weekday and weekend schedule throughout the year, this method needed to be modified in order to be applied for the school buildings due to the different pattern of school building energy uses. According to the interview with maintenance personnel of the case-study school, this building has 5 different schedules as followings (Personal communication 2006).

- Normal school days,

```
PACK
TRY  COLLEGE_STA
TRY    44444  -999     6 30.06 96.0330-BITSOLAR     23 10.  0.025
0.91  0.91  0.91  0.91  0.91  0.91  0.91  0.91  0.91  0.91  0.91  0.91
-999.
END
```

Figure 4.10 - Example of Instruction file

- Weekend and holidays,
- Summer vacation I (Staff is working),
- Summer vacation II (Between summer vacation I and III), and
- Summer vacation III (Staff & student vacation)

Therefore, instead of two (i.e., weekday & weekend) sets of schedules from the original RP-1093 method, this study generated a five different sets of lighting and receptacle schedules for use with the DOE-2 input file.

4.3.3 Calibration Step 3: Performance Curve for Scroll Chiller

Currently, DOE-2 provides the default chiller performance curves for absorption chiller, compression chiller (i.e., open centrifugal, hermetically-sealed centrifugal, open reciprocating, and hermetically-sealed reciprocating), double bundle chiller, and curves for cooling towers. Since the type of the chillers installed at the case-study school were air-cooled scroll chillers, the simulation results with default chiller performance curves would incorrectly simulate the scroll chiller's performance. In order to overcome this limitation of the DOE-2.1e defaults, the DOE-2 program allows a user to input and replace a custom chiller performance curve with the default performance curve (LBNL 2002). In order to input custom chiller performance curves, users should input three sets of coefficients (i.e., three curves). The following are the names and descriptions of each curve.

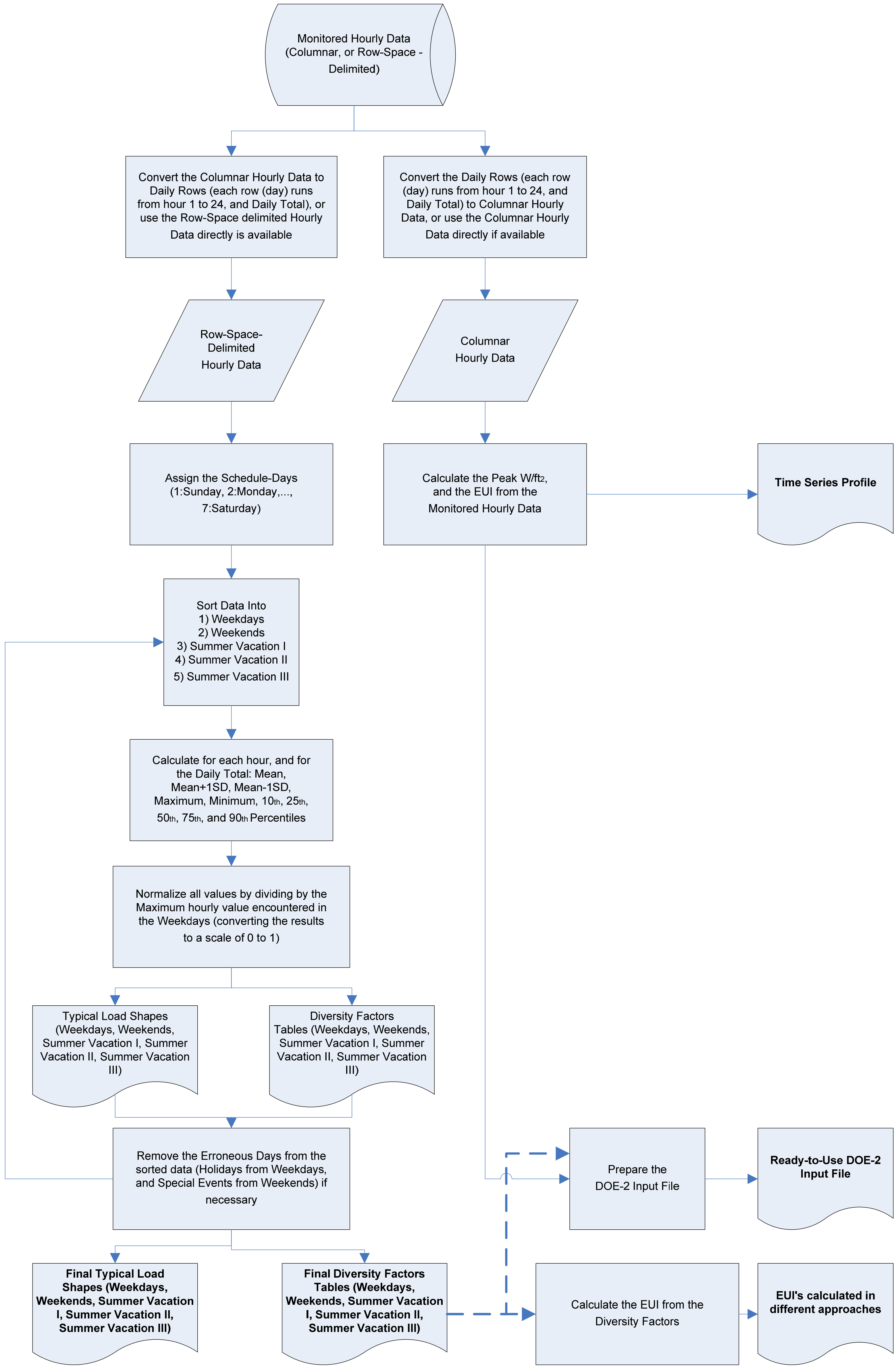


Figure 4.11 - Flowchart of the RP-1093 Method (Modified for the Case-study School Building)

1) *CAPFT* – a curve that represents the available capacity as a function of evaporator and condenser temperatures
2) *EIRFT* – a curve that represents the full-load efficiency as a function of evaporator and condenser temperatures.
3) *EIRFPLR* – a curve that represents the efficiency as a function of the part load ratio

The format of the curves is as follows:

$$CAPFT = a_1 + b_1 \cdot t_{chws} + c_1 \cdot t^2_{chws} + d_1 \cdot t_{cws/oat} + e_1 \cdot t^2_{cws/oat} + f_1 \cdot t_{chws} \cdot t_{cws/oat} \quad (4.7)$$

$$EIRFT = a_2 + b_2 \cdot t_{chws} + c_2 \cdot t^2_{chws} + d_2 \cdot t_{cws/oat} + e_2 \cdot t^2_{cws/oat} + f_2 \cdot t_{chws} \cdot t_{cws/oat} \quad (4.8)$$

$$EIRFPLR = a_3 + b_3 \cdot PLR + c_3 \cdot PLR^2 \quad (4.9)$$

$$PLR = \frac{Q}{Qref \times CAPFT\ (tchws, tcws/oat)} \quad (4.10)$$

where

t_{chws} = the chilled water supply temperature (°F),
$t_{cws/oat}$ = the condenser water supply temperature (°F) for water-cooled equipment or the outdoor air dry-bulb temperature (°F) for air-cooled equipment,
Q = the capacity (ton),
Q_{ref} = the capacity (ton) at the reference evaporator and condenser temperatures where the curves come to unity,
PLR = a function representing the part-load operating ratio of the chiller.

For this study, the performance curves for scroll chillers were obtained from a previous research by California Energy Commission (California Energy Commission

1993). The California Energy Commission published a set of 7 default curves to represent four compressor types and two condenser conditions with the cooperation of ARI and the major manufacturers. The curves developed were adopted for use in modeling baseline chiller operation for the Standard Performance Contract program (California Energy Commission 1993) (See Tables 4.6 to 4.8). Using the coefficients shown in these tables, the coefficiens for DOE-2 chiller curves were developed and added to the as-built simulation input as shown in Figure 4.12.

Table 4.6 - Capacity Coefficients – Electric Air-Cooled Chiller

Coefficient	Scroll	Recip	Screw	Centrifugal
a	0.40070684	0.57617295	-0.09464899	N/A
b	0.01861548	0.02063133	0.03834070	N/A
c	0.00007199	0.00007769	-0.00009205	N/A
d	0.00177296	-0.00351183	0.00378007	N/A
e	-0.00002014	0.00000312	-0.00001375	N/A
f	-0.00008273	-0.00007865	-0.00015464	N/A

Table 4.7 - Efficiency EIR-FT Coefficients – Air-Cooled Chiller

Coefficient	Scroll	Reciprocating	Screw	Centrifugal
a	0.99006553	0.66534403	0.13545636	N/A
b	-0.00584144	-0.01383821	0.02292946	N/A
c	0.00016454	0.00014736	-0.00016107	N/A
d	-0.00661136	0.00712808	-0.00235396	N/A
e	0.00016808	0.00004571	0.00012991	N/A
f	-0.00022501	-0.00010326	-0.00018685	N/A

Table 4.8 - Efficiency EIR-FPLR Coefficients - Air-Cooled Chillers

Coefficient	Scroll	Recip	Screw	Centrifugal
a	0.06369119	0.11443742	0.03648722	N/A
b	0.58488832	0.54593340	0.73474298	N/A
c	0.35280274	0.34229861	0.21994748	N/A

```
$ NEW CURVE-FIT FOR SCROLL AIR-COOLED CHILLER

SCROLL-CURVE1 = CURVE-FIT
   TYPE = BI-QUADRATIC
   COEFFICIENTS = (0.4007070684,0.01861548,0.00007199,
   0.00177296,-0.00002014,-0.00008273)
   ..                              $END OF CURVEFIT COMMAND

SCROLL-CURVE2 = CURVE-FIT
   TYPE = BI-QUADRATIC
   COEFFICIENTS = (0.99006553,-0.00584144,0.00016454,
   -0.00661136,0.00016808,-0.00022501)
   ..                              $END OF CURVEFIT COMMAND

SCROLL-CURVE3 = CURVE-FIT
   TYPE = QUADRATIC
   COEFFICIENTS = (0.06369119,0.58488832,0.35280274)
   ..                              $END OF CURVEFIT COMMAND

$ EQUIPMENT-QUAD

EQUIPMENT-QUAD

OPEN-CENT-CAP-FT = SCROLL-CURVE1
OPEN-CENT-EIR-FT = SCROLL-CURVE2
OPEN-CENT-EIR-FPLR = SCROLL-CURVE3
..
```

Figure 4.12 - DOE-2 Input for Adding Chiller Performance Curves

4.3.4 Calibration Step 4: Winkelmann's Method for the Underground Floor

Because the case-study building, which is one story building, has relatively large ground floor area, the use of DOE-2's standard U-value for the floor yields unrealistic heat transfer to the ground. Therefore, the U-effective value described by Winkelmann (1998) was calculated and used for the underground floor in order to avoid unrealistic heat transfer to the ground. Underground surfaces in DOE-2 are walls or floors that are in contact with the ground temperature.

In general, DOE-2 calculates the heat transfer for the underground surface as follows:

$$Q=U*A*(T_g-T_i) \quad (4.11)$$

where U is the conductance of the surface,

A is the surface area,

T_g is the ground temperature, and

T_i is the inside air temperature.

However, if a standard U-value of the surface is used for this calculation as shown the equation above, the heat transfer through the underground surface would be overcalculated since the heat transfer occurs through the surface's exposed perimeter rather than uniformly over the whole surfaces. Therefore, an effective U-value using DOE-2's U-EFFECTIVE keyword were used to overcome this limitation. This gives

$$Q=[U\text{-}EFFECTIVE]*A*(T_g-T_i) \quad (4.12)$$

U-EFFECTIVE can be calculated as

$$U\text{-}EFFECTIVE = 1/\ R_{eff} \quad (4.13)$$

Where, R_{eff} = A/(F2 * P_{exp})

F2 = perimeter conduction factor

P_{exp} = length of exposed surface perimeter

Since the case-study building in this research has a slab-on-ground foundation which would be simulated as an underground floor. In order to be simulated as underground floor, a F2 factor was found in Table 4.9 (Huang et al. 1998). Then, the effective slab resistance (R_{eff}) was calculated using the slab exposed perimeter (P_{exp}) and slab surface area. The U-EFFECIVE was then calculated. In addition, the resistance of fictitious layer which is also required for DOE-2 input was calculated. The detailed calculation procedure and the calculated values are shown in th following:

F2 (Foundation 4ft deep, uninsulated, Uncarpeted) = 1.10 Btu/hr-F-ft

Slab surface area: A = 74,169 ft^2

Slab exposed perimeter: P_{exp} = 2,238 ft

Effective slab resistance: R_{eff} = A/(F2x P_{exp}) = 74169/(1.10 * 2238) = 30.13

Effective slab U-value: *U-EFFECTIVE* = 1/ 30.13 = 0.033

Actual slab resistance: R_{us} = 0.44 + R_{film} = 0.44+0.77 =1.21

Resistance of fictitious layer: $R_{fic} = R_{eff} - R_{us} - R_{soil}$

= 30.13-1.21-1.0 = 27.89

Figure 4.13 shows the input for U-EFFECTIVE input for DOE-2 input.

Table 4.9 - Perimeter Conduction Factors for Concrete Slab-On-Grade (Huang et al. 1998)

Slab-On-Grade			
Foundation depth	Insulation Configuration (see sketch for location of insulation)	PERIM-CONDUCT Btu/hr-F-ft (W/m-K)	
		Uncarpeted	Carpeted
2 ft	Uninsulated	1.10 (1.90)	0.77 (1.33)
	R-5 exterior	0.73 (1.26)	0.54 (0.93)
	R-10 exterior	0.65 (1.12)	0.49 (0.85)
	R-5 interior; R-5 gap	0.75 (1.30)	0.57 (0.98)
	R-10 interior	0.89 (1.54)	0.46 (0.79)
	R-10 interior; R-5 gap	0.70 (1.21)	0.53 (0.92)
	R-10 interior; R-10 gap	0.68 (1.17)	0.52 (0.90)
	R-5 2-ft perimeter; R-5 gap	0.78 (1.35)	0.60 (1.04)
	R-10 2-ft perimeter; R-5 gap	0.73 (1.26)	0.57 (0.98)
	R-10 4-ft perimeter	0.79 (1.36)	0.59 (1.02)
	R-10 15-ft perimeter, R-5 gap	0.39 (0.67)	0.34 (0.59)
	R-5 16-in exterior, R-5 2-ft horizontal	0.65 (1.12)	0.48 (0.83)
	R-5 16-in exterior, R-5 4-ft horizontal	0.58 (1.00)	0.43 (0.74)
	R-10 16-in exterior, R-5 2-ft horizontal	0.56 (0.97)	0.41 (0.71)
	R-10 16-in exterior, R-5 4-ft horizontal	0.47 (0.81)	0.35 (0.60)
4 ft	Uninsulated	1.10 (1.90)	0.77 (1.33)
	R-5 exterior	0.61 (1.05)	0.46 (0.79)
	R-10 exterior	0.50 (0.86)	0.37 (0.64)
	R-15 exterior	0.44 (0.76)	0.33 (0.57)
	R-20 exterior	0.40 (0.69)	0.30 (0.52)
	R-5 interior; R-5 gap	0.63 (1.09)	0.48 (0.83)
	R-10 interior; R-5 gap	0.54 (0.93)	0.42 (0.73)
	R-15 interior; R-5 gap	0.50 (0.86)	0.38 (0.66)
	R-20 interior; R-5 gap	0.47 (0.81)	0.36 (0.62)
	R-5 4-ft perimeter; R-5 gap	0.68 (1.17)	0.54 (0.93)
	R-10 4-ft perimeter; R-5 gap	0.61 (1.05)	0.49 (0.85)
	R-10 4-ft perimeter	0.79 (1.36)	0.59 (1.02)
	R-10 15-ft perimeter, R-5 gap	0.39 (0.67)	0.34 (0.59)
	R-5 16-in exterior, R-5 2-ft horizontal	0.65 (1.12)	0.48 (0.83)
	R-5 16-in exterior, R-5 4-ft horizontal	0.58 (1.00)	0.43 (0.74)
	R-10 16-in exterior, R-5 2-ft horizontal	0.56 (0.97)	0.41 (0.71)
	R-10 16-in exterior, R-5 4-ft horizontal	0.47 (0.81)	0.35 (0.60)

```
$ Slab-on-grade $

MAT-FIC-1 = MATERIAL RESISTANCE = 27.89 .. $ the Rfic value

SOIL-12IN = MATERIAL THICKNESS = 1.0 CONDUCTIVITY = 1.0
            DENSITY = 115 SPECIFIC-HEAT = 0.1 ..

LAY-SLAB-1 = LAYERS MATERIAL = (MAT-FIC-1,SOIL-12IN,CC03)
           INSIDE-FILM-RES = 0.77 ..

CON-SLAB-1 = CONSTRUCTION LAYERS = LAY-SLAB-1 ..

U-EFFECTIVE = 0.033
```

Figure 4.13 - DOE-2 Floor Input Using Winkelmann's Method

4.3.5 Calibration Step 5: The HVAC and Room Set-point Temperature and Schedules from the Measured Data

As described earlier, the six (6) portable loggers were installed to measure the HVAC and room temperatures. The initial as-built simulation input was developed based on the HVAC and room set-point temperatures and the operational schedules obtained from the original drawings and the interview with the school district officials. Those set-point temperatures and schedules were then compared against the measured data, and the appropriate values from the measured data replaced the original inputs. The major DOE-2 variables that were modified to reflect measured data are shown in Table 4.10.

Table 4.10 - DOE-2 Input Variables to be Compared with the Measured Data

Code for DOE-2 Input	
ZONE-CONTROL	
HEAT-TEMP-SCH	Set point of the zone heating thermostat
COOL-TEMP-SCH	Set point of the zone cooling thermostat
SYSTEM-CONTROL	
MIN-SUPPLY-T	Lowest allowable temperature for air entering the zones
MAX-SUPPLY-T	Highest allowable temperature for air entering the zones
COOL-SET-T	Cooling air supply temperature
SYSTEM-TERMINAL (for VAV System)	
REHEAT-DELTA-T	Maximum increase in temperature for supply air passing through the reheat coil
SYSTEM-FANS	
FAN-SCHEDULE	Fan schedule

4.3.6 Summary of As-built and Calibrated Simulation

This section has discusses how the initial as-built simulation input was developed based on the as-built drawing and onsite visit. The initial DOE-2 input was run using the

DOE-2 simulation program and TMY2-Houston, Texas weather file. Then, in order to match the simulation result to the measured use, several calibration procedures were performed including: 1) Using a weather file that reflects conditions during periods of the energy measurment, 2) Calibrating lighting & equipment loads using the RP-1093 method, 3) The use of scroll chiller performance curves, 4) Winkelmann's method for the underground surface heat transfer, and 5) The use of HVAC and room set-point temperatures and schedules from the measured data. In every calibration step, time series plots and scatter plots were generated, and the CV(RMSE) and NMBE was calculated in order to evaluate the progress of the calibration. The final calibrated simulation will then be used to estimate energy savings potential from adopting selected high performance measures and to verify the simplified tool developed in the final step of this research.

4.4 Study of Daylighting Simulation

In this section, the daylighting simulation applied to the base-case school building as one of high performance measures is described. First, this section discusses several daylighting strategies that can be applied for school buildings today. Then, one daylighting strategy is selected to demonstrate the effectiveness of the daylighting strategy in terms of energy savings. As mentioned in Chapter II, a simple skylight daylighting strategy was selected in this study since the algorithms with the current DOE-2 simulation program can reasonably simulate such as simple configuration. A simple classroom with and without skylight, then, was simulated using DOE-2 simulation program. The Desktop Radiance program (LBNL 2008) was then used to generate an image of the classroom with and without skylights to provide a better understanding.

4.4.1 Selection of Daylighting Strategy for the Case-study School

The 2006 CHPS Practice Manual (CHPS 2006) provides a design guideline for lighting and daylighting for schools. The daylighting strategies discussed in this manual include: 1) High sidelighting and clerestory, 2) High sidelighting and clerestory with light shelf or louvers, 3) Wall-wash toplighting, 4) Central toplighting, 5) Patterned toplighting, 6) Linear toplighting , and 7) Tubular skylights. Table 4.11 shows the different daylighting patterns and its design criteria. As shown, each daylighting pattern has its own strength and weakness. For example, the type of high sidelighting and clerestory provide relatively good uniform light distribution, low first cost, and low maintenance, while relatively poor view can be provided. Another example, the central & patterned toplight, which is selected for this study, provide extremely good uniform light distribution, reduced energy cist, low first cost, while relative limited view is provided.

In this research, as mentioned above, given the fact that 1) the DOE-2 simulation program can calculate the daylighting impact reasonably close to the more detailed daylighting simulation when using simple skylights and 2) good application for uniform light distribution, reduced energy cost, and low first cost, the patterned toplighting strategy was selected to demonstrate the methodology developed for daylighting simulation. In general, patterned toplighting is known as one of the most simple yet cost effect daylighting strategies.

Table 4.11- Selection Criteria for Daylighting Strategies

Design Criteria	Daylighting Patterns							
	View Windows	High Sidelight	High Sidelight w/ Light Shelf or Louvers	Wall Wash Toplight	Central & Patterned Toplight	Linear Toplight	Atria & Light Well	Tubular Skylights
Uniform Light Distribution	○○	⭘	●	●	●●	⭘	⭘	⭘
Low Glare	○	●	●●	●●	●	●	●	●/○
View	●●	○	○○	○○	○	●/○	●●	○○
Reduced Energy Costs	○	●	●	●	●●	●	●	●
Low First Cost	●	●	○	●	●●	●	○○	●●
Cost Effectiveness	●	●	●	●	●	●	●	●●
Safety/Security Concerns	○	●	●/○	●	●	●	●/○	●●
Low Maintenance	○	●	●	●	●	●	○	●

●● Extremely good application ● Good application ○ Poor application ○○ Extremely poor application ⭘ Depends on space layout and number and distribution of daylight apertures ●/○ Mixed benefits

Source: CHPS Best Practices Manual (CHPS 2006)

4.4.2 Daylighting for a Classroom

In this pilot study, one classroom unit instead of a whole school building was simulated with and without the selected daylighting strategy. The size of the classroom was the same as the case-study school, which is 812 sq.ft. (=28.5 ft x 28.5ft). The detailed information about the classroom and the toplights are shown in Table 4.12. Figure 4.14 shows the classroom and the classroom with the four toplights applied.

For the comparison, a daylighting reference point was located in the middle of the classroom above 30" from the floor. Based on the simulated lighting level at the reference point, if the level is above 50 fc, all the lighting fixtures would be turned off, if the level is between 25 to 50fc, half of the lighting fixtures would be turned off, and if the level is below 25fc, all the lighting fixtures would be turned on. Finally, the lighting and total energy savings from two classrooms are then compared.

Table 4.12- Toplights Information for Classroom

Original Classroom	
Classroom Size	812 sq.ft (= 28.5 x 28.5)
Floor-to-Ceiling Heights	9ft
Floor-to-Roof Heights	12ft
Size of the Window (Sidelight)	18sq.ft. (= 3 x 6)
Glazing for the original window	Single Pane, tinted glass
Original Classroom + Toplights	
Daylighting Pattern	Toplights
Number of Toplights	4
Size of Toplight	9 sq.ft each.
Skylight Area to Floor Area	4.5%
Glass for Toplights	Low-e double pane glass

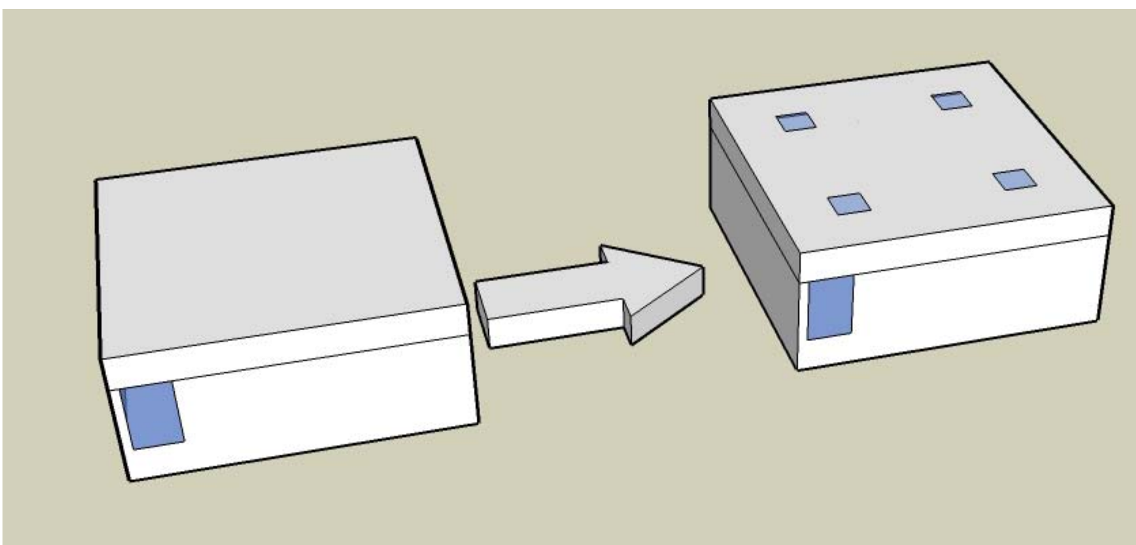


Figure 4.14 - Original Classroom vs. Classroom with 4 Toplights

4.4.4 Summary of Study of Daylighting Simulation

In this section, the daylighting simulation applied to the base-case school building as one of high performance measures is described. As a pilot study, a typical classroom with and without the selected daylighting strategy was simulated and the energy savings were simulated with DOE-2.

4.5 Estimation of Energy Savings from the Application of High Performance Measures

In this section, a method for estimating the energy savings potential from the application of the selected high performance measures to the base-case-study school is discussed. Before applying the measures, the case-study school simulation input was modified to be compliant with ASHRAE Standard 90.1-1999 because an ASHRAE 90.1-1999 compliant school was most often used as a base-case building when an energy saving were calculated in the previous liternature. In addition, the ASHRAE Advanced Energy Design Guide (AEDG) for K-12 schools, which is the main reference of this study to use for comparison, defines a ASHRAE 90.1-1999 compliant school as a base-case school.

4.5.1 ASHRAE Standard 90.1-1999 Compliant School

The purpose of ASHRAE Standard 90.1-999 is to provide minimum requirements for the energy efficient design of buildings except low-rise residential buildings. This standard provides three options for the code-compliant path, including: 1) Prescriptive option, 2) Trade-off option, and 3) Energy Cost Budget (ECB) option. There are also mandatory provisions in the envelope, lighting, and mechanical systems required for all compliance options. In the current study, the Energy Cost Budget method was used to modify the case-study school to be compliant to the ASHRAE Standard 90.1-1999. Basically, the method to evaluate the code compliance using the ECB method is to compare the energy cost between the annual energy cost budget (i.e., the code-compliant standard building) and the design building's annual energy cost (i.e., the proposed building to be compared to the code compliant building). When the annual energy cost for the proposed building is lower than the energy cost budget, it can be declared that the proposed building is code compliant. For the calculation, there are four general rules that always apply:

1) Both runs must use the same simulation program,
2) Both runs must use the same climate data,
3) Both runs must use the same purchased energy rates, and
4) Both runs must use the same schedules of operation.

For this study,

1) Both runs used the DOE-2 simulation program,
2) Both runs used the 1999 College Station TRY weather file,
3) Bothe runs used the purchased energy rates approved by the adopting authority, and
4) Both runs used the operational schedules from the case-study building.

Table 4.12 shows the summarized comparison for the simulation input of the case-study school and the ECB simulation model. As shown, the requirements for the envelope systems for the ECB model were referred to the ASHRAE Standard 90.1-1999 for the corresponding climate area. The HVAC systems for the ECB model were selected as instructed by ASHRAE Standard 90.1-1999. First, based on the Figure 4.15: the HVAC systems map, the type of the system was selected. Since the case-study building has an air-cooled condenser, the type of heating system was classified as fossil fuel, and the building is a multi-zone, the system 4 was selected from Figure 4.15. Table 4.13 describes the system types, and since the system 4 was selected for the ECM model, a “Packaged variable air volume with reheat” was used.

After defining all the inputs for ASHRAE Standard 90.1-1999 compliant school, which was modified from the case-study simulation input, the annual energy cost for the code compliant school was simulated and compared against the energy cost for the case-study school in order to verify whether the case-study school is code compliant or not.

4.5.2 ASHRAE Advanced Energy Design Guide for K-12 Schools

The ASHRAE Advanced Energy Design Guide (AEDG) for K-12 schools was developed to achieve the 30% more energy savings over an ASHRAE Standard 90.1-1999 compliant school building. In this study, the recommendations from the AEDG for K-12 schools for the same climates of the case-study school were simulated using the modified case-study school simulation input. Next, the ASHRAE Standard 90.1-1999 compliant school building input, which was developed the previous step, was compared to the AEDG compliant school building model, and the annual energy costs were compared. According to the climate zone classification from the AEDG K-12, the case-study school is located in the climate zone 2 (Figure 4.16). Next, based on the recommendations in the prescriptive table provided for the climate zone 2, the ASHRAE Standard 90.1-1999 compliant simulation input developed in previous step was modified and run with the same weather file for the case-study school. All the other inputs regarding the case-study school were set to be the same with the ASHRAE Standard 90.1-1999 compliant building.

Table 4.13 - Simulation Input Comparison (Case-study School vs. ECB Model)

Measures	Case-study School	ASHRAE 90.1-1999
Roof Insulation (Btu/ft2-F-hr)	0.053	0.063
Wall Insulation (Btu/ft2-F-hr)	0.085	0.089
Glazing (U-Value and SHGC)	U-1.12 SHGC - 0.72	U-1.27 SHGC - 0.25
Lighting Power Density (W/ft2)	1.2	1.5
Occupancy Control	Manual on off	Scheduled On Off
HVAC Type	VAV with Reheat Constant Air Volume Multi Zone Unit	Packaged Rooftop VAV system
Economizer	None	Yes
Cooling Efficiency (EER)	9.6 EER	10.1 EER
Boiler Efficiency (%)	82%	80%
SWH Efficiency (Et %)	78.6%	80%

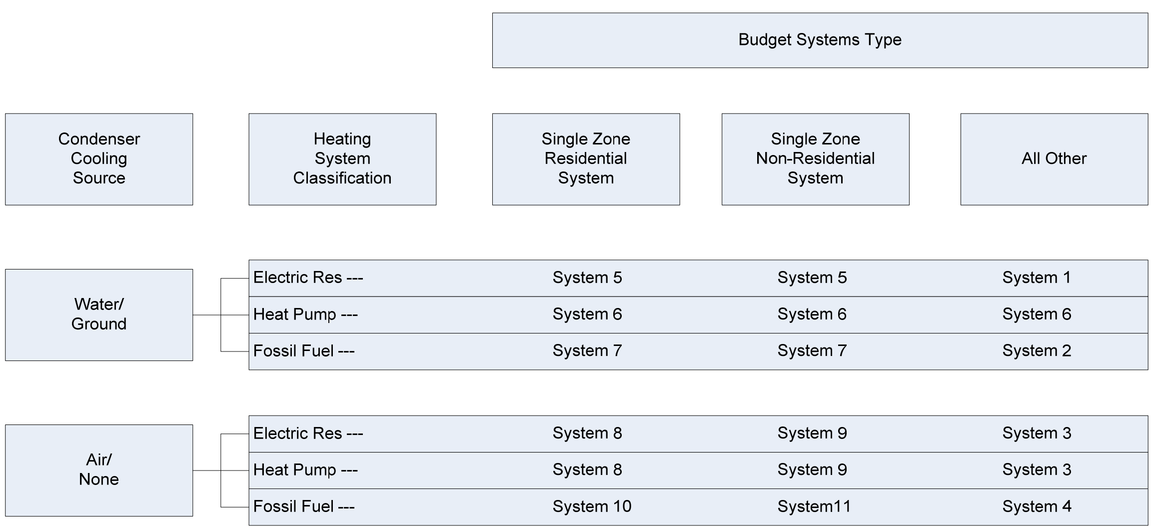


Figure 4.15 - HVAC Systems Map (Source: ASHRAE 90.1-1999 (ASHRAE 1999))

Figure 4.16 - Climate Zone 2 from AEDG for K-12 Schools (Source: AEDG for K-12 Schools)

4.5.3. Energy Savings above AEDG for K-12 Schools

After analyzing the energy savings potentials from the application of the AEDG for K-12 schools, other high performance measures not described in the AEDG were applied to the base-case school simulation in order to verify how much energy could be saved. Specifically, in this step of the research, renewable energy systems, such as solar PV and solar thermal were applied to the base-case school. Since the DOE-2 simulation program currently is not capable of simulating the solar PV and thermal systems, two other legacy programs, F-Chart (Klein and Beckman 1983) and PV F-Chart (Klein and Beckman 1994) were used for the solar thermal and PV simulations, respectively. In addition, the daylighting strategy, which was previously discussed was applied to the case-study school to calculate the energy savings due to the daylighting application. The detailed method to integrate the F-Chart and PV F-Chart results with the DOE-2 simulation result and the daylghting application methodology are described as following.

4.5.3.1 Building Space Heating and SWH Energy Uses

In order for the case-study building's space heating and service water heating natural gas energy use needed to be replaced by the energy provided by the solar thermal system. In order to decide the system-independent inputs required for simulating space heating and service water heating loads in the F-Chart solar thermal program, the methodology proposed in a previous work (Cho 2009) was used. In this integration procedure, the target building was first simulated using the DOE-2 program. Next, in order not to account for the natural gas boiler and water heater efficiencies from the PLANT simulation of the DOE-2 program, the DOE-2 monthly reports (i.e., DOE-2 Report SS-A and SS-P) from the SYSTEM output were extracted. In this way, the DOE-2 SYSTEMS monthly load summary report (SS-A) were used to report the space heating energy by month. Next, using: 1) the simulated monthly heating load, 2) and the corresponding average monthly temperatures from the DOE-2 weather file, the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2001) was used to calculate the monthly heating load as a function of outdoor temperature. From this regression model, the building's total heat transfer coefficient (building UA) and a change-point temperature (T_{bal}) were calculated, and the two values were used as inputs for the F-Chart program.

For the service water heating input parameters, the monthly energy use was obtained from DOE-2's SS-P report, using the Energy and Part Load DHW Tank Operation report. The monthly use was then used to match the DHW energy use calculated by F-Chart.

4.5.3.2 Building Electricity Uses

In this study, a part of the building's electricity use was to be provided by the power generated from the installed solar PV system. There are several types of solar PV systems such as stand-alone system, grid-tied system, and battery back-up system, etc. For this study, a grid-tied solar PV system was selected due to the cost effectiveness and the space available for the PV installations. In order to integrate the PV systems with the target school, first, the building's reduced monthly electricity use was simulated using the DOE-2 program. Based on the monthly electricity required for the building, the solar PV system was sized to provide whole or some percentage of the electricity demand. Then, the PV generated electricity was estimated using the PV F-Chart with the corresponding simulation input and the same weather data for the DOE-2 simulation, and the solar-generated electricity use was subtracted from the total electricity use.

4.5.3.3 Daylighting Application

The daylighting strategy discussed previously for one prototype classroom was extended to cover the whole building. To accomplish this, two daylighting reference points were located in each zone of the school, and the resultant reduced lighting loads simulated.

4.5.4 Summary of the Energy Savings from the Application of High Performance Measures

A method for estimating the energy savings potential from the application of the selected high performance measures to the base-case-study school was discussed in this section. In this methodology, three different simulations were performed and compared to estimate the energy savings potentials. First, the original case-study school simulation input was modified in order to be complaint with ASHRAE Standard 90.1-1999 using the ECB requirements. This simulation input was then used as the base-case school. Then, the recommendations from the ASHRAE's AEDG for K-12 schools for the same climate zone of the case-study school were applied for the base-case school, and the energy savings potentials were calculated. As a final step, the selected high performance measures were applied, which included ASHRAE AEDG for K-12 recommendations, as well as solar PV and solar thermal systems. Since the DOE-2 simulation program is not capable of simulating solar PV and thermal systems, the F-Chart and PV F-Chart program were used to calculate the hot water and the electricity generation from a solar thermal and PV system, respectively. In addition, the daylighting strategy discussed previously for one classroom was applied to whole building as one of high performance measures.

4.6 Methodology for Developing an Easy-to-use Simulation Input

As a final step of the study, the specifications for an easy-to-use simulation tool were developed. Although the final tool is intended to be a web-based tool, this study developed specifications for the DOE-2 simulation input, which will be a part of the calculation engine for the final tool as well as specifications for including easy-to-use solar thermal and PV analysis capabilities. The proposed easy-to-use simulation input will thus allow the user to input parameters related to the building envelope with fixed values for the HVAC system related inputs. The proposed simulation input was developed using DOE-2's input macro commands and DOE-2 include file options. With these predefined input commands and a fixed schematic f the school with selected variable parameters, users will be able to define a school building by changing only groups of pre-defined input parameters (i.e, ultimately using a web page) without having to modify the original DOE-2 input file itself.

In the following section, the methodology for dynamically modifying the building geometry, and the size of the building, using a minimum number of input parameters will be discussed.

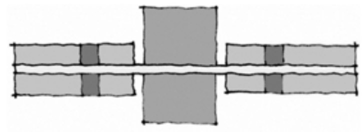
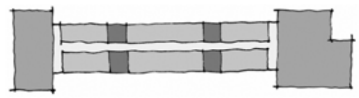
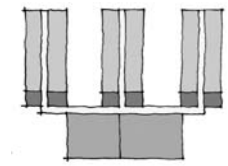
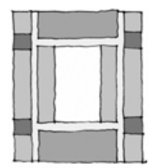
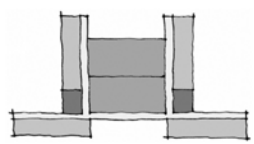
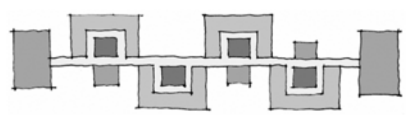
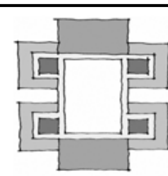
4.6.1 School Building Configuration

The first step in developing a prototype school is to define the most common school configuration in hot and humid climates based on a literature review and a survey of existing schools. Perkins (2001) reviewed several possible school building configurations. According to Perkins, even though there are limitless possible building configurations for schools, most of these configurations can be categorized by a few common shapes. Figure 4.17 shows the most common configurations used in school design according to Perkins. All the configurations contain classrooms, shared facilities such as auditoriums, a library, a gym, and classroom nodes. Based on Perkins' configurations, a survey was then conducted to identify the most common school shape in a nearby city in Central Texas. School shapes were identified using an overhead satellite view of the schools. Each school shape was then classified by using Perkins' building configurations shown in Figure 4.17.

After defining the most common shapes of the schools from the survey, the most common school shape was defined as the final school geometry for the easy-to-use tool. This final school geometry was hen further simplifed to faciliate the easy-to-use inputs.

4.6.2 School Spaces and Size

In general, existing simplified building simulation tools still require users to input detailed building information such as the width and depth of each zone in order to define a building geometry. Unfortunately, this procedure frustrates inexperienced users who are not familiar with simulation procedures to simplify simulation. To help resolve this problem, the easy-to-use simulation tool developed in this study uses only a few simple input parameters such as the number of students to define the building geometry. Once this variable is known, the gross square footage per student can then be used to size the school building by using simple projections of classroom, cafeteria, gymnasium, and office space requirements. According to 2007 construction report by School Planning & Management (SP&M 2007), the median space per student was 112.5, 122.2, and 131.2 sq.ft. for large, medium, and small schools, respectively (see Table 4.14). Therefore, once users input the number of students for their school building, the total gross square footage of the school can be calculated by the tool using a simple ratio. Then, the total gross square footage will be divided into several spaces that are required in school buildings in general.

Name	Configuration
The Centralized resource plan	
The dumbbell plan	
The spine plan	
The courtyard plan	
A spine with single-loaded classroom wings	
A classroom-clustering model	
A courtyard with classroom-clastering plan	

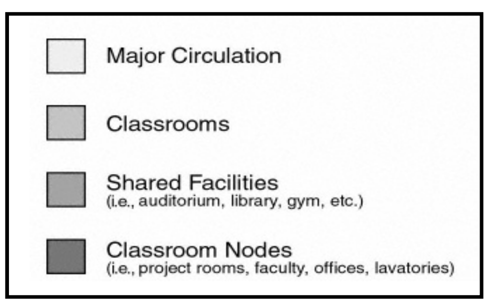


Figure 4.17 - Most Common School Building Shapes (Drawings from Perkins, 2001)

In the proposed simplified tool, a school building has 4 major spaces: 1) classrooms, including a library or media center, 2) a cafeteria, 3) a gymnasium, and 4) an administration office. The major spaces required in K-5 schools were determined based on the information from both the 2007 construction report (SP&M 2007) and Perkins (2001). According to the 2007 construction report, over 90% of the new elementary schools built in 2007 have those 4 major spaces. In order to verify the percent area of the total square footage, several local K-5 school buildings' space profiles were reviewed including a typical K-5 school in North Carolina, and a case-study elementary school building in central Texas. For the verification, the percent space areas were compared to definition from Perkins (2001). Table 4.15 shows the percent of total square footage of each school. Most of the school building areas (i.e., 65 to 72% of total square feet) were occupied with the classrooms. The gymnasium, dining area, and the office areas were each about 10% of the total building area. Figure 4.18 shows the relationship between number of students and the total gross square footage.

Table 4.14 - Gross Square Footage per Student

	Median Number of Students	**Median Size of Building (Sq.Ft.)**	**Median Space per student (Sq.Ft)**
Smallest quarter (fewer than 540 students)	450	59,965	131.2
National Median	700	88,000	122.2
Largest quarter (800 to 1,800 students)	865	98,000	112.5

Table 4.15 – Percent Space Area of the Total Conditioned Area Based on the Number of Students

Number of Student	Area (sq.ft.) per Student	Percent Classroom + Media Center (or Library)	Percent Dining Area	Percent Gym Area	Percent Admin. Office Area
From 200 to 540	131.2	65%	10%	13%	12%
541 to 799	122.2	71%	10%	9%	10%
800 to 1,800	112.5	72%	10%	8%	10%

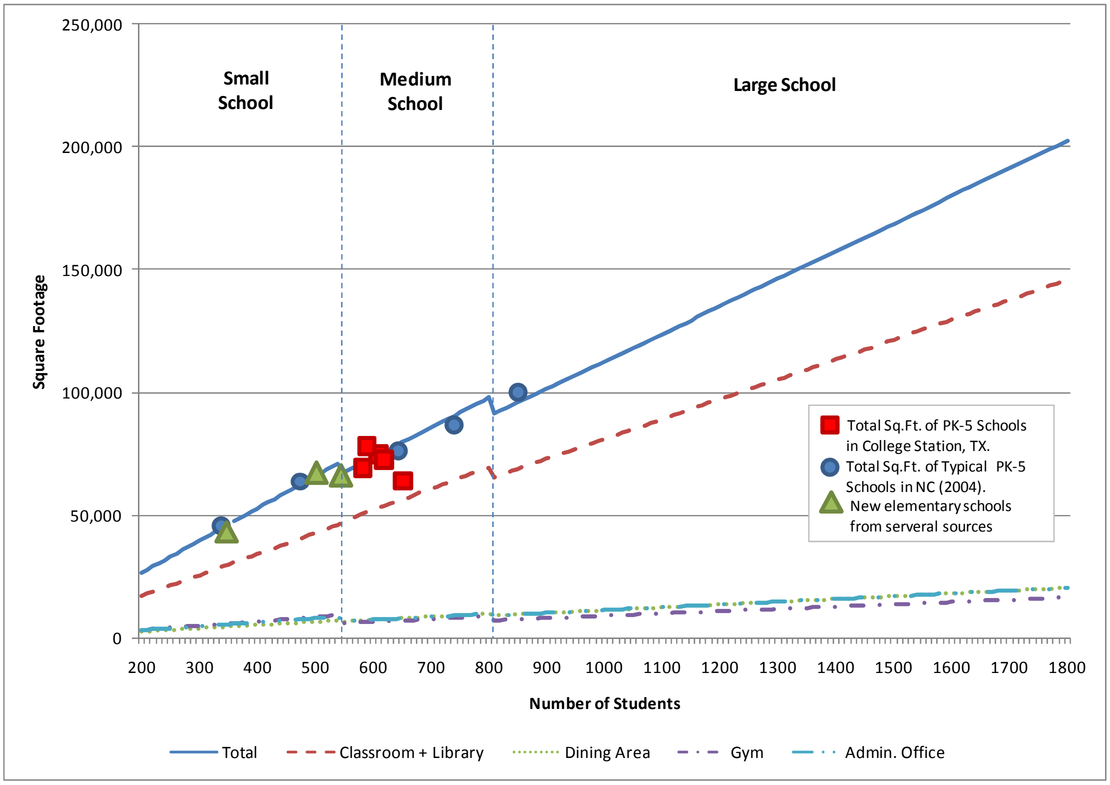


Figure 4.18 – Conditioned Area Requirements versus the Number of Students from Several Sources

In order to validate these relationships, several actual building data points are superimposed over the graph in Figure 4.18. One set of the data points was from a typical K-5 school. Also, the data points of relatively new school buildings that have been built in 2002 through 2006 from the neaby town in central Texas are plotted. Finally, the data point of the case-study elementary school in Central Texas is plotted. The percentage difference between the actual gross square footage of these schools and the calculated gross square footage (i.e., sq.ft./student times number of student) is about 6%, which is considered acceptable.

4.6.3 Development of the DOE-2 Input File

As described earlier, after defining the prototype school building geometry, a simplifiedDOE-2 input was developed for the building using DOE-2's input macro commands. According to the DOE-2 manual (LBNL 1993), the Input Macros features was added to the Building Description Language in DOE-2.1D to increase the flexibility of BDL. By using this command, developers can selectively accept or skip portions of the input, perform arithmetic and logical operations on the input values, and incorporate external files containing separate pieces of BDL into the main DBL input file. Therefore, this Input Macro command was used for the prototype school input file so that a user could change the building shape and other parameters without modifying the original input itself.

4.6.4 Verification of the Tool

After developing the DOE-2 simulation input for the easy-to-use tool, the simulation results from the easy-to-use input were verified by comparing with the ASHRAE Standard 90.1-1999 compliant case-study simulation result. Since the current version of the tool only has LOAD Input Macros, the simulation results for the LOAD part (i.e., Report LS-D: Building Monthly Loads Summary) was compared to each other.

The report LS-D provides the monthly cooling, heating and electrical energy needed for the building without HVAC system integration.

4.6.5 Summary of Development of an Easy-to-use Simulation Input

As a final step of the study, the specification for the easy-to-use simulation tool were developed, including the methodology to develop a flexible DOE-2 simulation input which will be the calculation engine for the proposed web-based final tool. As a first step, the standard school building shape, school size, and common spaces required for the K-12 school buildings were reviewed from a set of survey, literature review, and the published construction statistics. After defining the standard school building, a DOE-2 simulation input was developed using DOE-2's "Input Macros", so that users can change the school simulation only using only a set of limited input parameters without modifying the original DOE-2 simulation input file.

4.7 Summary of the Methodology

A methodology to develop a simplified simulation tool for investigating the preliminary design of new high performance schools in hot and humid climates has been described in this section. The methodology includes: 1) A survey of high performance measures for schools to select a group of high performance measures for hot and humid climates; 2) An analysis of a base-case-study school to better understand the patterns of school energy consumption; 3) Performing an as-built, calibrated simulation for the case-study building; 4) An analysis of a daylighting simulation using the DOE-2 program; 5) Applying the selected high performance measures to the case-study school to calculated the energy saving potential; and finally 6) A methodology for developing and verifying an easy-to-use simulation tool for schools. The results of the application of the methodology described in this section will be discussed in the following chapters.

CHAPTER V

RESULTS: ANALYSIS OF A CASE-STUDY SCHOOL

This chapter presents the results of the analysis of a case-study school. As described in Chapter IV, this analysis includes a detailed description of the school, the data measurement results, and an evaluation of the indoor conditions.

5.1 Case-study School Building Description

Table 5.1 describes the detailed building characteristics of the case-study school that were used for the as-built simulation. Figures 4.2 and 4.3 provide a plan view of the case-study school. As previously described, the case-study school is a single-story building with approximately 74,000 square feet of total conditioned floor area. The front facade of the building is oriented northeast. The school employs a 2"x6" stud wall construction with 3" face brick, 1" air layer, 2" of rigid insulation, 6" of light weight concrete masonry, and ½" gypsum board, which gives a U-value of 0.085 Btu/hr-sqft-F (i.e., 11.76 R-value). The roofing is a built-up type roof with ¾" rigid insulation and 3 ½" batt insulation above the acoustic ceiling tiles, which gives a U-value of 0.054 Btu/hr-sq.ft.-F (i.e., 18.52 R-value). The floor is an uninsulated light weight 4" concrete slab construction, which gives a U-value of 0.43 Btu/hr-sq.ft.-F. The building has seven HVAC systems that consist of three types of HVAC systems, including three VAV systems, three constant volume systems, and one multizone system. Each system with the corresponding spaces served is shown in Table 5.1. The building has two air-cooled scroll chillers, one boiler, and two service water heaters. Figures 5.1 through 5.4 are pictures of the chiller, boiler, service water heater and pumps. The size and the efficiency of this equipment is also shown in Table 5.1.

Table 5.1 - Case-study Building Characteristics

Description		Case Study School
General		
	Location (Logitude & Latitude)	Longitude: 96.30 Latitude: 30.57
	Floor Area, ft2	74,905
Architectural Features		
	Number of Floors	1
	Window-to-Wall Ratio	10%
	Floor-to-Ceiling Height	
	Classroom	9
	Gymnasium	23.5
	Admin. Office	9
	Cafeteria	23.5
	Exterior Wall	
	Structure	3” face brick + 1” air layer + 2” rigid insulation + 6” light weight concrete masonry + ½” gypsum board
	Calculated U-Factor (Btu/hr-ft2-F)	0.085
	Roof	
	Structure	¾” rigid insulation + 3 ½” batt insulation above the acoustic ceiling tiles
	Calculated U-Factor (Btu/hr-ft2-F)	0.054
	Slab-On-Grade Floor	
	Structure	light weight 4” concrete slab construction
	Calculated U-Factor (Btu/hr-ft2-F)	0.043
	Windows	
	Structure	Single Pane Glass
	Calculated U-Factor (Btu/hr-ft2-F)	1.09
	Shading Coefficient	0.59
Internal Loads		
	Number of Student	600
	Occupancy Schedule and Density (in separate table)	
	People Load (Sensible and Latent heat gain)	
	Lighting Fixture	T-8 with Electronic Ballas
	Lighting Density (W/sqft)	1.2
	Equipment Density (W/sqft)	0.6
	Lighting & Equipment Schedule (in separate table)	

Table 5.1 - Continued

Description		Case Study School
HVAC Systems		
	System type and assigned spaces	3 VAV with reheat: Classrooms + library 3 CV with reheat: Common area (i.e., cafeteria, gymnasium, and kitchen) 1 MZU: Administration office
	Set temperature for each space	Cooling: 72F Heating: 72F
	Space T-stat setup/setback	Cooling: 80F Heating: 55F
	Design Supply Air	55F
Plant		
	Chiller	
	Number of chiller	2
	Size	95.7 tons each
	Chiller COP	2.8 COP
	Boiler	
	Number of Boiler	1
	Size	2.05 MBtu/hr
	Boiler Thermal Efficiency	0.82
	SWH	
	Number of Service Water Heaters	2
	Size	100 gallon
	SWH Efficiency	78.6 E_t
	Pump	
	Number of Pump	2 for Chiller, 1 for Boiler

Figure 5.1 - Air-Cooled Scroll Chiller for the Case-study School

Figure 5.2 - Hot Water Boiler for the Case-study School

Figure 5.3 - Service Water Heaters for the Case-study School

Figure 5.4 - 2 Pumps for Chillers (2) and for Boiler (1)

5.1.1 Building Schedules

The building's occupancy schedules, lighting & equipment schedules, and the HVAC operational schedules were determined from interviews with the maintenance personnel of the school district. Table 5.2 presents the occupancy schedule for the case-study school. Table 5.3 shows the HVAC operational schedules for each space of the case-study school, which was also developed based on the interviews.

5.2 Results: Data Measurement

As described earlier, several datasets have been either measured or collected from previous studies in order to verify the indoor conditions at the school and to be used for the calibrated simulation. These data include the hourly electricity use from the previously installed data logger, the monthly utility bills from the school district, temperature and RH measurements from six portable loggers, and CO_2 concentration levels measured using a CO_2 sensor and data logger.

5.2.1 Energy Use: Hourly Electricity Use and Utility Bills

The pre-installed data logger at the site recorded the hourly electricity use for the chillers, the motor control center (MCC), and the whole-building electricity. Since the natural gas use was not being recorded by the logger, the monthly utility bills were used to identify the natural gas use. In addition, the monthly electricity use from the utility bills was compared to the electricity use measured by the data logger in order to verify the data measured from the data logger. For this study, the hourly electricity use during

Table 5.2 – School Occupancy Schedule by Space

Grade	# Student	Conference (Gym)	Lunch (Cafeteria)	Recess (Outdoor)	Library
HS	18		11:35 -12:05	8:30-9:30	TH 10 -10:30
PPCD	10			8:30-9:30	TH 1:30 - 1:45
K	22	1:15-2:15	11:09 - 11:39	10:25 -10:55	F 12:30 - 1:00
K	22	1:15-2:15	11:12 - 11:42	10:25 -10:55	Th12:30 - 1:00
K	22	1:15-2:15	11:00 - 11:30	10:25 -10:55	W 12:30 -1:00
K	22	1:15-2:15	11:06 - 11:33	10:25 -10:55	M 12:00 - 12:30
K	22	1:15-2:15	11:03 - 11:33	10:25 -10:55	Tu 12:30 -1:00
Sub-total	110				
1	22	12:10 - 1:10	11:32 - 12:02	1: 55 -2:25	M 9:00 - 9:30
1	22	12:10 - 1:10	11:23 - 11:53	1: 55 -2:25	F 9:00 - 9:30
1	22	12:10 - 1:10	11:29 -11:59	1: 55 -2:25	Th 10:30 -11:00
1	22	12:10 - 1:10	11:26 - 11:56	1: 55 -2:25	Tu 10:30 -11:00
1	22	12:10 - 1:10	11:17 - 11:47	1: 55 -2:25	W 9:00 - 9:30
1	22	12:10 - 1:10	11:20 - 11:50	1: 55 -2:25	W 10:30 - 11:00
Sub-total	132				
2	22	10:10 - 11:10	11:49 - 12:19	11:30 1- 1:00	M 8:30 - 9:00
2	22	10:10 - 11:10	11:43 - 12:13	11:30 1- 1:00	Tu 2:00 -2:30
2	22	10:10 - 11:10	11:52 - 12:22	11:30 1- 1:00	F 8:30 - 9:00
2	22	10:10 - 11:10	11:46 - 12:16	11:30 1- 1:00	W 9:30 -10:00
2	22	10:10 - 11:10	11:40 - 12:10	11:30 1- 1:00	M 2:00 - 2:30
Sub-total	110				
3	22	9:05 - 10:05	12:06 - 12:36	11:20 - 11:50	Th 1:00 - 1:30
3	22	9:05 - 10:05	12:00 - 12:30	11:20 - 11:50	W 8:30 - 9:00
3	22	9:05 - 10:05	12:03 - 12:33	11:20 - 11:50	Th 8:30 - 9:00
3	22	9:05 - 10:05	11:57 - 12:27	11:20 - 11:50	W 2:00 - 2:30
3/4	22	9:05 - 10:05	12:09 - 12:39	11:20 - 11:50	M 10:30 - 11:00
Sub-total	110				
3/4	22	8:00 - 9:00	12:14 - 12:44	2:25 - 2:55	M 10:00 - 10:30
4	22	8:00 - 9:00	12:23 - 12:53	2:25 - 2:55	F 9:30 - 10:00
4	22	8:00 - 9:00	12:17 - 12:47	2:25 - 2:55	Tu 9:30 - 10:00
4	22	8:00 - 9:00	12:26 - 12:56	2:25 - 2:55	F 1:30 - 2:00
4	22	8:00 - 9:00	12:20 - 12:50	2:25 - 2:55	Tu 1:30 - 2:00
Sub-total	110				
Total	600				

2006 was downloaded, and hourly time series plots and daily scatter plots were generated. Figures 5.5 and 5.6 show the time series and the daily scatter plots, respectively. As shown in the scatter plot for the whole building electricity use, there is a distinctly different weekday energy use group (i.e., the upper group) and weekend energy use group (i.e., the lower group). In addition, between the weekday and weekend energy use groups, there are a few days that fall outside the weekday-weekend group.

Table 5.3 - HVAC Operational Schedule

All HVAC except Administration Office and South Common

	Normal School Weekdays	Summer Vacation (Staff Working)	Summer Vacation (Staff Vacation)
Monday	5:00 am ~ 4:55 pm	5:00 am ~ 11:00 am	5:00 am ~ 11:00 am
Tuesday	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Wednesday	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Thursday	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Friday	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Saturday	Turned Off	Turned Off	Turned Off
Sunday	Turned Off	Turned Off	Turned Off

Administration Office and South Common

	Normal School Weekdays	Summer Vacation (Staff Working)	Summer Vacation (Staff Vacation)
Monday	5:00 am ~ 4:55 pm	5:00 am ~ 4:55 pm	5:00 am ~ 11:00 am
Tuesday	6:00 am ~ 4:55 pm	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am
Wednesday	6:00 am ~ 4:55 pm	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am
Thursday	6:00 am ~ 4:55 pm	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am
Friday	6:00 am ~ 4:55 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Saturday	Turned Off	Turned Off	Turned Off
Sunday	Turned Off	Turned Off	Turned Off

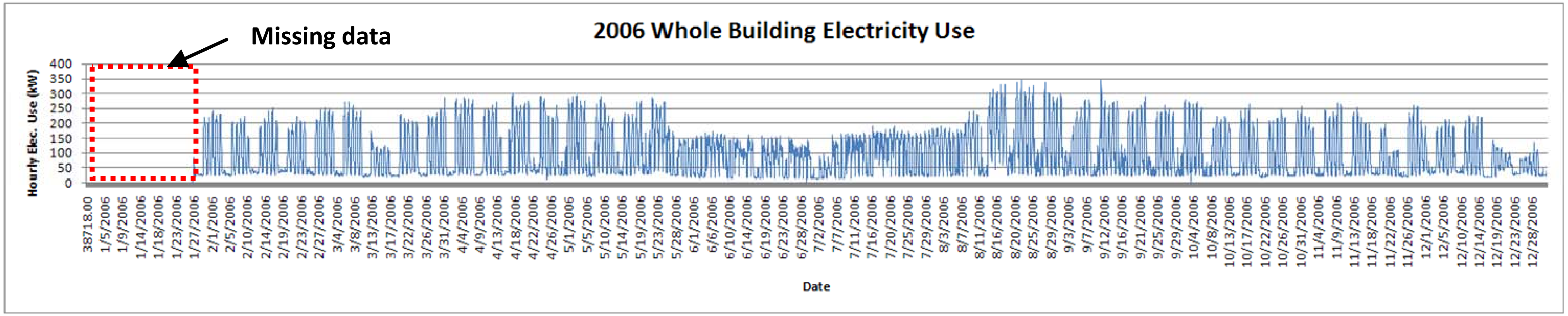
Kitchen

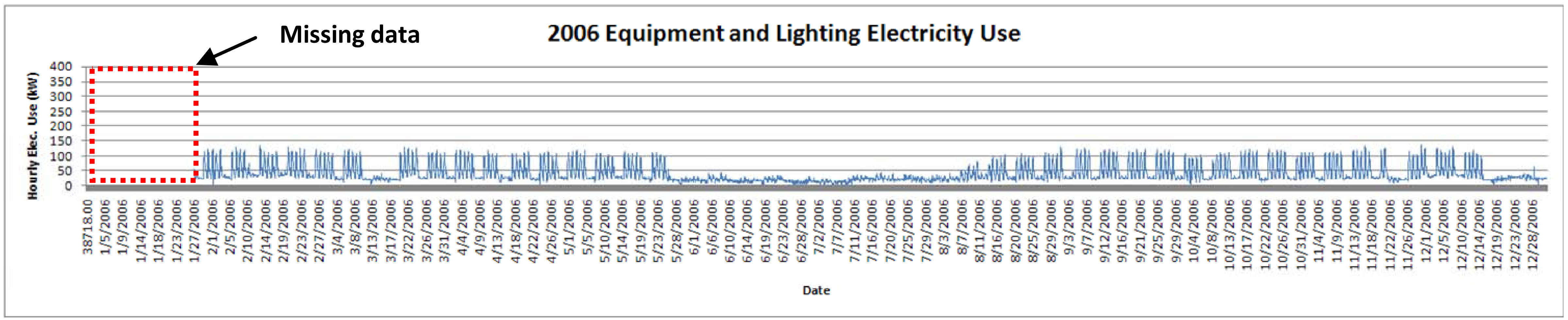
	Normal School Weekdays	Summer Vacation (Staff Working)	Summer Vacation (Staff Vacation)
Monday	5:00 am ~ 3:00 pm	5:00 am ~ 11:00 am	5:00 am ~ 11:00 am
Tuesday	6:00 am ~ 3:00 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Wednesday	6:00 am ~ 3:00 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Thursday	6:00 am ~ 3:00 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Friday	6:00 am ~ 3:00 pm	6:00 am ~ 11:00 am	6:00 am ~ 11:00 am
Saturday	Turned Off	Turned Off	Turned Off
Sunday	Turned Off	Turned Off	Turned Off

Set Point Temperature for Occupied and Un-occupied

	Occupied	Non-occupied
Heating	68 F	55 F
Cooling	72 F	80 F

In order to analyze these days in further detail, a scatter plot for the whole-building electricity by month was developed in Figure 5.7. As shown in this figure, the summer energy uses (i.e., part of May, June, July, and part of August) are in between the weekday and the weekend group because of the different summer schedules of the school. Also, part of March, November and December energy use was in between the weekday and weekend energy use. These days include the spring break, Thanksgiving day, and the Christmas-New Years vacation, respectively. Due to these varied patterns of energy use, the schedules of the school were carefully adjusted in the school simulation modeling procedure. The time series and the scatter plots shown in Figure 5.5 and 5.6 were used to





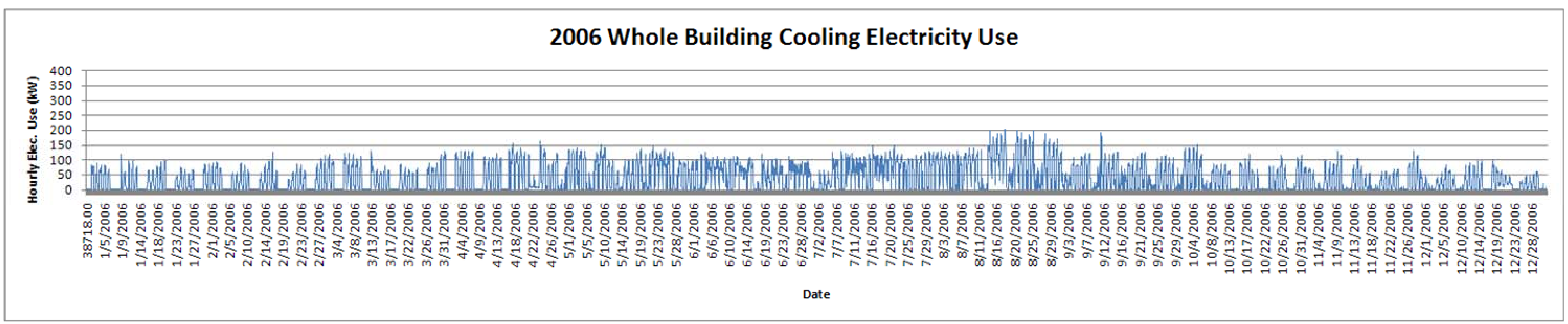


Figure 5.5 - 2006 Time Series Plots from the Data Logger Installed at the Case-study School

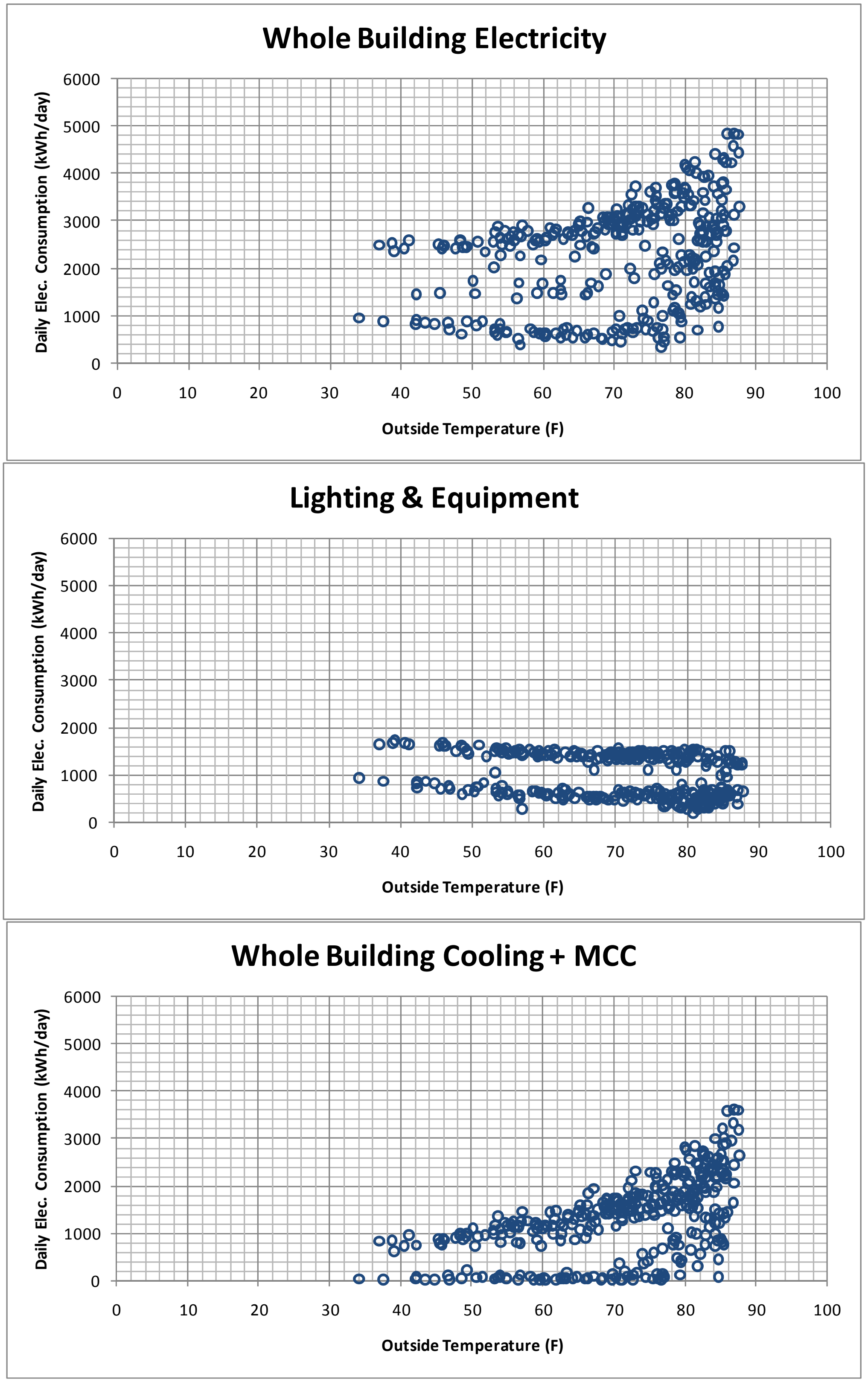


Figure 5.6 - Scattered Plot: Outside Temperature (F) vs. Daily Electricity Use (kWh/day)

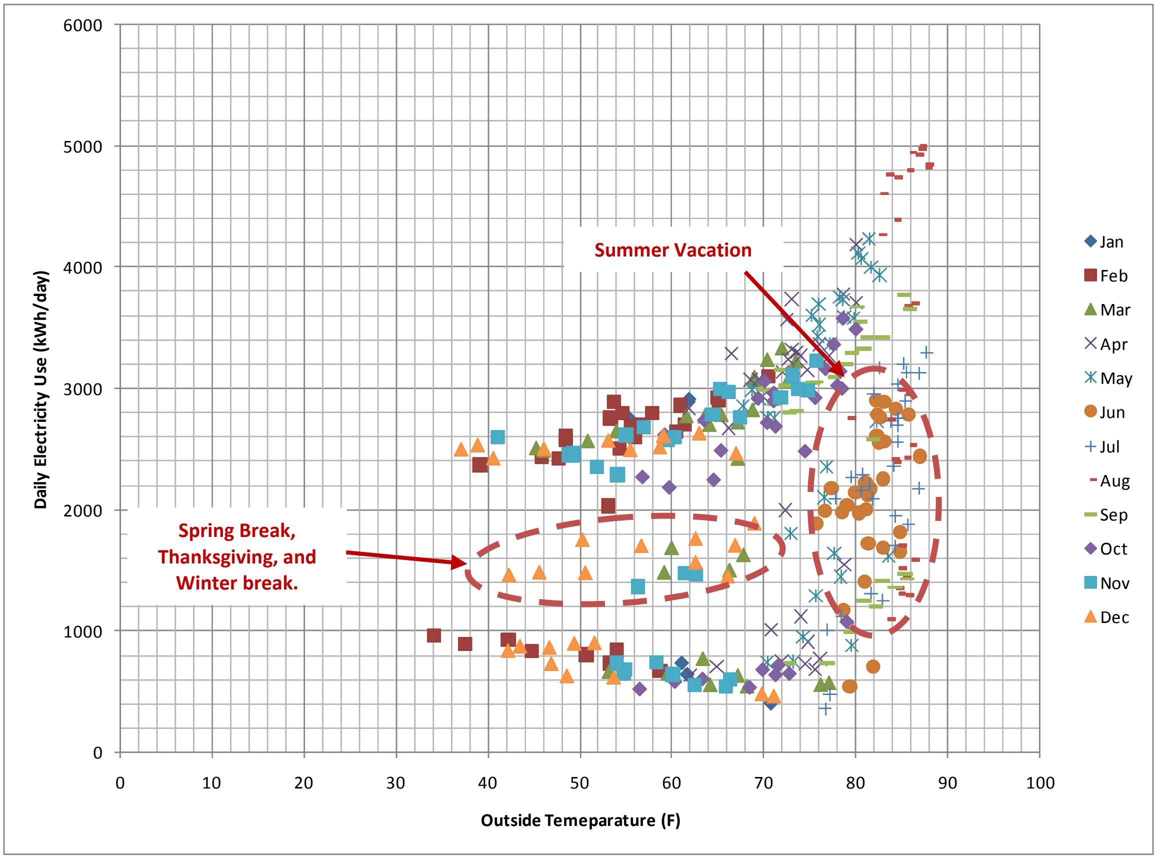


Figure 5.7 - Scattered Plot: Whole-Building Electricity Use (kWh/day) by Month vs. Outside Temperature (F)

calibrate simulation results by comparing the two uses (i.e., measured vs. simulated) using a graphical and statistical methods as described in Chapter IV.

As mentioned earlier, the monthly utility bills were compared with the measured data from the data logger. Table 5.4 and Figure 5.8 show the comparisons between the measured data and the data from the utility bills. In order to compare the hourly data to the monthly data, based on the meter reading date, the measured hourly WBE was summed and compared for the corresponding monthly billing period. As shown in the table, the differences between the utility bills and the measured data were about -1.4% to 1.6%. These differences were most likely caused by the unknown meter reading time for

Table 5.4 - Monthly Utility Bills vs. Measured Data

Month	Year	Reading Date	Number of Days	Monthly Electricity Use (Utility Bills) (kWh)	Monthly Electricity Use (Data Logger) (kWh)	% Diff.
Feb	2006	2/28/06	28	59,160	59,987	-1.4%
Mar	2006	3/30/06	30	63,240	62,239	1.6%
Apr	2006	4/28/06	29	74,400	75,162	-1.0%
May	2006	5/31/06	33	87,960	87,044	1.0%
Jun	2006	6/30/06	30	62,640	62,792	-0.2%
Jul	2006	7/31/06	31	67,320	68,170	-1.3%
Aug	2006	8/31/06	31	100,200	100,725	-0.5%
Sep	2006	09/29/06	29	77,640	76,747	1.2%
Oct	2006	10/31/06	32	70,200	70,154	0.1%
Nov	2006	11/30/06	30	61,680	61,305	0.6%
Dec	2006	12/29/06	29	50,640	50,731	-0.2%

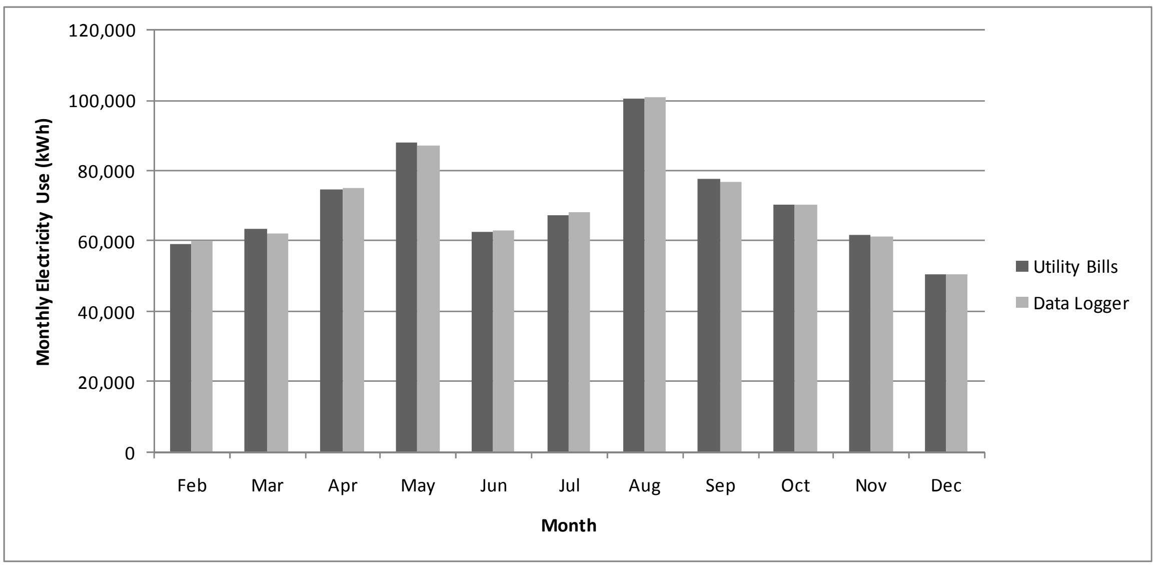


Figure 5.8 - Monthly Utility Bills vs. Measured Data

each reading day. Since the utility bill only provides the reading date, it was assumed that 12:00 AM was the reading time, and the measured data from the logger was summed.

Table 5.5 and Figure 5.9 present the monthly natural gas uses from the utility bills. In order to identify the natural gas use patterns, the daily average natural gas uses was plotted as a function of the corresponding average outdoor air temperature by month in Figure 5.10. As shown in Figures 5.9 and 5.10, the natural gas use during June through

Table 5.5 - Monthly Natural Gas Utility Bills

Month	Utility Bills						
	Billing Date	Days	Daily Average Temp. (F)	Monthly (CCF)	Monthly (MBtu)	Daily Average (CCF)	Daily Average (MBtu)
Jan	1/20/06	32	57.98	2,187	221.23	68.34	6.9
Feb	2/20/06	32	52.80	2,088	211.21	65.25	6.6
Mar	3/23/06	31	63.17	1,739	175.91	56.10	5.7
Apr	4/21/06	29	69.82	1,164	117.75	40.14	4.1
May	5/20/06	29	73.78	545	55.13	18.79	1.9
Jun	6/22/06	33	80.77	114	11.53	3.45	0.3
Jul	7/20/06	28	82.37	67	6.78	2.39	0.2
Aug	8/21/06	33	84.13	293	29.64	8.88	0.9
Sep	9/19/2006	29	81.64	255	25.79	8.79	0.9
Oct	10/19/2006	30	74.31	219	22.15	7.30	0.7
Nov	11/17/2006	29	62.98	673	68.08	23.21	2.3
Dec	12/18/2006	31	56.20	761	76.98	24.55	2.5
Total					1022		

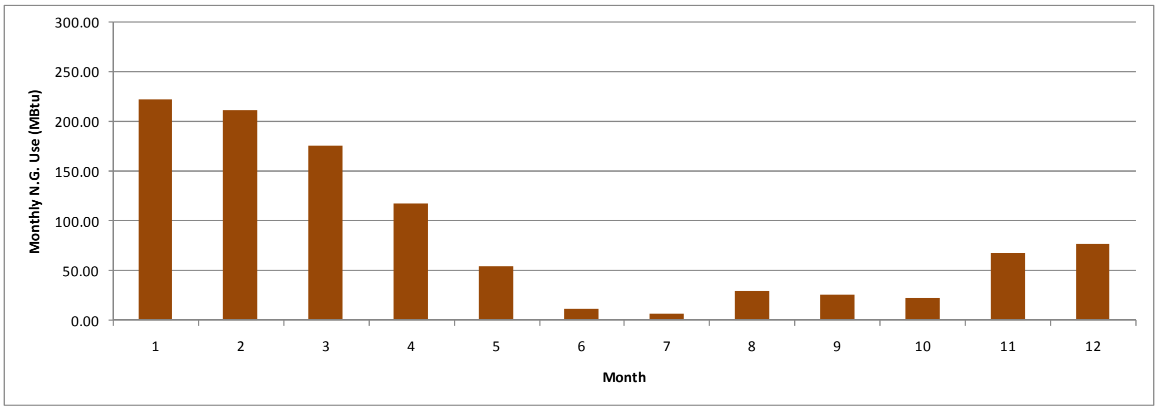


Figure 5.9 - Monthly Natural Gas Utility Bills

October was very small compared to the other months. According to the maintenance service in the school district office, the boiler in the school was turned-off manually during this period. In addition, the natural gas use during November and December was low compared to other months that have the same range of outdoor temperatures. Figure 5.10 is a scatter plot that shows the relationship between the daily natural gas use versus the corresponding outside air temperature for 2005 and 2006. As shown, the natural gas energy use in 2005 and in January through July in 2006 matches relatively well, whereas the natural gas use in August through December in 2006 is lower than 2005 and first half of 2006. Figure 5.11 that shows the monthly natural gas use from 2005 and 2006 with the average outside air temperatures also describes the same pattern of natural gas use. An interview with the maintenance personnel verified that there was a car accident in August 2006 at the school, which resulted in the replacement of the natural gas meter at the school. Therefore, one explanation could be that the new natural gas meter measured the correct natural gas use (i.e., old natural gas meter overestimated the natural gas use) or vice versa. This natural gas use pattern can be found from the comparison with the previous year's natural gas use. Given this uncertainty, the calibration of the simulated natural gas use to the measured use will not be a big concern in this study.

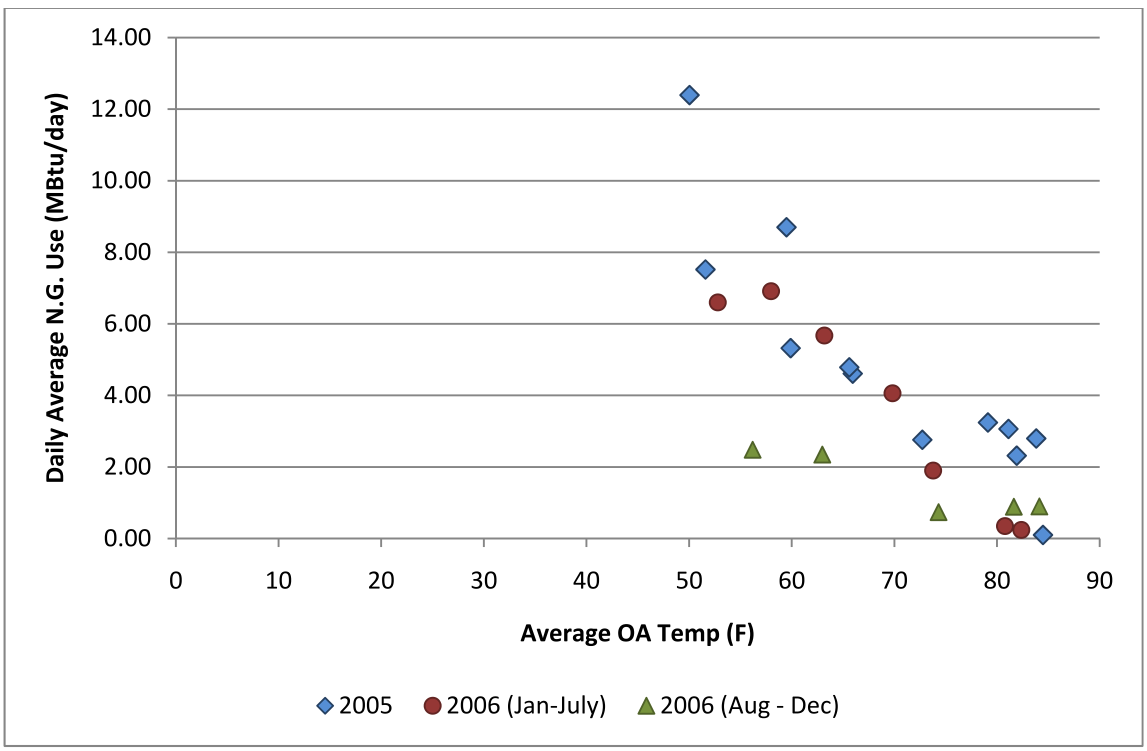


Figure 5.10 - Scatter Plot: Daily Average Natural Gas Use vs. Average Daily Temperature (F) in 2005 and 2006

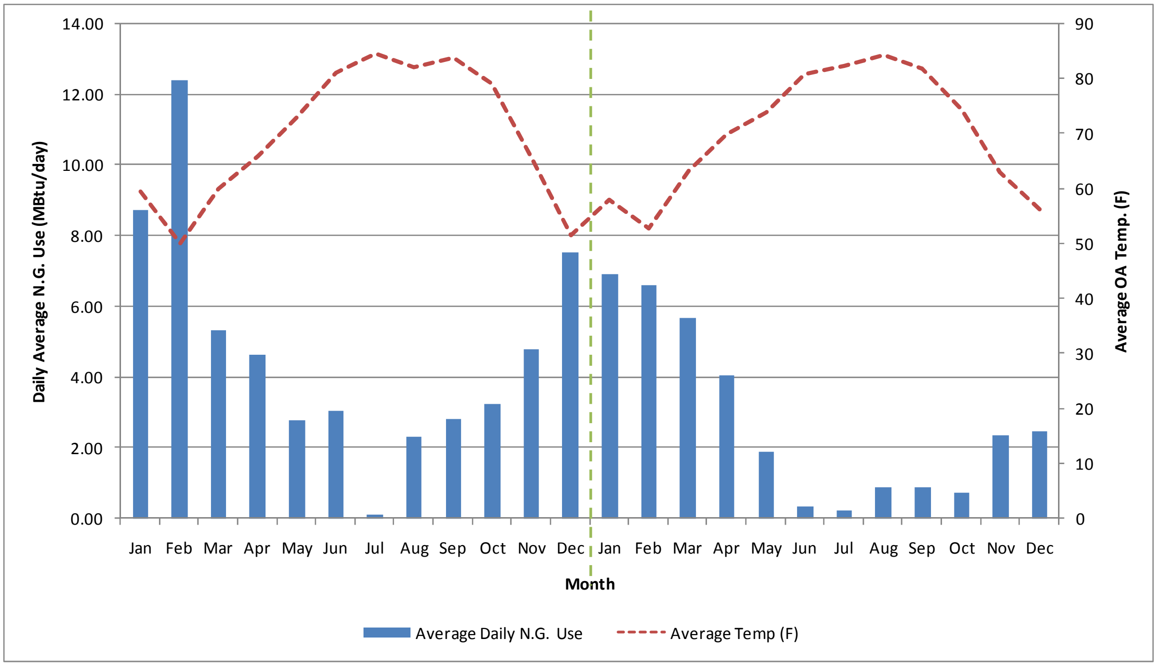


Figure 5.11 - 2005 and 2006 Natural Gas Use and Average Monthly Outside Air Temperature

5.2.2 Data Measurement: Temperature and RH Measurement

This section discuss the results of the temperature and RH measurement from six locations in a classroom and the AHU mechanical room serving the classroom in the case-study school during portions of 2006, including: 1) the spring semester before the summer vacation (i.e., May 3, 2006 to May 23, 2006), 2) the summer vacation (May 23, 2006 through July 26, 2006), and 3) the fall semester (i.e., August 23, 2006 through November 3, 2006). The time series graphs for the hourly temperatures and the relative humidities from the six locations during all the periods are presented in Appendix C.

Since the building's HVAC system was operated during the weekdays in general, in order to verify whether or not the indoor space conditions were in the thermal comfort zone defined by ASHRAE Standard 55-1999 during occupied hours, the raw data were divided into occupied hours and unoccupied hours. Next, data points representing the temperatures and relative humidities during the occupied hours were superimposed onto the psychometric chart shown in Figure 5.12. As shown in this chart, in general, the indoor conditions in this classroom are well within the comfort zone. The range of indoor temperatures was from 68 F to 78 F, which is almost from the lower to upper limitation of the comfort zone. The range of indoor RH was from 40% to 60%, which is distributed well within the comfort zone.

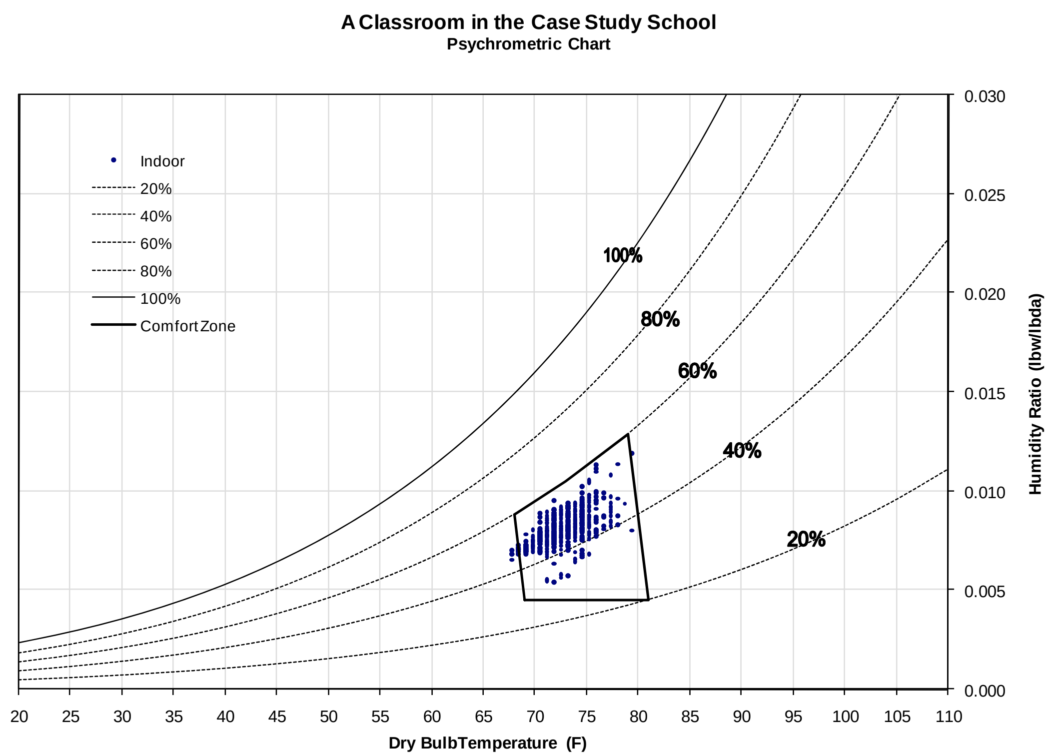


Figure 5.12 - Indoor Conditions in a Classroom

For a more detailed inspection, two typical days in the spring semester (i.e., May 15 & 16) were selected, and the data for the days were plotted as shown Figures 5.13 and in 5.14. As shown in Figure 5.13 and 5.14, the indoor classroom temperature range during occupied hours was from 69 F to 73 F. During the occupied hours, the relative humidity level was in the range of 40 to 50%.

The HVAC supply air temperature was in the range of 48 to 52 F during the occupied hours, and then rose to approximately 70 F when the AHU was turned-off. Since the HVAC supply temperature identified from the interview with the maintenance person was 55 F, the measured temperatures showed considerably lower temperature, which will be reflected in the as-built model.

One observation from the measurements is that it is a reflection of the portion of outside air in the mixed air. As shown in Figures 5.13 and 5.14, the HVAC mixed temperature is almost the same as the mixed room temperature during occupied hours. This would imply that a very small portion of outside air is being mixed with the return air. This is most likely the mean reason for the measured high CO_2 concentration in classrooms, which will be discussed next.

5.2.3 Data Measurement: CO_2 Concentration

Along with the temperature and RH measurements, the CO_2 concentration levels in the return duct were measured in order to evaluate the indoor air quality. Figure 5.15 presents the measured CO_2 levels during August 23 through September 17. Since the CO_2 level was measured in the return duct in the mechanical room when the air-handling unit was running, the CO_2 concentrations were from all the classrooms served by AHU #1. As

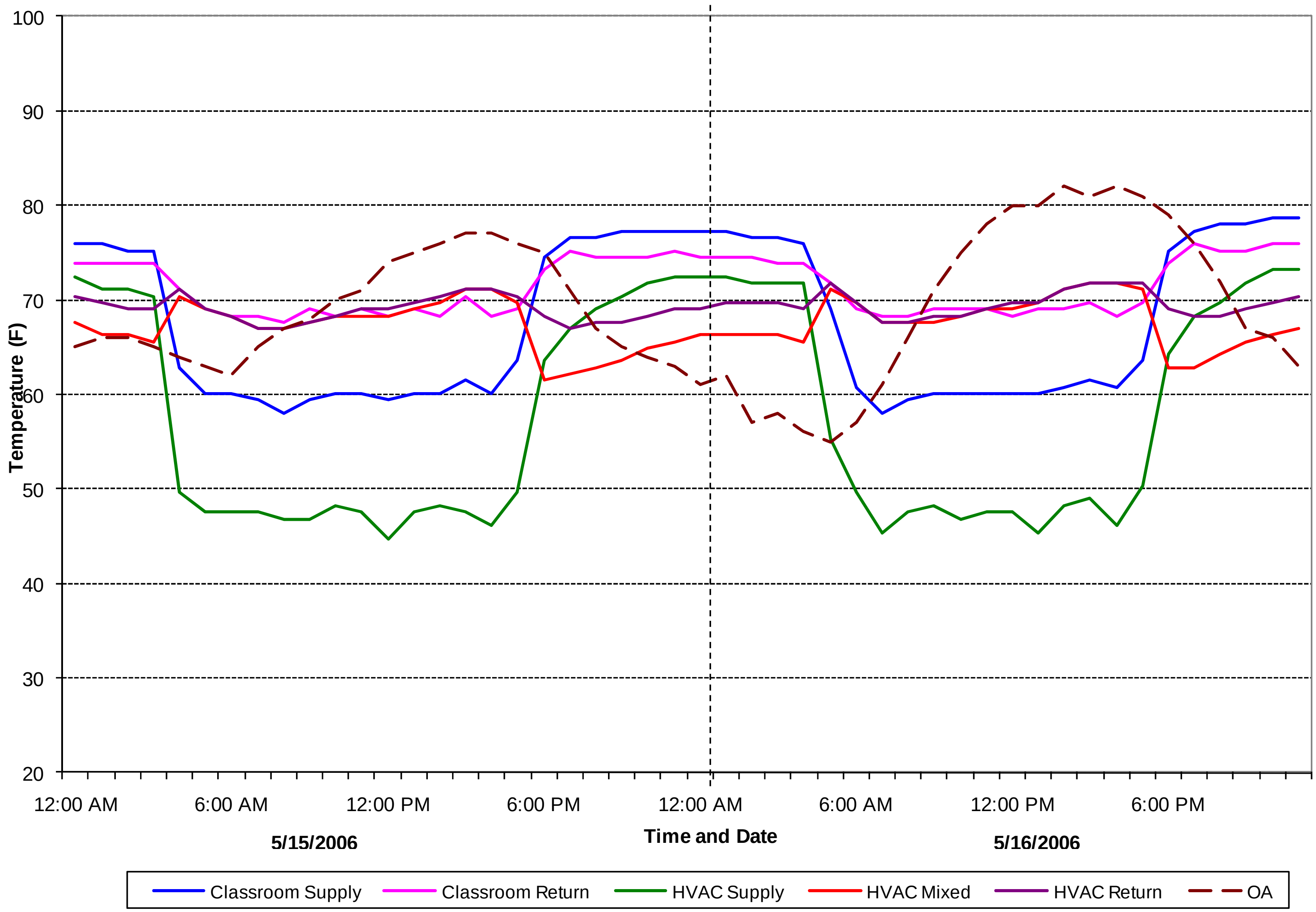


Figure 5.13 - Temperature Profiles for May 15 and May 16, 2006 (From the Case-study School)

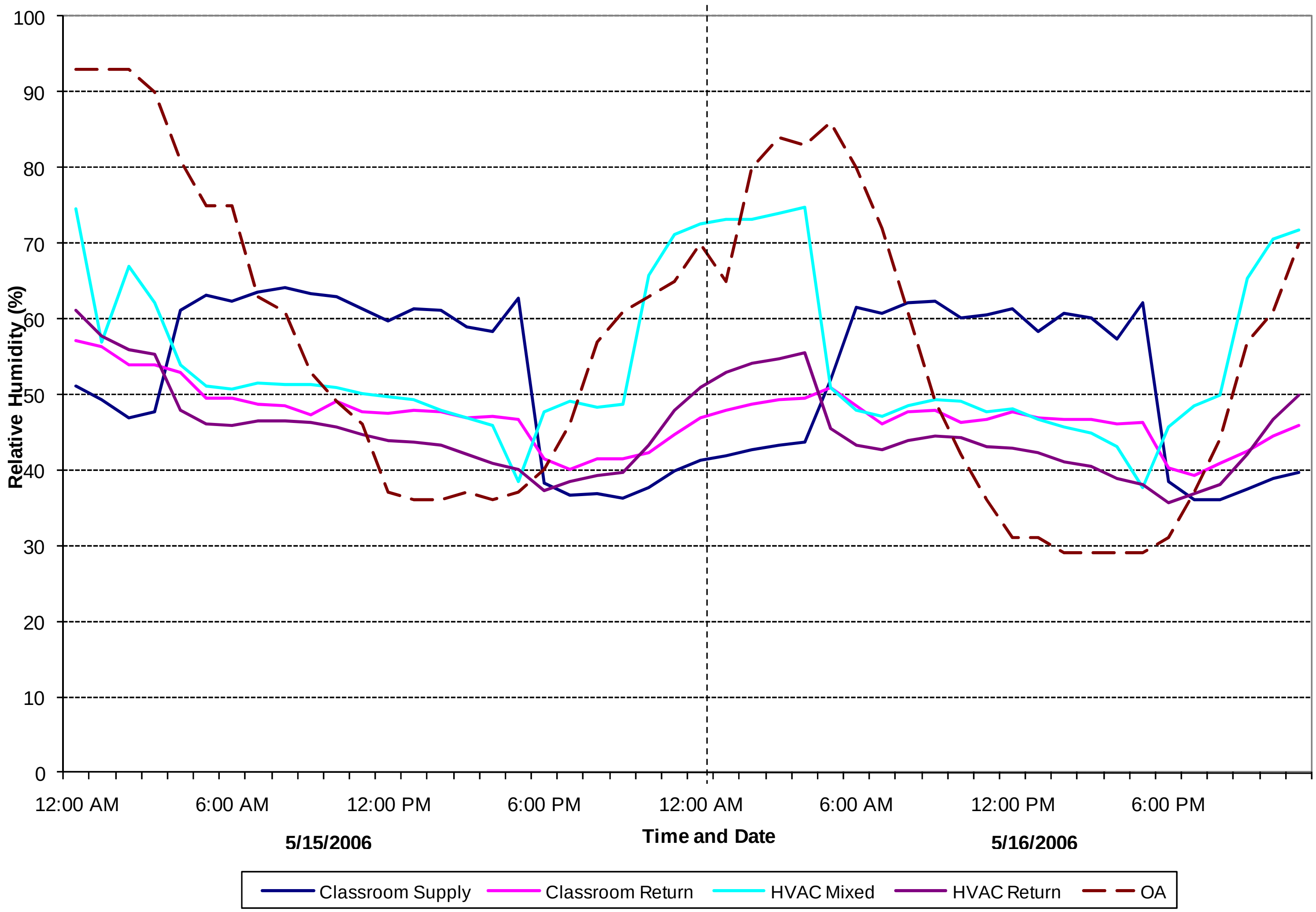


Figure 5.14 - Relative Humidity Profiles for May 15 and May 16, 2006 (From the Case-study School)

described in Chapter II, CO_2 concentrations are often considered as a surrogate for indoor air quality. CO_2 concentration over 1,000 ppm indicates indoor air quality problems (Seppanen et al., 1999; Apte et al., 2000). Such problems can be associated with several symptoms such as drowsiness, itchy eyes, coughing, asthma, etc. As shown in Figure 5.15, during the main portion of the day, the CO_2 concentrations are over 1,000 ppm (maximum 1,500 ppm). The most like cause of this is inadequate fresh air supply during occupied hours. Currently, ASHRAE 62-1999 recommends at least 15 CFM/person of ventilation rate for school building. Therefore, when the code-compliant school simulation is modeled in later phase of this research, the outdoor air ventilation rate will be increased from 5 CFM/person which is the value from the as-built design to be compliant to ASHRAE 62-1999 to provide outdoor air for the occupants. Another finding from the measurements was that the CO_2 concentration levels during unoccupied period drop almost to the ambient CO_2 concentration level. This may be indicating that too much outdoor air infiltrates into the building during unoccupied periods perhaps caused by continuous bathroom exhaust.

5.3 Summary of Data Measurement

The results of the analysis of the case-study school were discussed in this chapter. First, the detailed information of the case-study school was described and summarized in Table 5.1. An as-built simulation will then be modeled based on the information shown in this table. In order to be used in calibration procedure, several data were measured and the results were presented in this chapter. The findings from the analysis of the measured data are as followings.

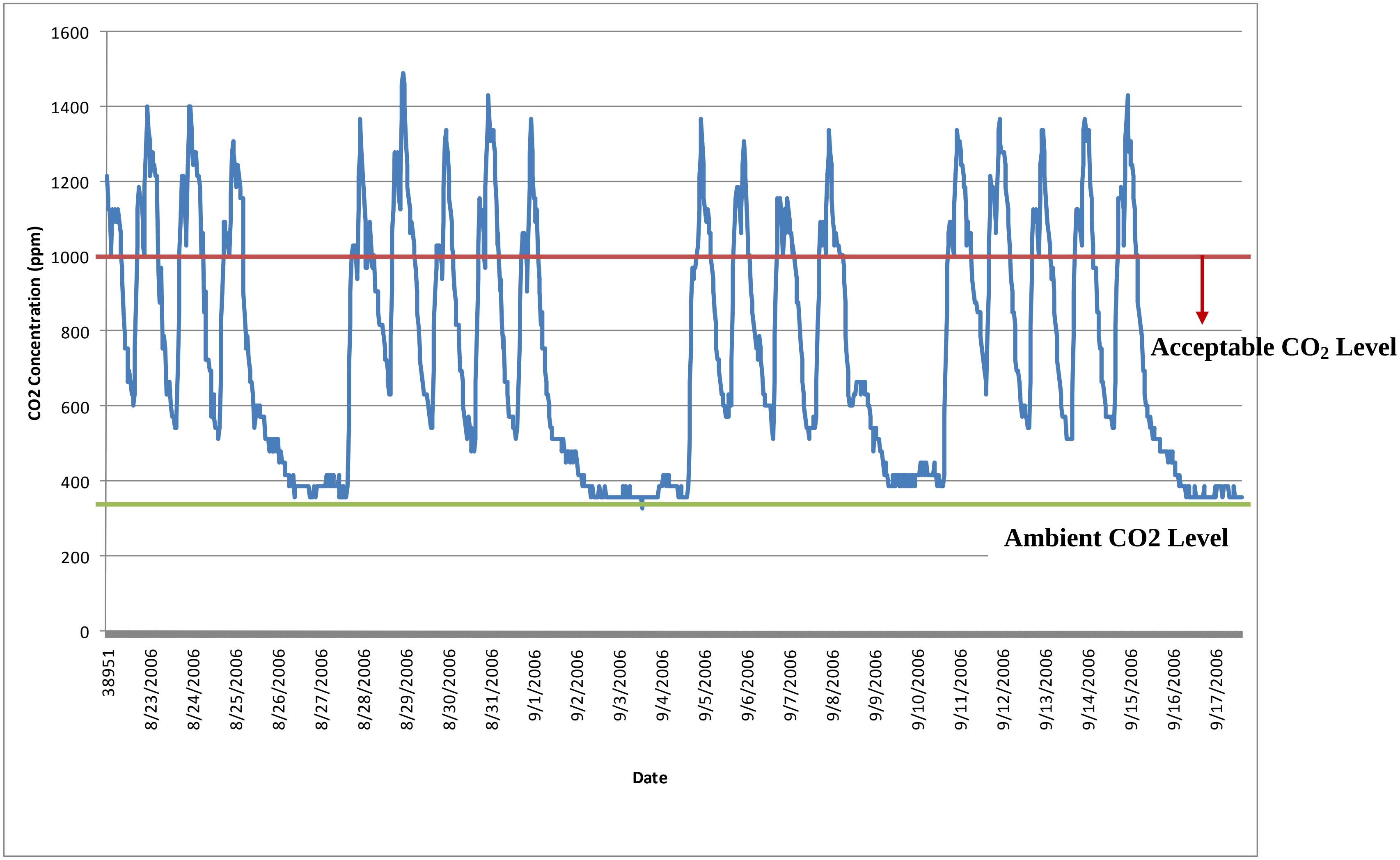


Figure 5.15 - CO_2 Concentration Profile

- The time series and the scatter plots for the hourly, whole-building electricity use described the patterns of the school energy use, including: summer use and several school holidays. Therefore, different schedules for these periods will be modeled in simulation procedure.
- The data measurement from the portable loggers showed that the indoor temperature and relative humidity in the classrooms during occupied hours were within the comfort zone defined in ASHRAE Standard 55-1999.
- The measured HVAC supply temperatures are about 48 to 52 F, which is lower than the supply temperature (i.e., 55F) identified from the interview with the maintenance personnel. The measured temperatures will be used in the calibration procedure.
- The measured CO_2 concentration levels show that the CO_2 concentration levels during major portion of the occupied hours are above 1,000 ppm, which is the recommended upper limit by ASHRAE (ASHRAE 1999). Inadequate outside air ventilation rates during occupied hours would be the main reason for this problem.
- Too much outside air may infiltrate into the building during unoccupied period based on the CO_2 level dropping nearly to the ambient level.

CHAPTER VI

RESULTS: CALIBRATED SIMULATION

This chapter presents the results of the calibrated simulations for the case-study school. As described in Chapter IV, five (5) calibration steps were performed to match the simulation results with the measured energy use. For each step of the calibrated simulation, the simulated energy use will be compared to the measured energy use, and the NMBE and CV(RMSE) calculated to assess the goodness-of-fit of a simulation model. This chapter shows the comparison plots, NMBE and CV(RMSE) for each step of the calibration.

6.1 As-built Simulation

The as-built simulation input was developed based on the information shown in Table 5.1 in Chapter V. The occupancy, lighting and receptacles and HVAC operating schedules were developed based on the interview with the maintenance personnel. The detailed building geometry used the architectural drawings. Figure 6.1 shows the DrawBDL (Huang 2000) image of the modeled geometry. Also, Figures 6.2 through 6.5 present the elevations for four orientations.

An as-built simulation using the DOE-2 simulation program and the Houston TMY2 weather file was performed, and the hourly simulation results extracted from the simulation output file. Figure 6.6

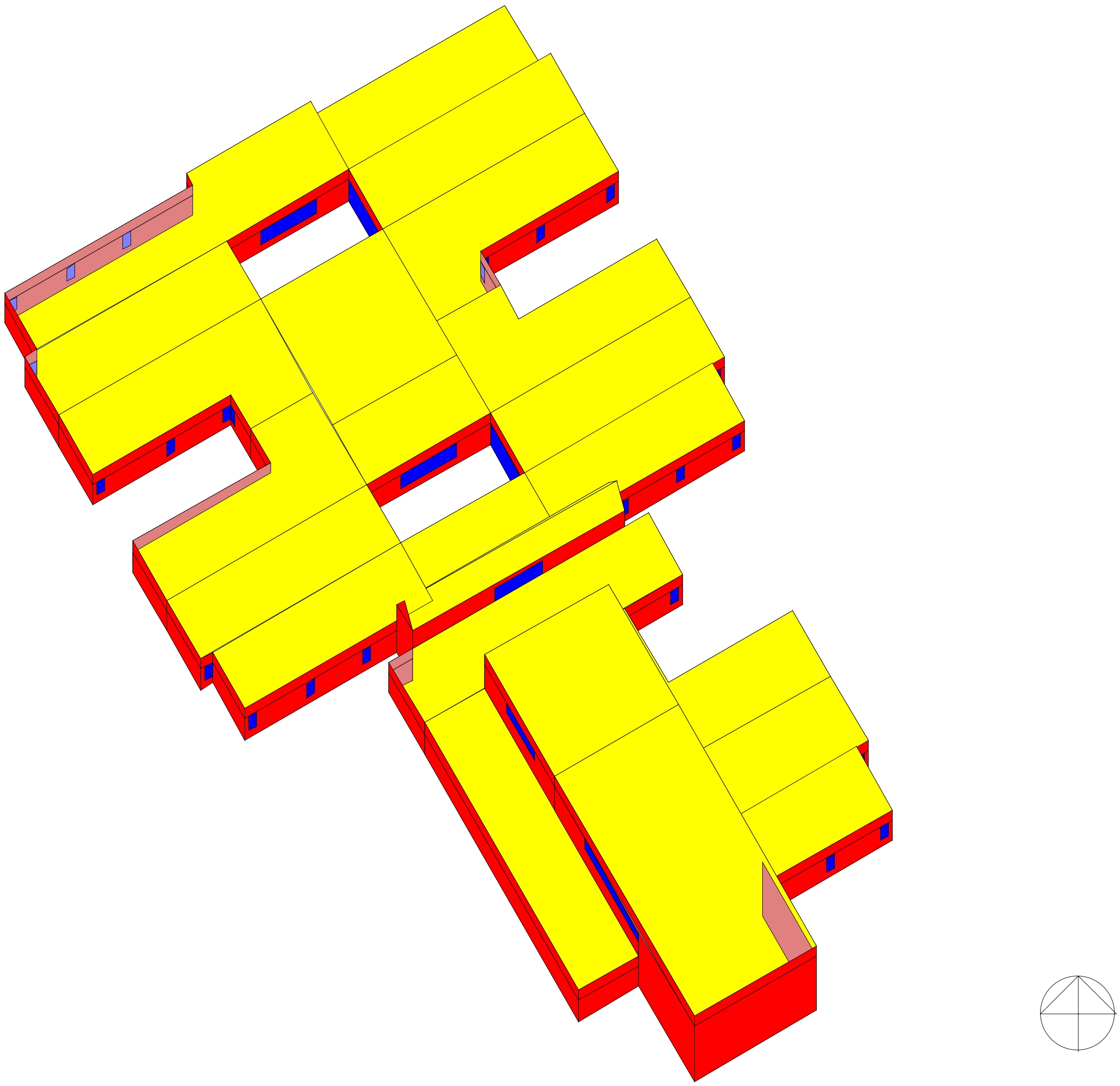


Figure 6.1 - DrawBDL of the Case-study School

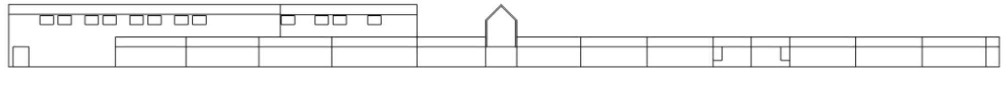


Figure 6.2 - Front (North) Elevation of the Case-study School

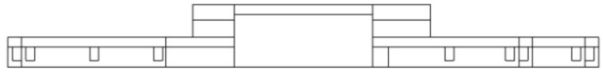


Figure 6.3 - Side (East) Elevation of the Case-study School

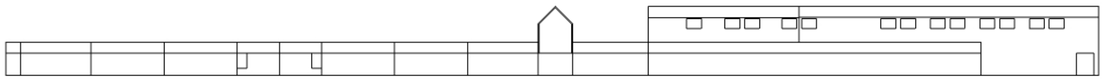


Figure 6.4 - Rear (South) Elevation of the Case-study School

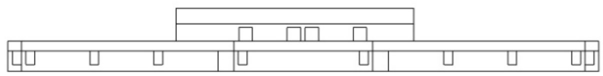


Figure 6.5 - Side (West) Elevation of the Case-study School

presents time-series and scatter plots for whole building electricity, lighting & equipment, whole building cooling, and natural gas end uses. Several findings from this comparison are as followings

1) The simulated lighting & equipment energy use was lower than the measured lighting and equipment data. An incorrect lighting & equipment schedule or lighting power density (W/sq.ft.) would be the main reason for this. Also, there appeared to be some lighting and equipment energy use even during weekends and summer vacation, whereas the simulation was assumed that there would be no lighting and equipment energy uses. This can be observed when the blue line (i.e., the simulated use) is zero during summer vacation and weekends, but the red line (i.e., the measured use) is not zero during the same period in Figure 6.6.
2) The simulated cooling energy use was also lower than the measured data.

3) The simulated natural gas use was higher than the measured use in all months.

As described in Chapter IV, the NMBE and CV(RMSE) for as-built simulation were calculated to assess the goodness-of-fit. The as-built simulation gave a NMBE of 10.2% and a CV(RMSE) of 35.5% for the WBE. The NMBE and CV(RMSE) for sub-uses are shown in Table 6.1.

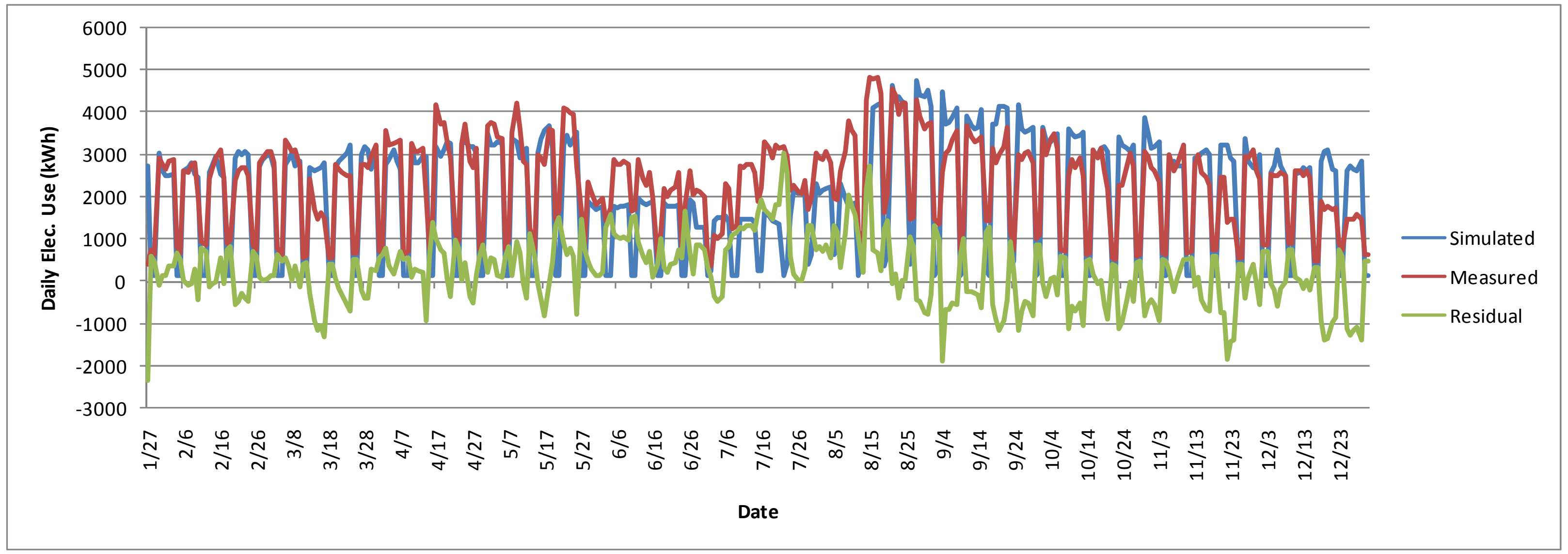
Table 6.1 - NMBE and CV(RMSE) for As-Built Simulation

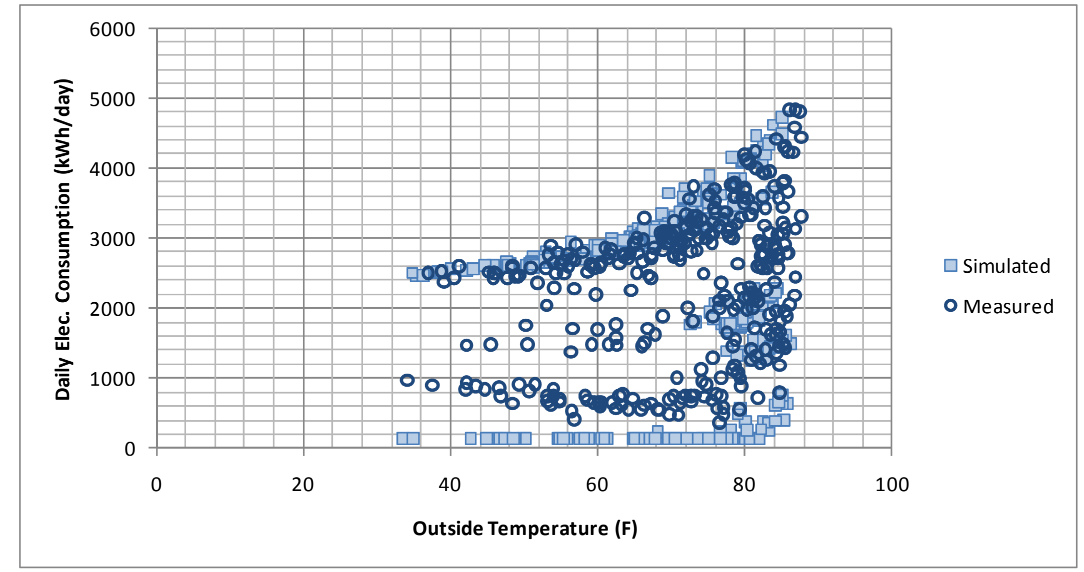
	Whole Building Electricity	Lighting & Equipment	Whole Building Cooling + Motor Control Center	Natural Gas
NMBE	10.18%	50.25%	-19.42%	-33.93%
CV(RMSE)	35.47%	56.71%	56.10%	50.48%

6.2. Step 1: Use of 2006 Measured Wether Data File

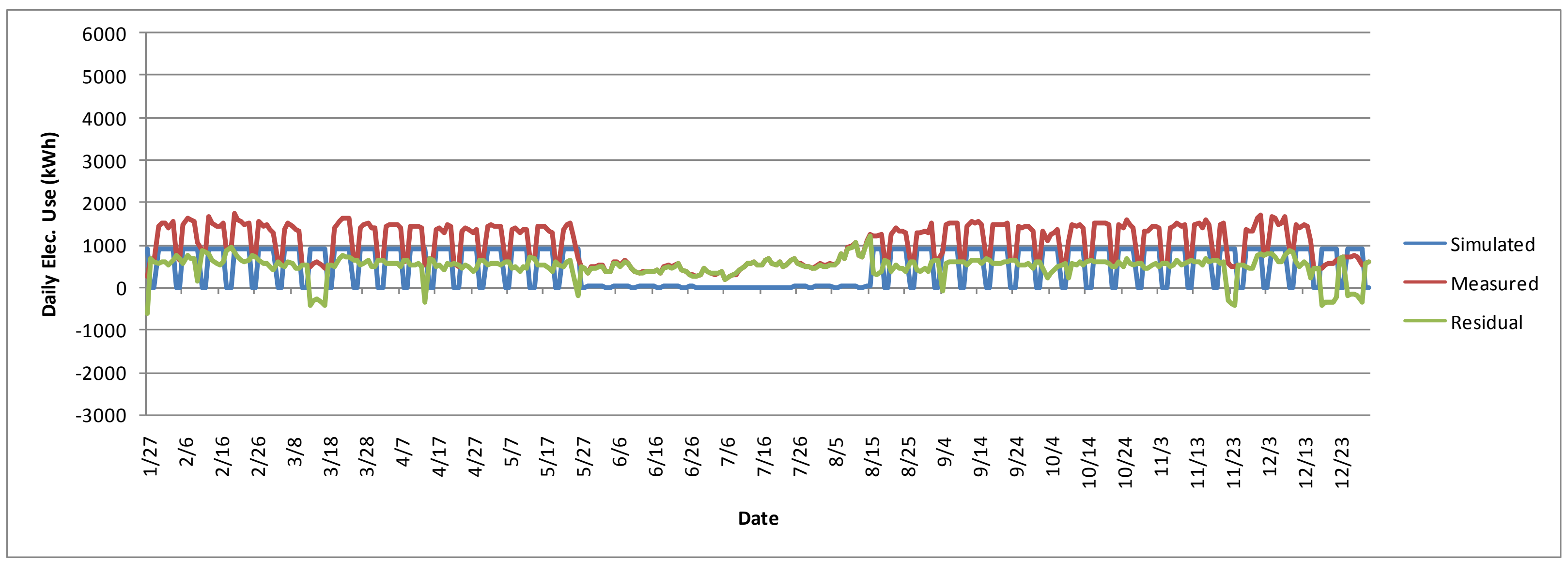
The first step of the calibration procedure was to use 2006 measured weather file instead of the Houston TMY2 average weather file. Using the coincident weather data obtained from the NOAA website for the City of College Station and local weather data, the 2006 weather file was packed as described in Chapter V. After the simulation, the monthly average weather data (i.e., dry bulb temperature, wet bulb temperature, wind speed, horizontal solar radiation, and direct normal solar radiation) were extracted from the simulation results. Then, the monthly average weather data from the 2006 weather file was compared to the monthly average weather data from the Houston TMY2 weather file in order to evaluate the impact of the change of the weather file.

1. Whole Building Electricity





2. Lighting & Equipment



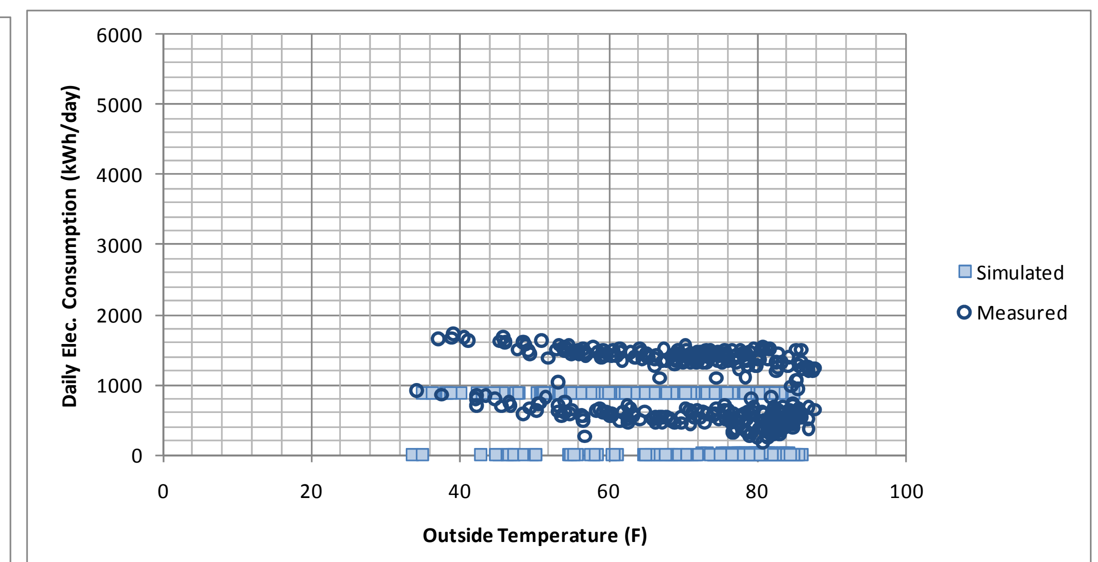
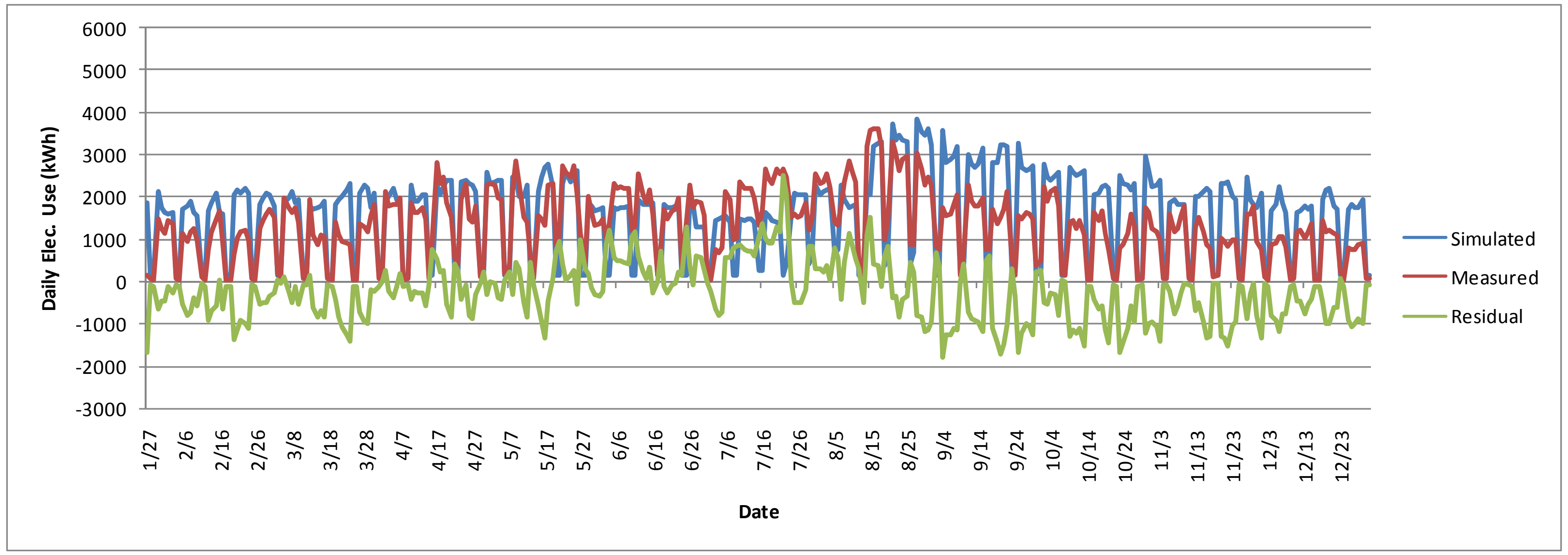
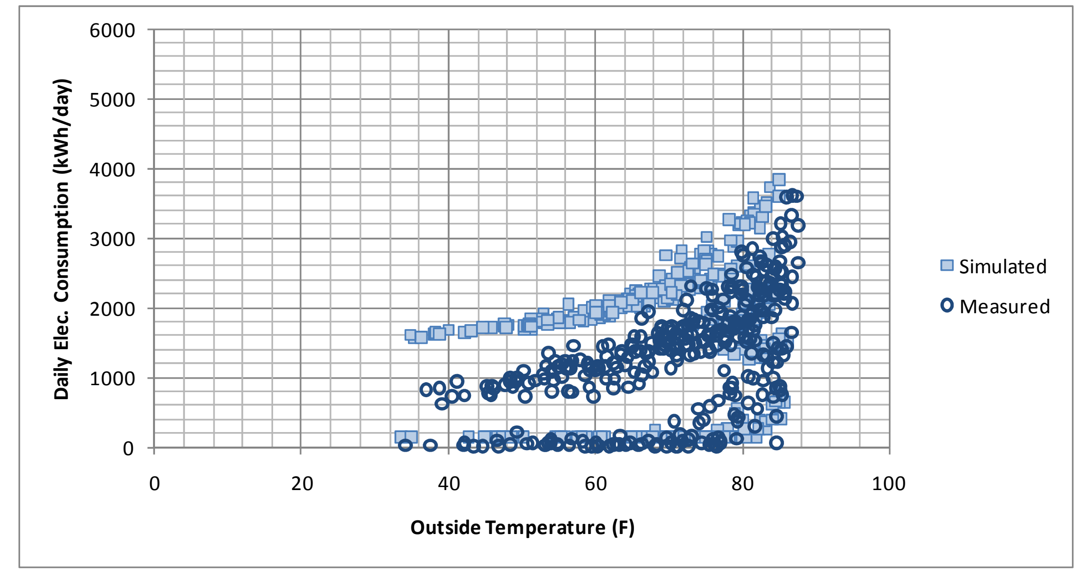


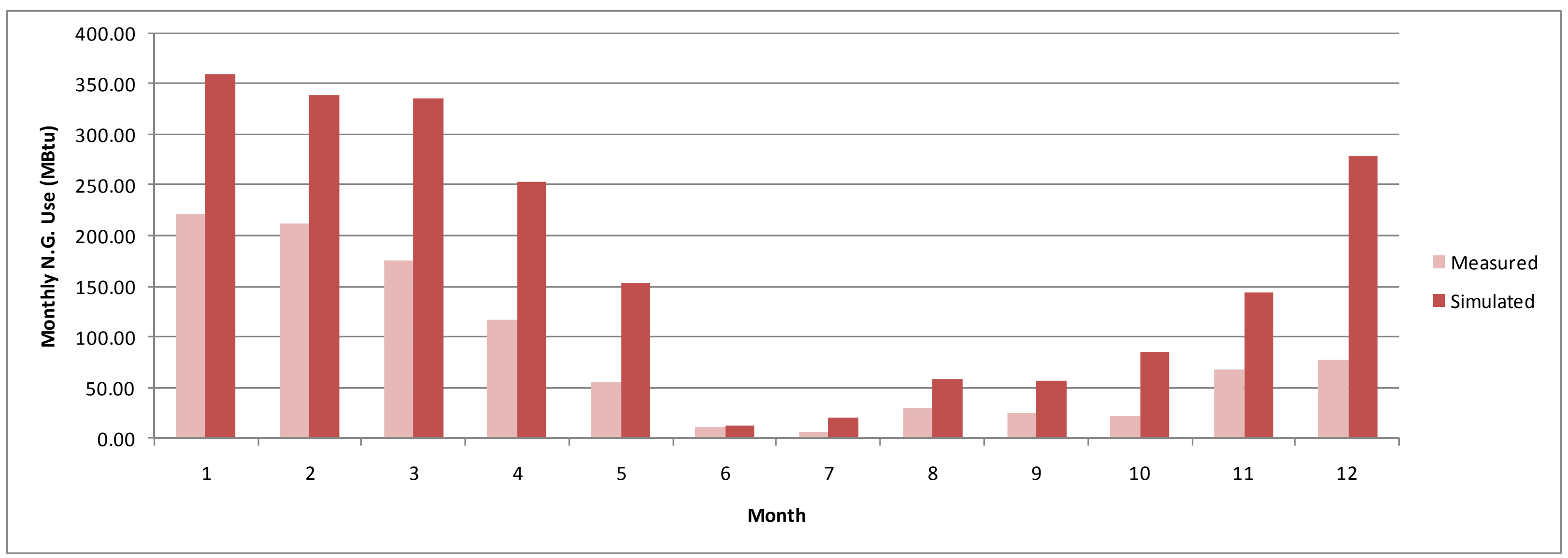
Figure 6.6 - As-Built Simulation Results

3. Whole Building Cooling + Motor Control Center





4. Natural Gas



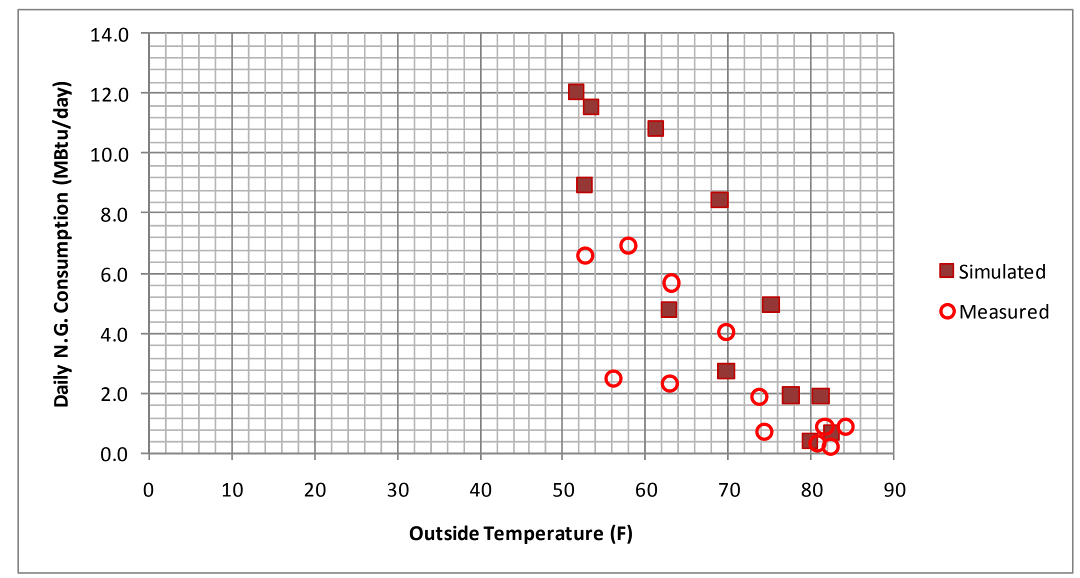


Figure 6.6 - Continued

Table 6.2 shows the monthly and yearly average weather data from two weather files and the percent differences.

As shown in Table 6.2, the overall weather patterns between two weather sets are similar, several differences can be observed including:

1) Annual average dry bulb temperatures from TRY are 2.4% higher than Houston TMY2 weather file.
2) In general, the direct normal solar radiations from two weather files show the biggest differences. As for direct normal solar radiation, the 2006 weather data shows 10.9% higher in April through August and 15.8% lower during September through December compared to the Houston TMY2 weather data.
3) Average dry bulb temperatures in the spring months from TRY is slightly warmer than the TMY2
4) TRY shows slightly dryer in fall months

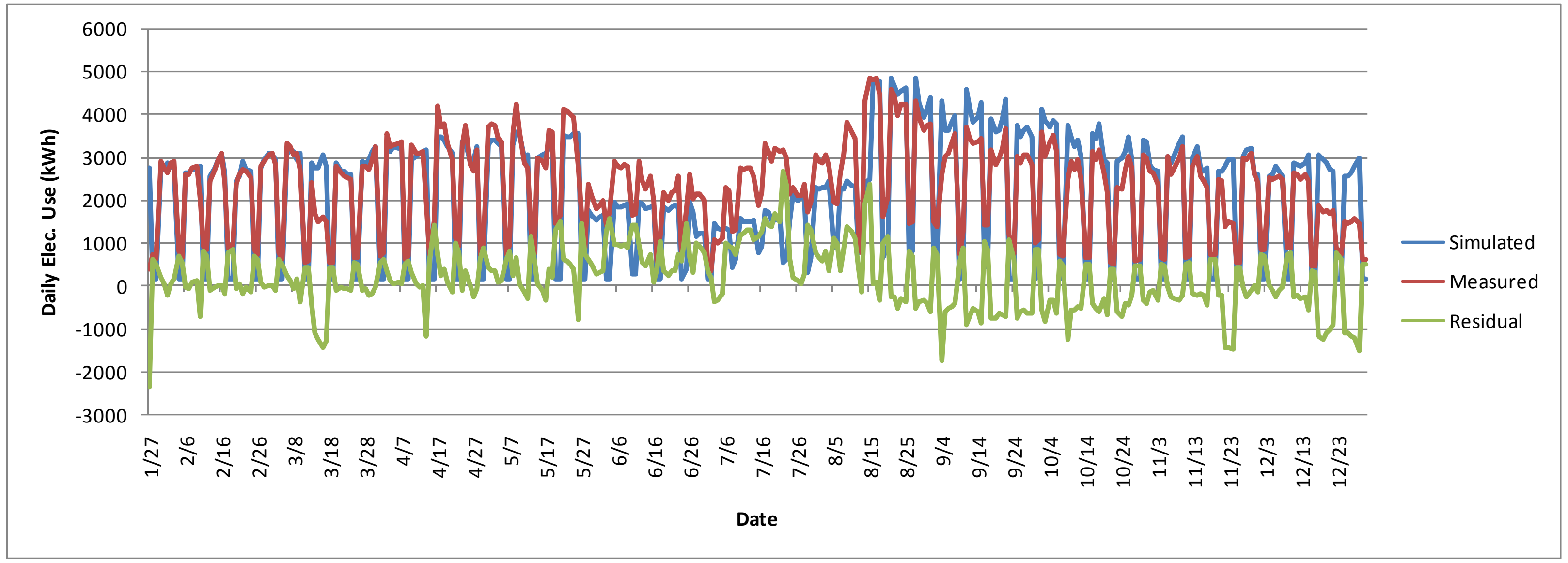
The complete hourly time series plots for the 2006 weather are presented in Appendix D.

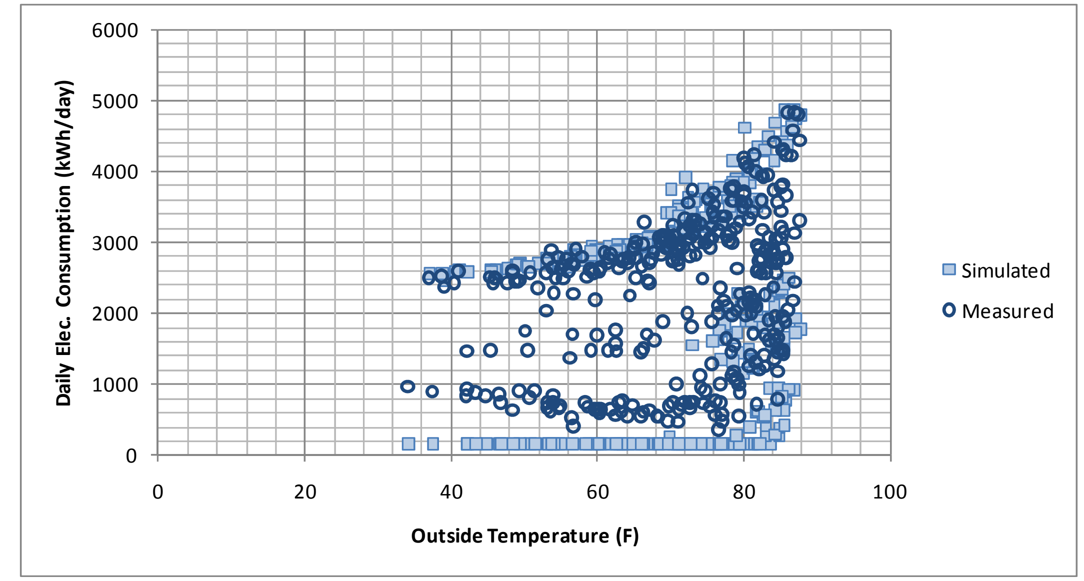
Figure 6.7 shows the simulation results from this calibration step. As shown in the figure, there were not many changes from the as-built simulation result. The similarity between the Houston TMY2 and the 2006 weather file would be the reason for this result. The calculated NMBE and CV(RMSE) for this calibration step are shown in Table 6.3. The NMBE and CV(RMSE) for Whole Building Electricity were reduced from 10.18% and 35.47% to 7.63% and 32.05%, respectively by using the 2006 weather data.

Table 6.2 - Weather Comparison (Houston TMY2 vs. 2006 Measured Data Using TRY Format)

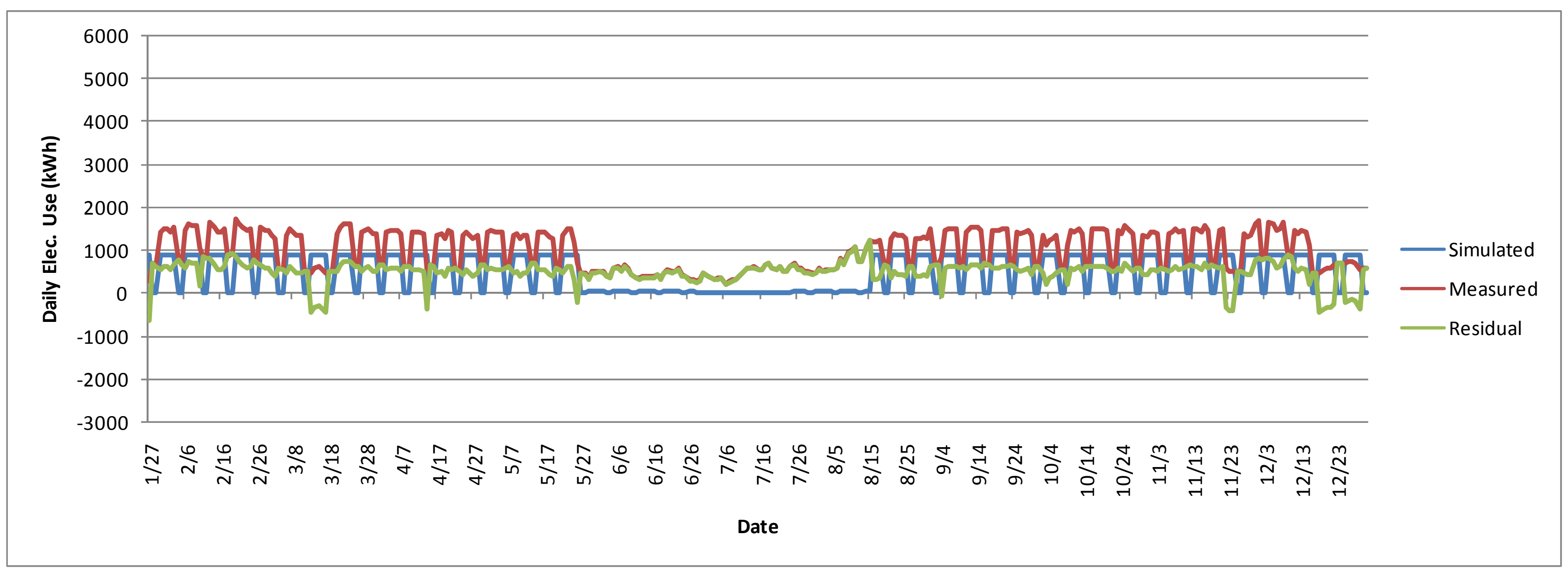
Month	Houston TMY2					2006 TRY									
	Monthly Average Dry Bulb (F)	Monthly Average Wet Bulb (F)	Monthly Average Direct Normal Solar Radiation (Btu/hr-sq.ft.)	Monthly Average Horizontal Solar Radiation (Btu/hr-sq.ft.)	Monthly Average Wind Speed (Knots)	Monthly Average Dry Bulb (F)	% Diff (2006 - TMY2)/TMY2	Monthly Average Wet Bulb (F)	% Diff (2006 - TMY2)/TMY2	Monthly Average Direct Normal Solar Radiation (Btu/hr-sq.ft.)	% Diff (2006 - TMY2)/TMY2	Monthly Average Horizontal Solar Radiation (Btu/hr-sq.ft.)	% Diff (2006 - TMY2)/TMY2	Monthly Average Wind Speed (Knots)	% Diff (2006 - TMY2)/TMY2
Jan	53.4	48.8	39.6	35.8	8.7	57.4	7.5%	48.7	-0.2%	50.0	26.3%	39.3	9.8%	8.0	-8.0%
Feb	51.6	47.8	41.1	44.3	7.1	53.0	2.7%	46.9	-1.9%	43.2	5.1%	40.2	-9.3%	7.9	11.3%
Mar	61.2	54.8	51.4	56.4	8.9	64.6	5.6%	56.8	3.6%	36.0	-30.0%	49.3	-12.6%	8.9	0.0%
Apr	68.9	63.1	45.3	64.9	7.6	72.5	5.2%	64.3	1.9%	51.6	13.9%	69.5	7.1%	8.4	10.5%
May	75.1	68.6	55.9	74.2	8.0	76.4	1.7%	67.2	-2.0%	57.4	2.7%	76.3	2.8%	8.0	0.0%
Jun	79.8	72.8	58.6	80.9	6.2	81.5	2.1%	69.8	-4.1%	69.1	17.9%	86.8	7.3%	5.5	-11.3%
Jul	82.4	75.5	54.6	77.7	6.7	82.6	0.2%	73.9	-2.1%	57.0	4.4%	78.8	1.4%	6.0	-10.4%
Aug	81.1	74.3	56.1	73.0	6.1	84.8	4.6%	73.9	-0.5%	64.8	15.5%	80.8	10.7%	5.7	-6.6%
Sep	77.5	70.6	55.1	64.7	7.0	78.7	1.5%	67.5	-4.4%	47.4	-14.0%	61.1	-5.6%	6.3	-10.0%
Oct	69.7	65.0	59.0	56.0	6.8	70.1	0.6%	62.3	-4.2%	48.0	-18.6%	50.7	-9.5%	6.0	-11.8%
Nov	62.8	57.7	47.8	42.1	7.2	60.5	-3.7%	53.8	-6.8%	43.4	-9.2%	40.6	-3.6%	7.4	2.8%
Dec	52.6	49.0	34.9	32.0	7.3	53.9	2.5%	48.1	-1.8%	27.0	-22.6%	29.7	-7.2%	6.7	-8.2%
Annual	**68.0**	**62.3**	**50.0**	**58.5**	**7.3**	**69.7**	**2.4%**	**61.1**	**-2.0%**	**49.6**	**-0.8%**	**58.6**	**0.2%**	**7.1**	**-3.2%**

1. **WBE**





2. **Lighting & Equip**



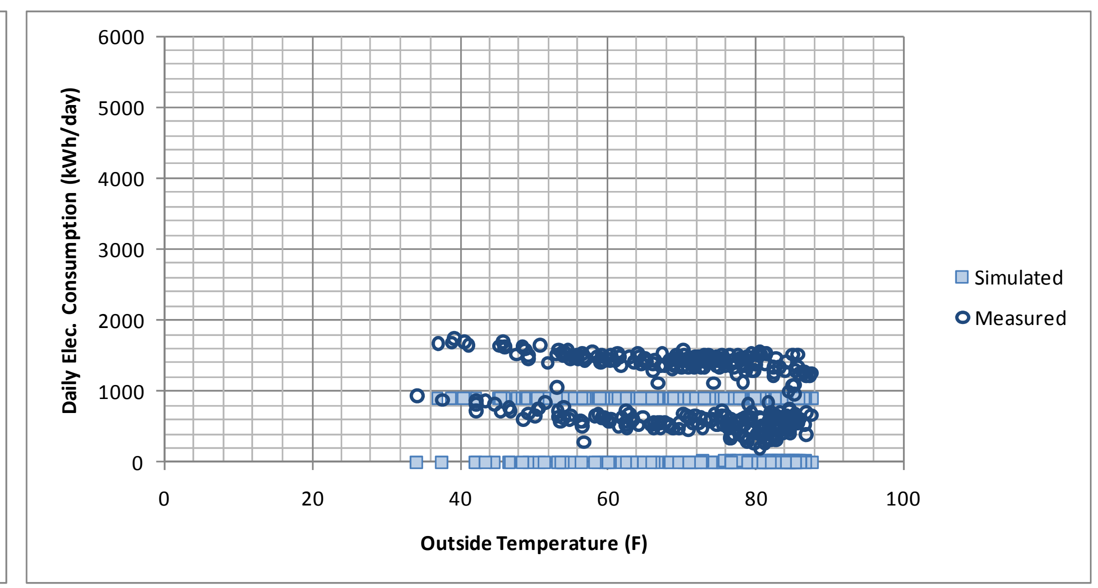
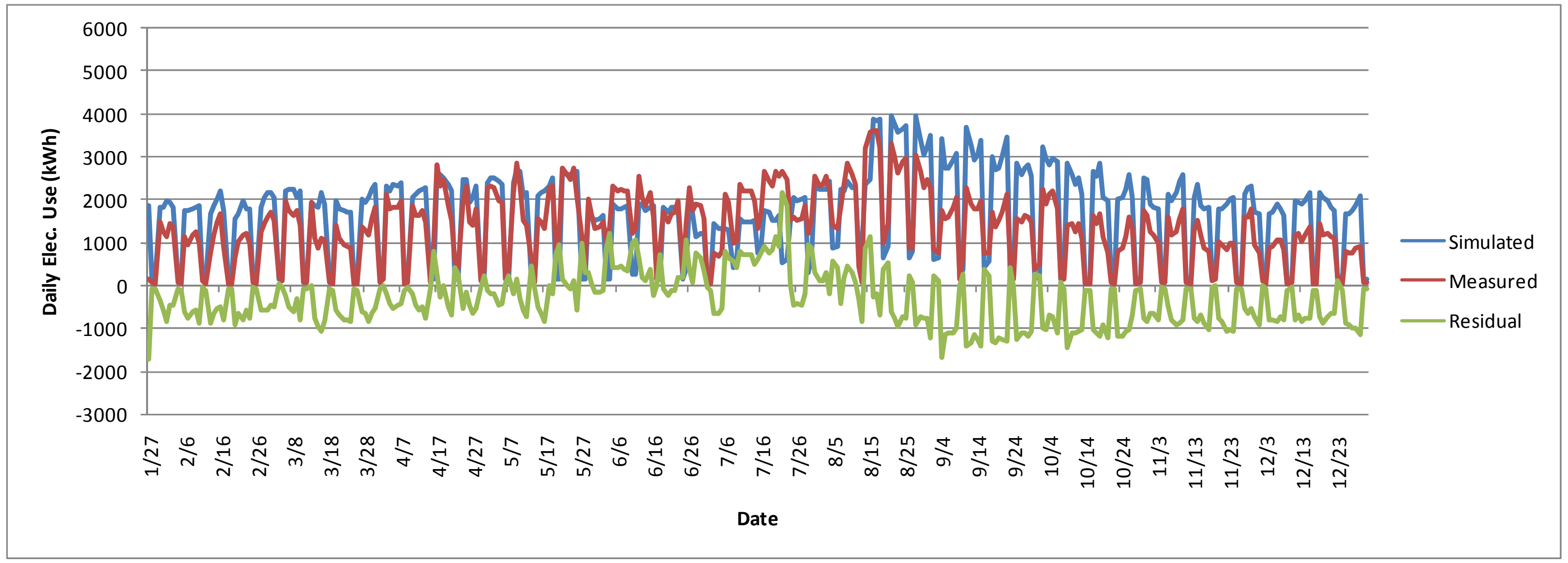
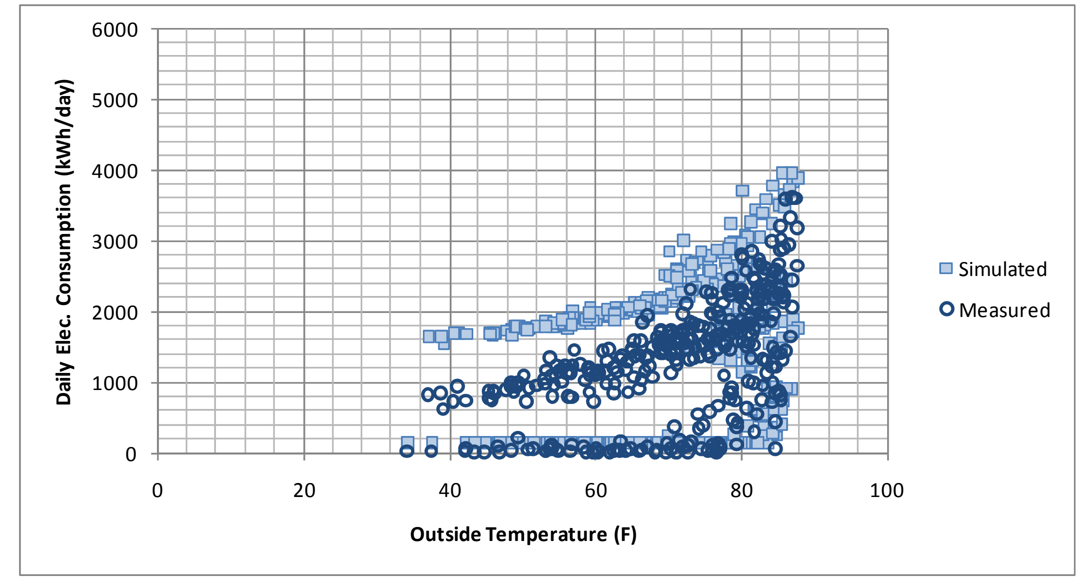


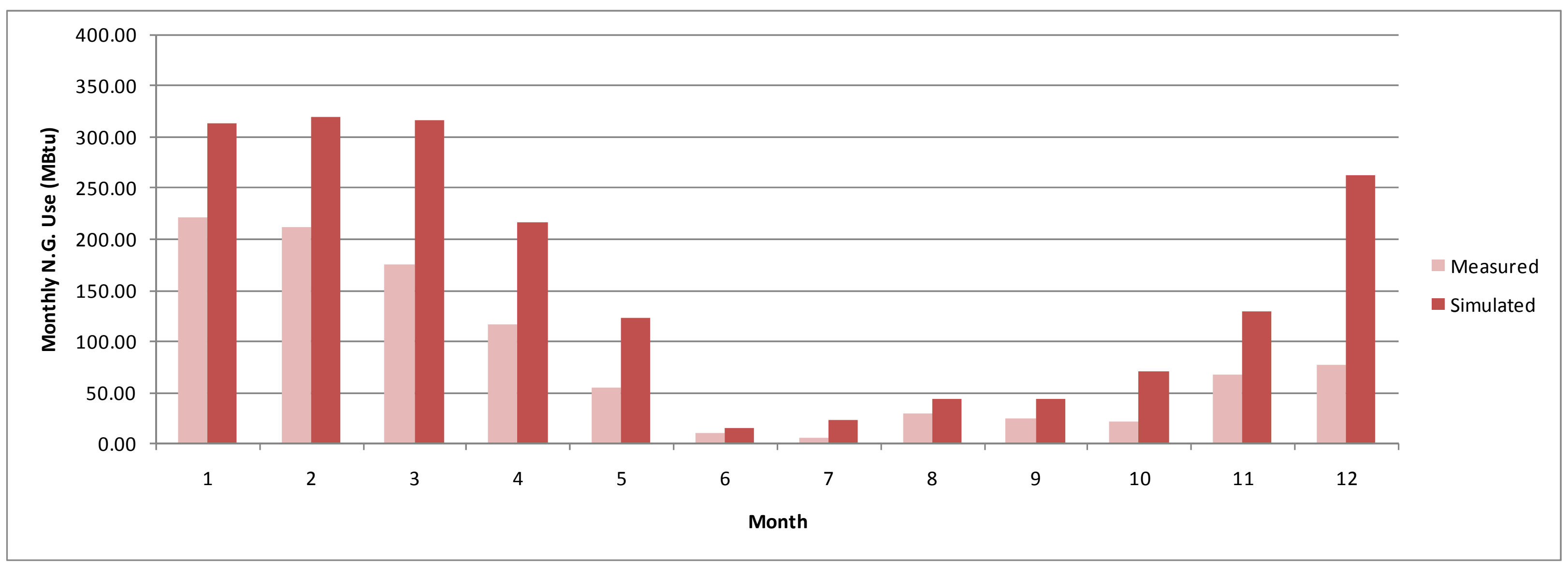
Figure 6.7 - Calibration Step 1 Results: Using 2006 Weather File

3. **WBC+MCC**





4. **Natural Gas**



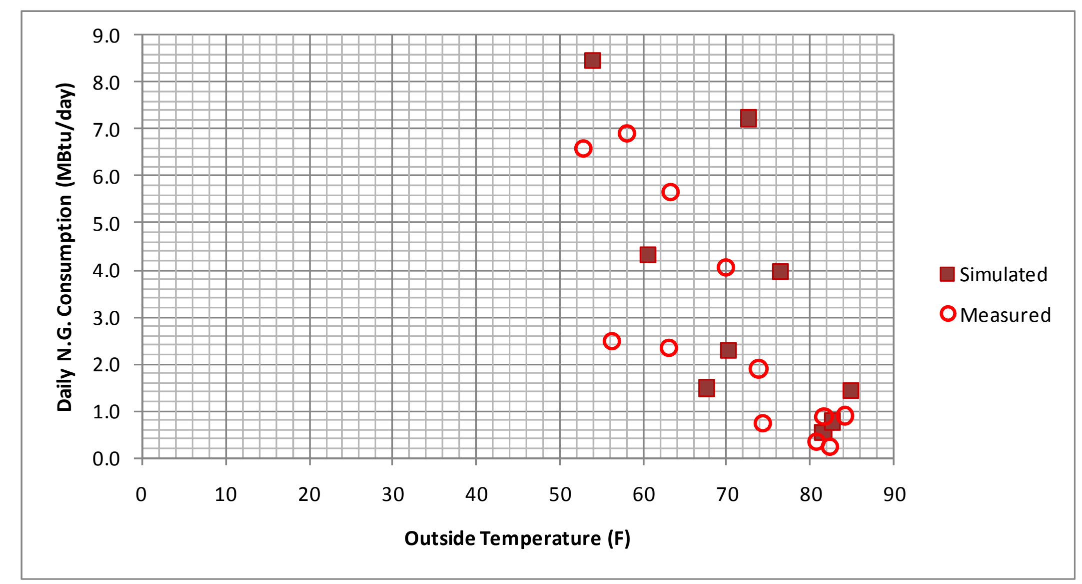


Figure 6.7 - Continued

Table 6.3 - NMBE and CV(RMSE) for Calibration Step 1

	Whole Building Electricity	Lighting & Equipment	Whole Building Cooling + Motor Control Center	Natural Gas
NMBE	7.63%	50.25%	-23.85%	-33.93%
CVRMSE	32.05%	56.71%	52.72%	50.48%

6.3. Step 2: Lighting and Equipment Schedule Calibrated using ASHRAE's RP-1093 Method (Abushakra et al. 2001)

As shown in last two simulations, the simulated lighting and equipment energy use were much lower than the measured use. In order to insert the measured electricity use into the simulation input, ASHRAE's RP-1093 toolkit was used to generate DOE-2's lighting and equipment schedules from the measured use.

As described in Chapter IV, the hourly lighting and equipment uses were divided into 5 different periods: 1) normal school days, 2) summer vacation I, and III (staff working), 3) summer vacation II (between summer vacation I and III), 4) summer vacation IV (staff & student vacation), and 5) spring break, Thanksgiving, and winter break). Using ASHRAE's RP1093 procedure, the 10th, 24th, 50th, 75th, and 90th percentiles of the energy uses were calculated for each hour of the day. The calculated profiles for the five different periods are presented in Figures 6.8 through 6.12. Then, in the next step, the 50th percentiles were extracted for use in the DOE-2's lighting and equipment schedules. The final lighting and equipment schedules generated for the DOE-2 input file are presented in the separate ESL's technical report.

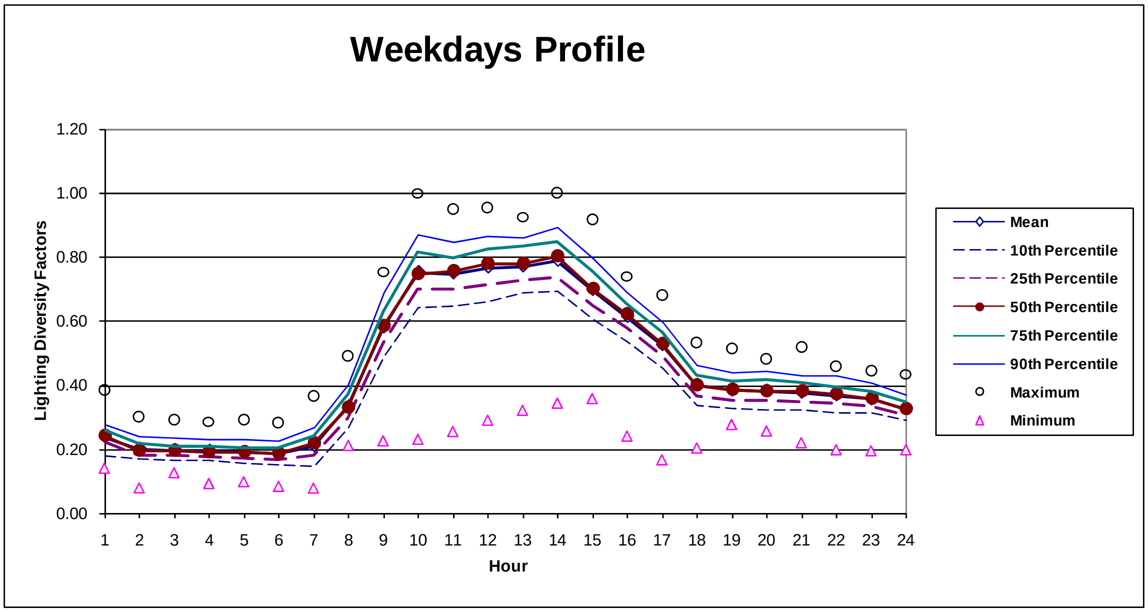
Using the new lighting and equipment schedules generated using RP-1093 method, calibration step 2 was then performed. The calibrated simulation result for the step 2 is shown in Figure 6.13. As shown in the figure, the hourly simulated lighting and equipment use are well matched with the measured use. In this step of the calibration, the NMBE and CV(RMSE) for the lighting and equipment use decreased to -0.77% and 12.89%, respectively, which were 50.25% and 56.71%, respectively in the previous simulation results. The NMBE and CV(RMSE) for whole building electricity are decreased to -16.67% and 31.73%, respectively. Table 6.4 presents the NMBE and CV(RMSE) for all the sub-energy uses.

Table 6.4 - NMBE and CV(RMSE) for Calibration Step 2

	Whole Building Electricity	Lighting & Equipment	Whole Building Cooling + Motor Control Center	Natural Gas
NMBE	-16.67%	-0.77%	-28.41%	-67.65%
CVRMSE	31.73%	12.89%	53.79%	99.32%

6.4. Step 3: Use of a Scroll Chiller Performance Curve

In this step of the calibration procedure, a scroll type chiller performance curve was used to replace the original DOE-2 chiller performance curve as described in Chapter IV. The scroll chiller performance curve used in the simulation are presented in Tables 4.6 through 4.8 in Chapter IV. The simulation results are shown in Figure 6.14.



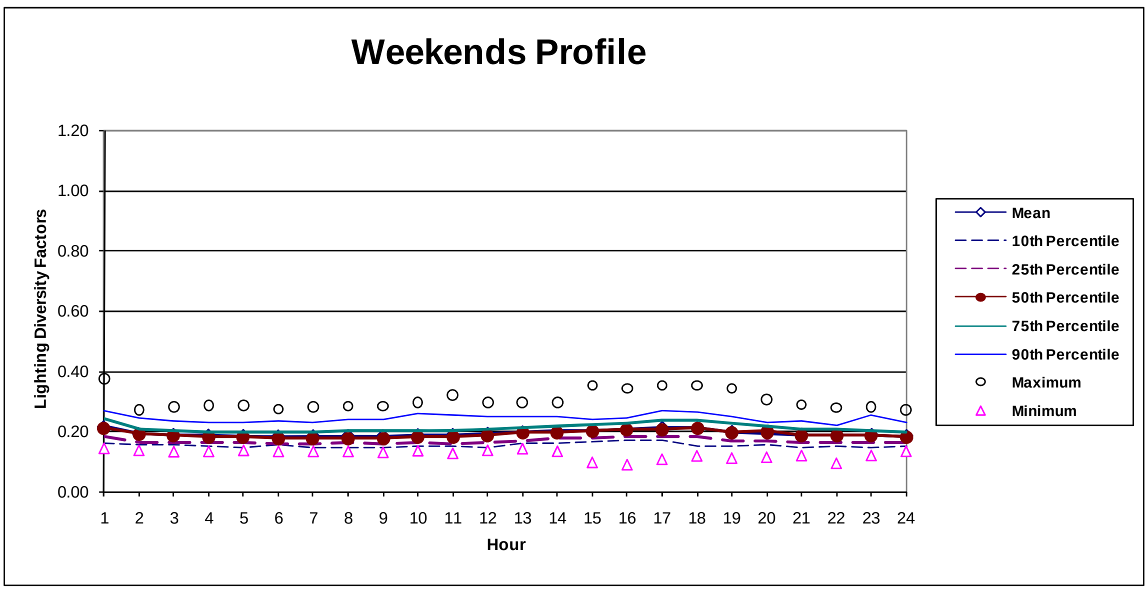
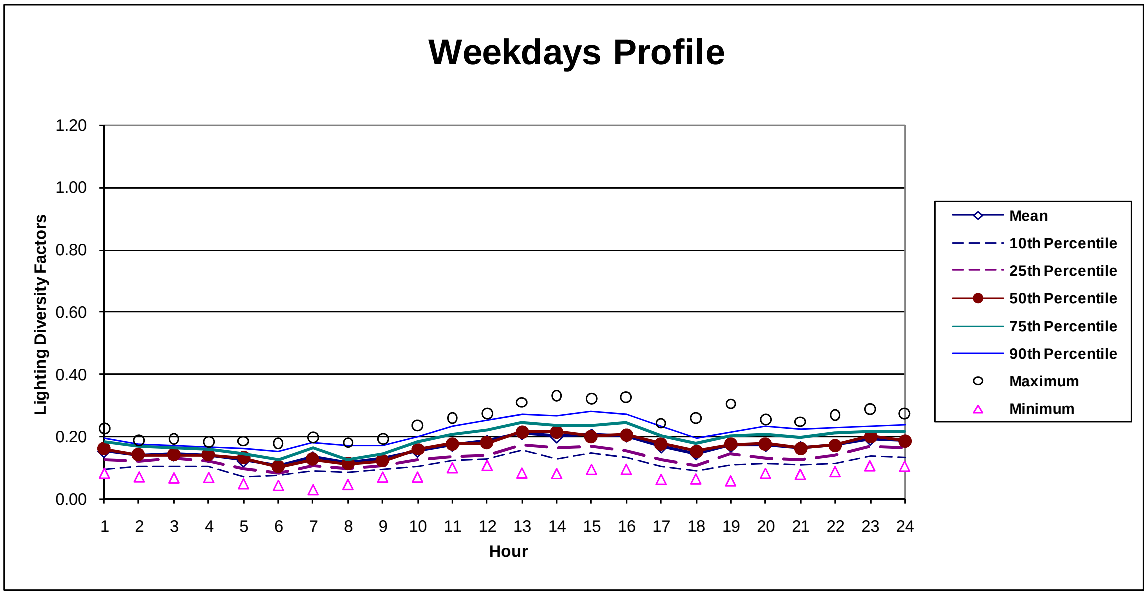


Figure 6.8 - Daytyping for Normal School Days



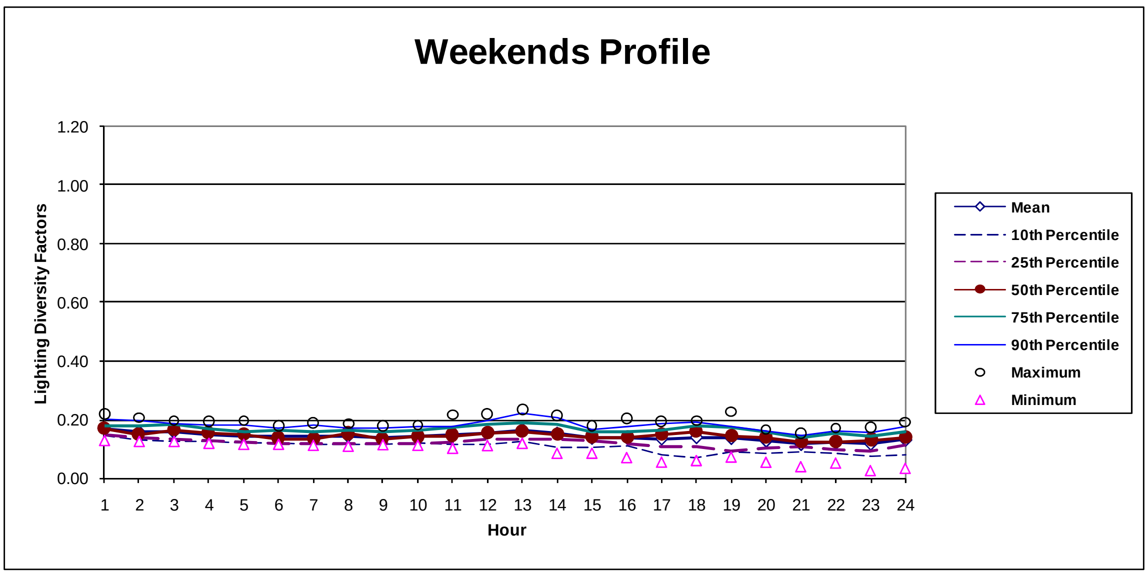
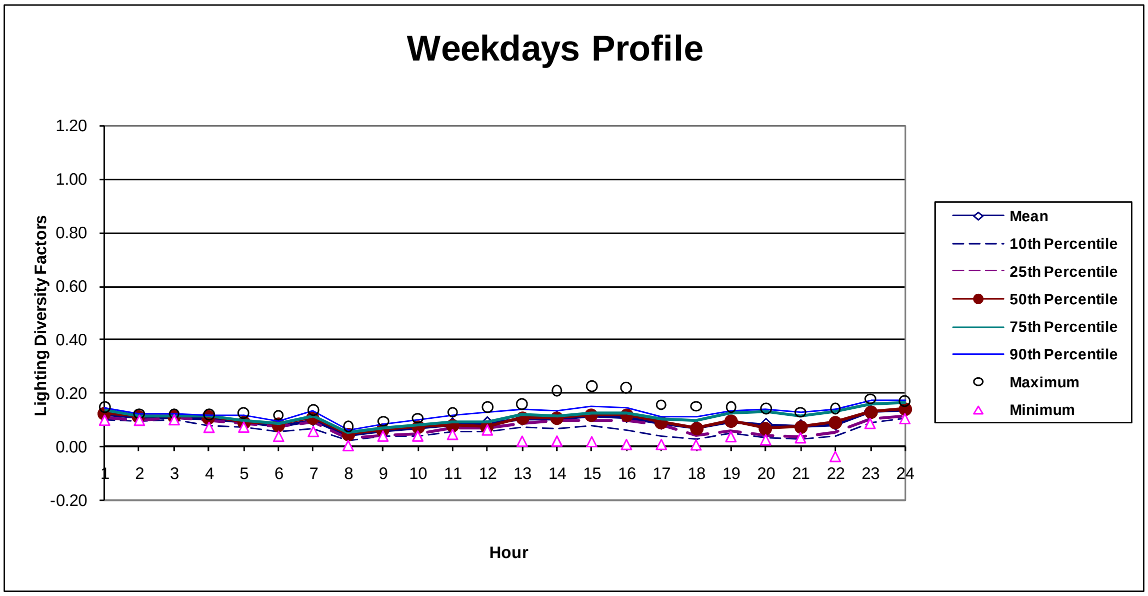


Figure 6.9 - Daytyping for Summer Vacation (I,III)



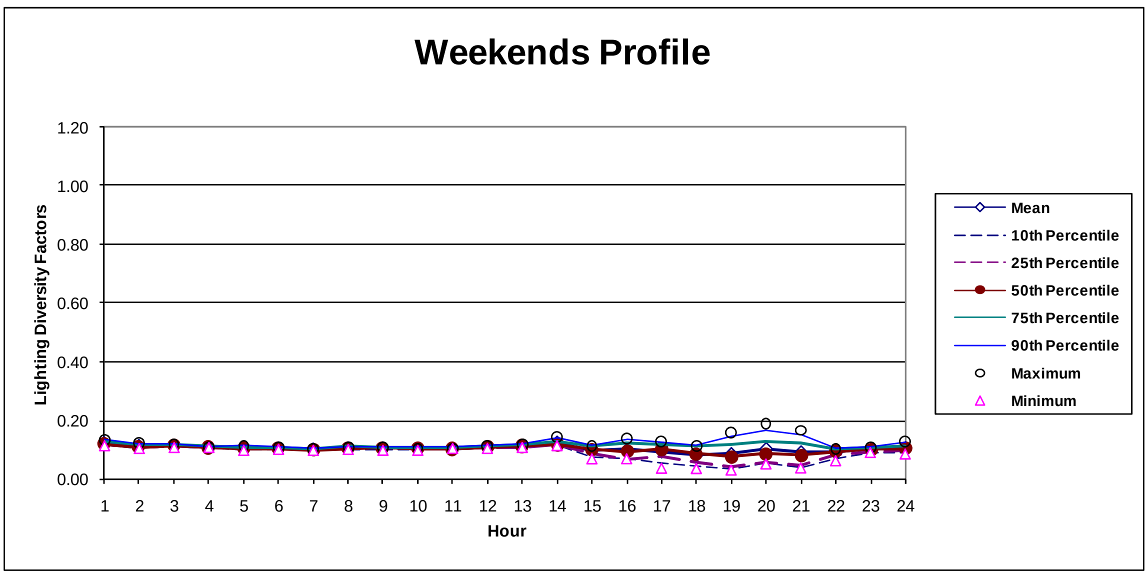
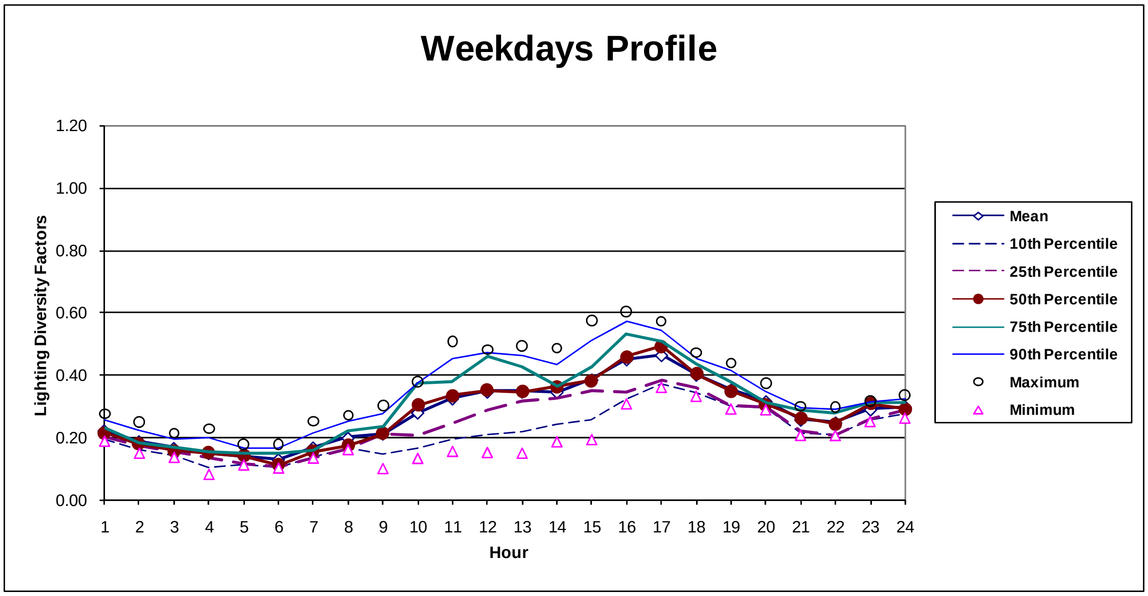


Figure 6.10 - Daytyping for Summer Vacation (II)



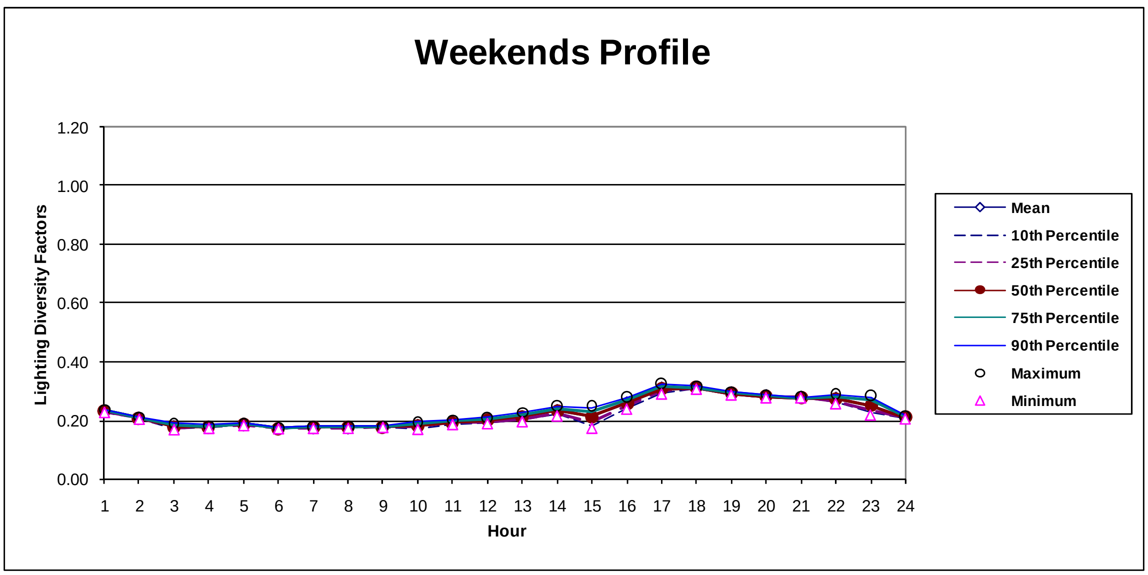
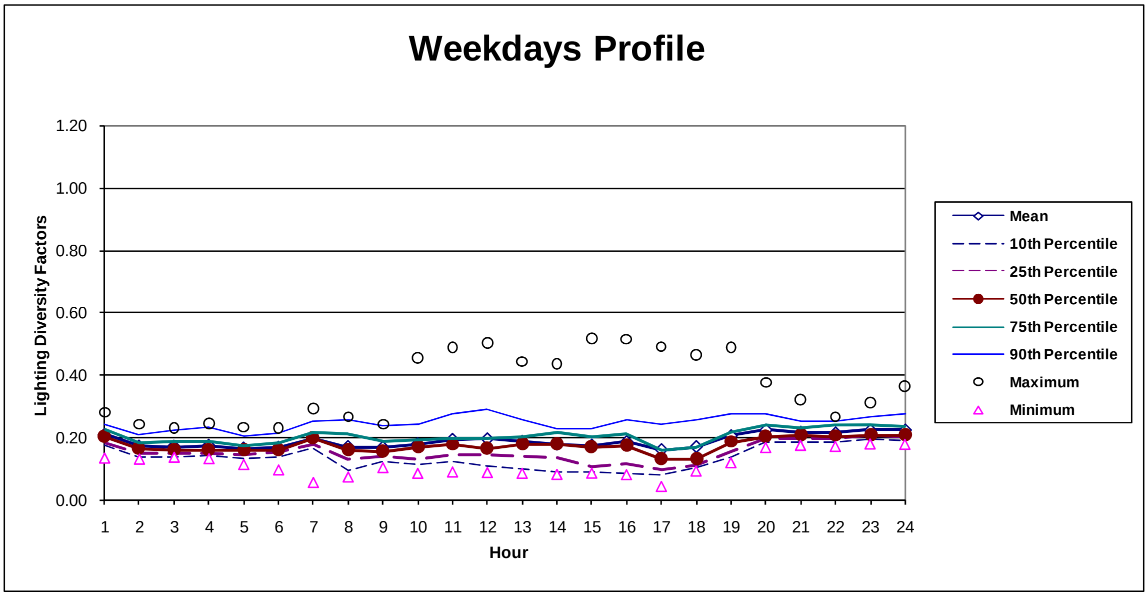


Figure 6.11 - Daytyping for Summer Vacation (IV)



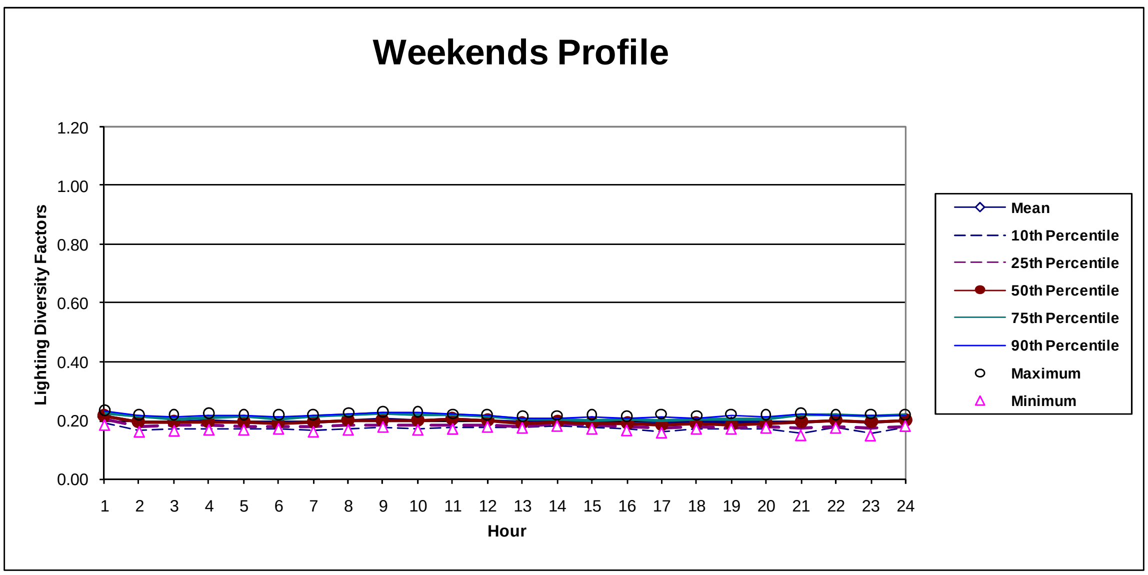
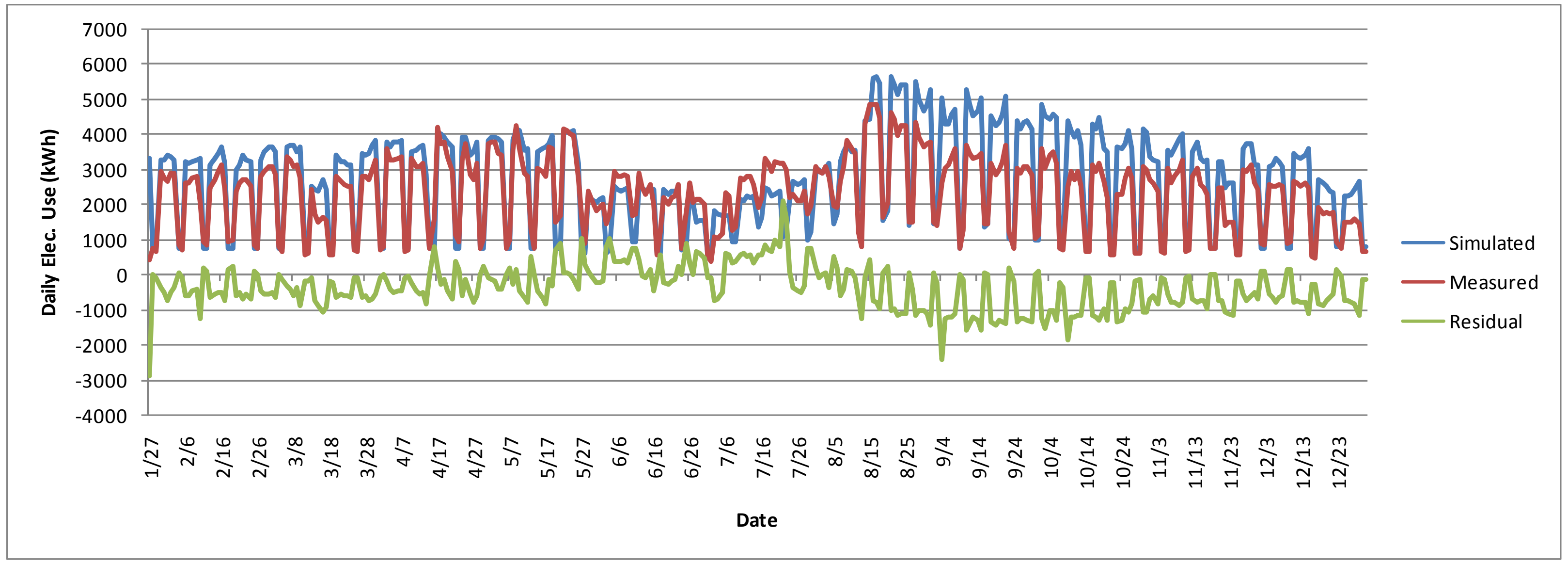
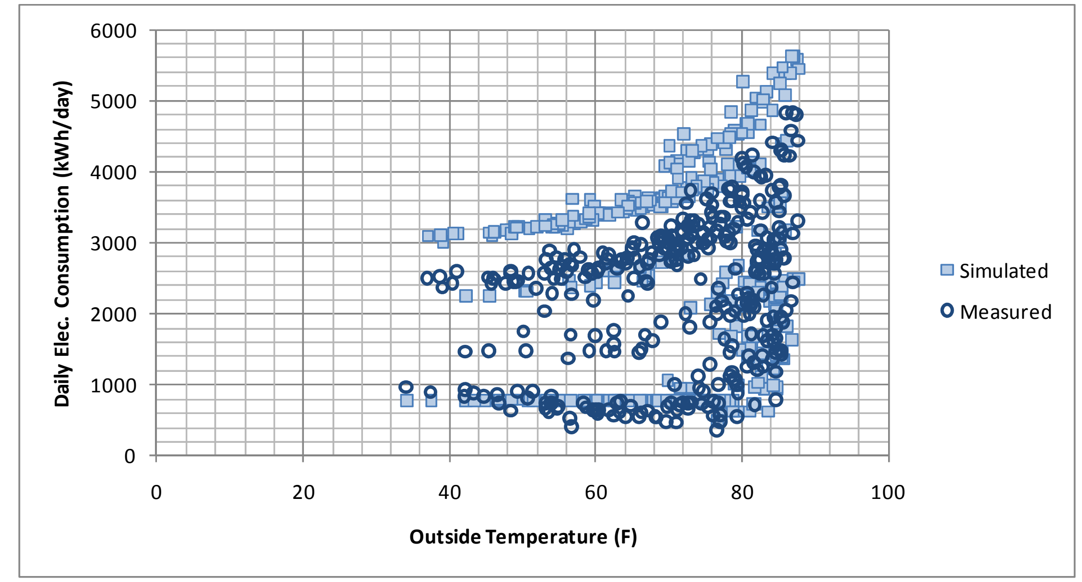


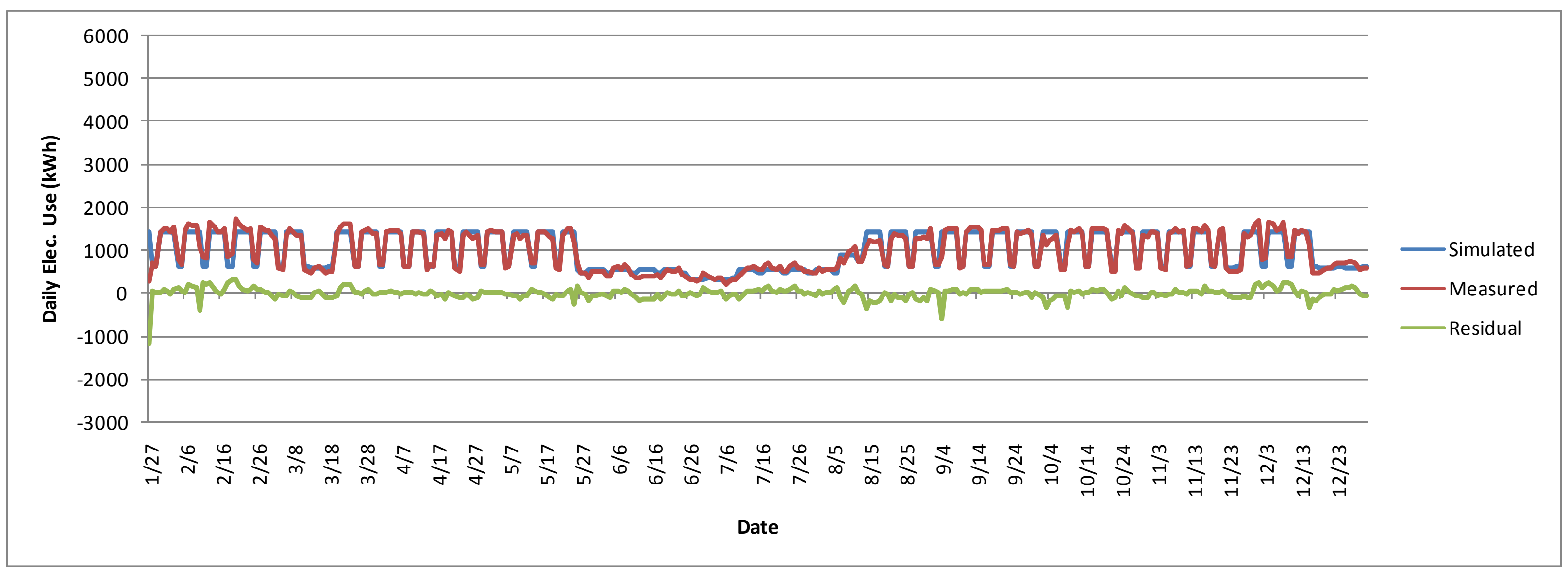
Figure 6.12 - Daytyping for Spring Break, Thanksgiving, and Winter Break

1. **Whole Building Electiricity**





2. **Lighting & Equipment**



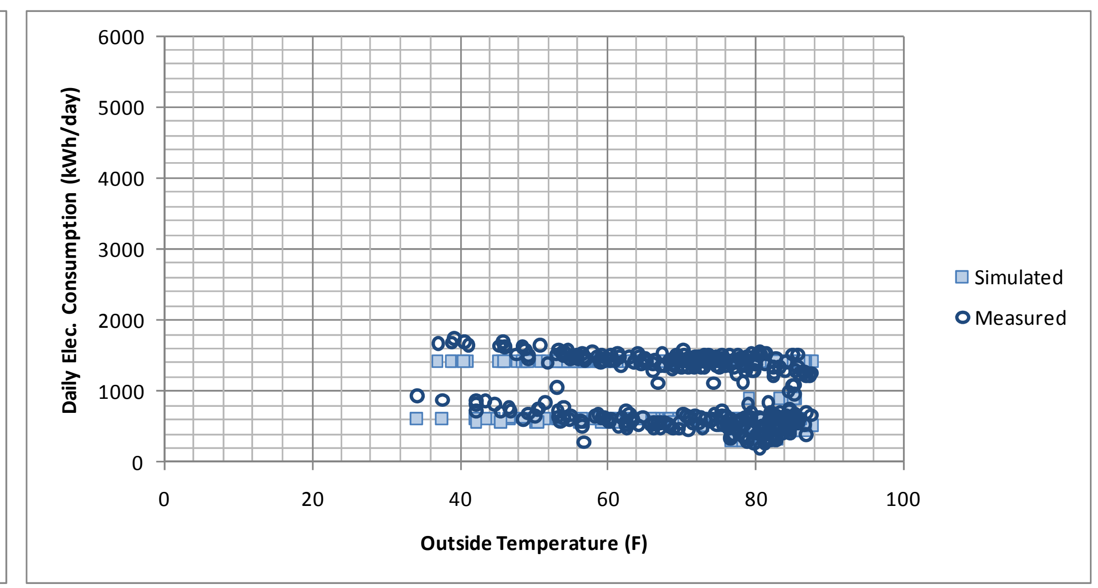
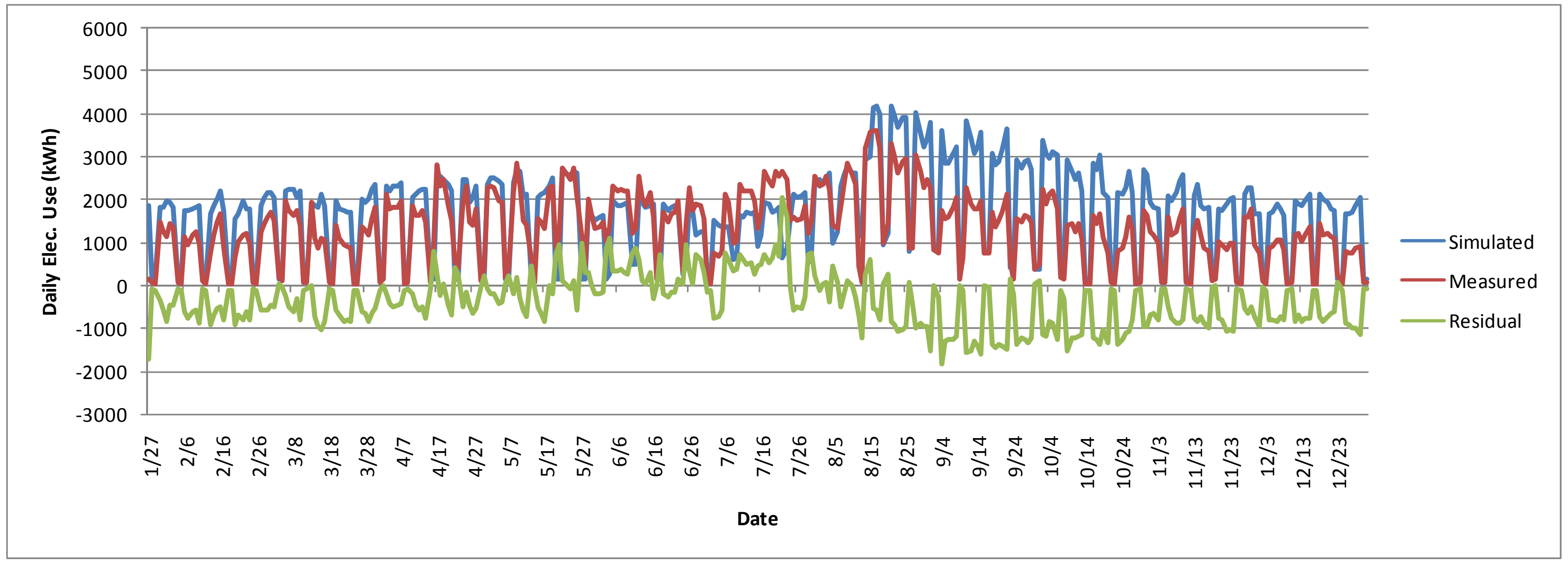
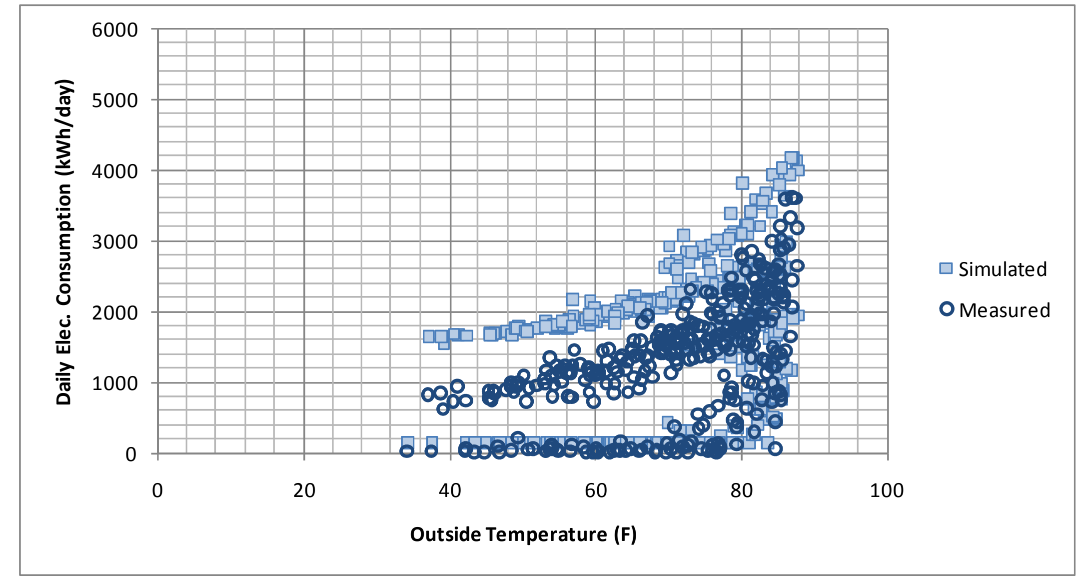


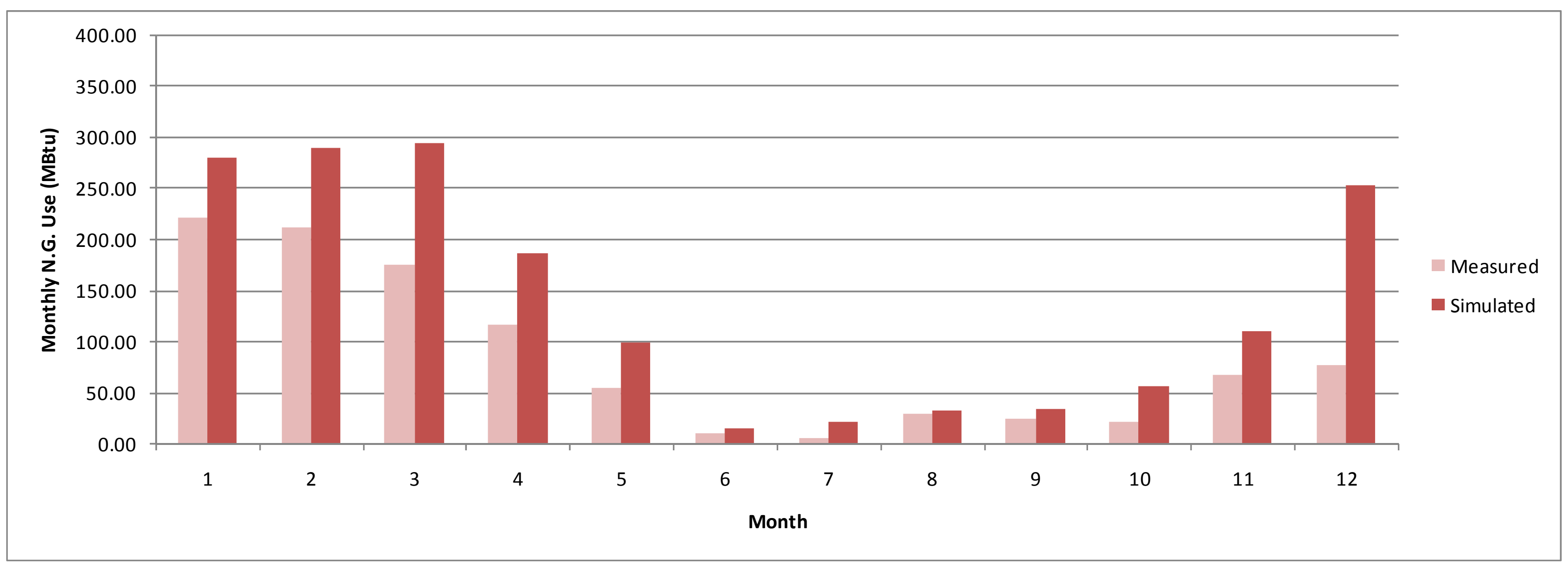
Figure 6.13 - Simulation Results: Calibration Step 2 – RP-1093 Method

3. Whole Building Cooling + Motor Control Center





4. Natural Gas



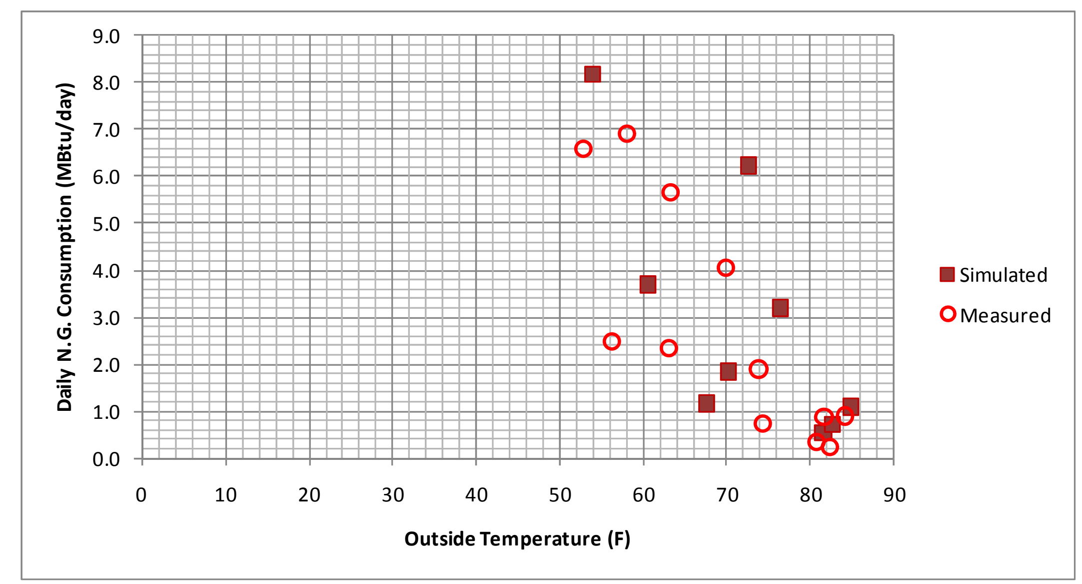


Figure 6.13 - Continued

The NMBE and the CV(RMSE) for whole building electricity was decreased to -7.86% and 25.86%, respectively. Table 6.5 presents the NMBE and CV(RMSE) for all the energy uses.

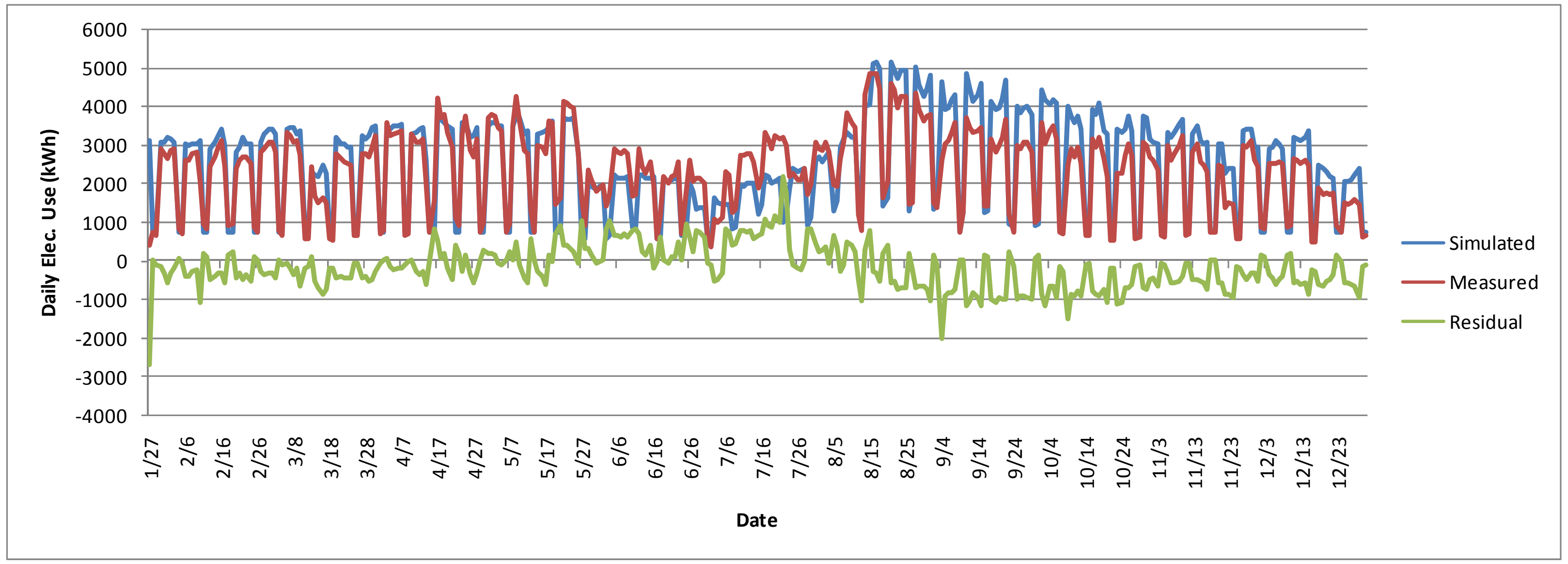
Table 6.5 - NMBE and CV(RMSE) for Calibration Step 3

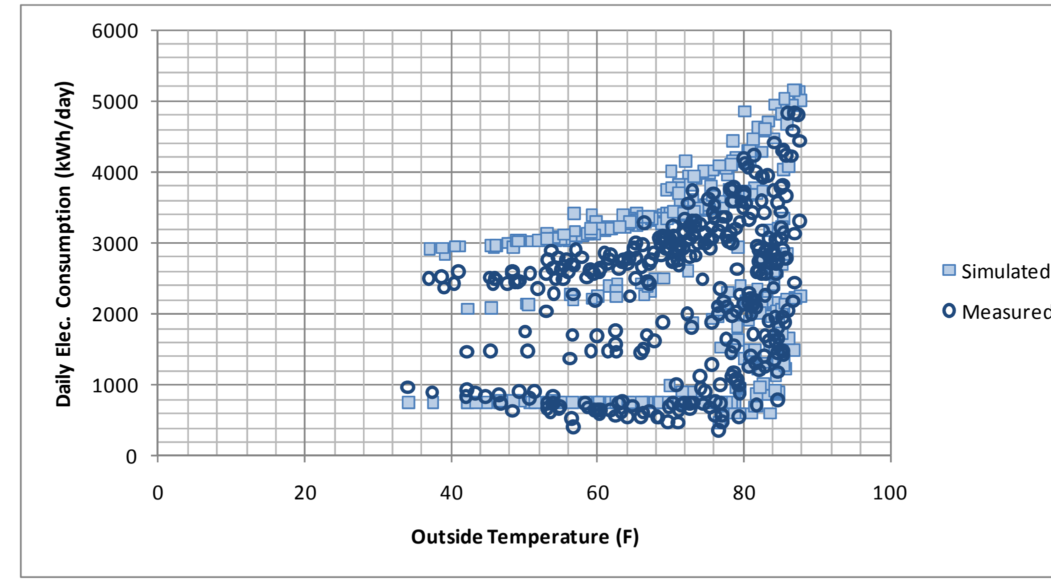
	Whole Building Electricity	Lighting & Equipment	Whole Building Cooling + Motor Control Center	Natural Gas
NMBE	-7.86%	-0.77%	-13.10%	-67.65%
CVRMSE	25.86%	12.89%	43.84%	99.32%

6.5. Step 4: Winkelmann's Method (U-effective Method) for Ground Conductance

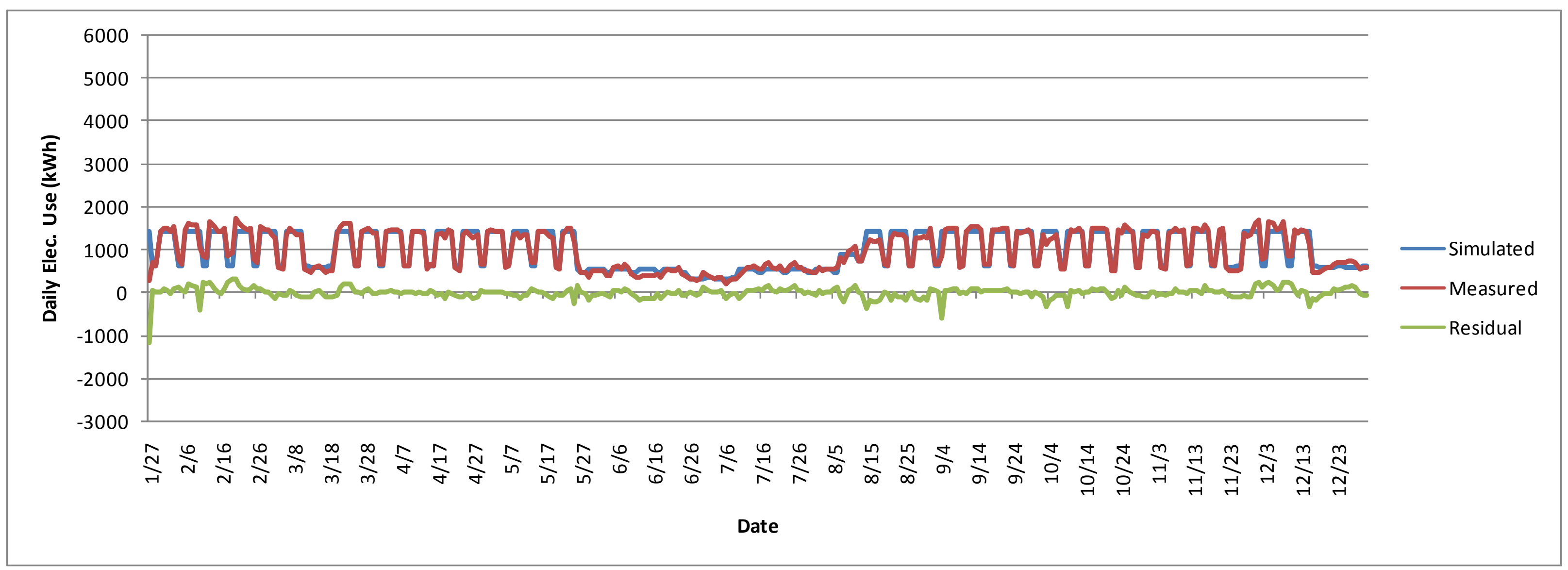
In this step of the calibration procedure, the U-effective value from Winkelmann's method was calculated as shown in Chapter IV, and used to replace the original underground U-value. As can be seen in Figure 6.14, the simulation results from the prevous step showed that the simulated cooling energy uses after the summer vacation was higher than the measured use, while the simulated cooling energy use before the summer vacation were relatively well matched with the measured use. As an effort to find the reason for this, the monthly ground temeperatures from the 2006 TRY file were extracted and plotted in Figure 6.15. As presented, the monthly ground

1. **Whole Building Electricity**





2. **Lighting & Equipment**



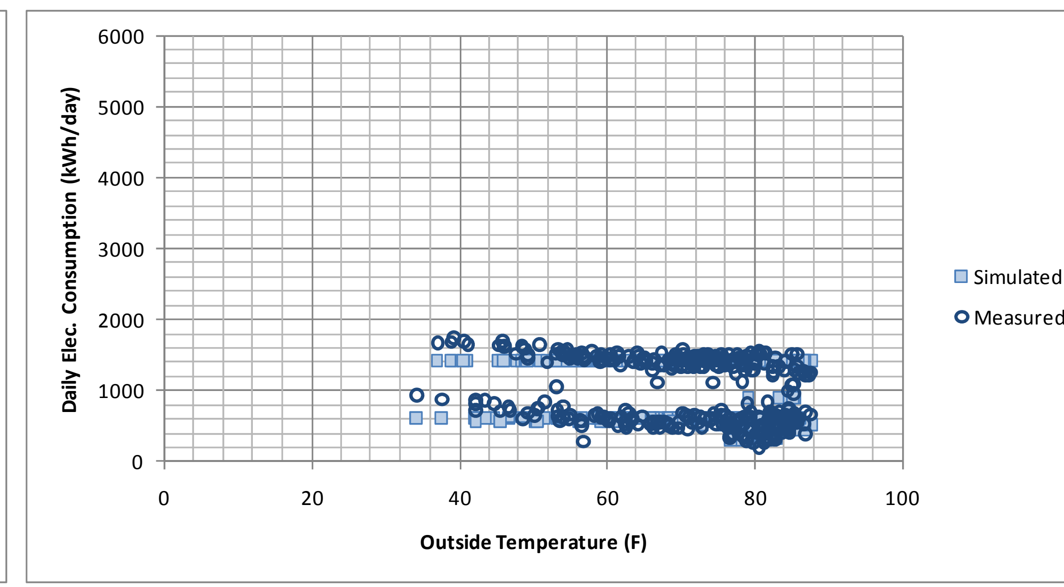
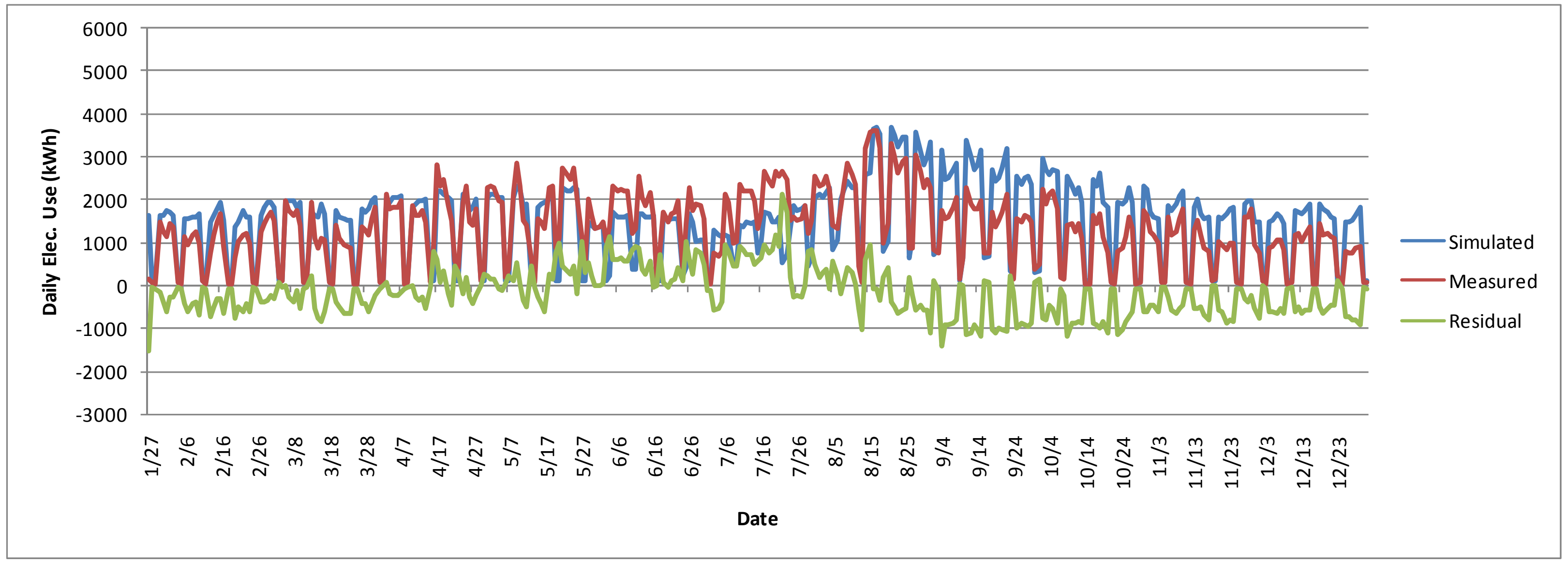
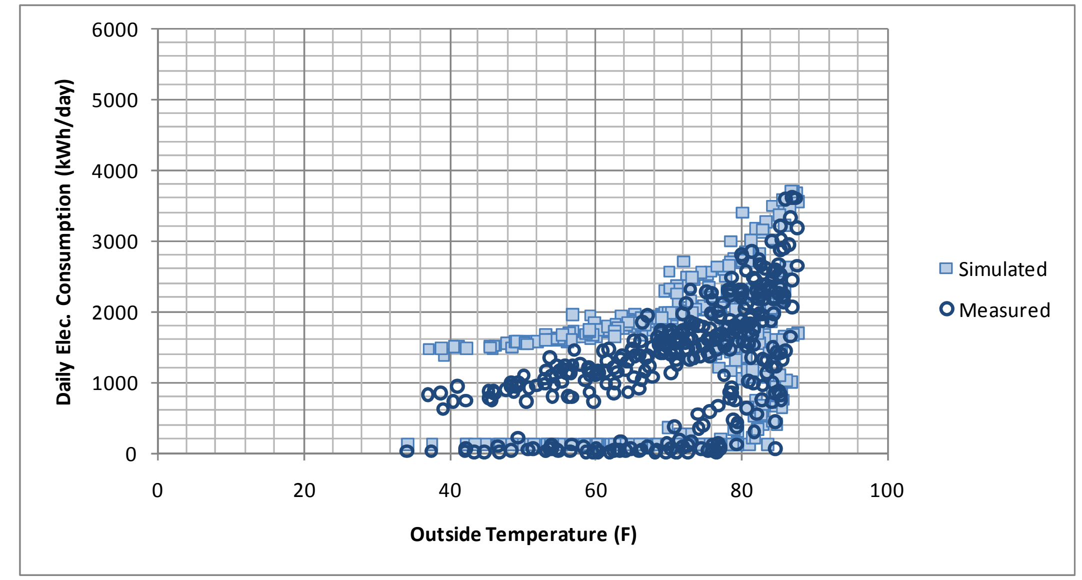


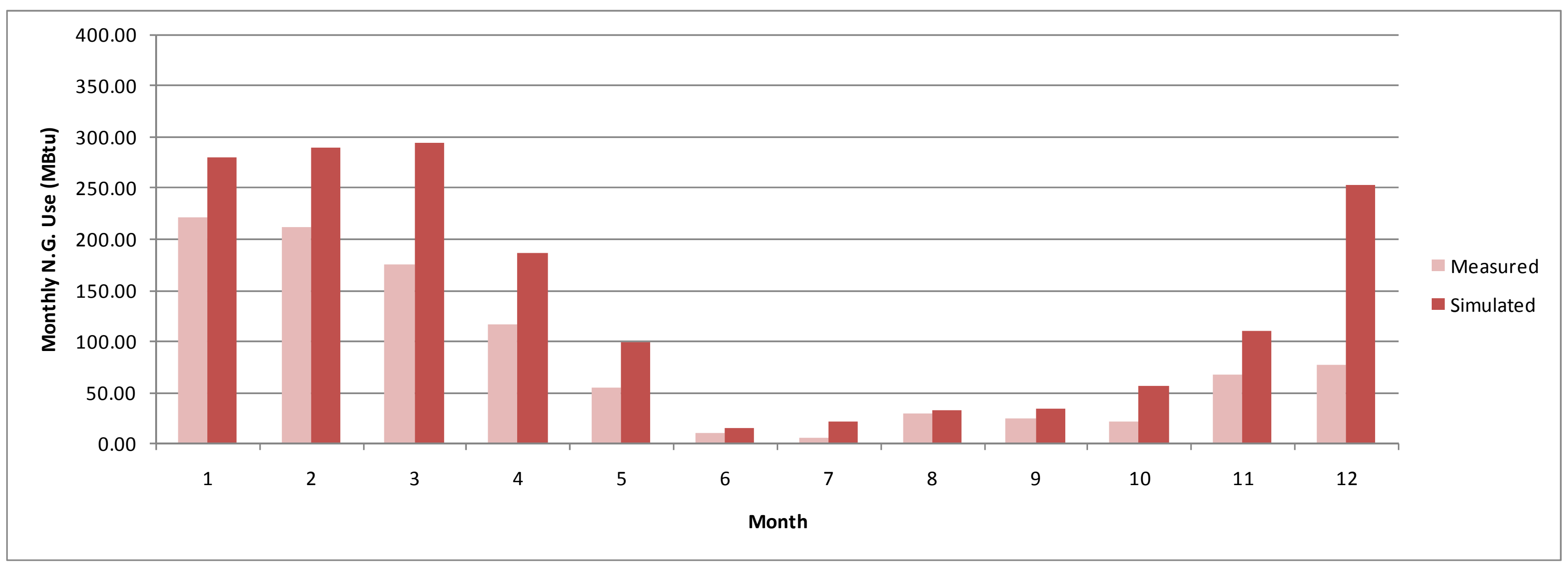
Figure 6.14 - Simulation Results: Calibration Step 3 – Scroll Chiller Curve

3. **Whole Building Cooling + Motor Control Center**





4. **Natural Gas**



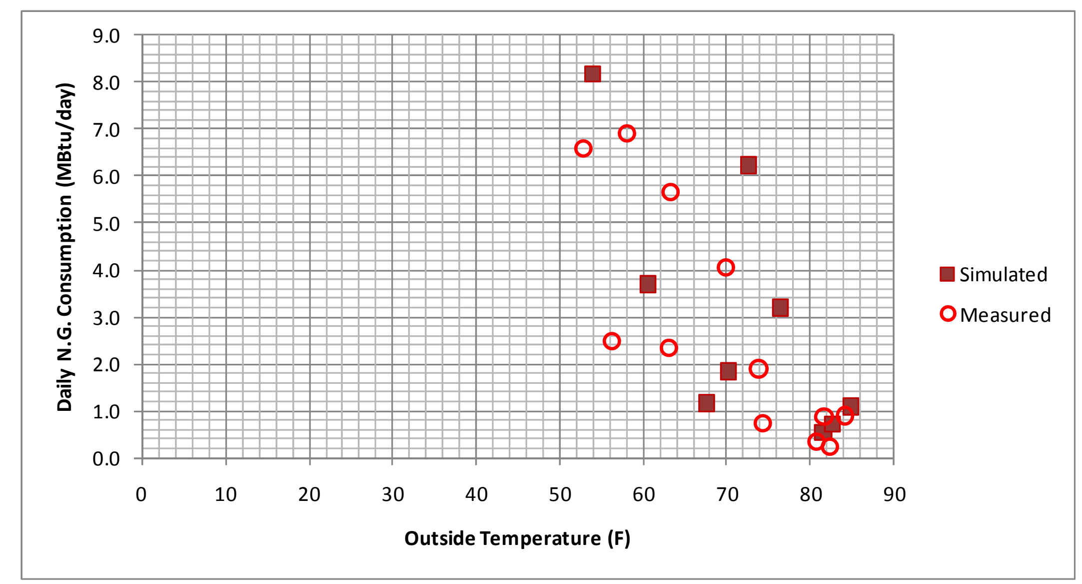


Figure 6.14 - Continued

temperatures during the first half of the year (i.e., Jan to June) are between 60 to 73 F, whereas the ground temepratures of the rest of the year (i.e., July to December) are between 69 to 79 F. As described in Chapter IV, the case-study building is a one story building that has a relatively large slab floor, which results in a large heat transfer to the ground when the U-value method was used instead of Winkelmann's U-effective value. Before calibration step 4, the simulation input used a U-value for the underground floor, which can overestimate the heat transfer from the ground to the building especially after the summer vacation period (i.e., August to December) because of the higher range of ground temperature (i.e., 69 to 79 F). In other words, additional heat gain from the slab floor during August to December would be added to the building, which causes additional cooling load for the building. Before the summer vacation period, the effect of heat gain from the slab would be relatively small since the slab temperature range during this period is relatively lower (i.e., 60 to 73 F). Therefore, the use of U-effective method reduces the heat transfer from the slab floor and results in the decreased cooling energy use after the summer vacation period. Figure 6.16 shows the simulation results, which shows that the simulated cooling energy use after the summer vacation period moved closer to the measured uses. The NMBE and CV(RMSE) for whole building electiricity was decreased to -1.34 % and 21.50 %, respectively. Table 6.6 presents the NMBE and CV(RMSE) for all the sub energy uses.

Table 6.6 - NMBE and CV(RMSE) for Calibration Step 4

	Whole Building Electricity	Lighting & Equipment	Whole Building Cooling + Motor Control Center	Natural Gas
NMBE	-1.34%	-0.77%	-1.77%	-14.18%
CVRMSE	21.50%	12.89%	36.90%	69.10%

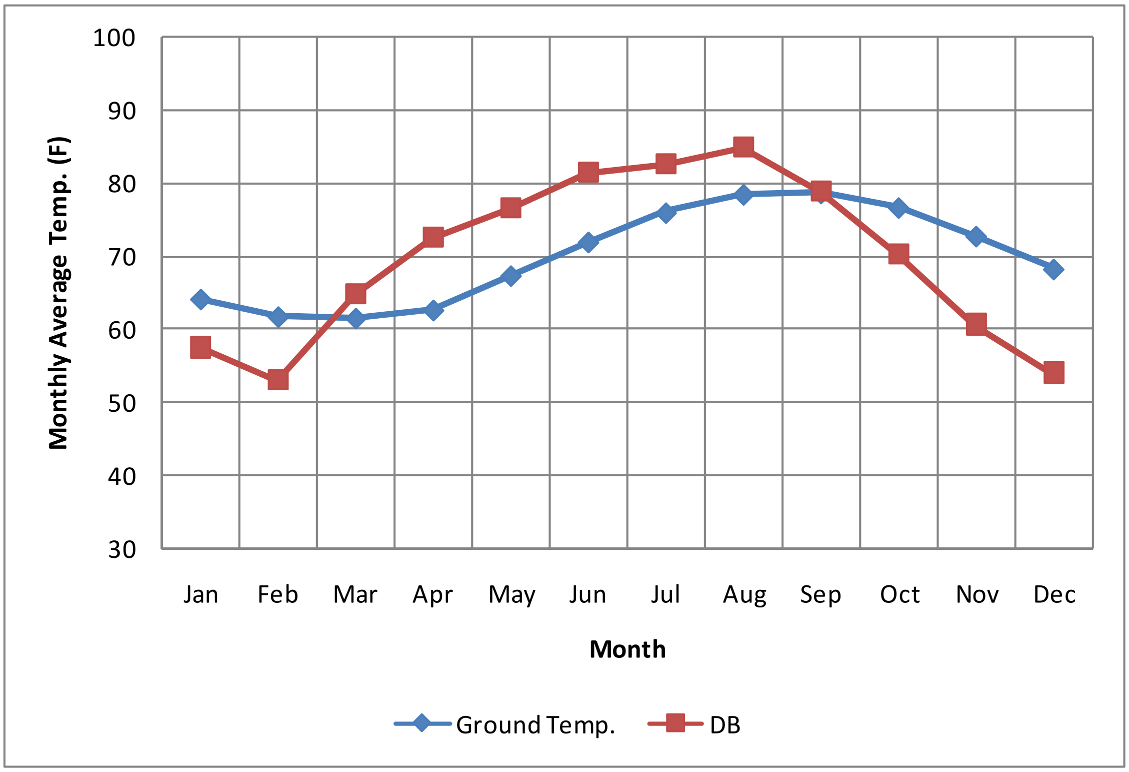
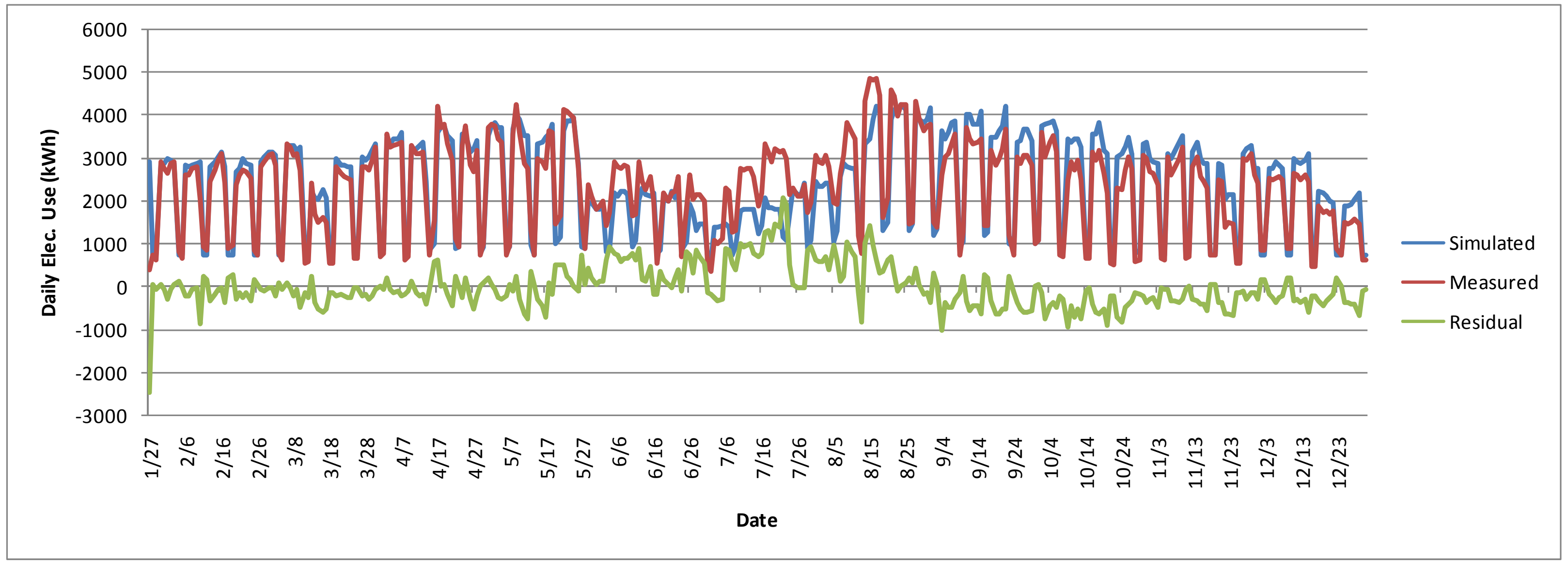


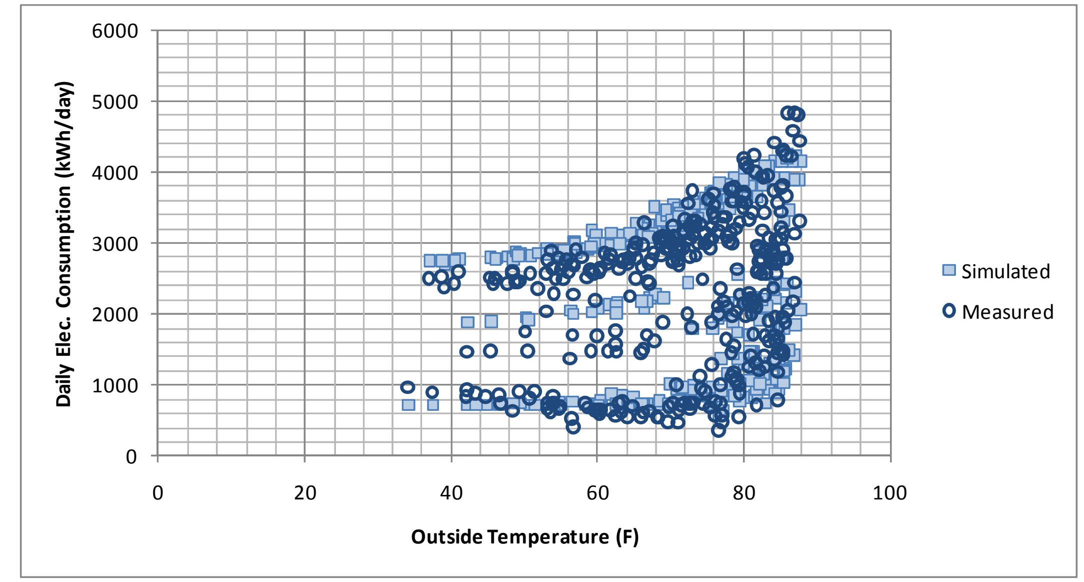
Figure 6.15 - Monthly Average Dry Bulb Temperature vs. Ground Temperature from the 2006 Measured Weather File

6.6. Step 5: The HVAC and Room Setpoint Temperature from the Measured Data

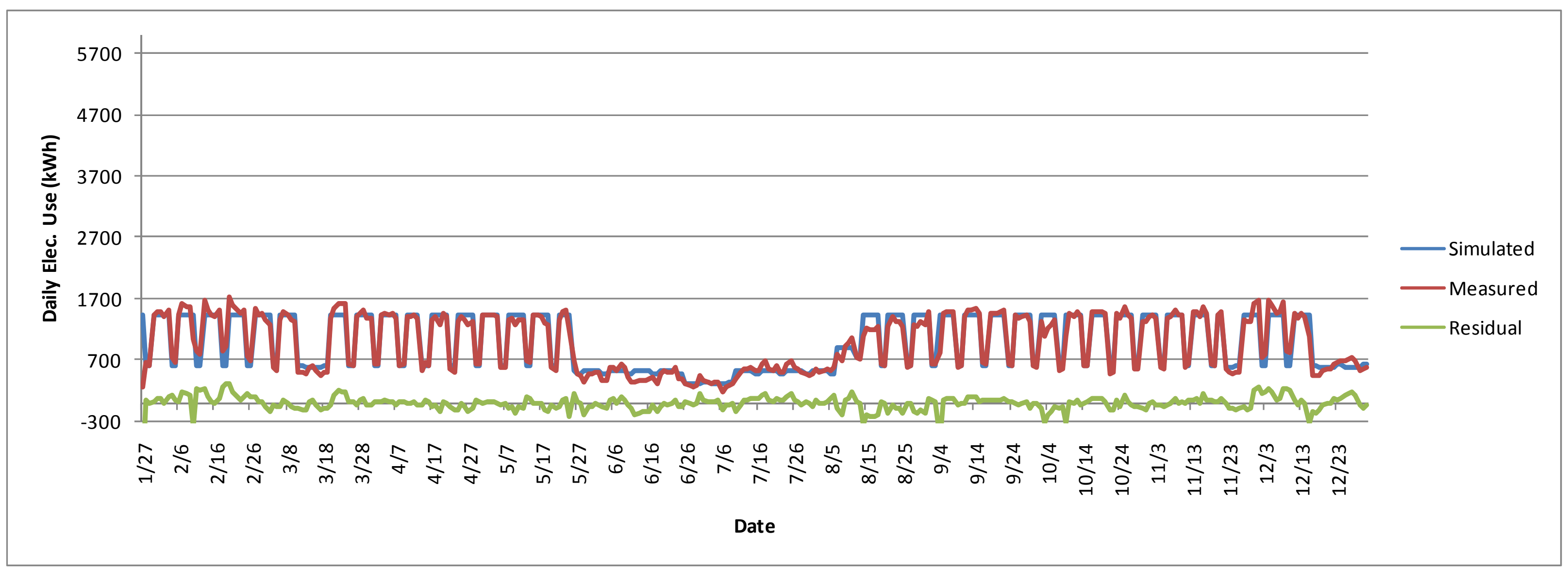
As a final step of the calibration, the simulation input was modified based on the measurements from the portable loggers. In general, the values from the SYSTEM input

1. **Whole Building Electricity**





2. **Lighting & Equipment**



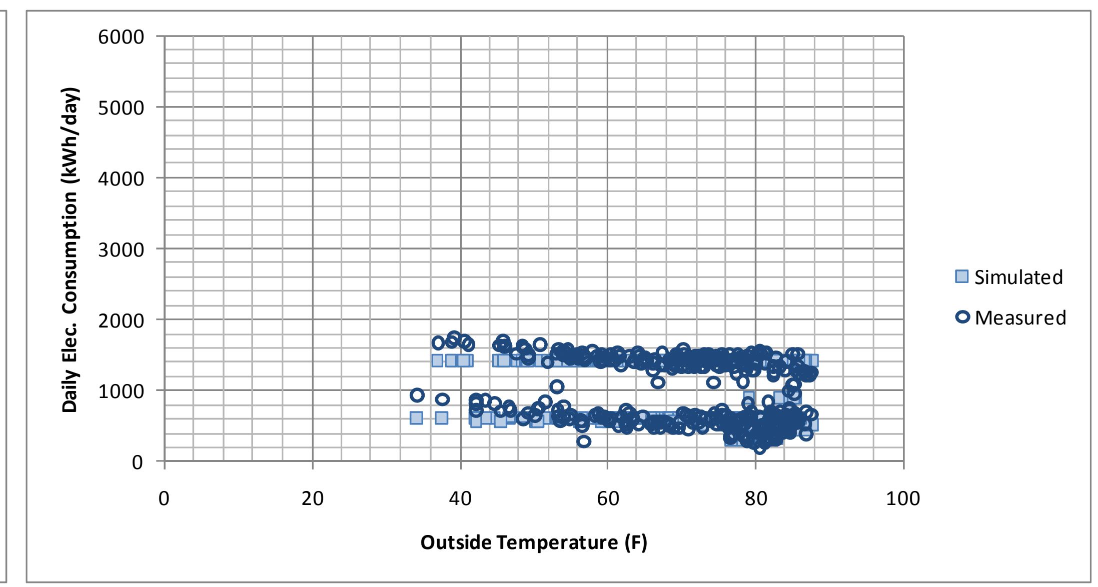
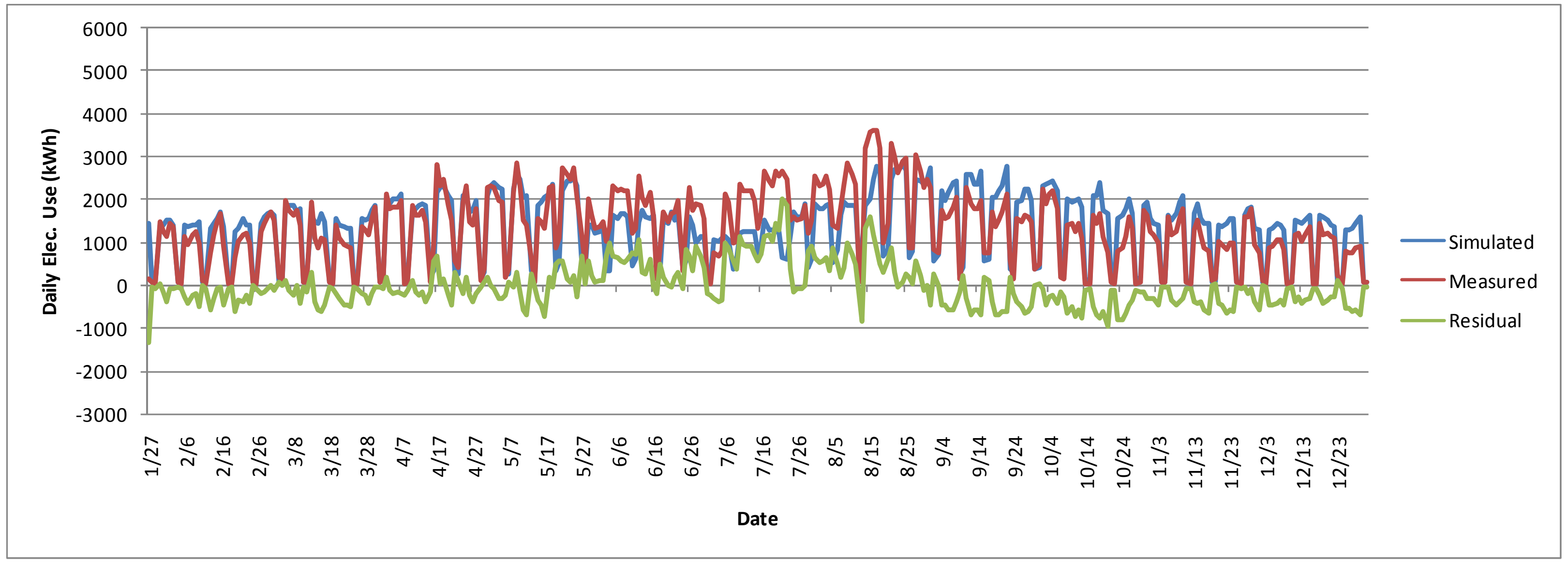
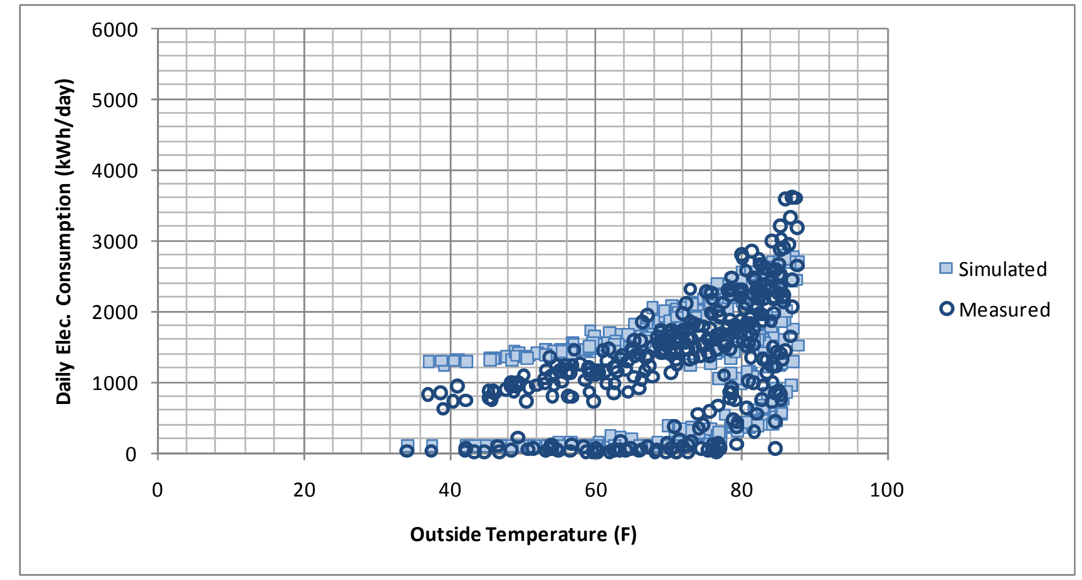


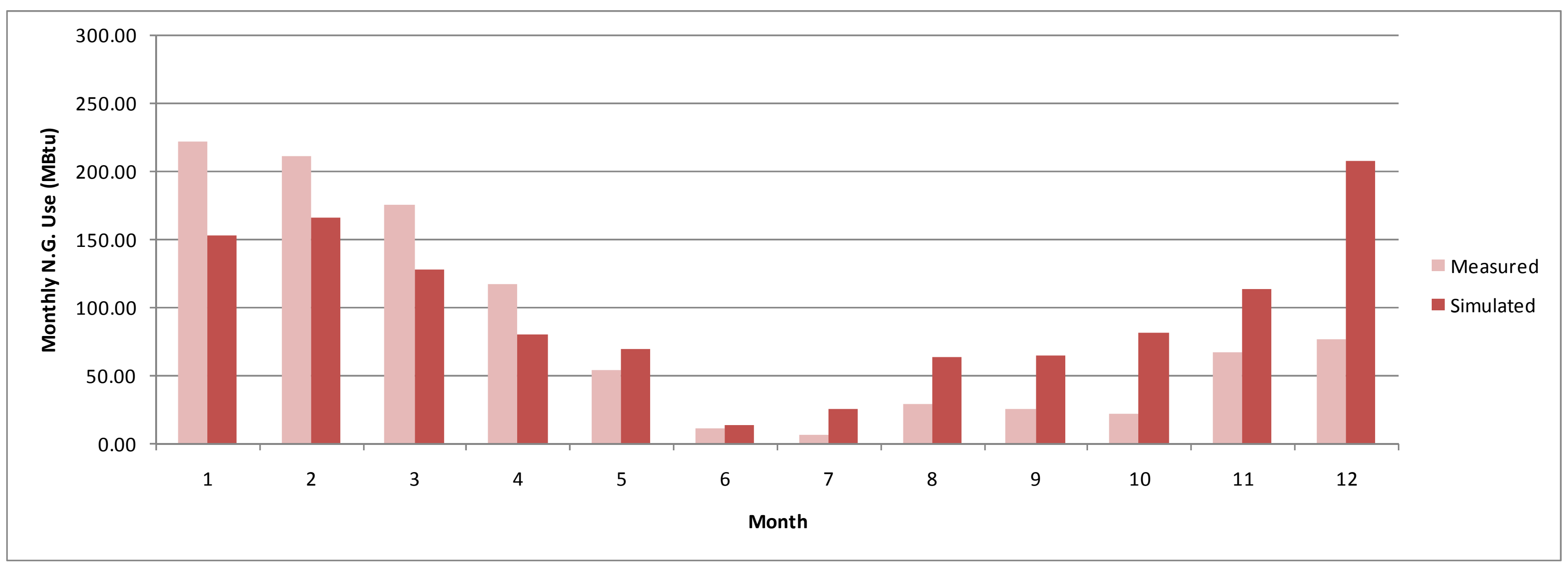
Figure 6.16 - Simulation Results: Calibration Step 4 – Winkelmann's Method (U-effective Method) for Ground Conductance

3. Whole Building Cooling + Motor Control Center





4. Natural Gas



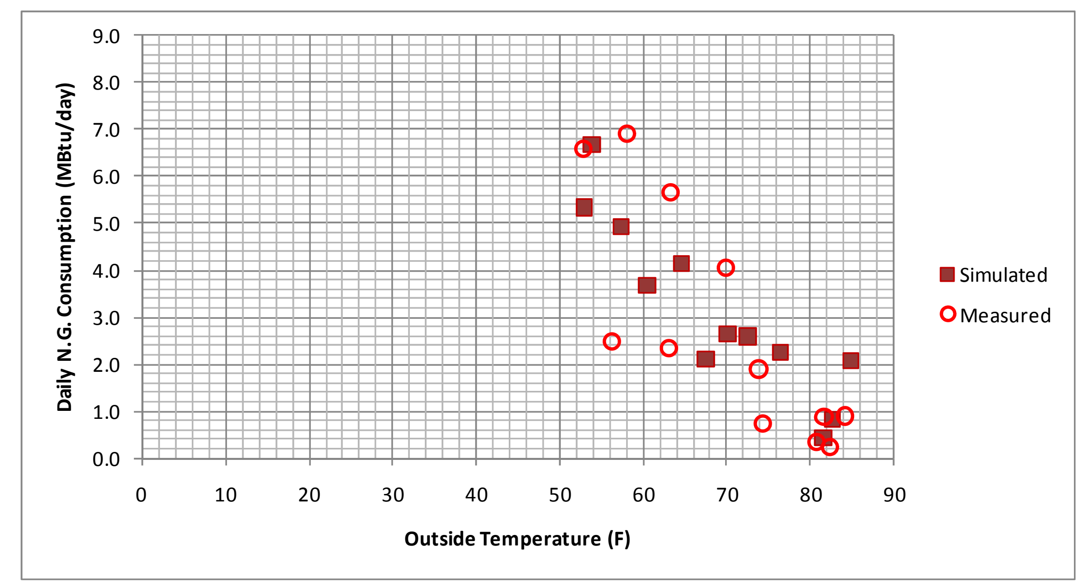


Figure 6.16 - Continued

in DOE-2 input are matched with the measured data. However, the measured cold deck temperature was about 50 F, while the as-built simulation has 55 F cold deck temperature from the interviews with the maintenance personnel. Figure 6.17 shows the measured cold deck temperatures during May 9, 2006 through May 23, 2006.

Based on this finding, the DOE-2 simulation input from the previous calibration step was modified. Figure 6.18 shows the simulation results, and the NMBE and CV(RMSE) for whole building electricity is 2.5 % and 16.8 %, respectively. Table 6.7 presents the NMBE and CV(RMSE) for all the sub energy uses.

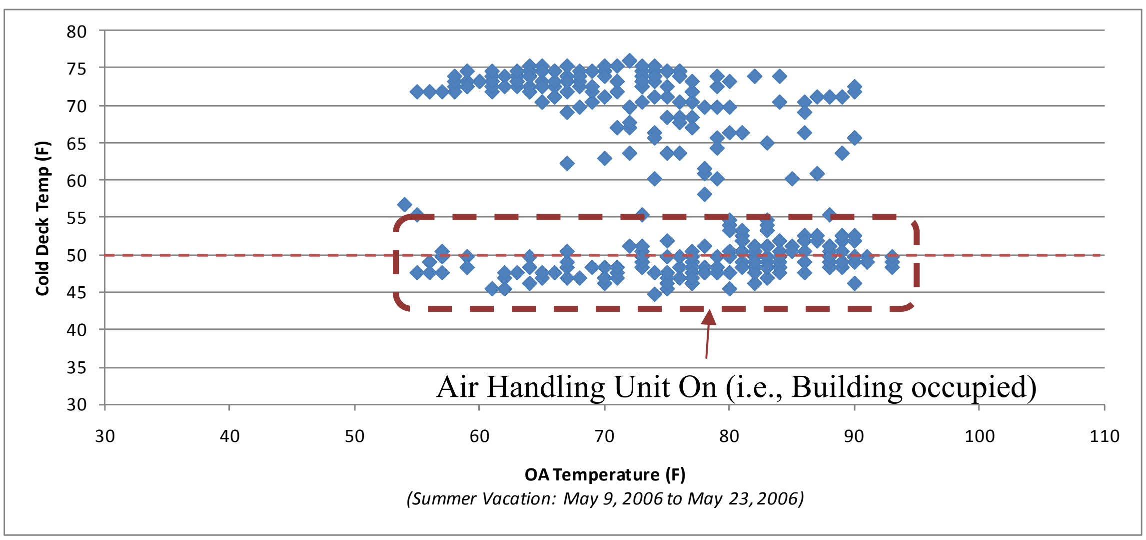


Figure 6.17 - Measured Cold Deck Temperature as a Function of OA Temperature

Table 6.7 - NMBE and CV(RMSE) for Calibration Step 5

	Whole Building Electricity	Lighting & Equipment	Whole Building Cooling + Motor Control Center	Natural Gas
NMBE	2.54%	-0.77%	4.98%	11.69%
CVRMSE	16.76%	12.89%	28.45%	35.73%

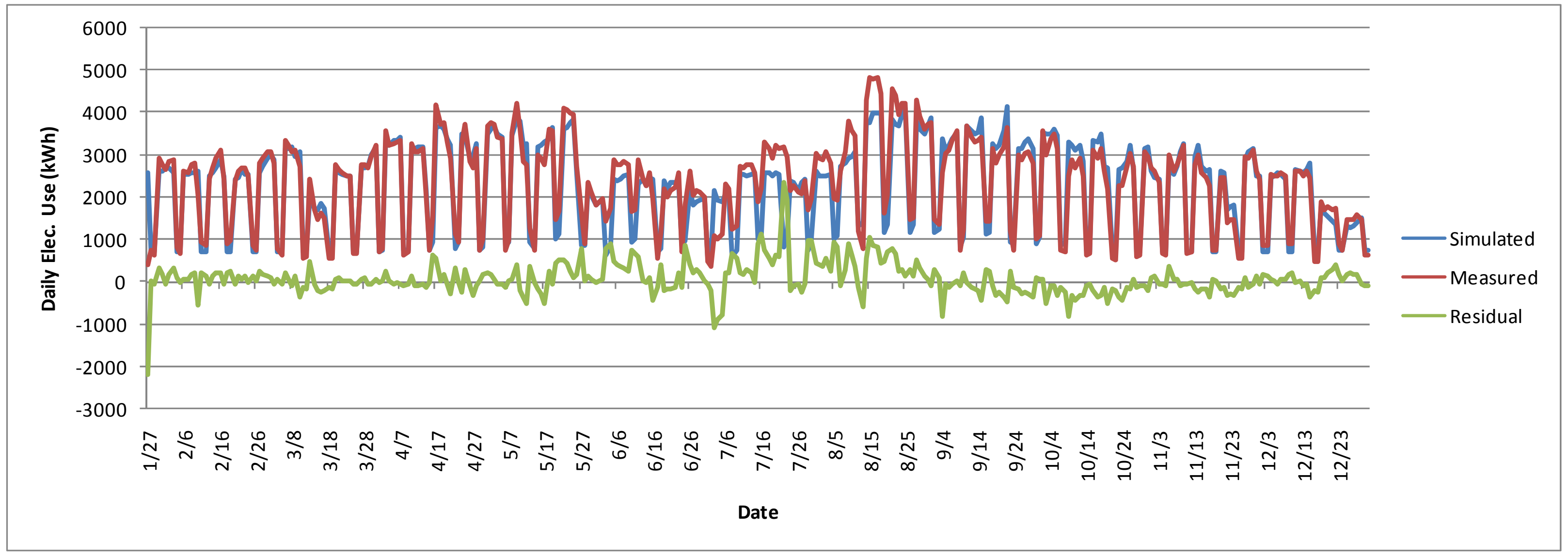
6.7. Analysis by Calibration Step

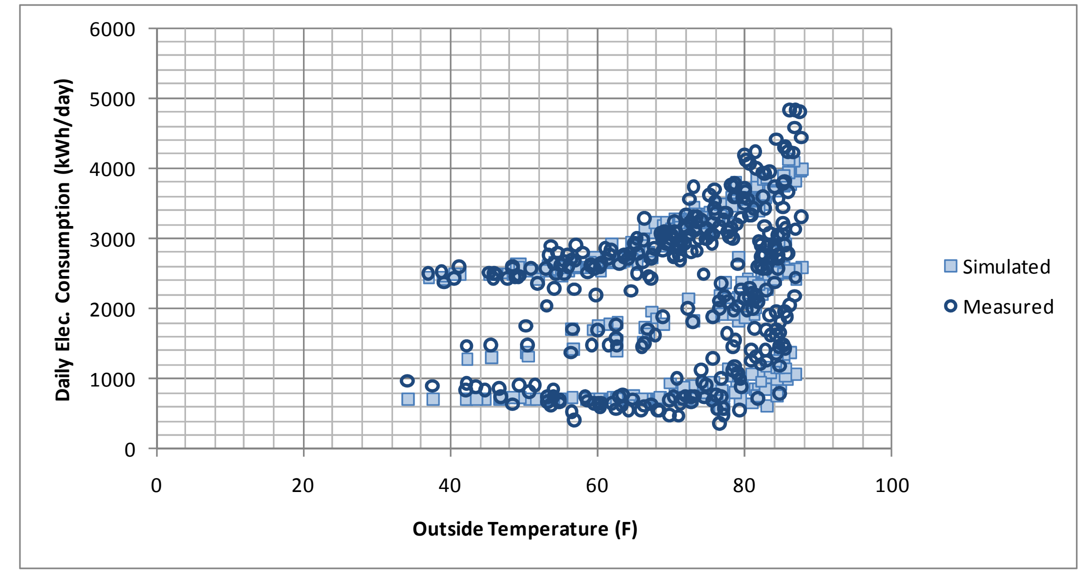
Table 6.8 and Figures 6.19 through 6.22 shows the NMBE and CV(RMSE) changes by calibration steps for whole building electricity, lighting & equipment, whole building cooling + motor control center, and natural gas, respectively. In addition, Figures 6.23 to 6.25 shows the DOE-s'2 BEPS changes by calibration step. In these figures, the calibrated simulation results were compared to the measured energy uses.

Table 6.8 - Changes in NMBE and CV(RMSE) by Calibration Step

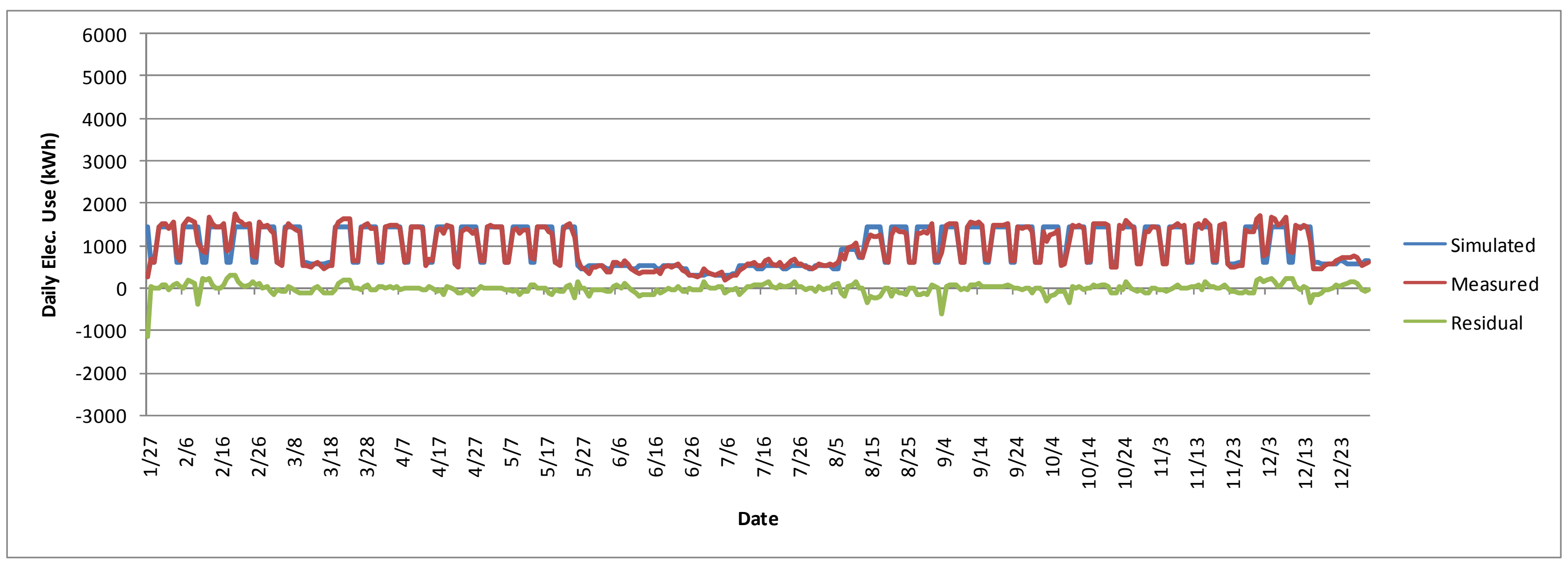
		AS-Built	Step 1	Step 2	Step 3	Step 4	Step 5
WBE	NMBE	10.2%	7.6%	-16.7%	-7.9%	-1.3%	2.5%
	CV(RMSE)	35.5%	32.1%	31.7%	25.9%	21.5%	16.8%
L&E	NMBE	50.3%	50.3%	-0.8%	-0.8%	-0.8%	-0.8%
	CV(RMSE)	56.7%	56.7%	12.9%	12.9%	12.9%	12.9%
WBC+MCC	NMBE	-19.4%	-23.9%	-28.4%	-13.1%	-1.8%	5.0%
	CV(RMSE)	56.1%	52.7%	53.8%	43.8%	36.9%	28.5%
natural gas	NMBE	-109.0%	-88.1%	-67.7%	-67.7%	-14.2%	11.7%
	CV(RMSE)	145.2%	120.8%	99.3%	99.3%	69.1%	35.7%

1. **Whole Building Electricity**





2. **Lighting & Equipment**



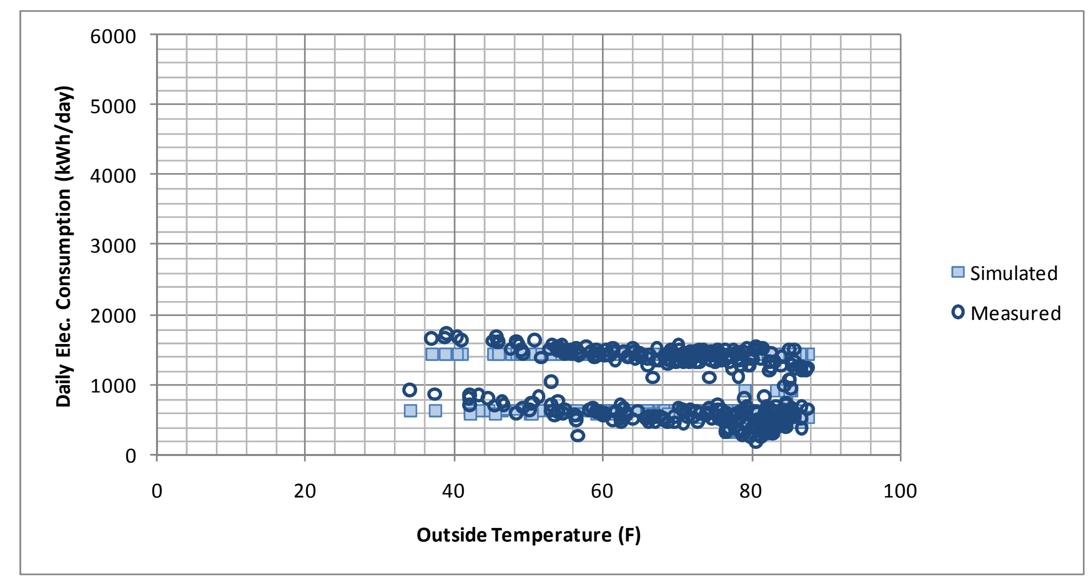
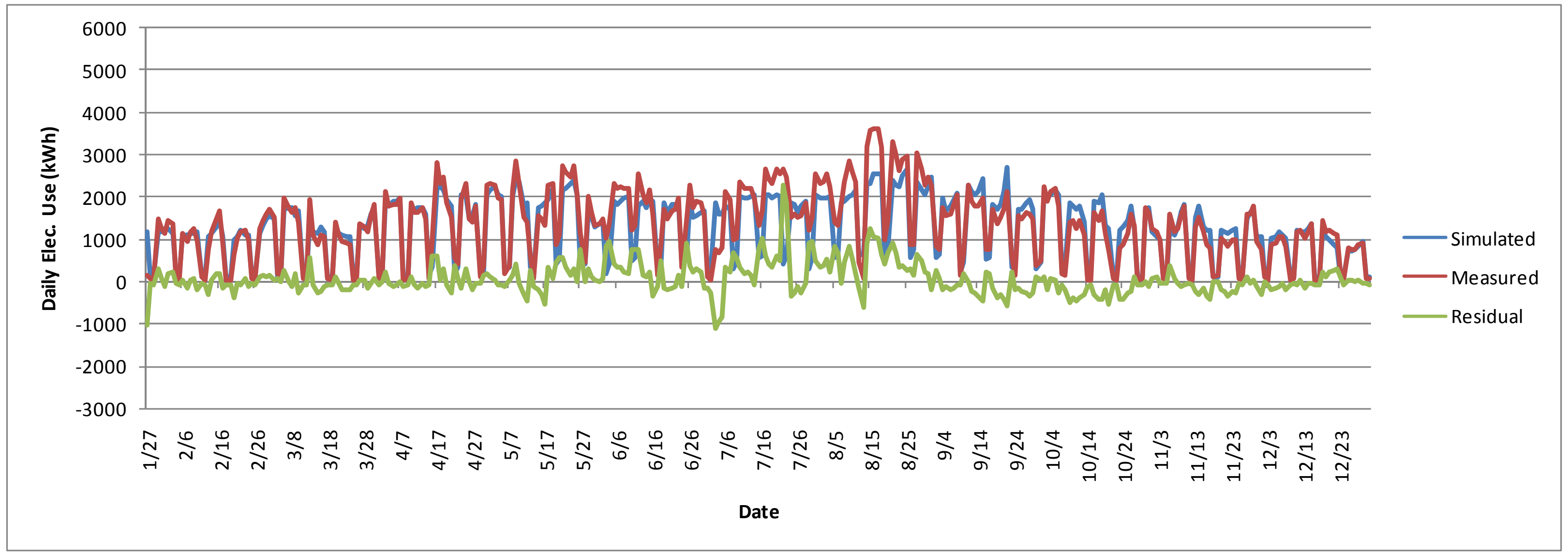
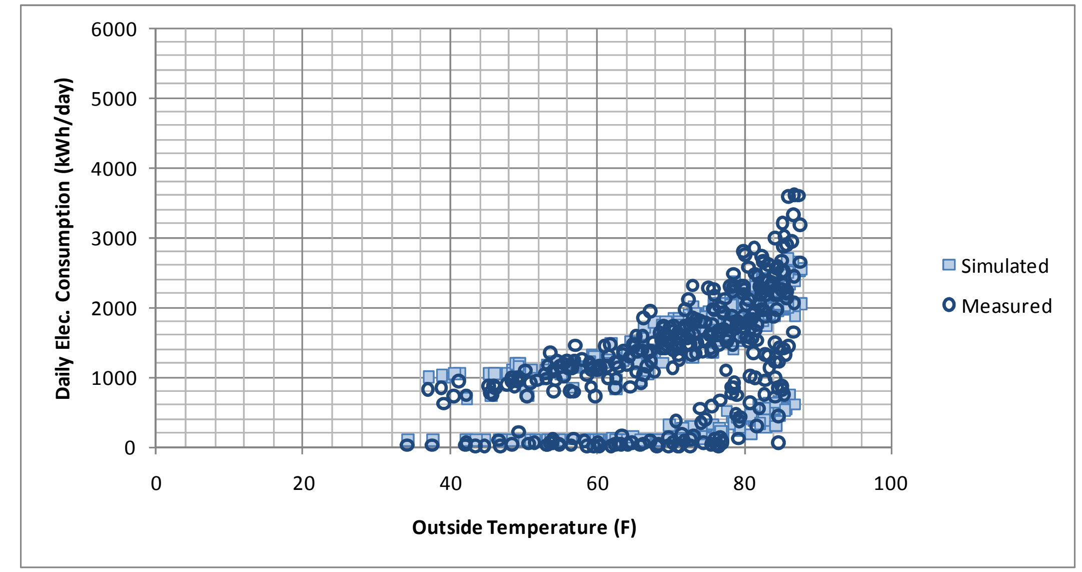


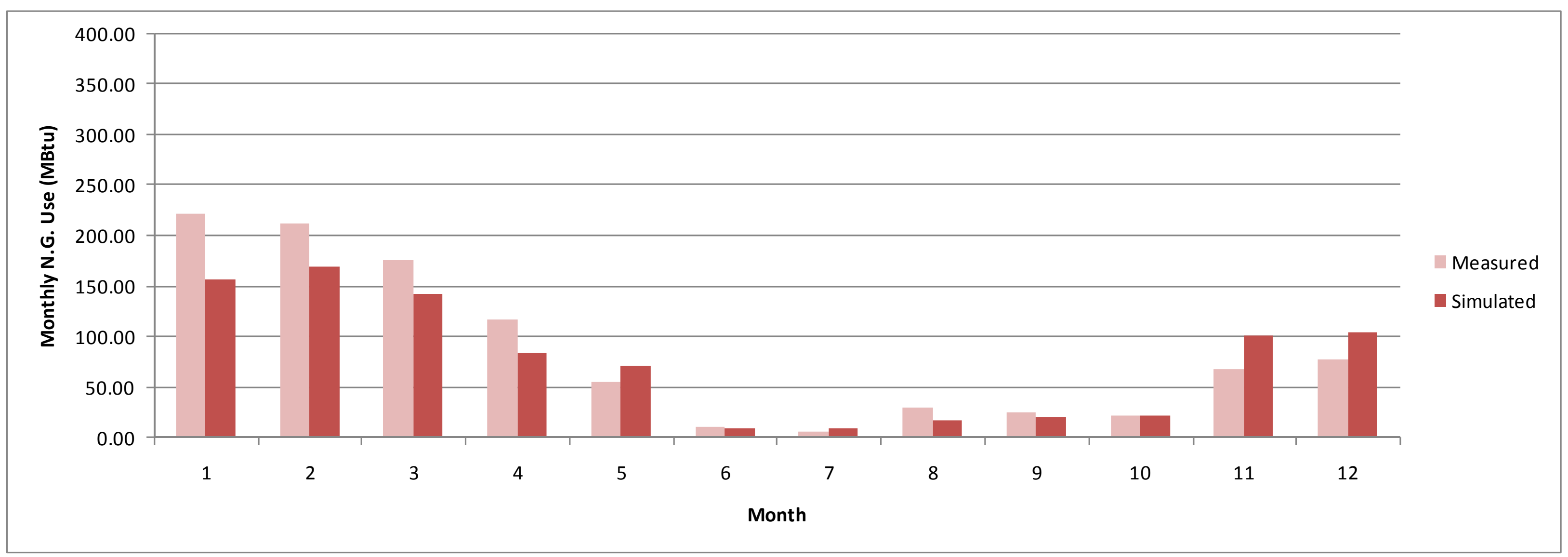
Figure 6.18 - Simulation Results: Calibration Step 5 – Correction from HOBO Measurement

3. Whole Building Cooling + Motor Control Center





4. Natural Gas



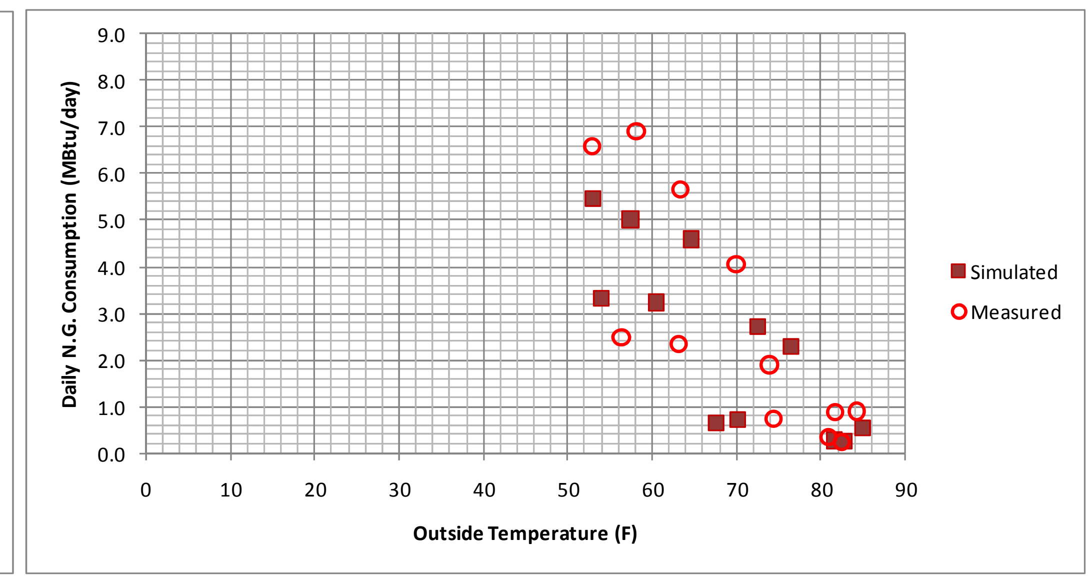


Figure 6.18 – Continued

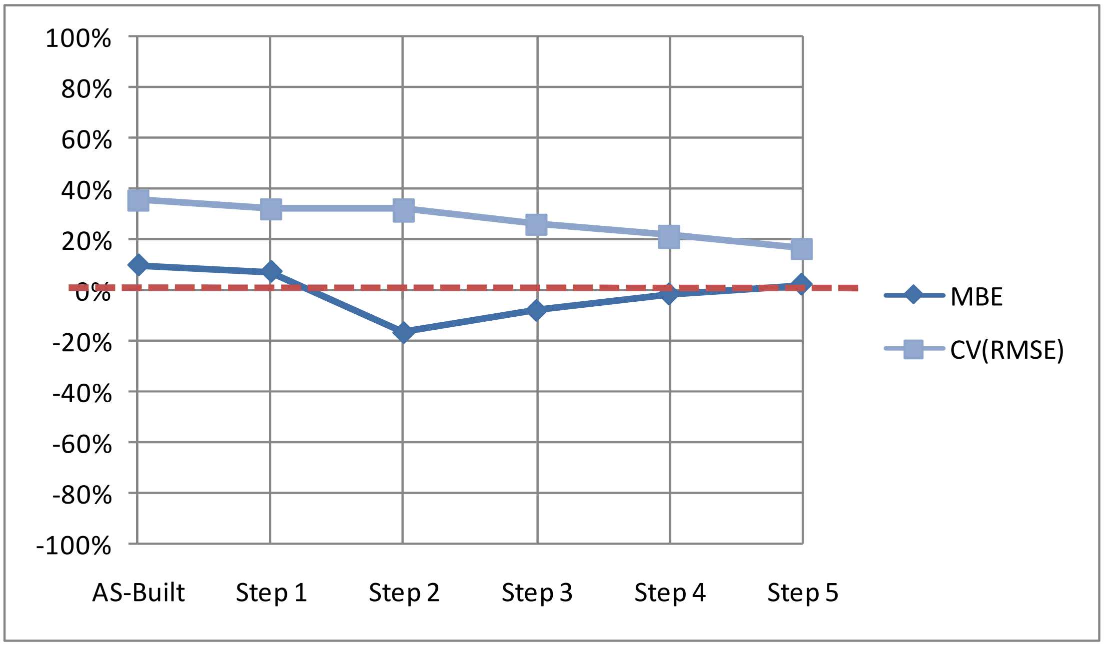


Figure 6.19 - NMBE and CV(RMSE) Changes for Whole Building Electricity by Calibration Step

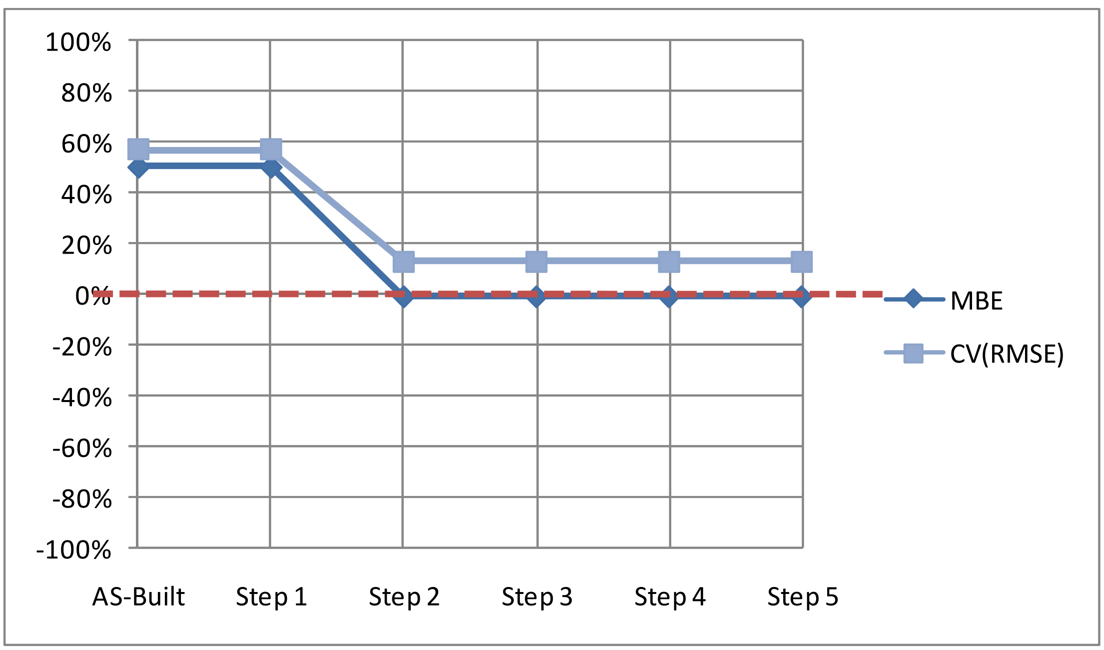


Figure 6.20- NMBE and CV(RMSE) Changes for Lighting and Equipment by Calibration Step

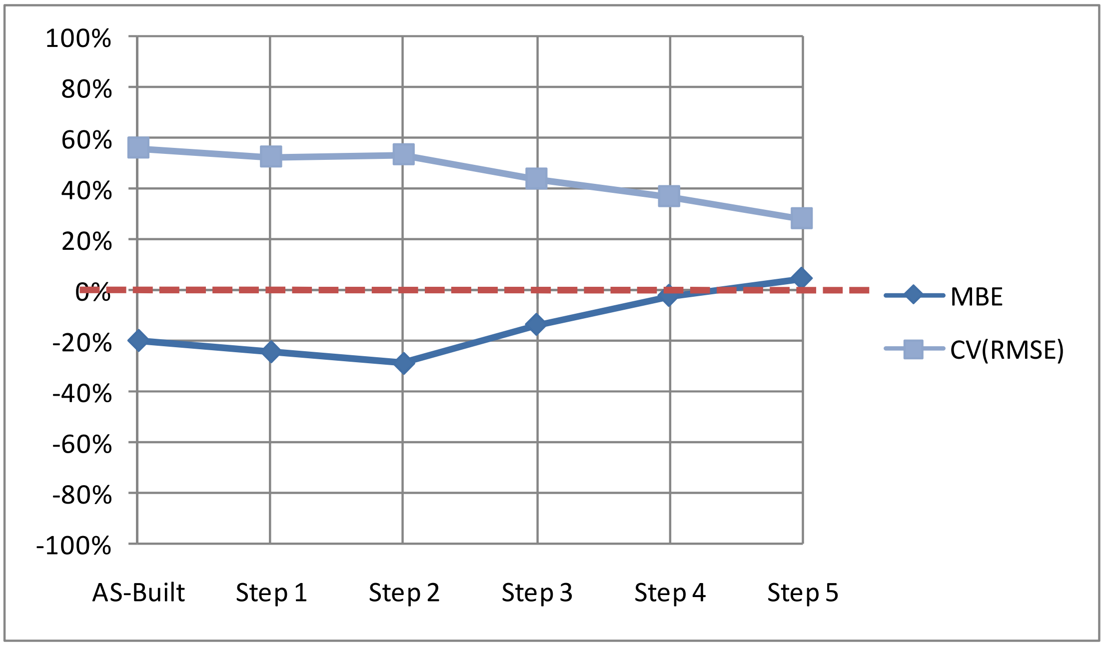


Figure 6.21 - NMBE and CV(RMSE) Changes for Whole Building Cooling + Motor Control Center by Calibration Step

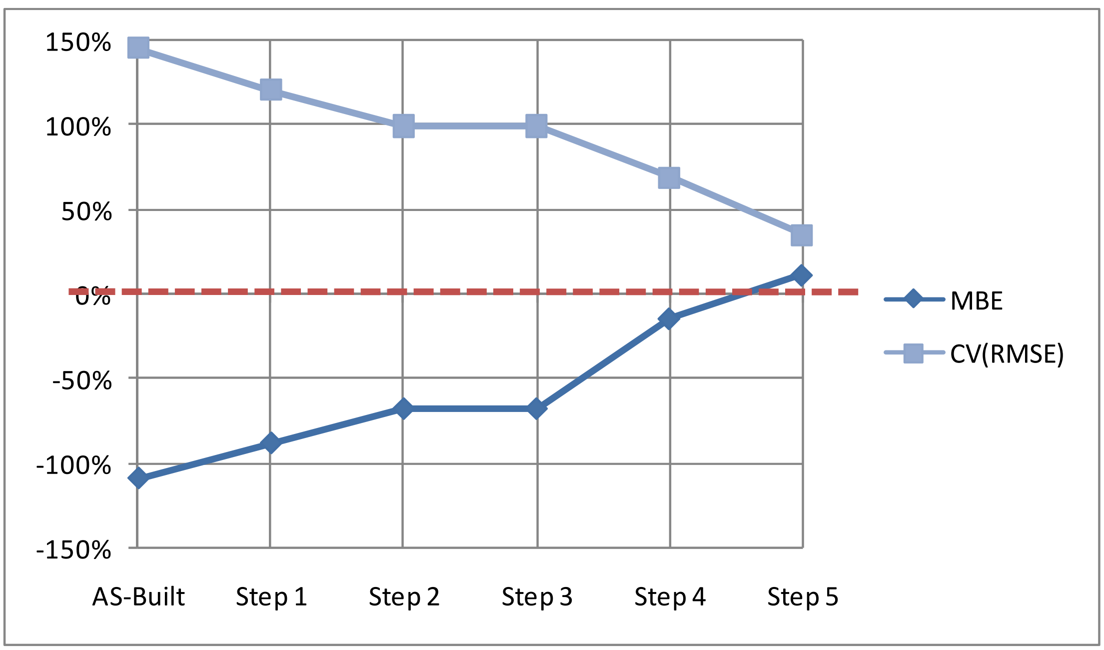
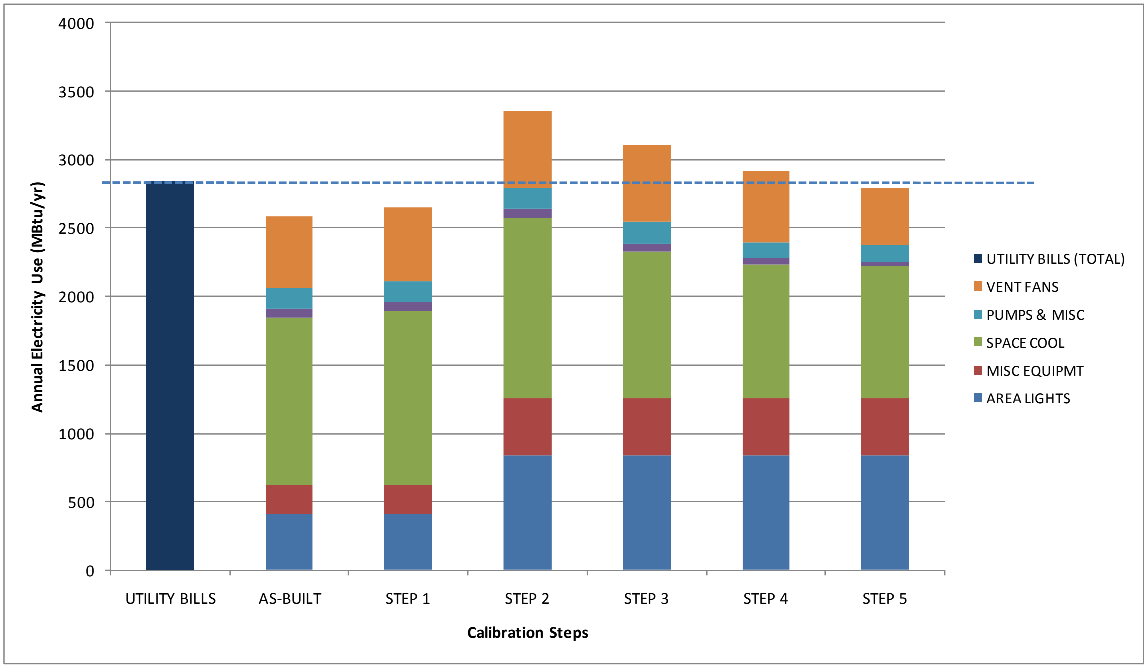
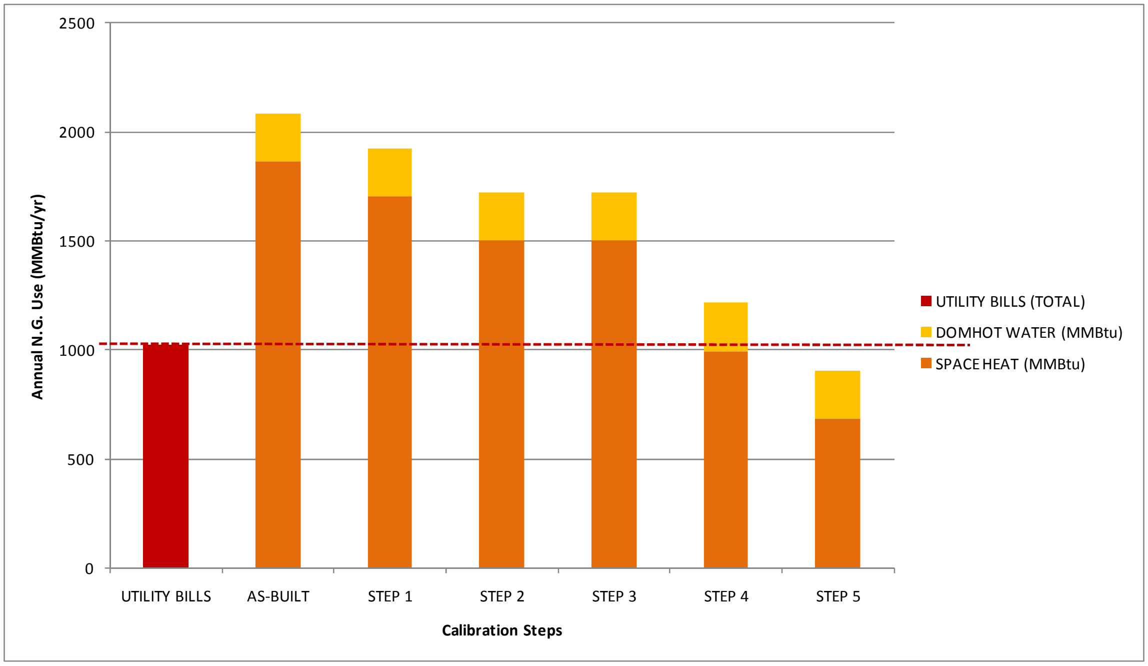


Figure 6.22 - NMBE and CV(RMSE) Changes for Natural Gas by Calibration Step



	UTILITY BILLS	AS-BUILT	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5
AREA LIGHTS (MMBtu)		415.20	415.20	834.70	834.70	834.70	834.70
MISC EQUIPMT (MMBtu)		207.60	207.60	417.30	417.30	417.30	417.30
SPACE COOL (MMBtu)		1,218.60	1,266.20	1,323.30	1,075.00	981.30	968.30
SPACE HEAT (MMBtu)		71.00	68.00	63.00	63.00	52.00	36.70
PUMPS & MISC (MMBtu)		147.90	152.20	152.90	152.90	114.10	116.10
VENT FANS (MMBtu)		520.20	541.80	558.70	558.70	514.10	419.10
UTILITY BILLS (TOTAL)	2,840.24						

Figure 6.23 - BEPS Changes by Calibration Step (Electricity Only)



	UTILITY BILLS	AS-BUILT	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5
SPACE HEAT (MMBtu)		1862.4	1704.7	1500.4	1500.4	994.3	685
DOMHOT WATER (MMBtu)		221.1	221.1	221.1	221.1	221.1	221.1
UTILITY BILLS (TOTAL)	1022						

Figure 6.24 - BEPS Changes by Calibration Step (Natural Gas Only)

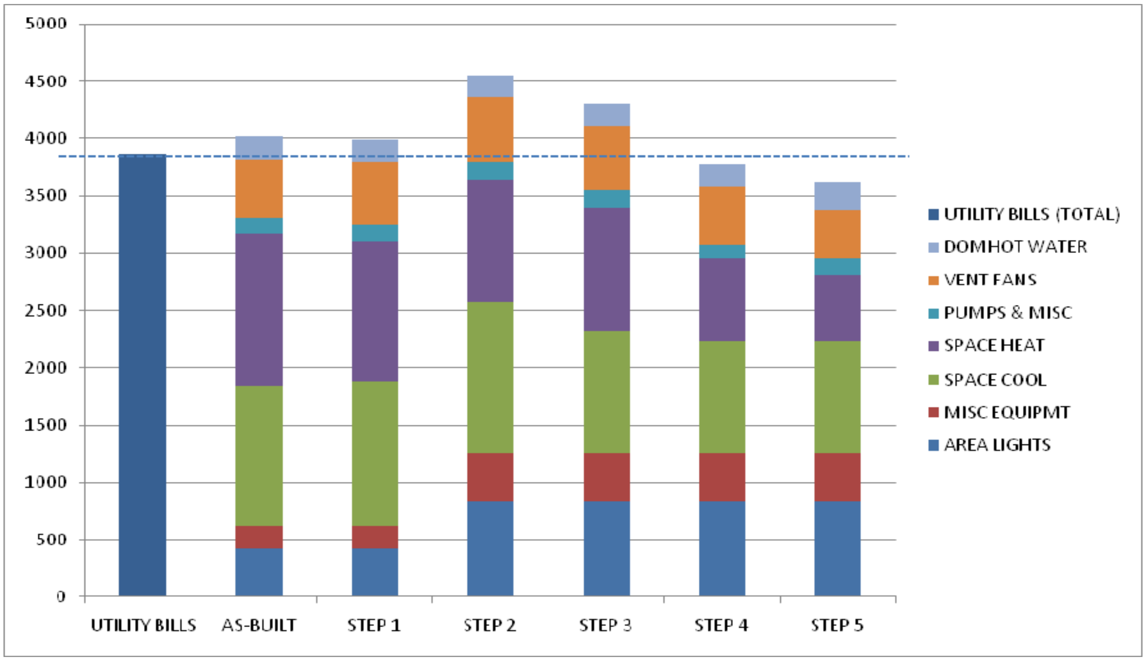


Figure 6.25 - BEPS Changes by Calibration Step (Total)

Below is the detailed description about the changes by each step.

6.7.1 As-Built to Step 1: Using Measured Weather File

By using the 2006 actual weather file instead of the Houston TMY2 weather file, the space cooling energy increased (i.e., 3.9% increase) and the space heating energy decreased (i.e., 8.2 % decrease). As described in section 6.2, the reason for this change could be that the weather condition in 2006 was warmer than the condition in the Houston TMY2 weather file.

6.7.2 Step 1 to Step 2: Using RP-1093 Method for Lighting and Equipment Schedule

Use of the RP-1093 method resulted in the increased lighting and equipment energy use (i.e., 101.0% increases). This was due to the under-estimated lighting and equipment energy use in the as-built simulation. As the lighting and equipment energy use increased, the space cooling energy increased (i.e., 4.5% increase) and the space heating energy reduced (i.e., 11.7% decrease) due to the increased internal heat gain from the lighting and equipment.

6.7.3 Step 2 to Step 3: Using Scroll Chiller Performance Curves

Use of the scroll chiller performance curves instead of the open centrifugal chiller decreased the space cooling energy by 18.8%.

6.7.4 Step 3 to Step 4: Using Winkelmann's Method

Use of the Winkelmann's method for the underground floor reduced both space cooling and heating energy (i.e., 8.7% and 32.8% respectively). By using the Winkelmann's method, the overestimated heat transfer through the underground floor was corrected, and this resulted reduced cooling and heating energy for the building.

6.7.5 Step 4 to Step 5: Correction from HOBO measurement

By replacing the cold deck temperature with 50F instead of 55F, the whole building electricity energy use decreased 4.1% mainly due to the decreased vent fan energy use.

6.8. Calculation of Seasonal NMBE and CV(RMSE)

From the calibration results shown in the previous section, it can be found that the simulated energy use in summer period is relatively difficult to calibrate with the measured use. According to an interview with the maintenance personnel in the school district, the inconsistent energy use patterns in summer period is partially due to the unscheduled building uses from several groups and communities during summer period. Therefore, this study proposes to calculate NMBE and CV(RMSE) only for normal school days (i.e., without summer period)[2]. The seasonal NMBE and CV(RMSE) can be compared to the whole year NMBE and CV(RMSE), and the usefulness of using the seasonal calculation for school building type could be validated.

The first step of this procedure is to separate the energy uses in summer periods from the energy uses in whole year. In this school, the summer period was from May 29 through August 14. Then, the same equation used in previous section (i.e., equation 4.1 and 4.2) was used to calculate the seasonal NMBE and CV(RMSE). Table 6.9 presents the calculation results. As presented, the NMBE and CV(RMSE) for WBE, Lighting & Equipment, and WBC & MCC for normal school days are decreased compared to the

[2] Since only monthly utility bills for natural gas are available for this study, the seasonal NMBE and CV(RMSE) was calculated only for electricity use.

values for whole year. The whole building electricity seasonal (i.e., no summer period) NMBE and the CV(RMSE) was calculated as -1.6% and 11.9%, respectively (i.e., compared with whole year's NMBE and CV(REMSE) of 2.5% and 16.8%, respectively).

For more examination of the seasonal variation, the NMBE and CV(RMSE) for summer period were also calculated. Table 6.9 also presents the calculation results. As shown, the NMBE and CV(RMSE) for summer period are increased. The whole building electricity summer NMBE and the CV(RMSE) was calculated as -10.6% and 27.8%, respectively. The increased NMBE and CV(RMSE) explains the inconsistent energy use patterns in summer period.

Table 6.9 - Seasonal NMBE and CV(RMSE)

		Step 5 (Whole Year)	**Seasonal (No Summer)**	**Seasonal (Only Summer)**
WBE	MBE	2.5%	-1.57%	10.55%
	CV(RMSE)	16.8%	11.88%	27.79%
L&E	MBE	-0.8%	-0.28%	-2.04%
	CV(RMSE)	12.9%	11.86%	18.39%
WBC+MCC	MBE	5.0%	-2.83%	14.22%
	CV(RMSE)	28.5%	20.47%	36.06%

6.9. Summary of Calibrated Simulation

The results of the calibrated simulation were discussed in this section. The initial as-built simulation shows the lower electricity uses than the measured use mainly due to the under estimated lighting and equipment energy use. The whole-building electricity NMBE and the CV(RMSE) for the as-built simulation was 10.2% and 35.5%, respectively. Through 5 calibration steps, the final NMBE and CV(RMSE) for whole building electricity were calculated as 2.5% and 16.8%, respectively, which could be considered to be calibrated based on the definition by the ASHRAE Guideline 14-2002 (2002). According to pp.41 in this Guideline, "Models are declared to be calibrated if they produce NMBE with ±10% and CV(RMSE) within ±30% when using hourly data, or ±5% and ±15% with monthly data.".

Further analysis was performed to identify seasonal (i.e., without summer period) NMBE and CV(RMSE). The calculated seasonal NMBE and CV(RMSE) confirms that the better calibration result can be achieved by removing summer period of energy use.

CHAPTER VII

RESULTS: DAYLIGHTING SIMULATION

In this chapter, the results of the daylighting simulations are discussed. As described in Chapter IV, a classroom with and without horizontal skylights was simulated using the Desktop Radiance and the DOE-2 simulation programs. First, the Desktop Radiance program was used to demonstrate the indoor daylighting quality by comparing the original and daylit classroom. Then, the DOE-2 simulation program was used to estimates the energy savings potentials from the application of a daylighting strategy.

7.1. Classroom without Skylights

First, a classroom without toplights (e.g., skylights) was simulated as the base line to be compared with the classroom with toplights. A DrawBDL (Huang 2000) rendering of the modeled classroom is shown in Figure 7.1. As described in Chapter IV, the width and the length of the classroom is 28.5 ft and the floor-to-ceiling height is 9 ft with a 4.5 ft plenum, which is the same size as a classroom in the case-study school in this dissertation. The classroom has one 6’ x 4’ single pane tinted window with blinds. Other input values (i.e., lighting & equipment schedule, envelope insulation level, etc.) for the LOADS input are the same as the calibrated simulation described in the previous section. A VAV system was used for the classroom simulation and the same type of the plant equipment as the case-study school were applied for the classroom. The annual simulated energy end use (i.e., BEPS Report) using the 2006 TRY weather file

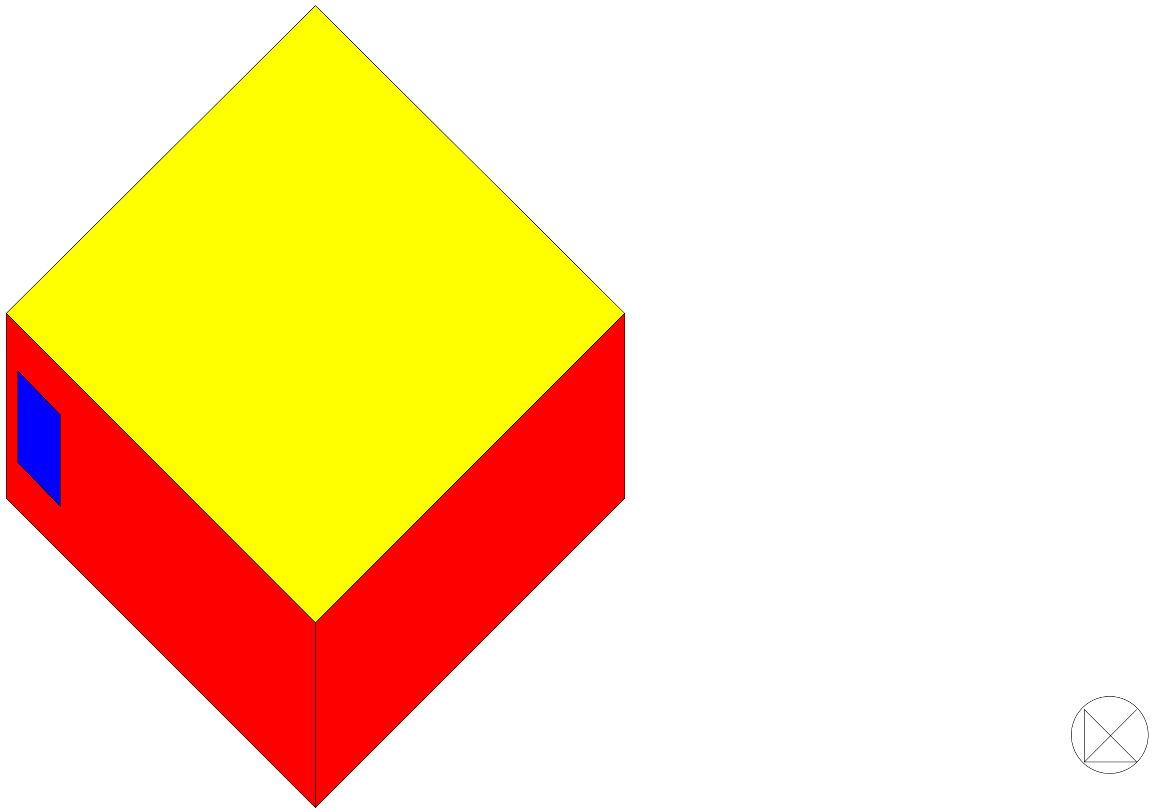


Figure 7.1 - The DOE-2 Classroom without Skylights Displayed with the DrawBDL Program (Huang 2000).

with measured data is presented in Table 7.1. In Table 7.1, the energy use for electrical lights shown to be is 28.8% of the total energy use, which is the most consumptive end use of the classroom, and the space cooling was the second most consumptive (i.e., 28.5% of total), which also includes some portion of the vent fans and pumps (shown separately). Domestic water heating was not included in the classroom.

In order to evaluate the use of daylighting in the classroom, the classroom was simulated using the Desktop Radiance without any electrical lighting fixtures. The

Table 7.1 - BEPS Report for a Classroom without Toplights

End Use	Annual Energy Use (MMBtu) Electricity	Natural Gas	Total	Percent of Total (%)
AREA LIGHTS	9	0	9	28.8%
MISC EQUIPMT	4.5	0	4.5	14.4%
SPACE HEAT	0.2	4.3	4.5	14.4%
SPACE COOL	8.8	0	8.9	28.5%
PUMPS & MISC	1.6	0	1.6	5.1%
VENT FANS	2.7	0	2.7	8.7%
TOTAL	**26.9**	**4.3**	**30.2**	**100%**

simulation conditions included: Clear day noon at March 15 at College Station, TX. The simulated images are shown in Figures 7.2 through Figure 7.4. As shown in Figure 7.4, without any artificial lights, the indoor lighting level was far below than 50 footcandle (fc) levels which is the minimum illumination level for classrooms recommended by IESNA Handbook (IESNA 2000) (i.e., using 1) Illumination category is “E”: performance of visual tasks of medium contrast or small size, 2) Demand for speed and accuracy is I (important), and 3) the average of workers’ age is under 40). For example, the illumination level in the middle of the classroom on March 15 was simulated using the Radiance program as 12.59 lux (i.e., 1.17 fc). Therefore, in the base-case classroom with only one window, artificial lights would be needed for the base-case classroom to be kept at the minimum recommended illumination level of 50 fc.

Figure 7.2 - Radiance Simulated Image of the Classroom with Luminance Option

Figure 7.3 - Radiance Simulated Image of the Classroom (Human Sensitivity)

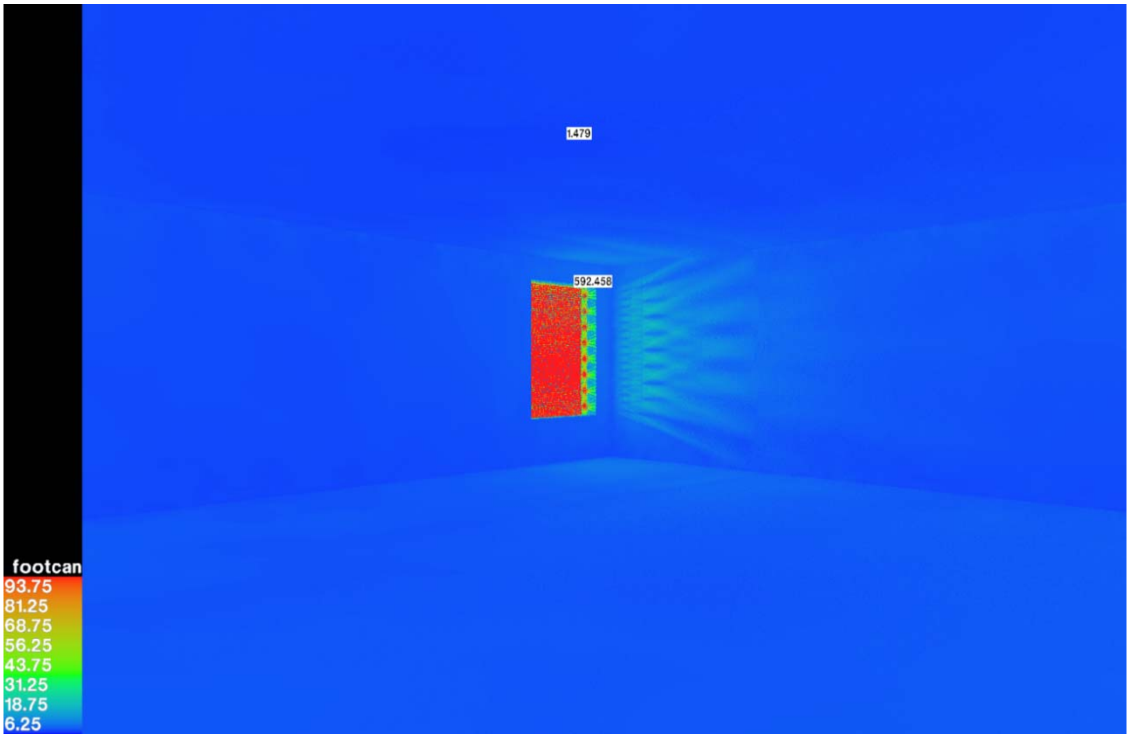


Figure 7.4 - Radiance Simulated Image of the Classroom (False Color)

7.2. Classroom with Skylights with the Original Lighting Schedule from the Calibrated Base-case Model

In this step of analysis, the classroom described above was modified to have four four horizontal toplights as described in Chapter IV. To evaluate the thermal impact from the toplights, a DOE-2 model was created for the base-case classroom that included four toplights. However, the reduced artificial lighting load due to the toplights (i.e., dimming light control) was not used in this step, so that only the thermal impact of adding the toplights to the classroom would be simulated. Figure 7.5 shows the DrawBDL image of the DOE-2 model used at this step. To accomplish this simulation only the LOADS input file of the DOE-2 model was changed without changing the

SYSTEM and PLANT portion of the input file of the base-case classroom discussed above. The annual simulated energy end use using the 2006 TRY weather file with on-site data is presented in Table 7.2 and Figure 7.6. As shown in Table 7.2, the space cooling energy increased by 6.7% and the space heating energy was reduced by 4.4% due to the heat gain from the toplights. The vent fan energy use also increased by 7.4%. The total annual energy was simulated as 31.0 MMBtu, which is an increase of 0.77 MMBtu (i.e., a 1.9% increases) compared with the original classroom.

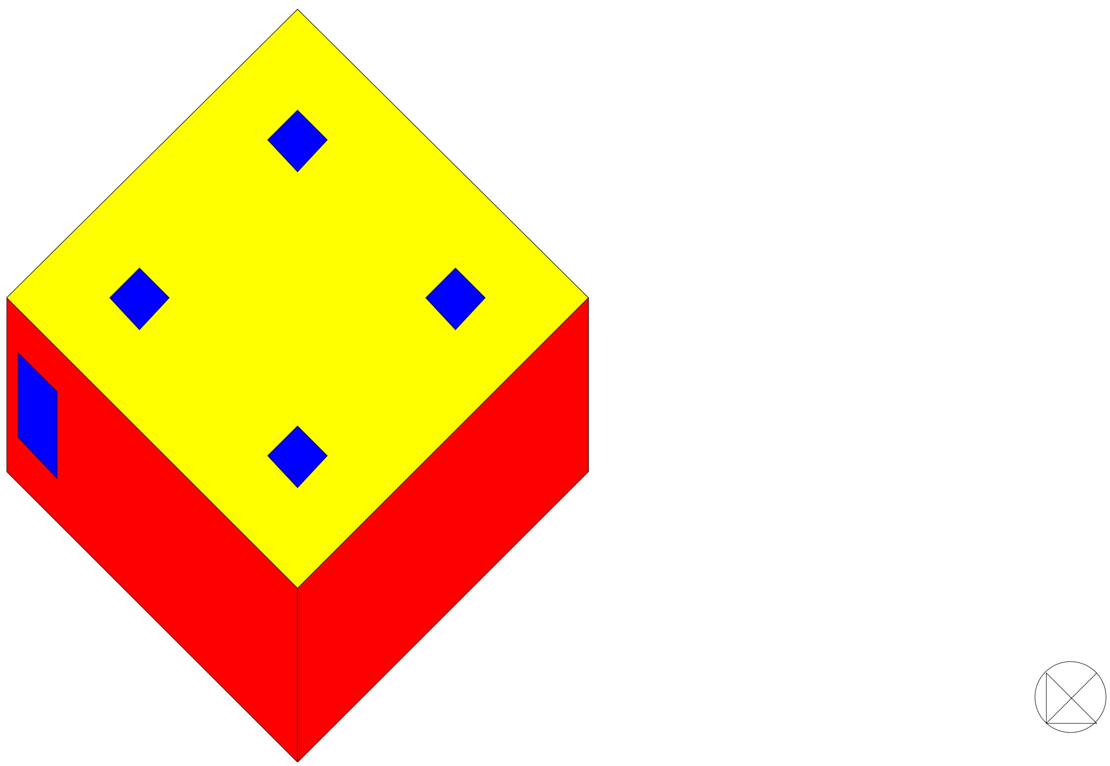


Figure 7.5 - A DOE-2 Classroom with Skylights

Table 7.2 - BEPS Report for a Classroom with Four Toplights Using the Original Lighting Schedule of the Base-case Classroom without Automatic Dimming of the Artificial Lighting

End Use	Annual Energy Use (MMBtu)			% diff vs. Base-case Classroom		
	Electricity	N.G.	Total	Electricity	N.G.	Total
AREA LIGHTS	9	0	9	0.0%		0.0%
MISC EQUIPMT	4.5	0	4.5	0.0%		0.0%
SPACE HEAT	0.2	4.1	4.3	0.0%	-4.7%	-4.4%
SPACE COOL	9.5	0	9.5	6.7%		6.7%
PUMPS & MISC	1.6	0	1.6	0.0%		0.0%
VENT FANS	2.9	0	2.9	7.4%		7.4%
TOTAL	**27.7**	**4.1**	**31.8**	**3.0%**	**-4.7%**	**1.9%**

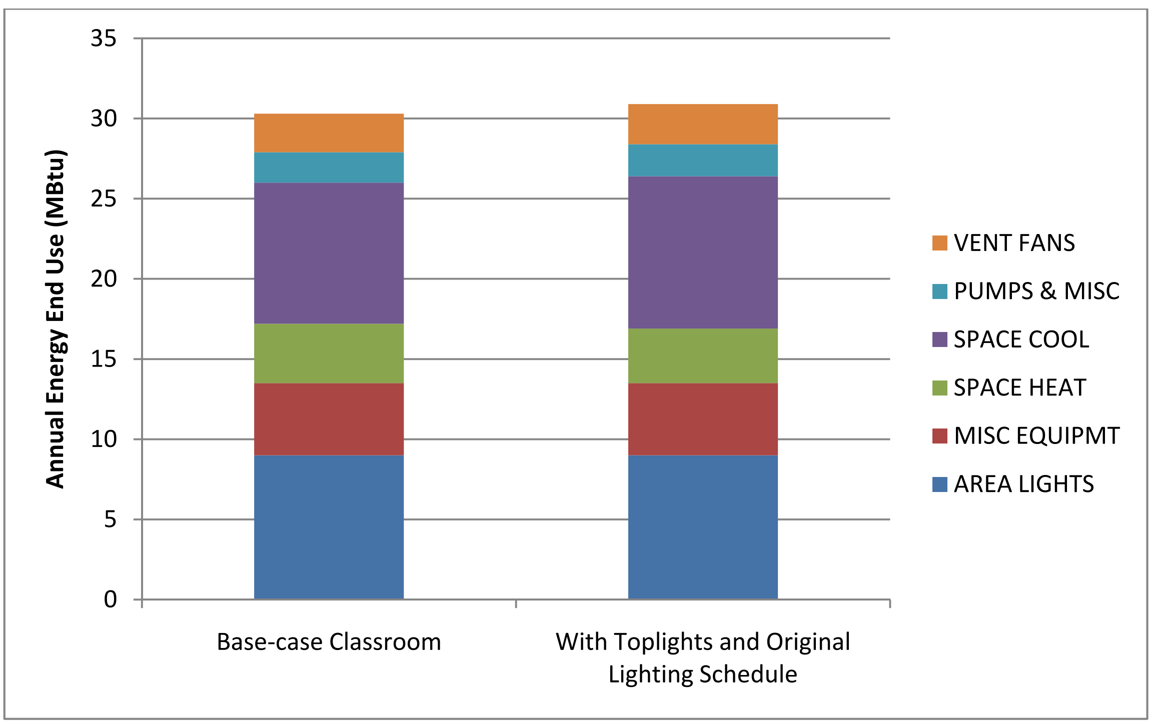


Figure 7.6 - BEPS Report for a Classroom w/ Four Toplights Using the Original Lighting Schedule of the Base-case Classroom without Automatic Dimming of the Artificial Lighting

In order to evaluate the daylighting impact on the classroom with the addition of four toplights, a daylighting model was developed using the Desktop Radiance program. The image of the cross section of the model is shown in Figure 7.7. The final image of the classroom with skylights using AutoCAD is presented in Figure 7.8. The other conditions in the classroom remained the same as the simulation without skylights. The Radiance daylighting simulation was performed at: Noon on March 15 in College Station, TX., clear sky model. The simulated image is shown in Figures 7.9 through 7.11. As shown in Figure 7.11, the illuminance level inside of the classroom at the floor level is about 100 to 150 footcandles (fc), which is in the acceptable illuminance levels for classrooms recommended by IESNA (IESNA 2000). For example, the illumination level in the middle of the classroom at March 15 was simulated as 1,406 lux (i.e., 130.6 fc).

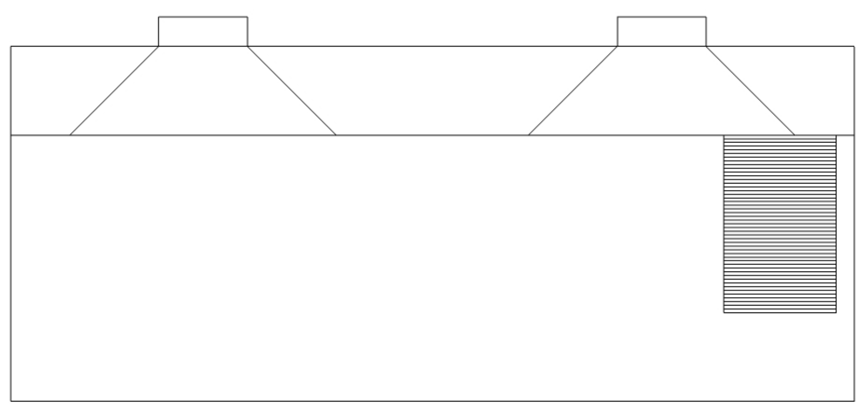


Figure 7.7 – Cross Section - Daylighting Model for a Classroom with Four (4) Toplights Using Desktop Radiance

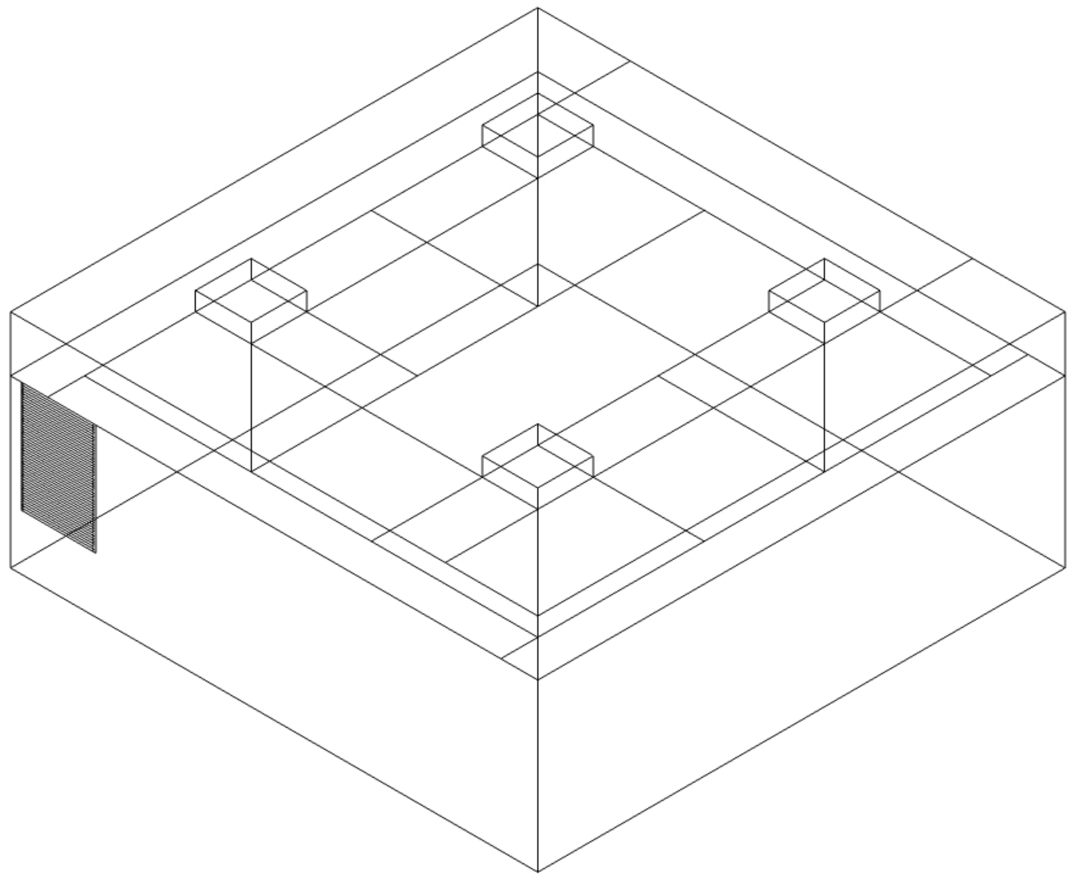


Figure 7.8 – Wireframe View of the Daylighting Model for a Classroom with Four (4) Toplights Using Desktop Radiance

7.3. Classroom with Skylight and Dimming Device

As a final step of the analysis, the final DOE-2 simulation with skylight and a dimming device was performed to verify the impact of the daylighting strategy in terms of energy use. For the simulation, one reference point (i.e., illuminance level measurement) was located in the middle of the classroom. Then, the lighting level was dimmed based on the illuminance level at the reference point. In this simulation, two steps of dimming was defined (i.e., 50 fc for no supplement light needed, between 25 to

Figure 7.9 - Radiance Simulated Image of the Classroom with Luminance Option

Figure 7.10 - Radiance Simulated Image of the Classroom (Human Sensitivity)

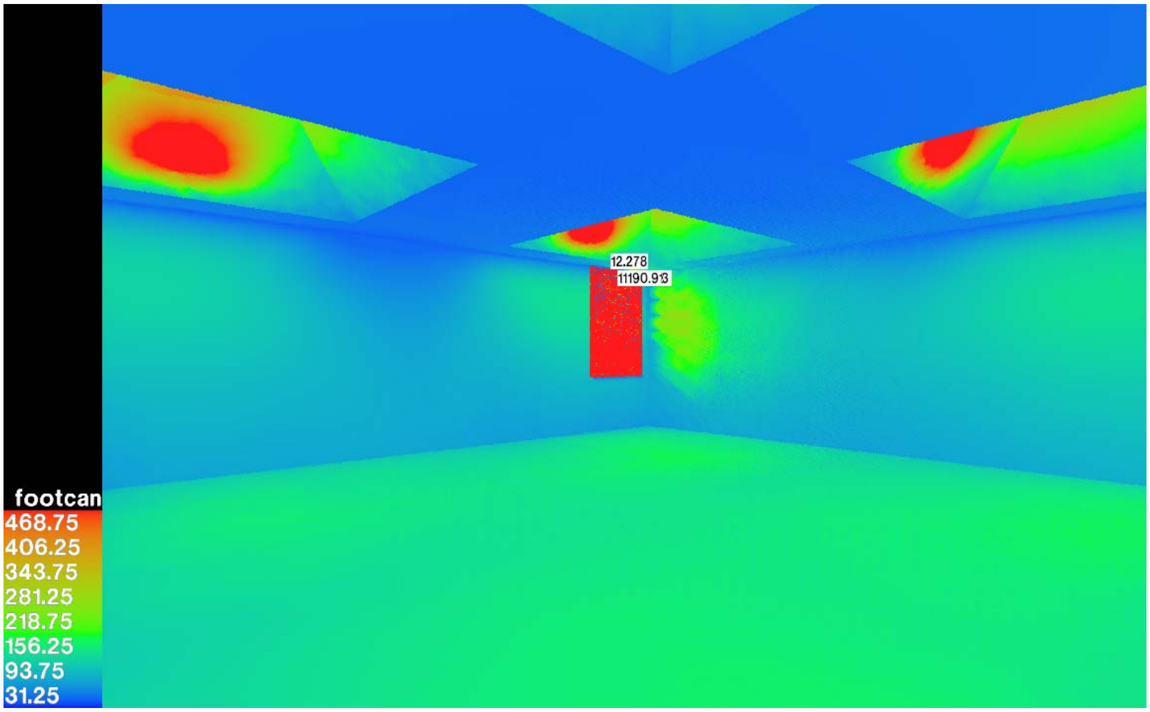


Figure 7.11 - Radiance Simulated Image of the Classroom (False Color)

50 fc for half of supplemental lightings turned on, and below 25 fc for all supplemental lightings turned on). Figure 7.12 and Table 7.3 shows the simulation results. The total annual energy consumption was decreased to 27.0 MMBtu, which is 3.23 MMBtu less energy use than the original classroom (i.e., a 10.7% decrease). The area lighting energy use was reduced by 36.7% (i.e., 9 MMBtu to 5.7 MMBtu). The simulation showed that space heating energy increased due to the reduced internal heat gain from the reduced lighting loads. Even though there was a 0.7 MMBtu increase in the previously simulated space cooling when the toplights only were added due to the added solar heat gain (Table 7.2), the space cooling energy use when the dimming was activated is less in the final daylighting simulation because the reduced heat gain from the reduced lighting load is larger than

Table 7.3 – Annual BEPS Report for a Classroom with Four Toplights, Using the Automatic Dimming Schedule

	Annual Energy Use (MMBtu)			% diff vs. Base-case Classroom		
End Use	**Electricity**	**N.G.**	**Total**	**Electricity**	**N.G.**	**Total**
AREA LIGHTS	4.7	0	4.7	-47.8%		-47.8%
MISC EQUIPMT	4.5	0	4.5	0.0%		0.0%
SPACE HEAT	0.2	5.1	5.3	0.0%	18.6%	17.8%
SPACE COOL	8.5	0	8.5	-4.5%		-4.5%
PUMPS & MISC	1.7	0	1.7	6.2%		6.2%
VENT FANS	2.5	0	2.5	-7.4%		-7.4%
TOTAL	**22.1**	**5.1**	**27.2**	**-13.9%**	**18.6%**	**-12.8%**

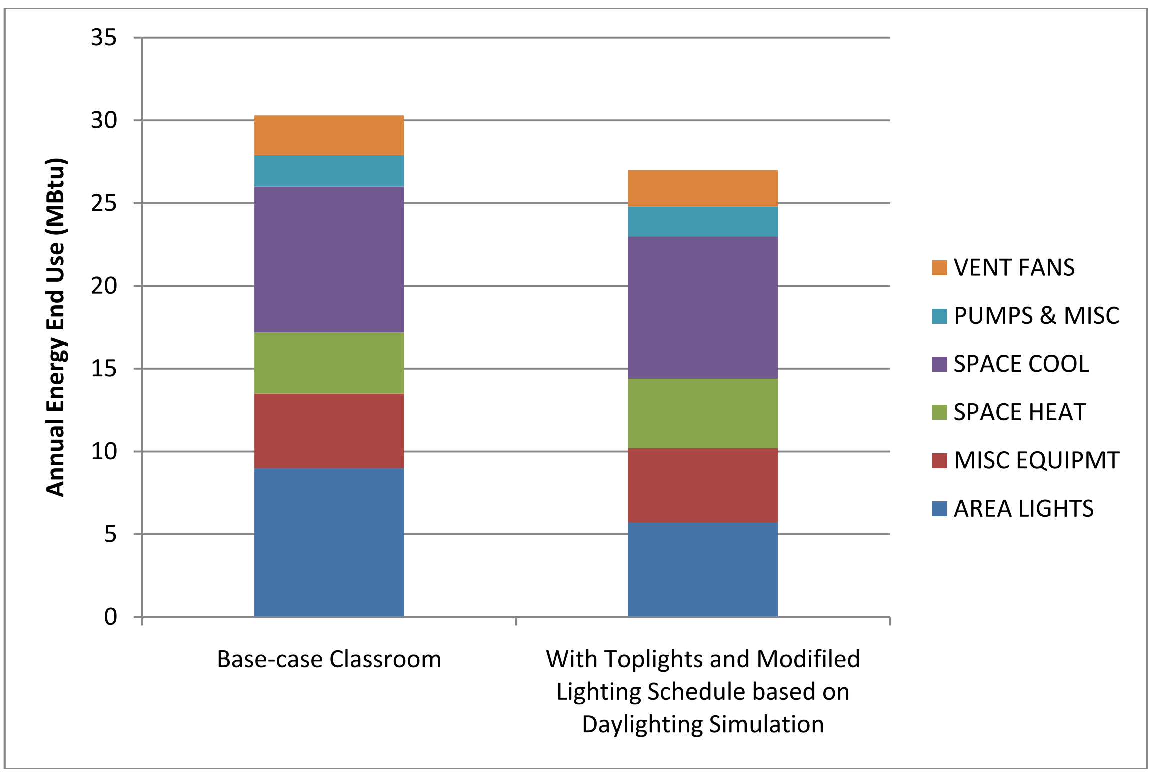


Figure 7.12 - Annual BEPS Report for a Classroom with Four Toplights, Using the Automatic Dimming Schedule

the added solar heat gain from the toplights. Therefore, the space cooling energy decreased by 2.3% (i.e., 8.8 MMBtu to 8.6 MMBtu).

7.5. Summary of Daylighting Simulation

An analysis of the energy savings due to the application of a daylighting strategy to the typical classroom was presented in this chapter. The results show that the total annual energy consumption was decreased by 12.8%, which includes a lighting energy use reduction of 47.8% compared to the original classroom without the skylights. In addition, the simulation results show that skylights with the automatic dimming schedule increased the space heating energy use due to the decreased heat gain from the reduced lighting load. Based on this study of the classroom, the simulation model of the entire school will be modified and simulated in next chapter to verify the energy savings potential by applying a daylighting strategy.

CHAPTER VIII

RESULTS: ESTIMATION OF ENERGY SAVINGS FROM THE APPLICATION OF SELECTED HIGH PERFORMANCE MEASURES

This chapter discusses the energy savings estimated by applying the selected high performance measures to the case-study school. In this phase of the study, the final calibrated simulation of the case-study school was modified to be compliant the ASHRAE Standard 90.1-1999, so that the modified simulation result could be used as the baseline energy use. Then, the energy saving measures recommended in the AEDG for K-12 schools buildings were applied to the baseline simulation. Finally, additional high performance measures were applied to calculate the total energy savings potential for the case-study school. Along with the analysis of the energy savings potential, the indoor thermal comfort was discussed for each step of the simulation modification to assure that thermal comfort would be maintained at each step of the process.

8.1. ASHRAE Standard 90.1-1999 Compliant Simulation

8.1.1. Modified Calibrated Simulation (15 CFM/person of OA Ventilation Rate)

One of the purposes of an ASHRAE 90.1-1999 compliant simulation is to compare the energy consumption of the case-study school to a code-compliant school. However, since the OA ventilation rate of the case-study school is currently too low (i.e., about 5 CFM/person in each classroom) compared to the ASHRAE Standard 62-1999 requirements, the OA ventilation rate should be increased to 15 CFM/person for a valid comparison.

Therefore, the OA ventilation rate in the calibrated simulation was modified to be 15 CFM/person. The simulation results from this modification with the calibrated simulation are shown in Figure 8.1 and Table 8.1. As shown in Table 8.1, the cooling and heating energy increased 12.3% and 3.8 %, respectively. This energy increase occurred because an increased amount of hot and humid outside air is being drawn-in during the cooling season which requires more cooling energy. During the heating season more energy is required to heat the cold outside air. The EUI for the calibrated simulation and the modified calibrated simulation are 49.3 kBtu/sq.ft.-yr and 51.6 kBtu/sq.ft.-yr, respectively (i.e., a 4.7 % increase).

Table 8.1 - Building End Uses (Calibrated Simulation vs. the Calibrated Simulation with 15 CFM/person OA Ventilation Rate)

	Calibrated Simulation				Calibrated Simulation with 15CFM/person OA Ventilation Rate				% Difference			
	Electricity (MBtu)	N.G. (MBtu)	Total (MBtu)	EUI (kBtu/sqft-yr)	Electricity (MBtu)	N.G. (MBtu)	Total (MBtu)	EUI (kBtu/sqft-yr)	Electricity	N.G.	Total	EUI
AREA LIGHTS	834.7	0	834.7	11.1	834.7	0	834.7	11.1	0.0%		0.0%	0.0%
MISC EQUIPMT	417.3	0	417.3	5.6	417.3	0	417.3	5.6	0.0%		0.0%	0.0%
SPACE HEAT	36.7	685	721.7	9.6	37.8	711.6	749.4	10.0	3.0%	3.9%	3.8%	3.8%
SPACE COOL	968.3	0	968.3	12.9	1087.1	0	1087.1	14.5	12.3%		12.3%	12.3%
PUMPS & MISC	116.1	0	116.1	1.5	142.6	0	142.6	1.9	22.8%		22.8%	22.8%
VENT FANS	419.1	0	419.1	5.6	419.3	0	419.3	5.6	0.0%		0.0%	0.0%
DOMHOT WATER	0	221.1	221.1	2.9	0	221.1	221.1	2.9		0.0%	0.0%	0.0%
TOTAL	**2792.2**	**906.1**	**3698.3**	**49.3**	**2938.8**	**932.7**	**3871.5**	**51.6**	5.3%	2.9%	4.7%	4.7%

8.1.2. ASHRAE Standard 90.1-1999 Compliant Simulation

As described in Chapter IV, the Energy Cost Budge (ECB) option was used to develop an ASHRAE 90.1-1999 compliant simulation input. The final input values for the ASHRAE 90.1-1999 compliant simulation based on the ECB option are shown in

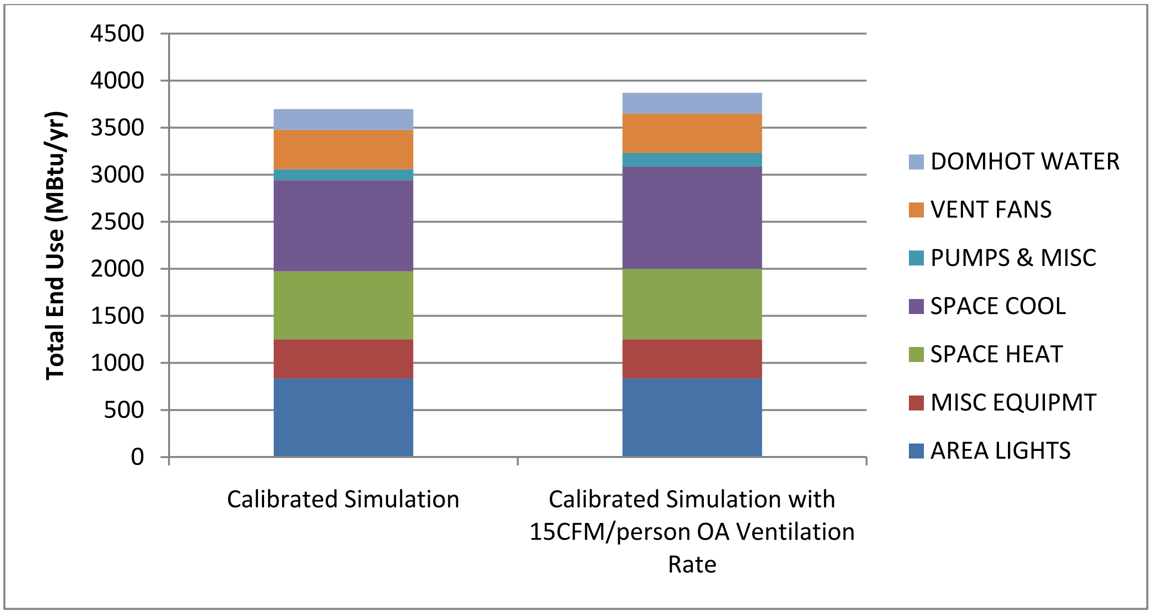


Figure 8.1 - Building End Uses (Calibrated Simulation vs. Calibrated Simulation with 15 CFM/person OA Ventilation Rate)

Table 8.2. The code-compliant simulation results are shown in Figure 8.2 and Table 8.3 compared with the previously modified calibrated simulation results. The most noticeable change in the end use is the area lighting energy use. In the 90.1-1999 simulation, the 834.7 MMBtu of lighting energy use from the calibrated simulation was increased to 1,043.3 MMBtu in the code-compliant simulation (i.e., a 25% increase). This is because the lighting power density for school required from the ASHRAE 90.1-1999 is 1.5 W/sq.ft., while the case-study school had a 1.2 W/sq.ft of the lighting power density. Therefore, the total lighting energy use increased even though the same lighting schedule was used. The space already heating energy use decreased (i.e., 48% decrease)

in the code compliant simulation as internal heat gain increased due to the increased lighting power

Table 8.2 - Simulation Input for the Case-study School vs. ASHRAE Standard 90.1-1999

Measures	Case-study School	ASHRAE 90.1-1999
Roof Insulation (Btu/ft2-F-hr)	0.053	0.063
Wall Insulation (Btu/ft2-F-hr)	0.085	0.089
Glazing U-Value (Btu/ft2-F-hr)	1.12	1.27
Glazing SHGC (%)	72	25
Lighting Power Density (W/ft2)	1.2	1.5
HVAC Type	VAV with Reheat Constant Air Volume Multi Zone Unit	Packaged Rooftop VAV system
Fan Control (VAV)	Variable speed motor	Inlet vanes
Economizer	None	Yes
Cooling Efficiency (EER)	9.6	10.1
Boiler Efficiency (%)	82	80
SWH Efficiency (Et %)	79	80

density. The space cooling energy increased (i.e., a 5.4% increase) partially due to the lighting energy increase (i.e., increased internal heat gain) although some portion of the cooling energy was reduced due to the decreased SHGC and increased cooling efficiency (i.e., EER). The EUI for the as-built simulation and the code-compliant simulation are 51.6 kBtu/sq.ft.-yr and 48.7 kBtu/sq.ft.-yr, respectively (i.e., 5.7 % decreased). Therefore, the case-study school was 5.7% more efficient than the code-compliant building in terms of the energy uses.

Since an ASHRAE 90.1 the code-compliance check is based on the total energy costs in the ECB method[3], the total energy costs for two scenarios were calculated.

Table 8.3 - Building End Uses (Calibrated Simulation with 15 CFM/person OA Ventilation Rate vs. ASHRAE 90.1-1999 Compliant Simulation)

	Calibrated Simulation				ASHRAE 90.1-1999 Compliant Simulation				% Difference		
	Electricity (MBtu)	N.G. (MBtu)	Total (MBtu)	EUI (kBtu/sqft-yr)	Electricity (MBtu)	N.G. (MBtu)	Total (MBtu)	EUI (kBtu/sqft-yr)	Electricity	N.G.	Total
AREA LIGHTS	834.7	0	834.7	11.1	1,043.3	0.0	1,043.3	13.9	25.0%		25.0%
MISC EQUIPMT	417.3	0	417.3	5.6	417.3	0.0	417.3	5.6	0.0%		0.0%
SPACE HEAT	37.8	711.6	749.4	10.0	13.7	378.9	392.6	5.2	-63.8%	-46.8%	-47.6%
SPACE COOL	1087.1	0	1087.1	14.5	1,146.0	0.0	1,146.0	15.3	5.4%		5.4%
PUMPS & MISC	142.6	0	142.6	1.9	4.4	0.0	4.4	0.1	-96.9%		-96.9%
VENT FANS	419.3	0	419.3	5.6	434.0	0.0	434.0	5.8	3.5%		3.5%
DOMHOT WATER	0	221.1	221.1	2.9	0.0	212.3	212.3	2.8		-4.0%	-4.0%
TOTAL	2938.8	932.7	3871.5	51.6	3,058.7	591.2	3,649.9	48.7	4.1%	-36.6%	-5.7%

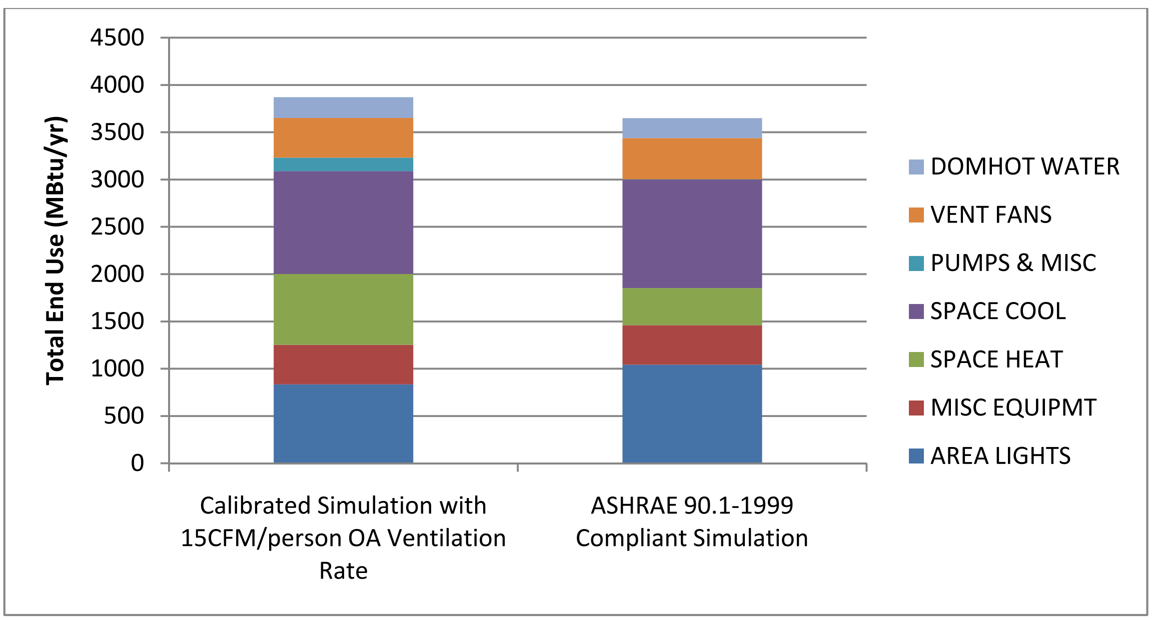


Figure 8.2 - Building End Uses (Calibrated Simulation with 15 CFM/person OA Ventilation Rate vs. ASHRAE 90.1-1999 Compliant Simulation)

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[3] In ECB Method, the demand charge is not used for the compliance check.

The energy rate for the calculation used the 2006 statewide average commercial price of electricity and natural gas[4]. According to EIA (EIA 2008a), the average commercial price of electricity for Texas in 2006 was $0.0985/kWh.[5] The same source shows that the average commercial natural gas rate for Texas in 2006 was $10.25/MCF.[6] The calculated total annual energy cost for two scenarios are shown in Table 8.4. The as-built building consumes $94,400 annually, while the code-compliant building consumes $94,361 annually. Therefore, the energy cost for the case-study school is almost the same as the cost for the code compliant school (i.e., annually $39 more cost for the case-study school and 0.04% more consumptive).

Table 8.4 - Total Annual Energy Cost (As-built vs. Code Compliant)

Electricity Rate	0.0985 ($/kWh) =	28.87	($/MBtu)
Natural Gas Rate	10.25 ($/kcf) =	10.25	($/MBtu)

	Calibrated Simulation with 15CFM/person OA Ventilation Rate				**ASHRAE 90.1-1999 Compliant Simulation**				**% Diff.**			
	Electricity	N.G.	Total	EUI	Electricity	N.G.	Total	EUI	Electricity	N.G.	Total	EUI
	(MBtu)	(MBtu)	(MBtu)	(kBtu/sqft-yr)	(MBtu)	(MBtu)	(MBtu)	(kBtu/sqft-yr)				
TOTAL	2,938.8	932.7	3,871.5	51.6	3,058.7	591.2	3,649.9	48.7				**5.72%**
TOTAL COST	**$84,839**	**$9,561**	**$94,400**		**$88,301**	**$6,060**	**$94,361**		**-4.08%**	**36.61%**	**0.04%**	

As mentioned earlier, the changes in the thermal comfort (i.e., temperature and RH) of a classroom were examined, and the results were displayed on a psychometric chart as shown Figures 8.3 through Figure 8.5. The figures also present the time series

[4] According to a communication with a ASHRAE 90.1-1999 specialist, Professor Larry Degelman (Personal communication 2008), a local utility rate could be used in the ECB option as long as the same energy rate used for both case (i.e., proposed vs. code compliant)
[5] The electricity rate was obtained from the EIA website (EIA 2008a)
[6] The natural gas rate was obtained from the EIA website (EIA 2008b)

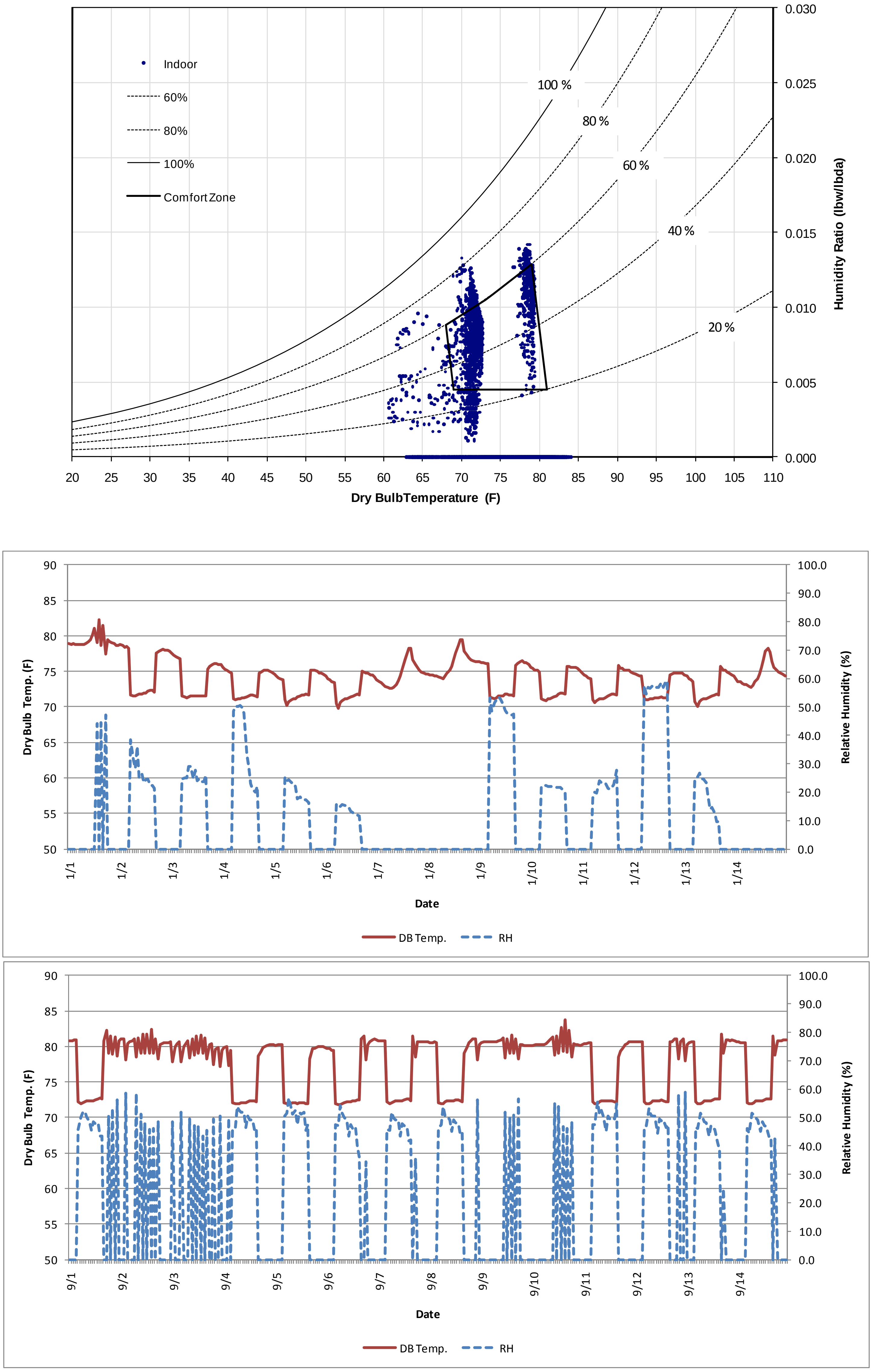


Figure 8.3 - Indoor Thermal Comfort for the Calibrated Simulation (Scattered and Time series)

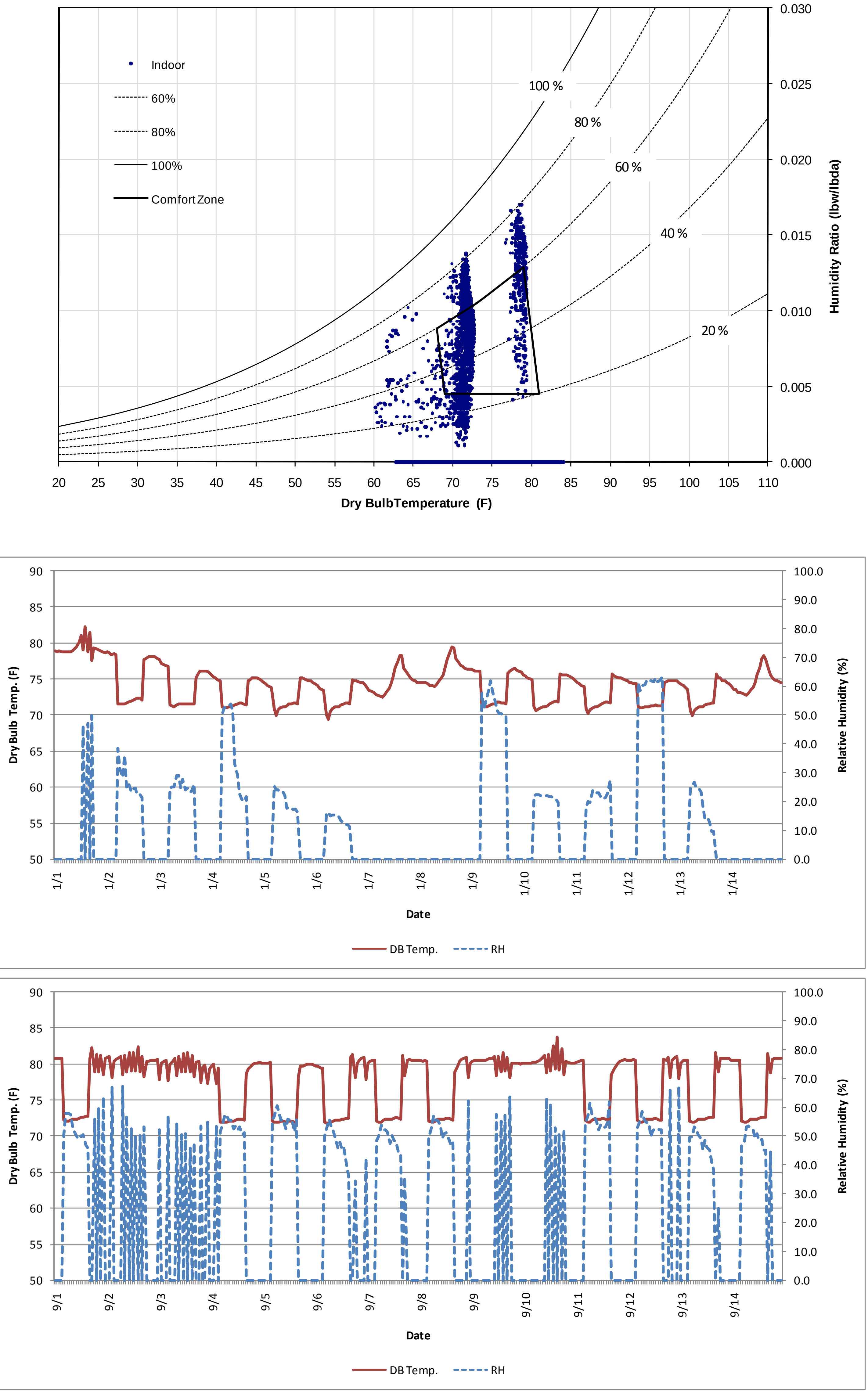


Figure 8.4 - Indoor Thermal Comfort for the Calibrated Simulation with 15CFM/person of OA Ventilation Rate (Scattered and Time series)

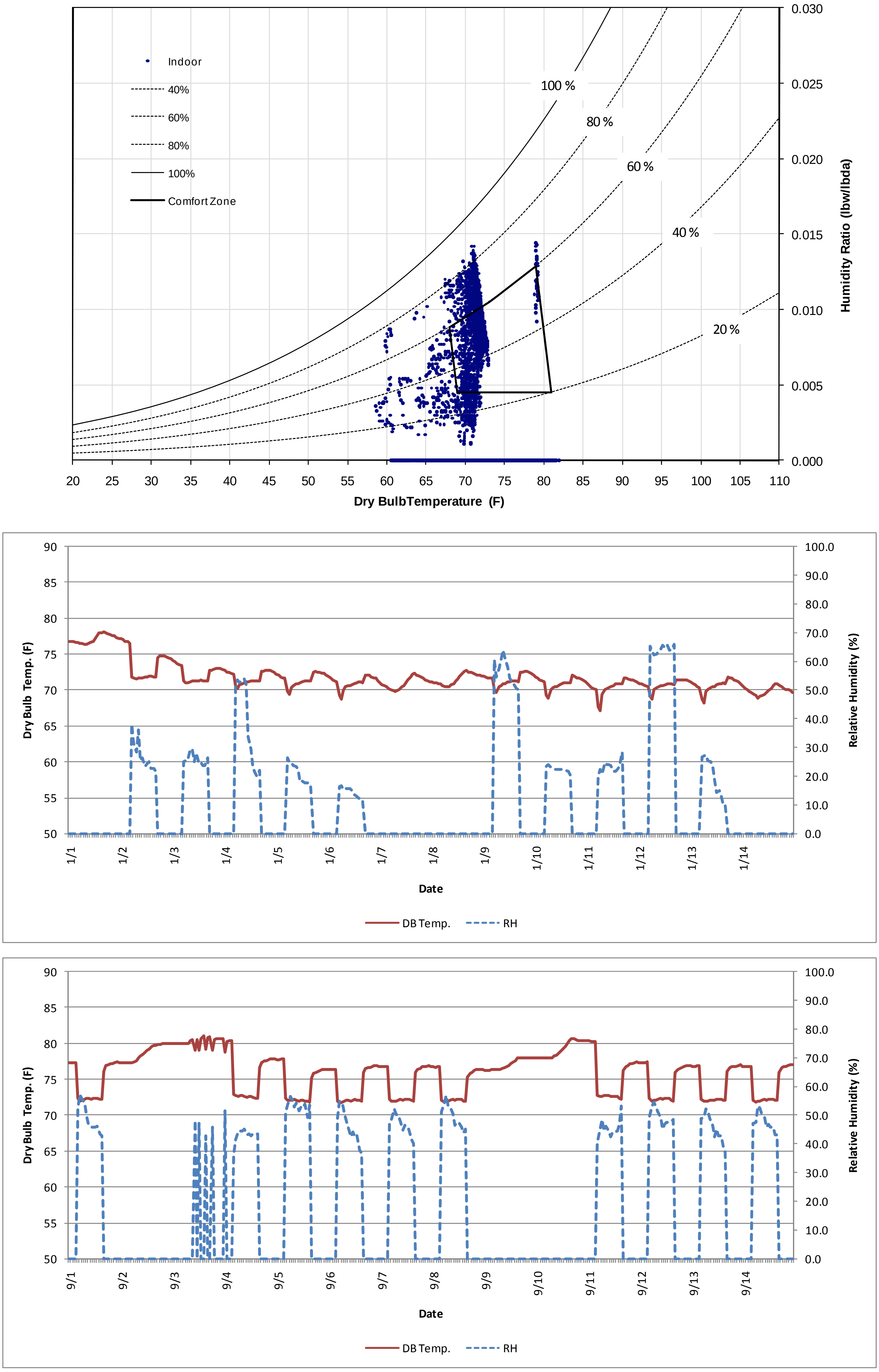


Figure 8.5 - Indoor Thermal Comfort for the ASHRAE 90.1-1999 Compliant School (Scattered and Time series)

plots for two weeks from winter and summer (i.e., Jan 1 to Jan 14 & Sept 1 to Sept 14). Unfortunately, in the DOE-2 simulation program, the humidity ratio cannot be obtained in the hourly report (i.e., zero for humidity ratio) when the AHU was turned off. Therefore, the plots in Figures 8.3 to 8.5 show scattered plots that have a significant number of points with a zero humidity ratio (i.e., a line on X axis).

Figure 8.3 presents the indoor thermal comfort of the final calibrated simulation. In the final simulation, there were two different room temperature settings for occupied and unoccupied periods in the cooling and heating mode, which can be observed in Figure 8.3. The data points in 68 to 74 F temperature range represent the indoor conditions during the occupied periods, whereas the data points in upper 78 to 80 F range of temperature presents the unoccupied period during summer. The data points lower than 68F represents the indoor conditions during the unoccupied periods in winter.

In general, the temperature ranges during occupied periods are inside of the comfort zone, while a significant number of the data points fall outside of the RH comfort zone. As the OA ventilation rate increases (Figure 8.5), the maximum RH increases as well due to the increased humidity from the outside air. As the case-study school was changed to the code compliant school, there was also a change in the pattern of the scattered plots as shown in Figure 8.5. The reason that there are less data points in upper 78 to 80 F range in the code compliant school can be verified from the time series plot. The time series plot in summer time shows that during the unoccupied periods, the AHU in the code compliant school was not turned on frequently as the case-study school did since the indoor temperature was not high enough to turn on the AHU, and as a result, the RHs from the hourly report show zero values (i.e., AHU turned off). The main reason for this difference would be the use thermal mass effect. The case-study school used the thermal mass (i.e., delayed calculation), while the code compliant school used quick calculation mode for the thermal mass to make it easy to change the roof and wall R-value later in the procedure of the high performance measures application and the simplified toolkit development. Therefore, the simulation results for high performance measures application will not consider thermal mass effect, and the integration of the thermal mass in the simulation for more accuracy would be investigated as one of the future studies. The temperature ranges during occupied hours for the code-compliant school are still inside of the comfort zone.

8.2. AEDG Recommended School Building Simulation

As a next step, the energy saving measures recommended in the ASHRAE AEDG for K-12 school buildings were applied to the baseline simulation. The location of the base-case school corresponds to climate zone 2 according to the AEDG for K-12 schools. Table 8.5 shows the energy features that were changed from the baseline school due to the recommendations from the AEDG for K-12 school buildings. There are 8 steps in the simulation input modifications to change the baseline school to the AEDG recommended school. Each step of the modification was separately simulated, and the result of the each step was compared to the baseline school energy use to verify the impact of each measure. In addition, the cumulative energy savings from applying all the steps were also simulated and compared to the baseline energy consumption.

Table 8.5 - Energy Efficient Measures Recommended by AEDG for K-12 School Buildings

Step	Measures	Baseline (ASHRAE 90.1-1999)	Recommendations from the AEDG for K-12 Schools
1	Roof R-Value (ft^2-F-hr/Btu)	R-15	R-25
2	Glazing U-value (Btu/ ft^2-F-hr) & SHGC	U-1.27	U-0.45
		SHGC - 0.287	SHGC - 0.25
3	Shading & Orientation	No Shading	Projection Factor = 0.5
4	Lighting Power Density (W/ ft^2)	1.5	1.1
5	Occupancy Control for Lighting	Scheduled on off	Occupancy sensor
6	Cooling COP (EER)	10.1	10.6
7	SWH efficiency (%)	80 %	90 %
8	Fans (CFM)	1.7 hp/1000	1.3 hp/1000

Table 8.6 and Figure 8.6 present the energy and cost savings from the application of the individual energy saving measures. As shown, the most effective energy saving measures in terms of energy consumption was step 5, which was the use of occupancy sensors. The installation of the occupancy sensors saved 8.7 % of the total energy use compared to the baseline energy use. In terms of cost savings, the use of occupancy sensor results in even more savings (i.e., 13.7 % of cost savings). The next largest savings was achieved by reducing the lighting power density (i.e., step 4) from 1.5 W/sq.ft. to 1.1 W/sq.ft (i.e., 6.7% of total energy savings and 9.5% of cost savings). In order to estimate the total cumulative energy savings from the application of all the recommendations of the AEDG for K-12 schools, the cumulative savings were simulated step-by-step and summarized in Table 8.7 and Figure 8.7. By applying all eight

Table 8.6 - Energy and Cost Savings by Individual Application Step

	Baseline School (ASHRAE 90.1-1999)	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
AREA LIGHTS (MBtu/yr)	1,043.3	1,043.3	1,043.3	1,043.3	765.1	595.2	1,043.3	1,043.3	1,043.3
MISC EQUIPMT (MBtu/yr)	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3
SPACE HEAT (MBtu/yr)	392.6	287.4	325.0	395.6	499.2	593.8	392.6	392.6	392.6
SPACE COOL (MBtu/yr)	1,146.0	1,160.8	1,126.3	1,130.9	1,088.8	1,083.8	1,088.4	1,146.0	1,146.0
PUMPS & MISC (MBtu/yr)	4.4	4.2	4.3	4.4	4.7	5.0	4.4	4.4	4.4
VENT FANS (MBtu/yr)	434.0	437.4	428.4	429.8	419.2	423.8	434.0	434.0	331.9
DOMHOT WATER (MBtu/yr)	212.3	212.3	212.3	212.3	212.3	212.3	212.3	193.3	212.3
TOTAL (MBtu/yr)	3,649.9	3,562.7	3,556.8	3,633.7	3,406.7	3,331.3	3,592.3	3,630.9	3,547.8
% Diff (vs. Baseline)	-	**2.4%**	**2.5%**	**0.4%**	**6.7%**	**8.7%**	**1.6%**	**0.5%**	**2.8%**
$ Elec.	$88,301	$88,753	$87,529	$87,746	$78,254	$73,392	$86,637	$88,301	$85,354
$ N.G.	$6,060	$5,005	$5,381	$6,091	$7,134	$8,088	$6,060	$5,865	$6,060
$ Total	$94,361	$93,759	$92,909	$93,837	$85,388	$81,480	$92,697	$94,166	$91,414
% Diff (vs. Baseline $)	-	**0.6%**	**1.5%**	**0.6%**	**9.5%**	**13.7%**	**1.8%**	**0.2%**	**3.1%**

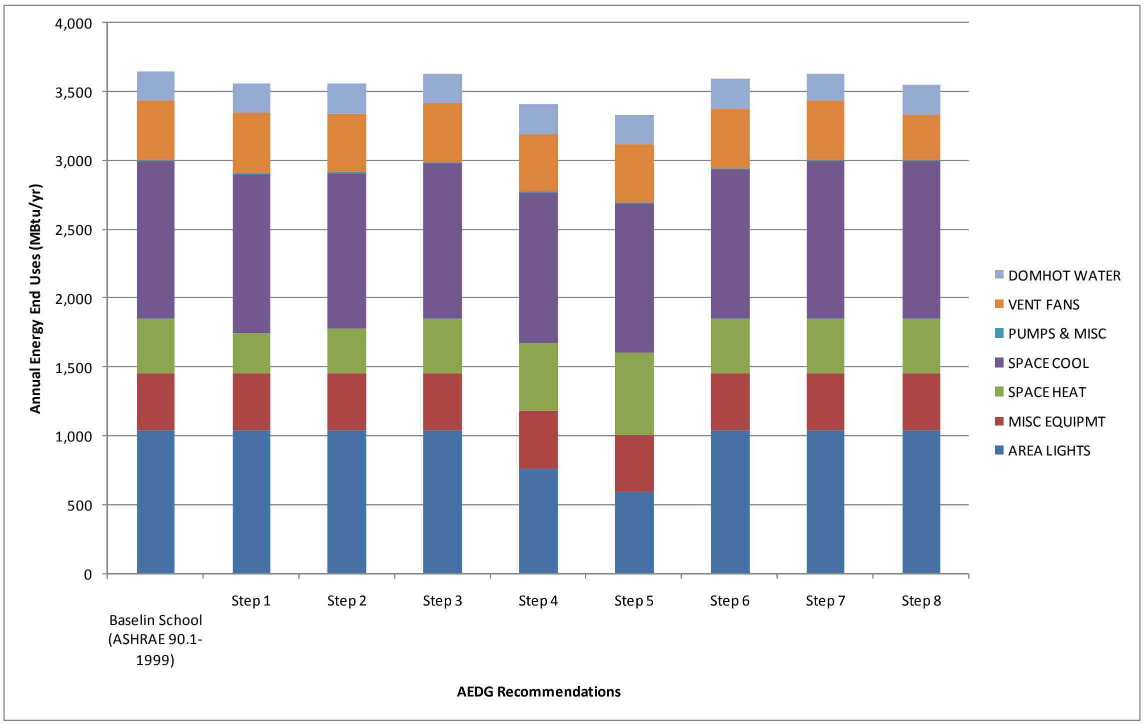


Figure 8.6 - Energy Savings by Individual Application Step

Table 8.7 - Cumulative Energy Savings by Application Step

	Baseline School (ASHRAE 90.1-1999)	Step 1	Step 1 + 2	Step 2+3	Step 3 +4	Step 4+5	Step 5+6	Step 6+7	Step 7+8
AREA LIGHTS (MBtu/yr)	1,043.3	1,043.3	1,043.3	1,043.3	765.1	436.5	436.5	436.5	436.5
MISC EQUIPMT (MBtu/yr)	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3
SPACE HEAT (MBtu/yr)	392.6	301.8	216.3	223.0	329.0	498.8	498.8	498.8	498.8
SPACE COOL (MBtu/yr)	1,146.0	1,166.2	1,142.4	1,126.2	1,062.7	1,011.4	960.6	960.6	960.6
PUMPS & MISC (MBtu/yr)	4.4	4.2	4.0	4.0	4.5	4.9	4.9	4.9	4.9
VENT FANS (MBtu/yr)	434.0	438.7	432.5	428.2	411.3	402.5	402.5	402.5	307.8
DOMHOT WATER (MBtu/yr)	212.3	212.3	212.3	212.3	212.3	212.3	212.3	193.3	193.3
TOTAL (MBtu/yr)	**3,649.9**	**3,583.9**	**3,468.1**	**3,454.4**	**3,202.2**	**2,983.7**	**2,932.9**	**2,913.9**	**2,819.2**
% Diff (vs. Baseline)	-	**1.8%**	**5.0%**	**5.4%**	**12.3%**	**18.3%**	**19.6%**	**20.2%**	**22.8%**
$ Elec.	$88,301	$88,960	$88,018	$87,434	$77,188	$66,075	$64,607	$64,607	$61,873
$ N.G.	$6,060	$5,150	$4,297	$4,364	$5,416	$7,123	$7,123	$6,927	$6,927
$ Total	$94,361	$94,110	$92,315	$91,797	$82,605	$73,199	$71,730	$71,534	$68,800
% Diff (vs. Baseline $)	-	**0.3%**	**2.2%**	**2.7%**	**12.5%**	**22.4%**	**24.0%**	**24.2%**	**27.1%**

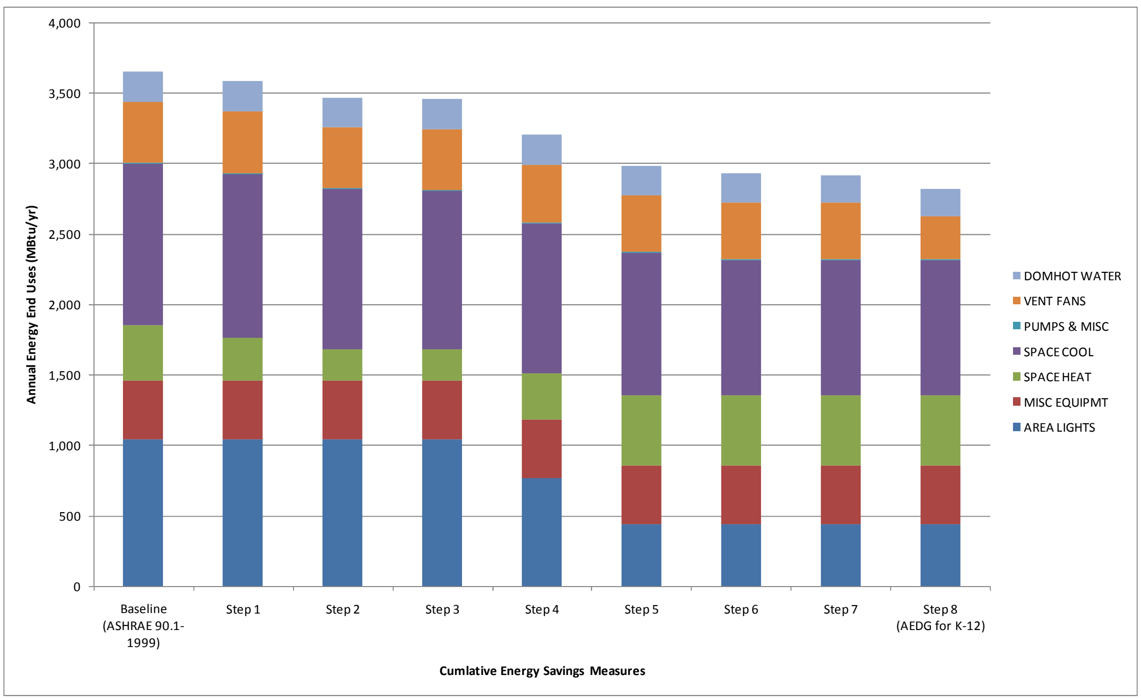


Figure 8.7 - Cumulative Energy Savings by Application Step

measures, the AEDG recommended school would achieve a 22.8 % of reduction in the total annual energy savings compared to the baseline 90.1-1999 compliant school. When converting this energy savings to a cost savings basis using the same energy rates used in the previous section, the AEDG recommended school will save $25,561 annually, which is 27.1% less energy costs than the baseline school (See Table 8.7). When the all the AEDG measures are applied together, the EUI for the school was reduced from 48.7 kBtu/sqft-yr to 37.6 kBtu/sqft-yr.

The indoor thermal comfort for each step was tabulated in Figures 8.8 to 8.15. For each step, the temperature range during the occupied periods is inside comfort zone for all 8 steps, while some portion of the RH range during occupied hours is outside of the comfort zone. Since the indoor thermal comfort is often ignored when energy savings are calculated using a simulation program, inspecting the indoor condition during each calibration step helps to assure comfort condition are being maintained.

8.3. High Performance School Simulation

In this section, several additional high performance measures were applied to the ASHRAE AEDG recommended school. The selected high performance measures are: 1) lower glazing U-value, 2) use of a VFD instead of inlet vane for fan control, 3) cold deck reset, 4) variable speed for the pump, and 5) higher boiler efficiency. These measures are summarized in Table 8.8. In the same fashion of the previous section, the energy savings by individual steps and the cumulative savings were calculated in order to verify the individual energy savings and the final cumulative savings.

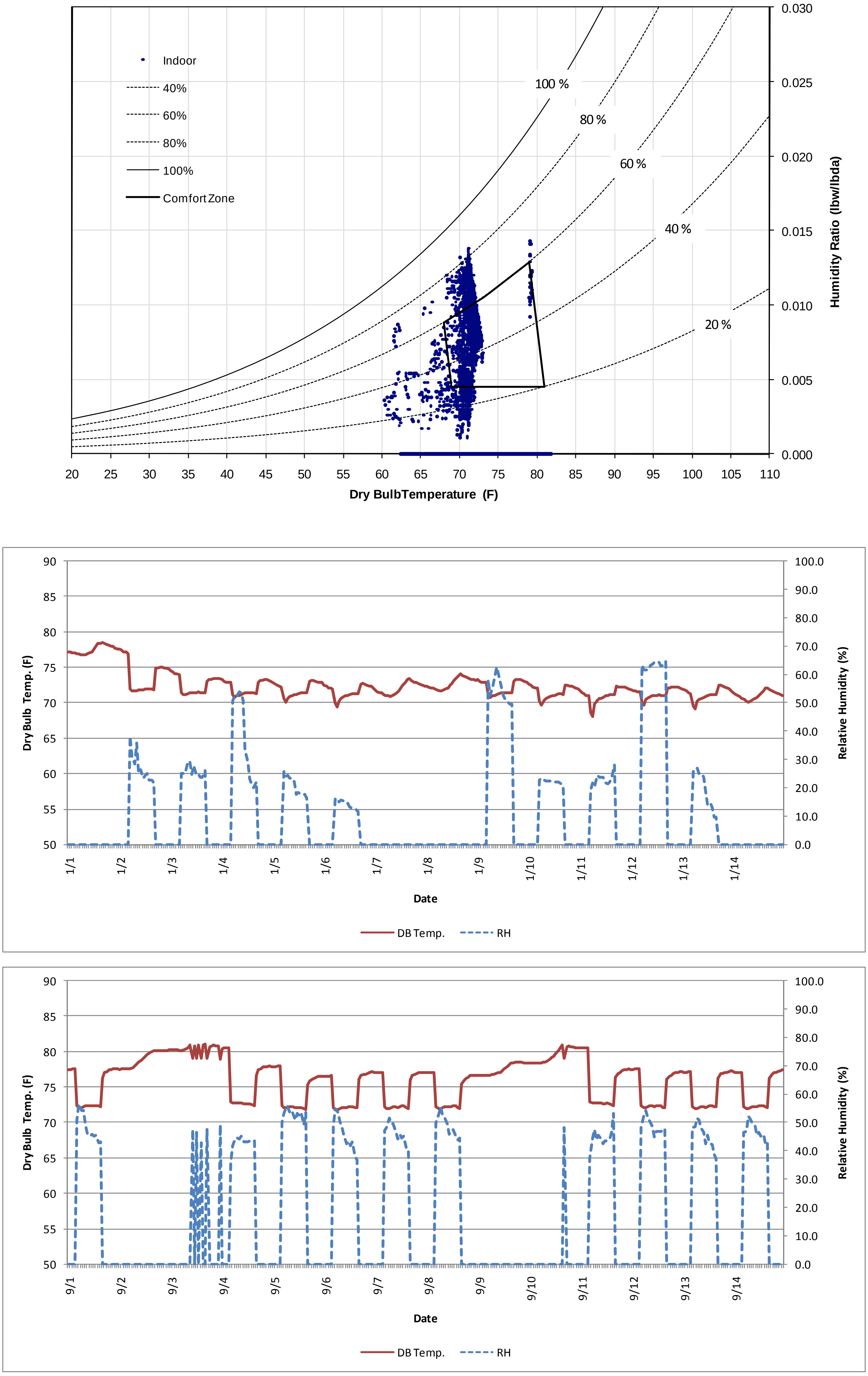


Figure 8.8 - Indoor Thermal Comfort for AEDG for K-12: Step 1

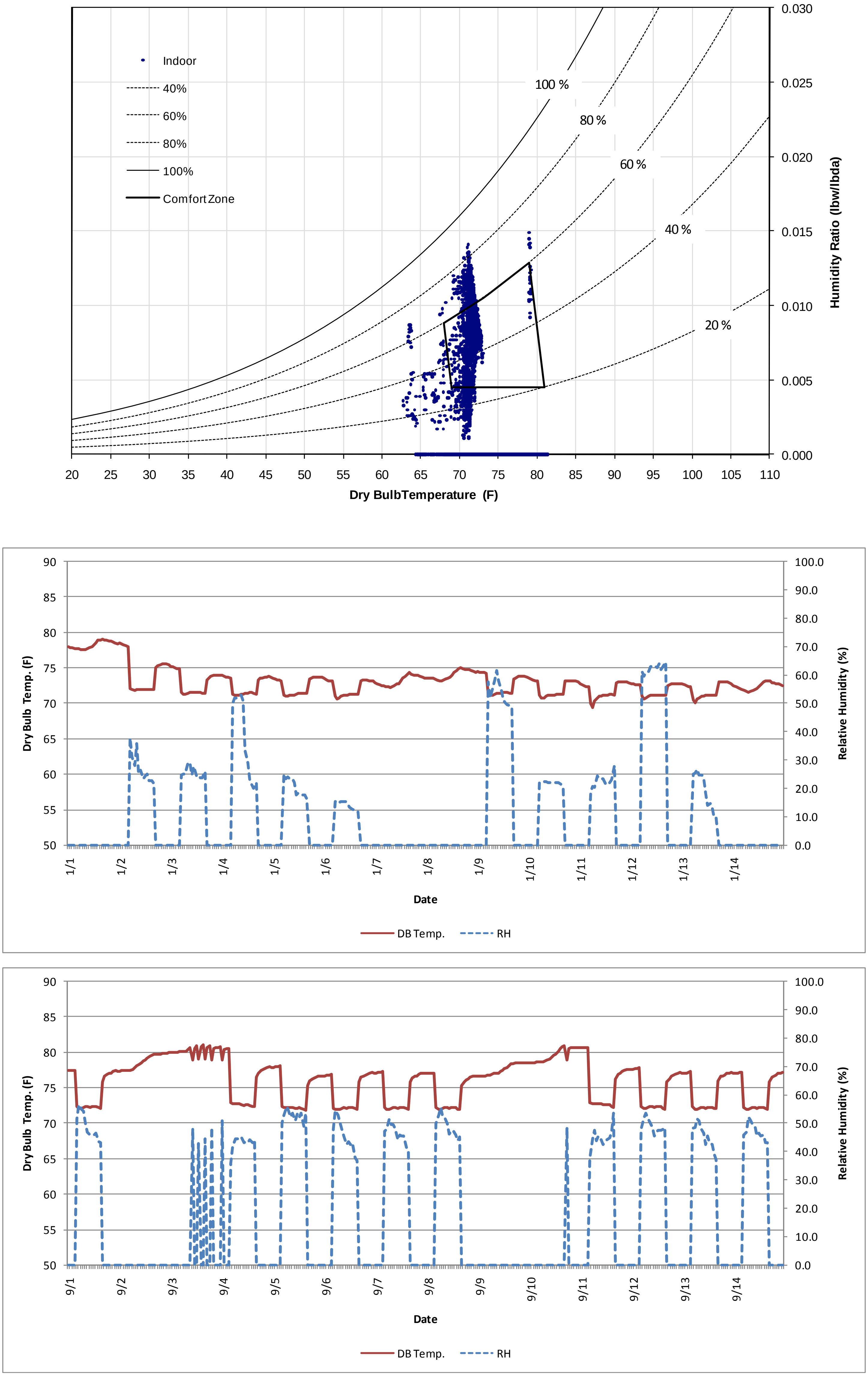


Figure 8.9 - Indoor Thermal Comfort for AEDG for K-12: Step 1+2

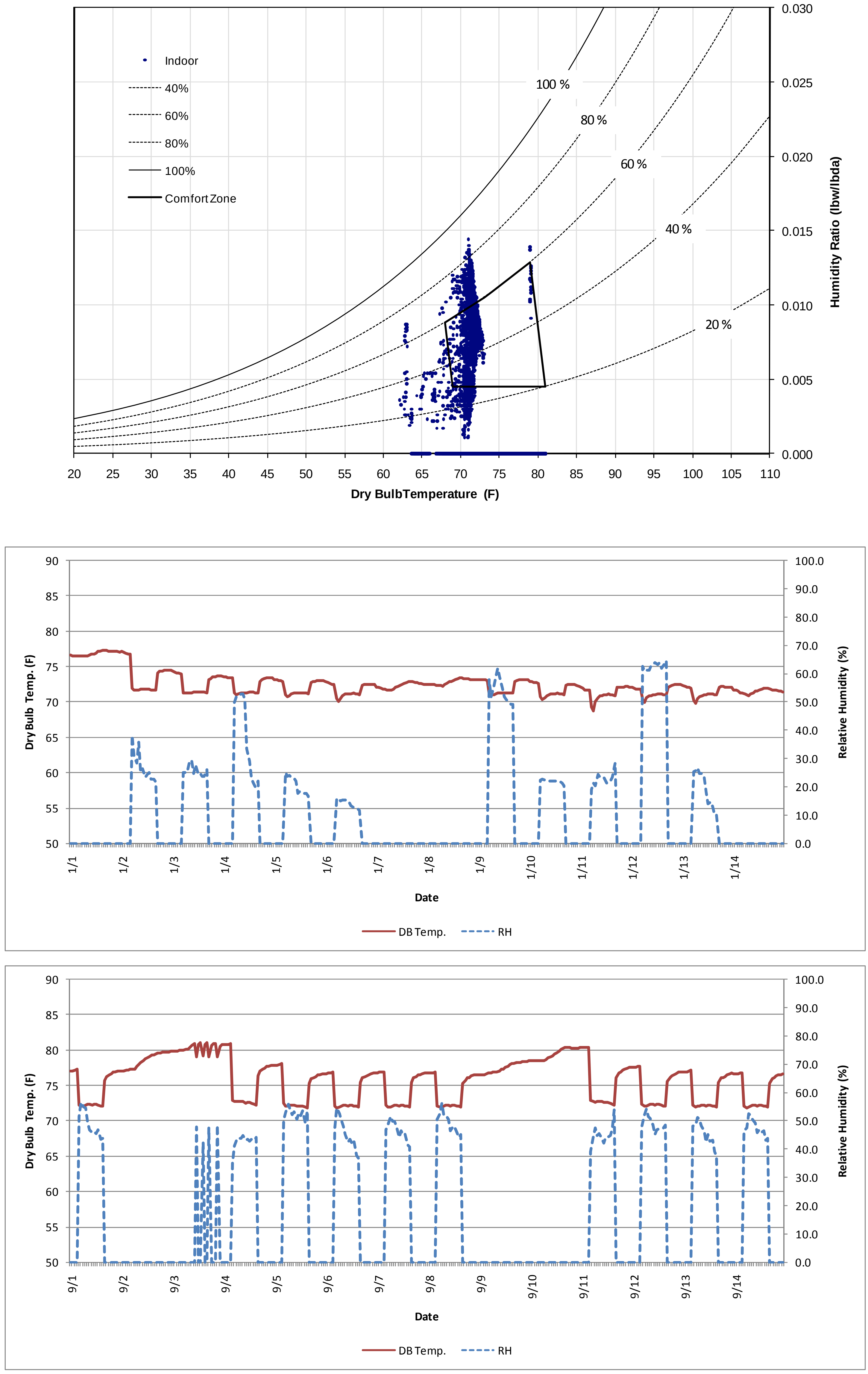


Figure 8.10 - Indoor Thermal Comfort for AEDG for K-12: Step 2+3

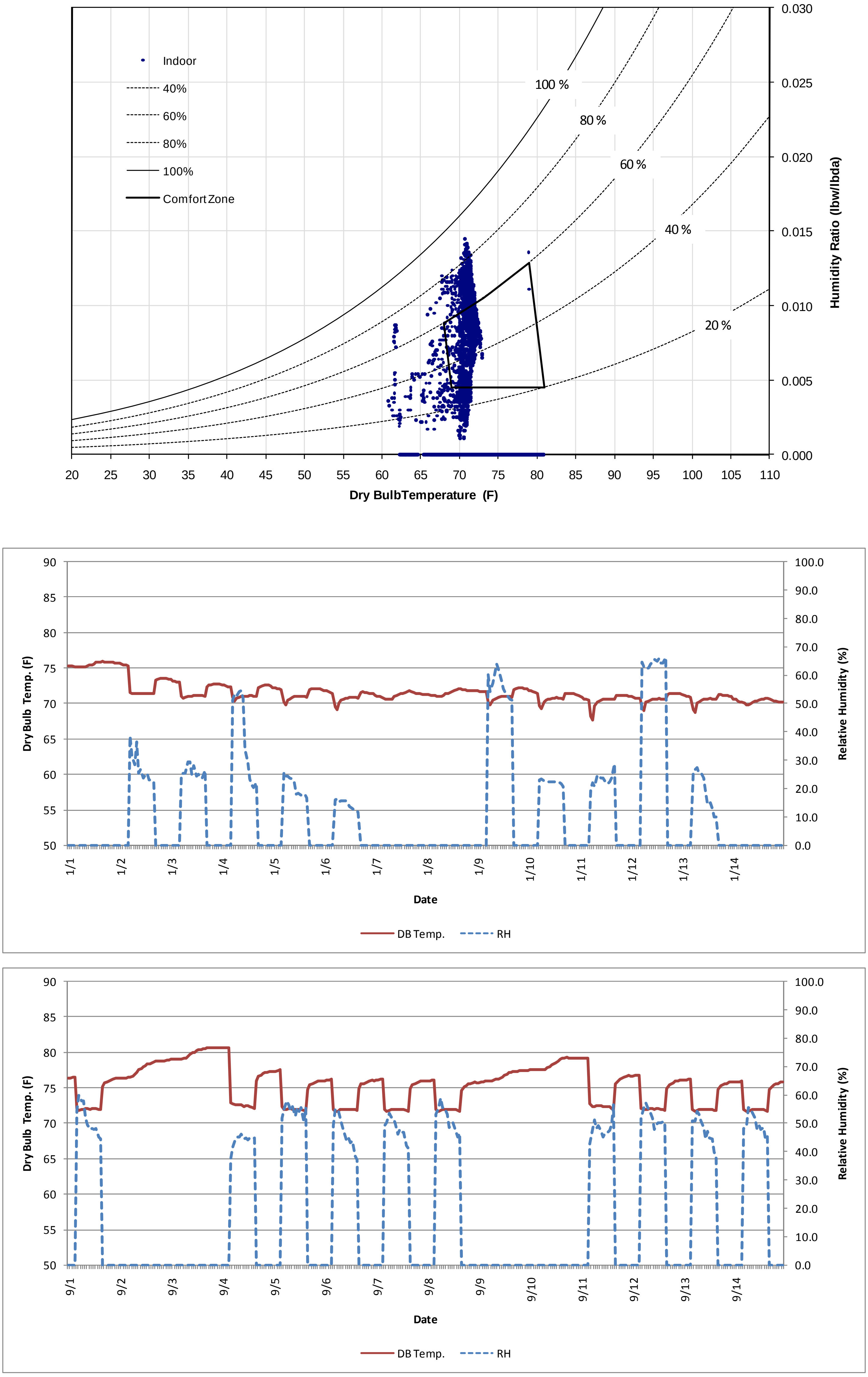


Figure 8.11 - Indoor Thermal Comfort for AEDG for K-12: Step 3+4

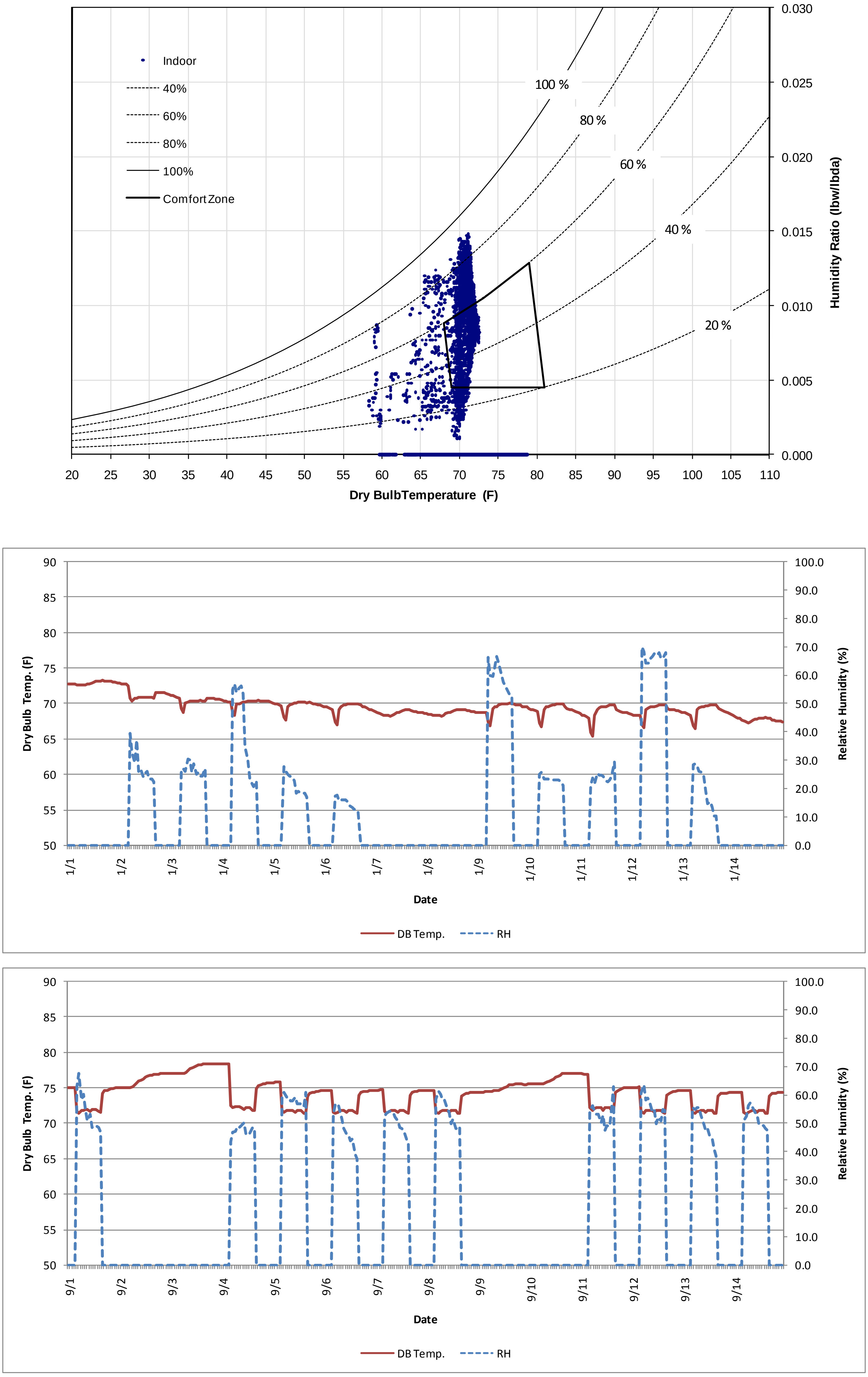


Figure 8.12 - Indoor Thermal Comfort for AEDG for K-12: Step 4+5

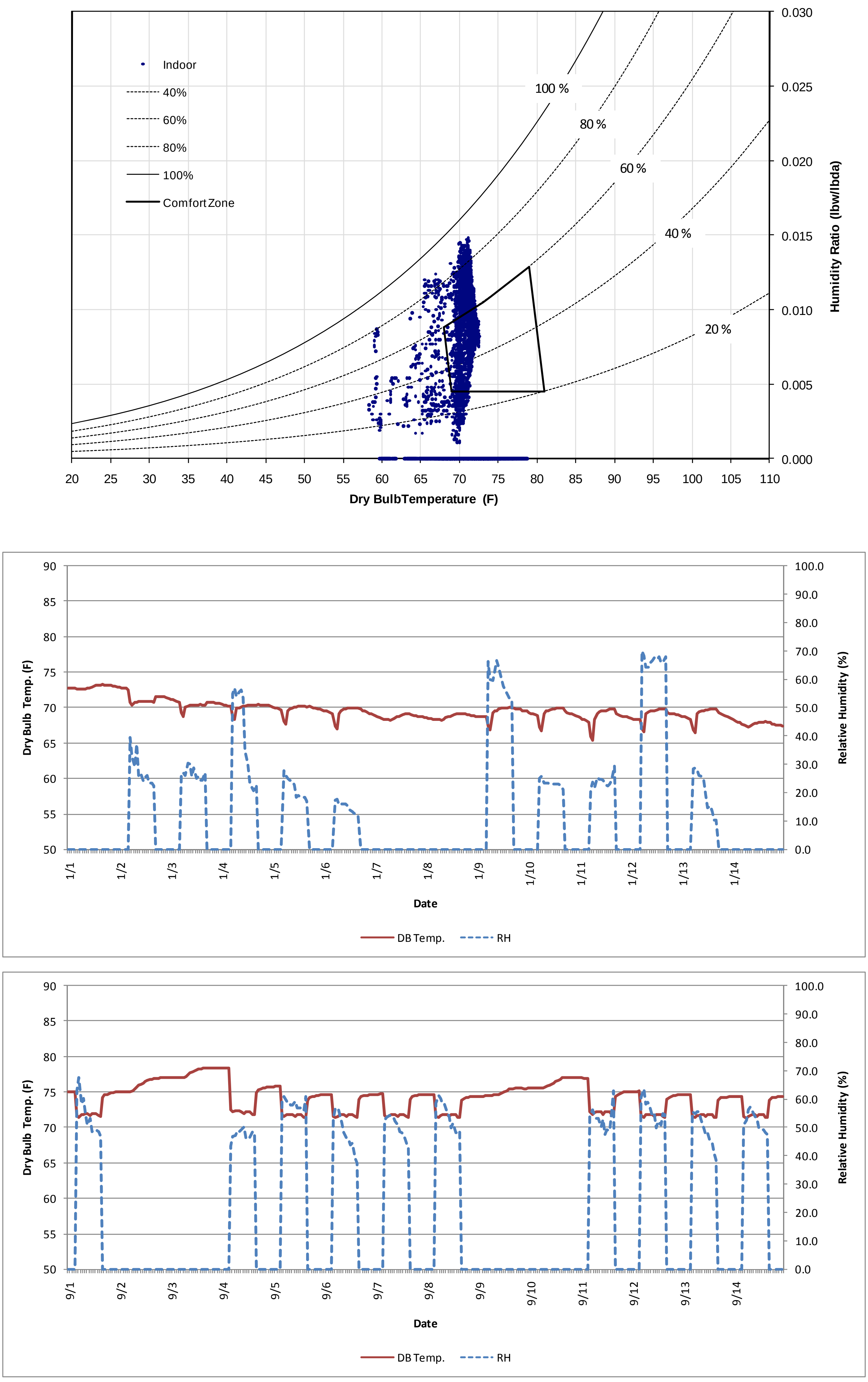


Figure 8.13 - Indoor Thermal Comfort for AEDG for K-12: Step 5+6

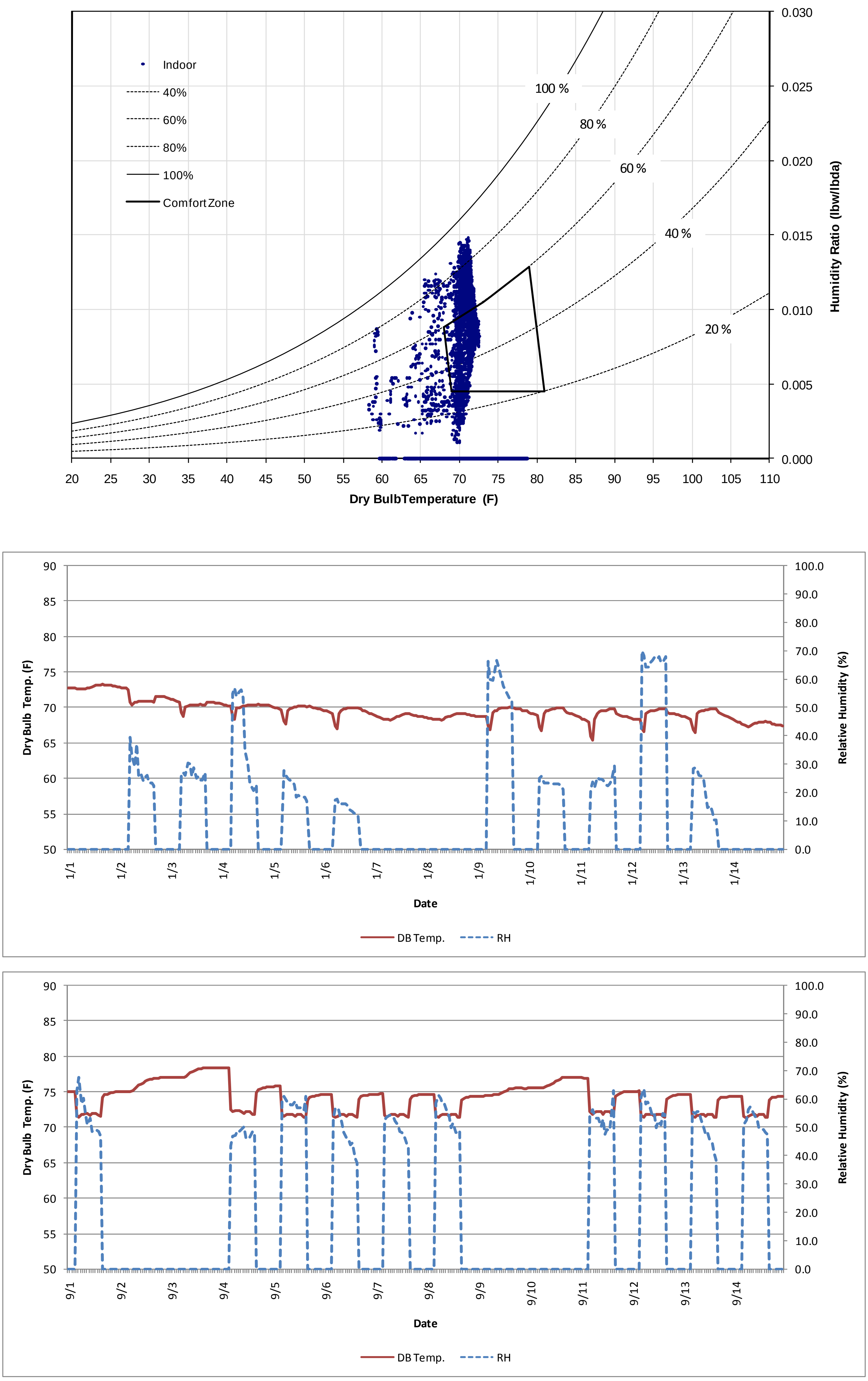


Figure 8.14 - Indoor Thermal Comfort for AEDG for K-12: Step 6+7

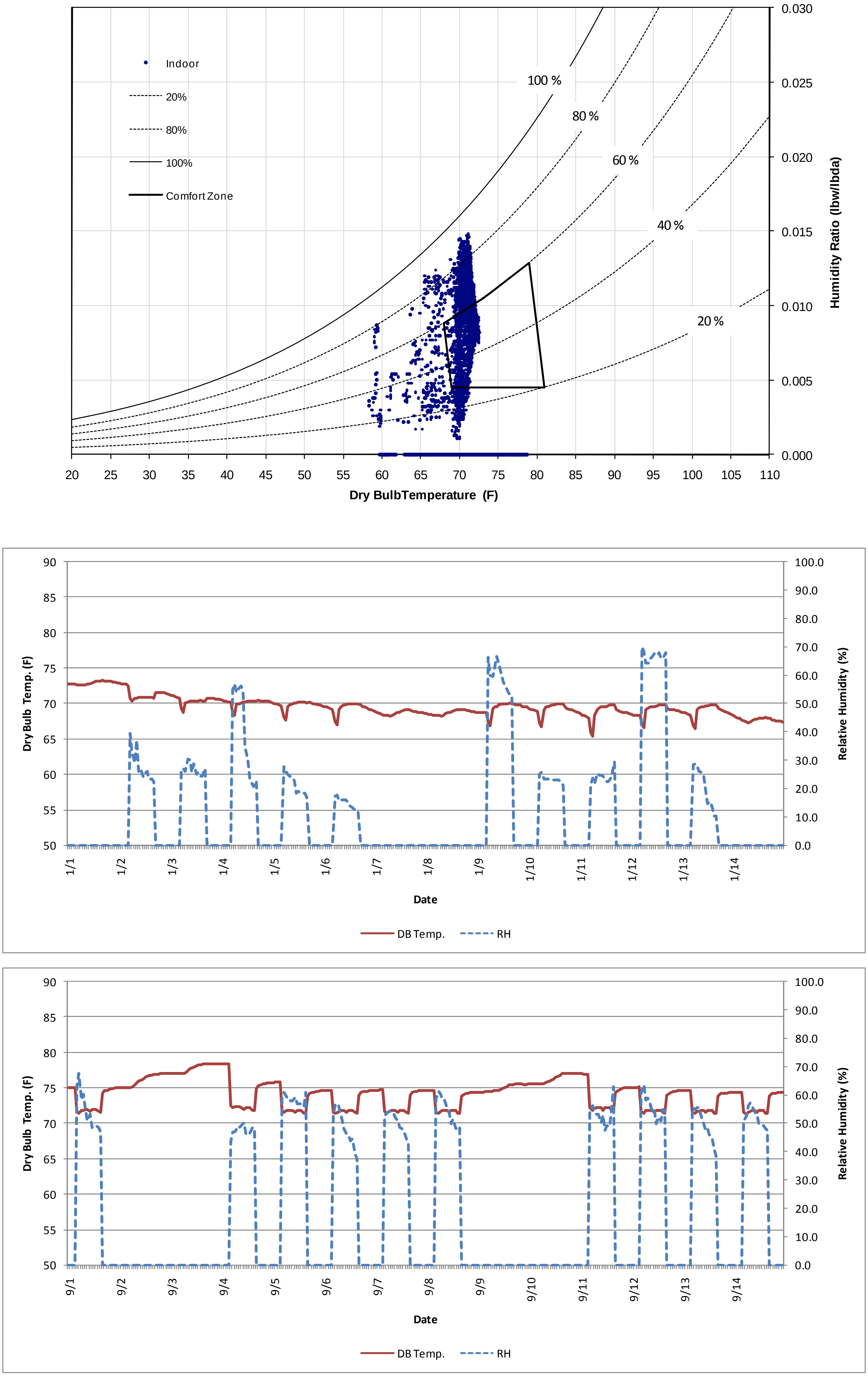


Figure 8.15 - Indoor Thermal Comfort for AEDG for K-12: Step 7+8

Table 8.8 - Energy Efficient Measures for the Above AEDG Recommended School

Step	Measures	AEDG Recommended School	High Performance Measures
9	Glazing U-value	U-0.45	U-0.20
10	Fan Control	Inlet Vane	VFD
11	Cold Deck reset	Constant	Reset Schedule
12	Variable Speed for Pump	Constant	Variable
13	Boiler Efficiency	80%	85%

The energy savings by applying the individual energy efficient measures were shown in Table 8.9 and Figure 8.16. As shown in this figure, of the five measures, the most energy savings were achieved by applying VFD fan control instead of inlet vane (i.e., 8.6% of total energy savings against the AEDG for K-12). Not surprisingly, most of this savings are from the decreased fan energy. The second most energy savings were achieved from the application of the cold deck reset. The constant cold deck temperature was modified to have reset schedule based on the outside air temperature. Figure 8.17 describes the cold deck temperature as a function of outside air temperature. By applying this measure, both of the space cooling and heating energy uses were decreased (i.e., 7.6 % of total energy savings against the AEDG for K-12)

The cumulative energy savings are shown in Figure 8.18 and Table 8.10. Instead of showing the results from steps 9 to 13, in this comparison, the final cumulative savings are compared against the baseline code compliant simulation results in order to estimate the final total energy savings based on the code compliant school. By applying the all 13 measures, the final energy efficient school would achieve a 36.8% reduction in the total annual energy savings compared to the baseline school. When converting this

energy

Table 8.9 - Energy Savings by Individual Application Step

	Annual End Uses (MMBtu/yr)					
	AEDG for K-12	Step 9	Step 10	Step 11	Step 12	Step 13
AREA LIGHTS	436.5	436.5	436.5	436.5	436.5	436.5
MISC EQUIPMT	417.3	417.3	417.3	417.3	417.3	417.3
SPACE HEAT	498.8	468.8	505.0	356.4	491.9	470.2
SPACE COOL	960.6	951.0	923.9	882.9	960.6	960.6
PUMPS & MISC	4.9	4.8	4.9	4.7	3.2	4.9
VENT FANS	307.8	306.1	95.1	313.2	307.8	307.8
DOMHOT WATER	193.3	193.4	193.4	193.4	193.4	193.4
TOTAL	**2,819.2**	**2,777.9**	**2,576.0**	**2,604.3**	**2,810.6**	**2,790.7**
% Diff (vs. AEDG for K-12)	**-**	**1.5%**	**8.6%**	**7.6%**	**0.3%**	**1.0%**

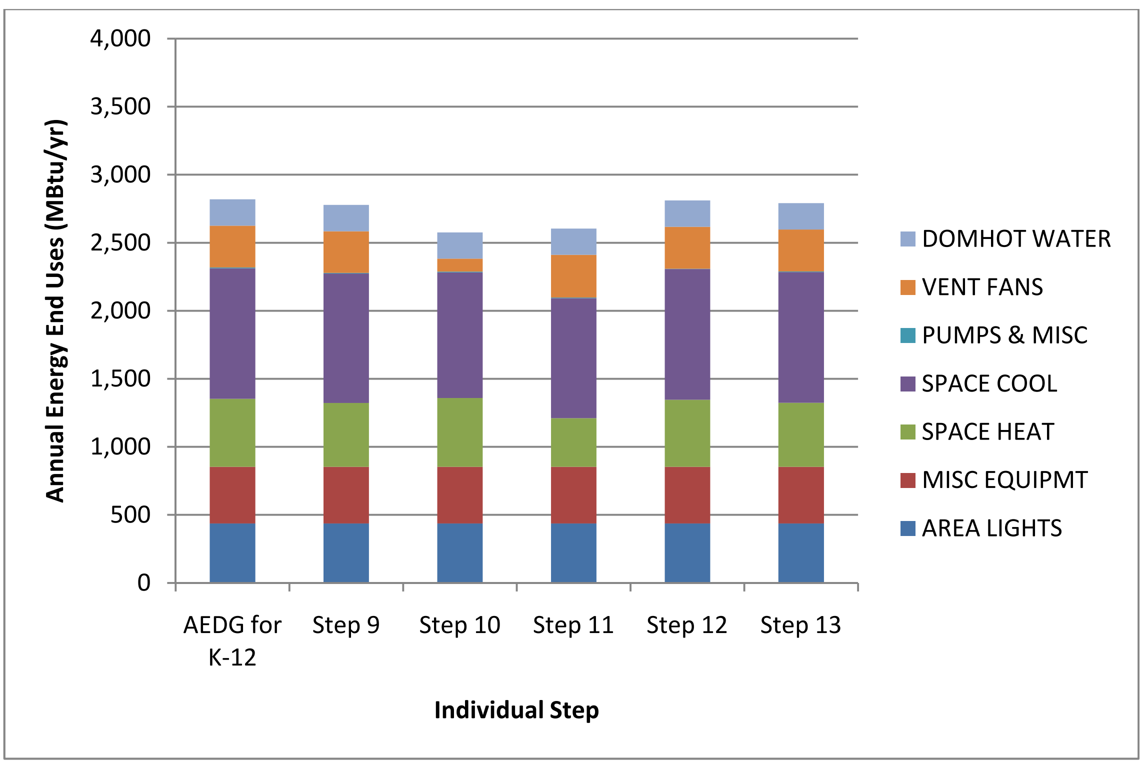


Figure 8.16 - Energy Savings by Individual Application Step

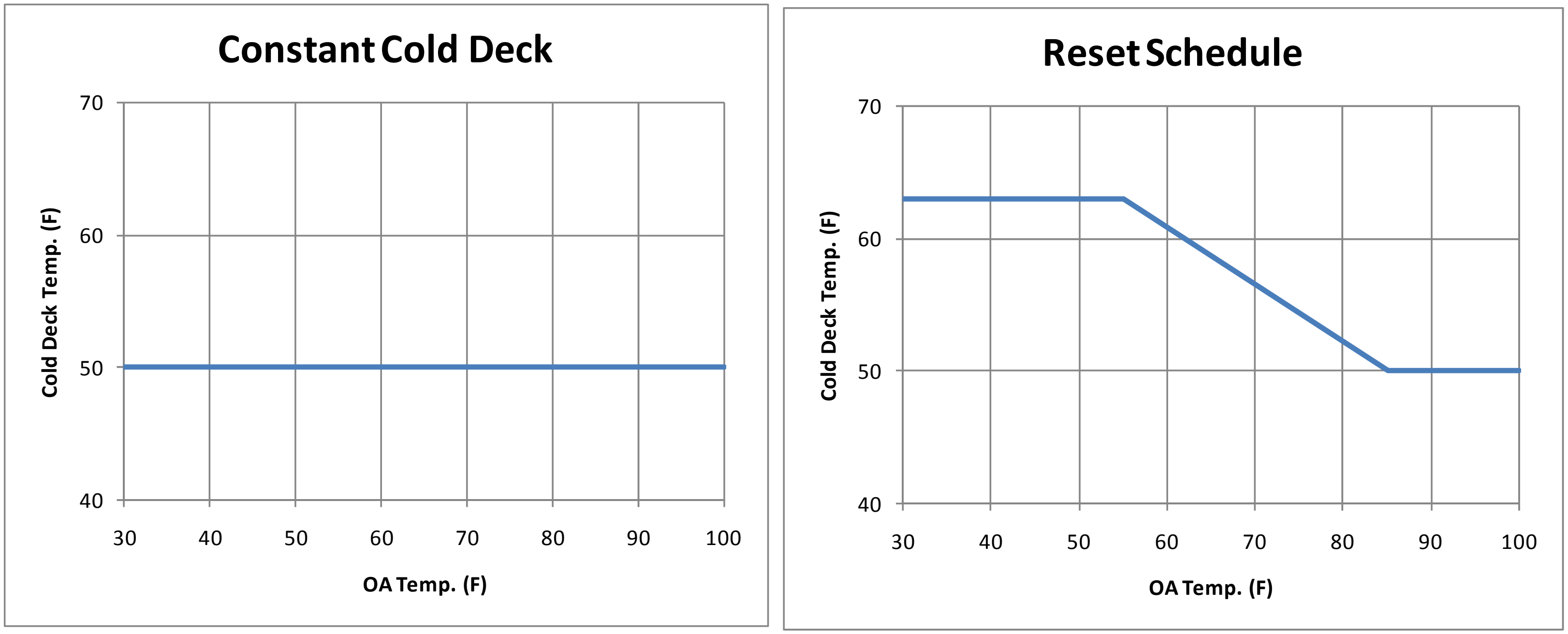


Figure 8.17 – Cold Deck Temperature: Constant vs. Reset Schedule (Step 11)

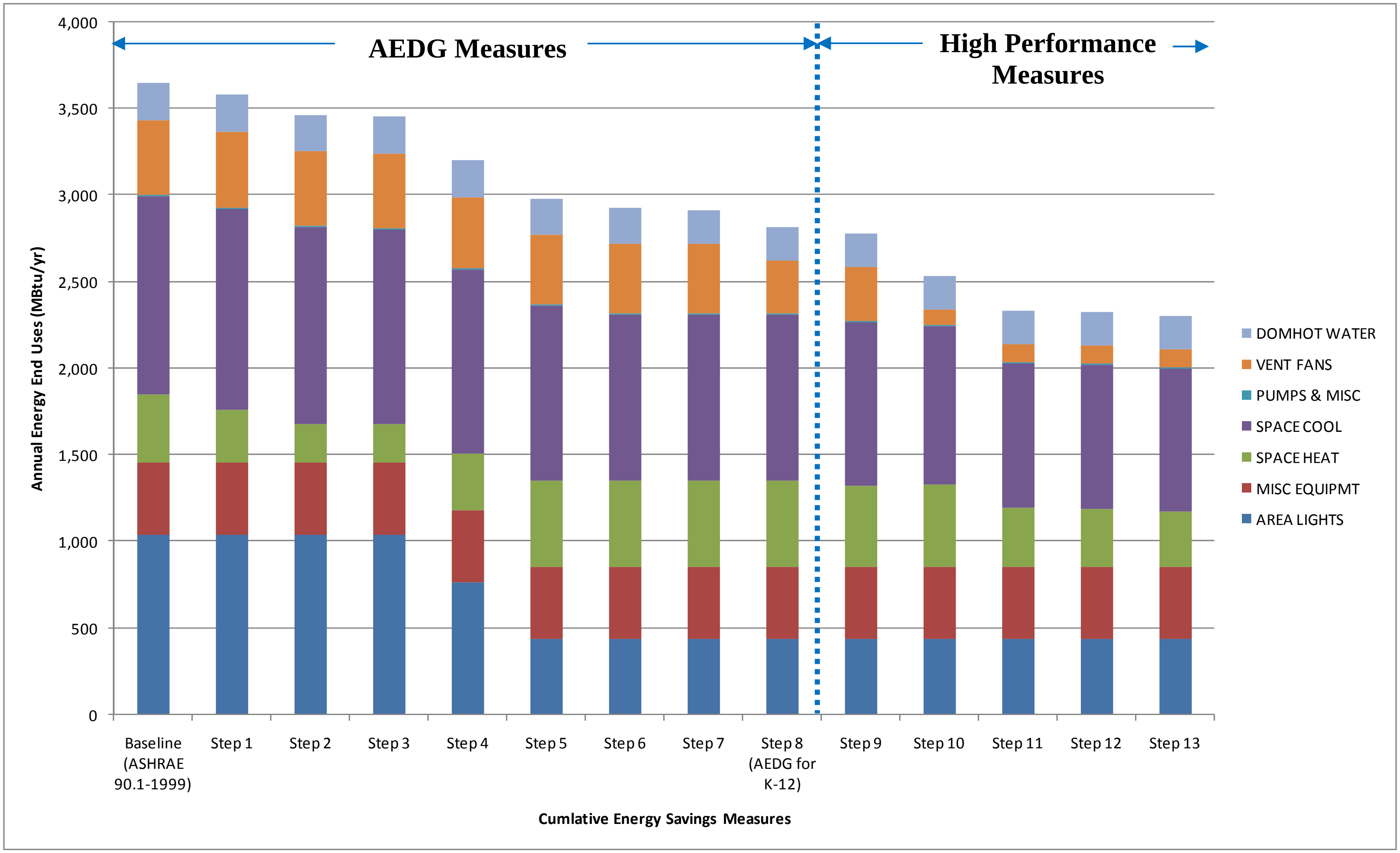


Figure 8.18 - Cumulative Energy Savings by Application Step

Table 8.10 - Cumulative Energy Savings by Application Step

	Annual End Uses (MBtu/yr)													
		AEDG Recommended								High Performance				
	Baseline School (ASHRAE 90.1-1999)	Step 1	Step 1 + 2	Step 2+3	Step 3 +4	Step 4+5	Step 5+6	Step 6+7	Step 7+8	Step 8+9	Step 9+10	Step 11	Step 12	Step 13 (Final)
AREA LIGHTS (MBtu/yr)	1,043.3	1,043.3	1,043.3	1,043.3	765.1	436.5	436.5	436.5	436.5	436	436	436	436	436
MISC EQUIPMT (MBtu/yr)	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417	417	417	417	417
SPACE HEAT (MBtu/yr)	392.6	301.8	216.3	223.0	329.0	498.8	498.8	498.8	498.8	469	475	345	337	318
SPACE COOL (MBtu/yr)	1,146.0	1,166.2	1,142.4	1,126.2	1,062.7	1,011.4	960.6	960.6	960.6	951	915	833	833	833
PUMPS & MISC (MBtu/yr)	4.4	4.2	4.0	4.0	4.5	4.9	4.9	4.9	4.9	5	5	5	3	3
VENT FANS (MBtu/yr)	434.0	438.7	432.5	428.2	411.3	402.5	402.5	402.5	307.8	306	94	106	106	106
DOMHOT WATER (MBtu/yr)	212.3	212.3	212.3	212.3	212.3	212.3	212.3	193.3	193.3	193	193	193	193	193
TOTAL (MBtu/yr)	**3,649.9**	**3,583.9**	**3,468.1**	**3,454.4**	**3,202.2**	**2,983.7**	**2,932.9**	**2,913.9**	**2,819.2**	**2,777.9**	**2,536.1**	**2,336.2**	**2,326.5**	**2,307.3**
% Diff (vs. Baseline)	-	**1.8%**	**5.0%**	**5.4%**	**12.3%**	**18.3%**	**19.6%**	**20.2%**	**22.8%**	**23.9%**	**30.5%**	**36.0%**	**36.3%**	**36.8%**

Table 8.11 - Total Annual Energy Cost (Code Compliant vs. Final High Performance School)

Electricity Rate	0.0985 ($/kWh) =	28.87 ($/MBtu)
Natural Gas Rate	10.25 ($/KCF) =	10.25 ($/MBtu)

	ASHRAE 90.1-1999 Compliant Simulation				**ASHRAE AEDG for K-12 Schools**			
	Electricity (MBtu)	N.G. (MBtu)	Total (MBtu)	EUI (kBtu/sqft-yr)	Electricity (MBtu)	N.G. (MBtu)	Total (MBtu)	EUI (kBtu/sqft-yr)
TOTAL	3,058.7	664.2	3,649.9	48.7	1,808.7	498.5	2,307.2	30.8
TOTAL COST	**$88,301**	**$6,808**	**$95,109**		**$52,215**	**$5,110**	**$57,325**	

savings to the cost savings using the same energy rate used in the previous section, the final high performance school will save $37,784 annually, which is 66% less than the baseline school (See Table 8.11). The EUI for the school was reduced from 48.7 kBtu/sqft-yr to 30.8 kBtu/sqft-yr by applying the all 13 measures.

In a similar fashion as the previous step, the indoor comfort conditions were evaluated as shown in Figures 8.19 through Figure 8.23.

8.4. Application of a Daylighting Strategy

This section presents the result of application of a daylighting strategy to the ASHRAE 90.1-1999 compliant school building. The daylighting strategy selected for this application was the same design discussed in Chapter VII. However, due to the complexity of the building geometry, only the gymnasium, the library, and the cafeteria of the school building were modified to have simple horizontal skylights. The potential energy savings with the skylight application for the entire building would be greater than this case. As described in Chapter VII, about 4.5% of total roof area for the selected spaces was replaced with the simple horizontal skylights. Then, a lighting reference point for each space was defined with two steps of dimming lights. Figure 8.24 shows the DrawBDL rendering of the modified school input which shows the skylight application. After the simulation, the energy saving over the ASHRAE 90.1-199 compliant school building was calculated individually and cumulatively.

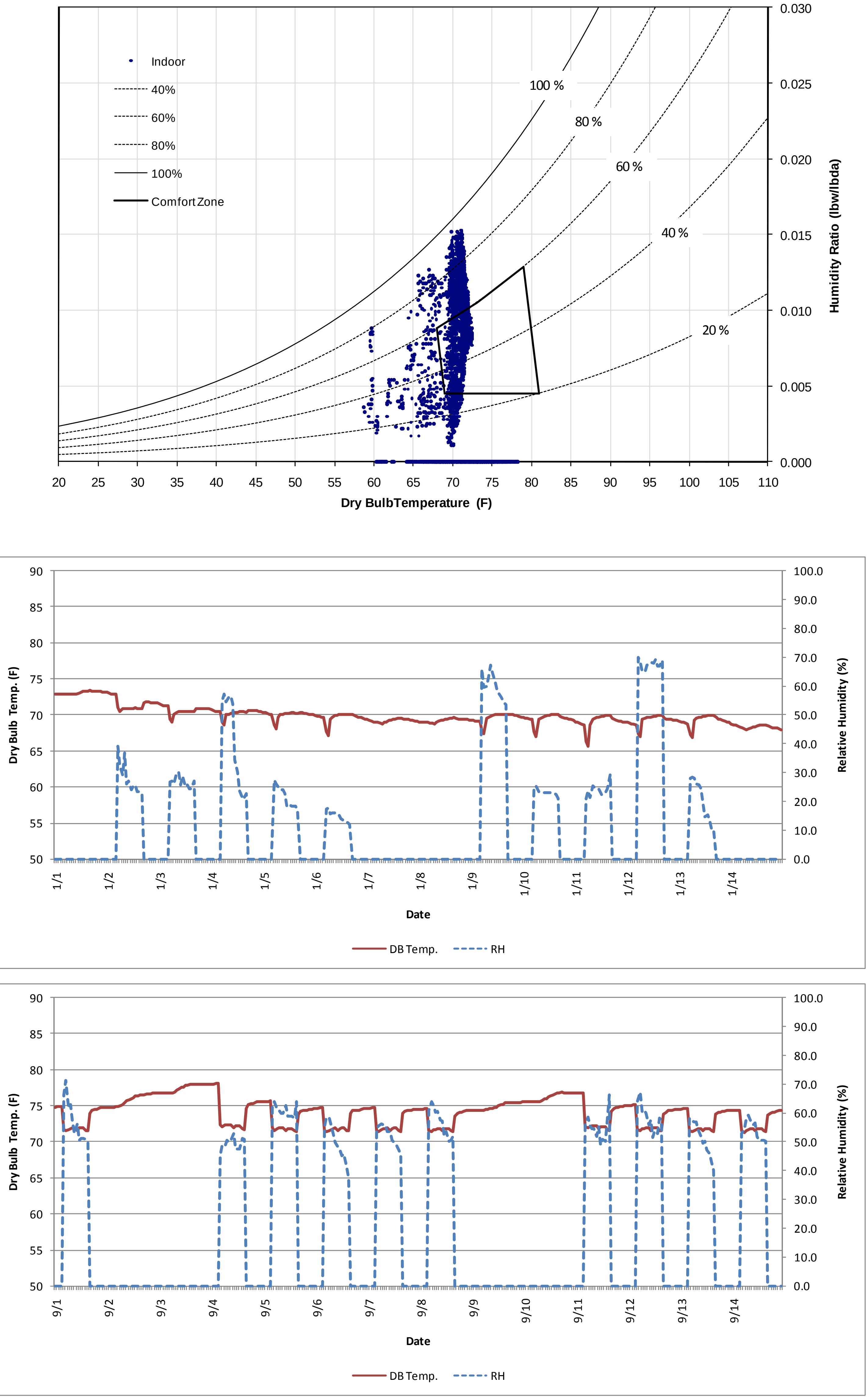


Figure 8.19 - Indoor Thermal Comfort for High Performance Measures: Step 8+9

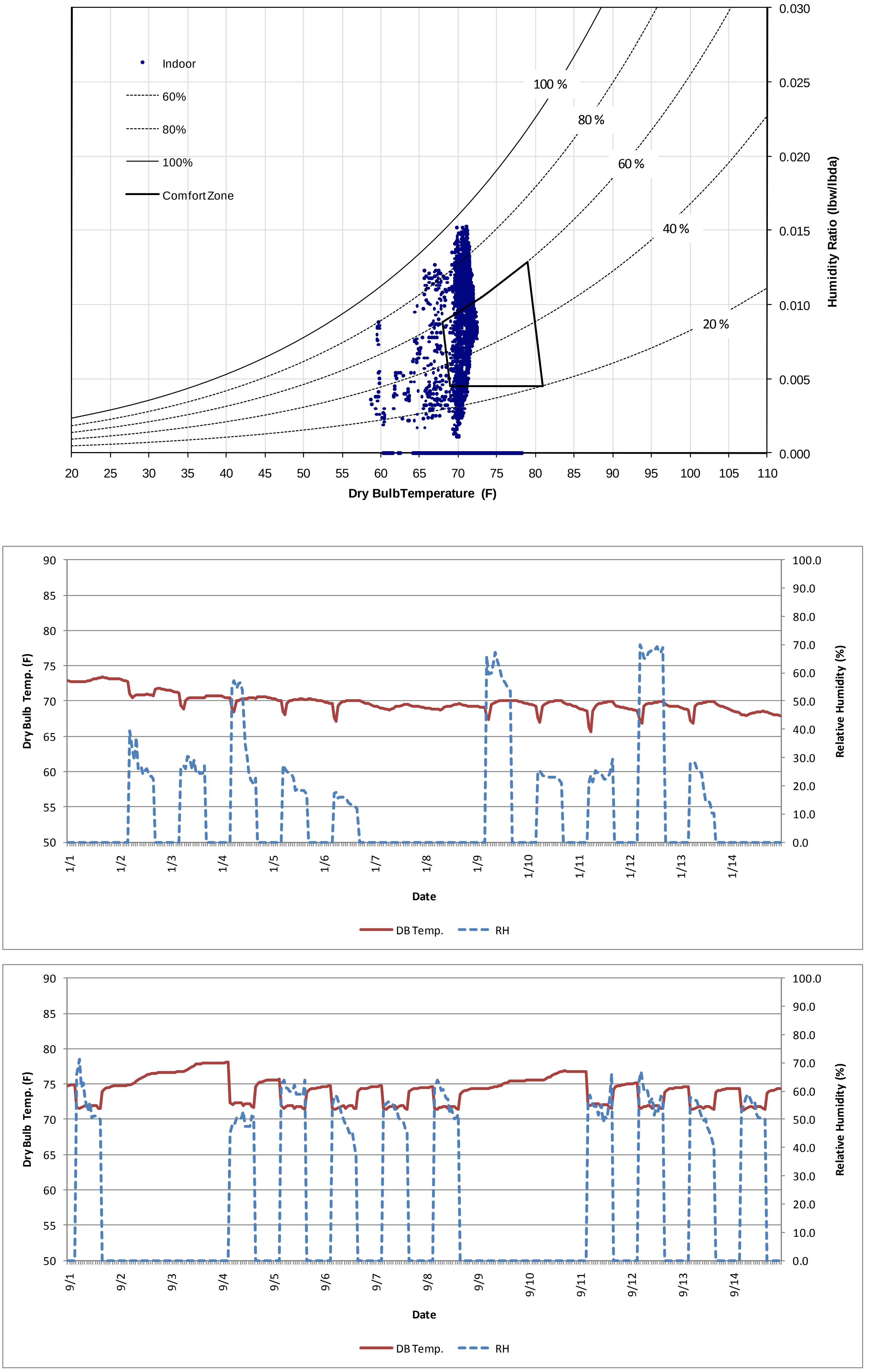


Figure 8.20 - Indoor Thermal Comfort for High Performance Measures: Step 9+10

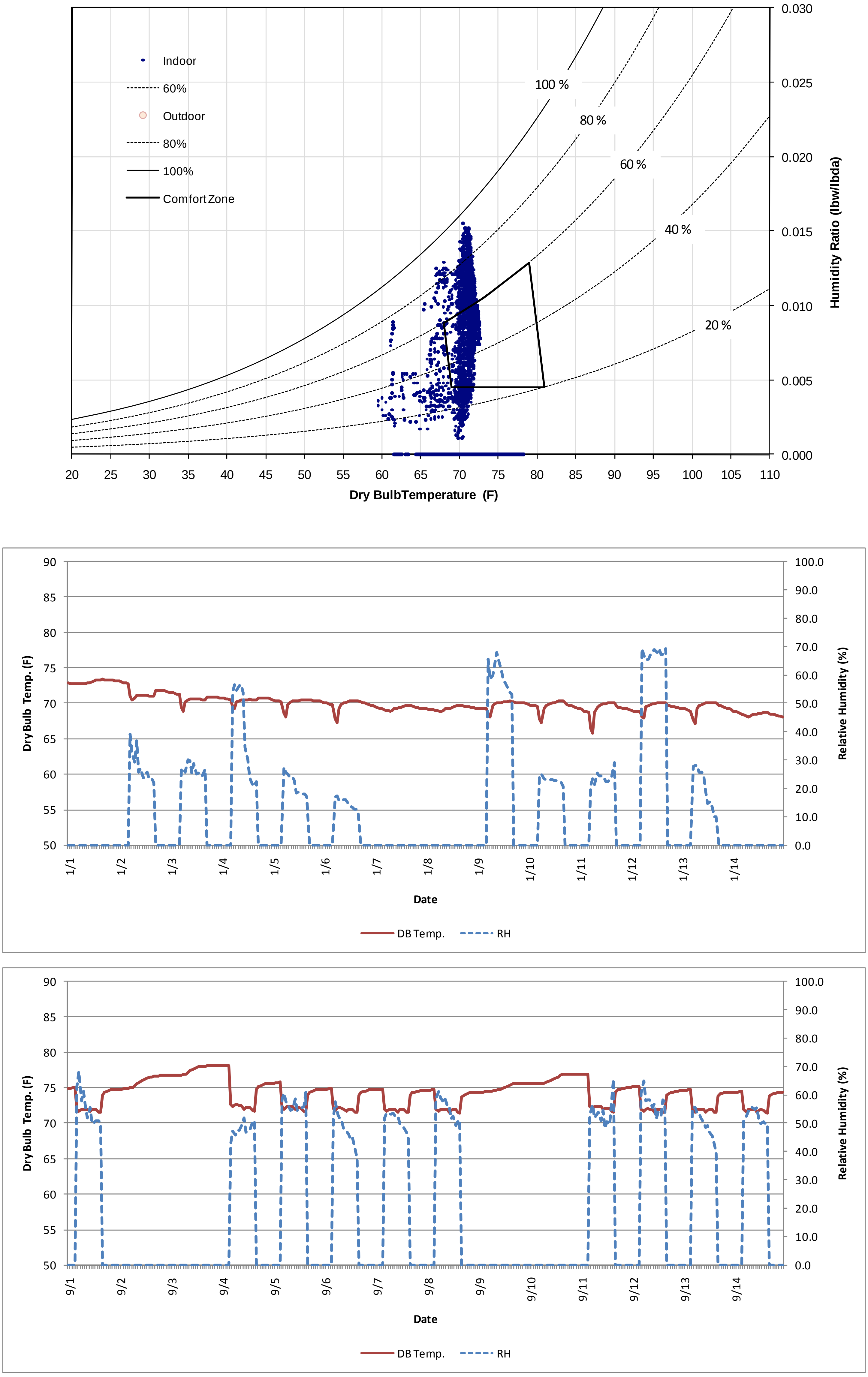
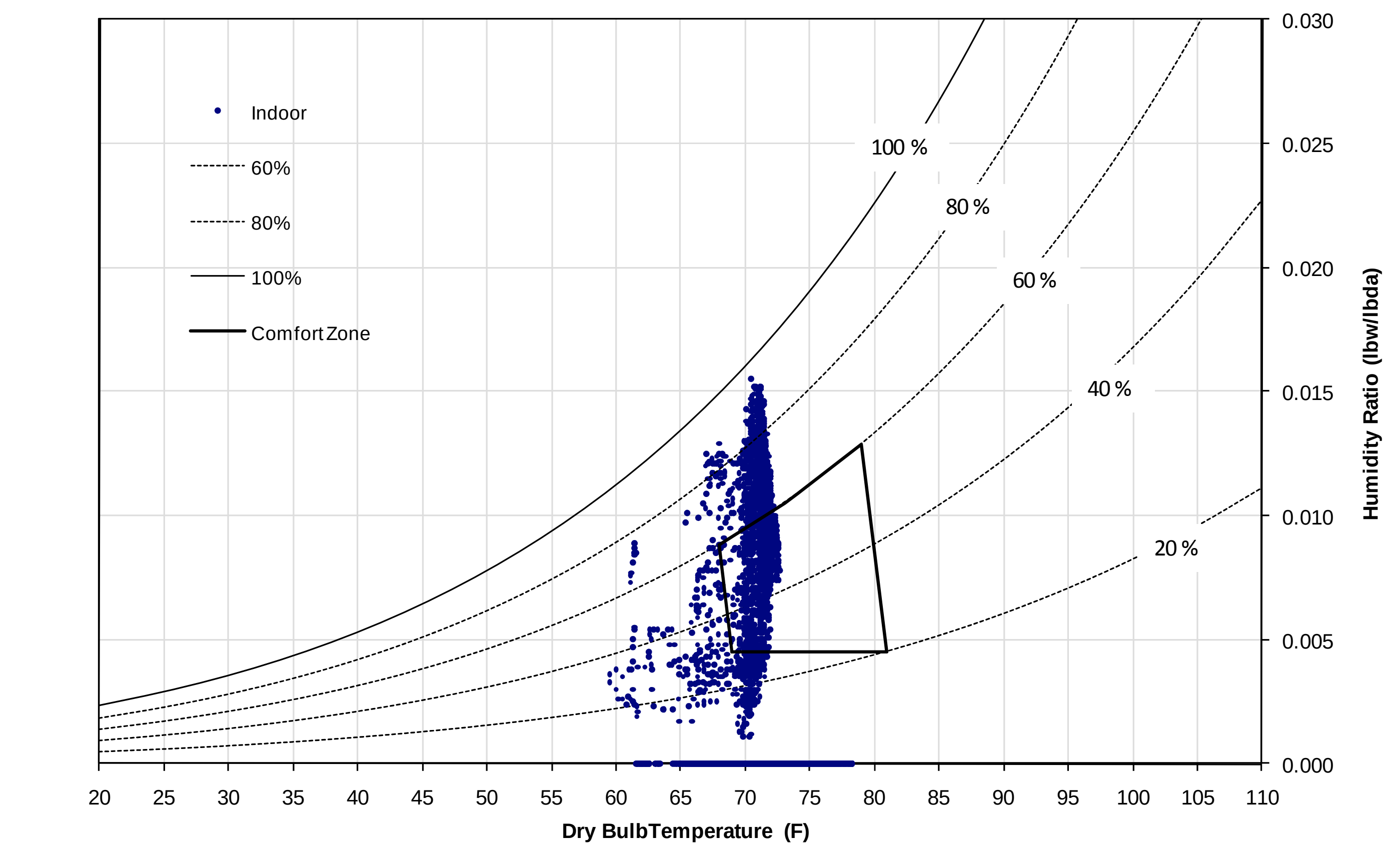
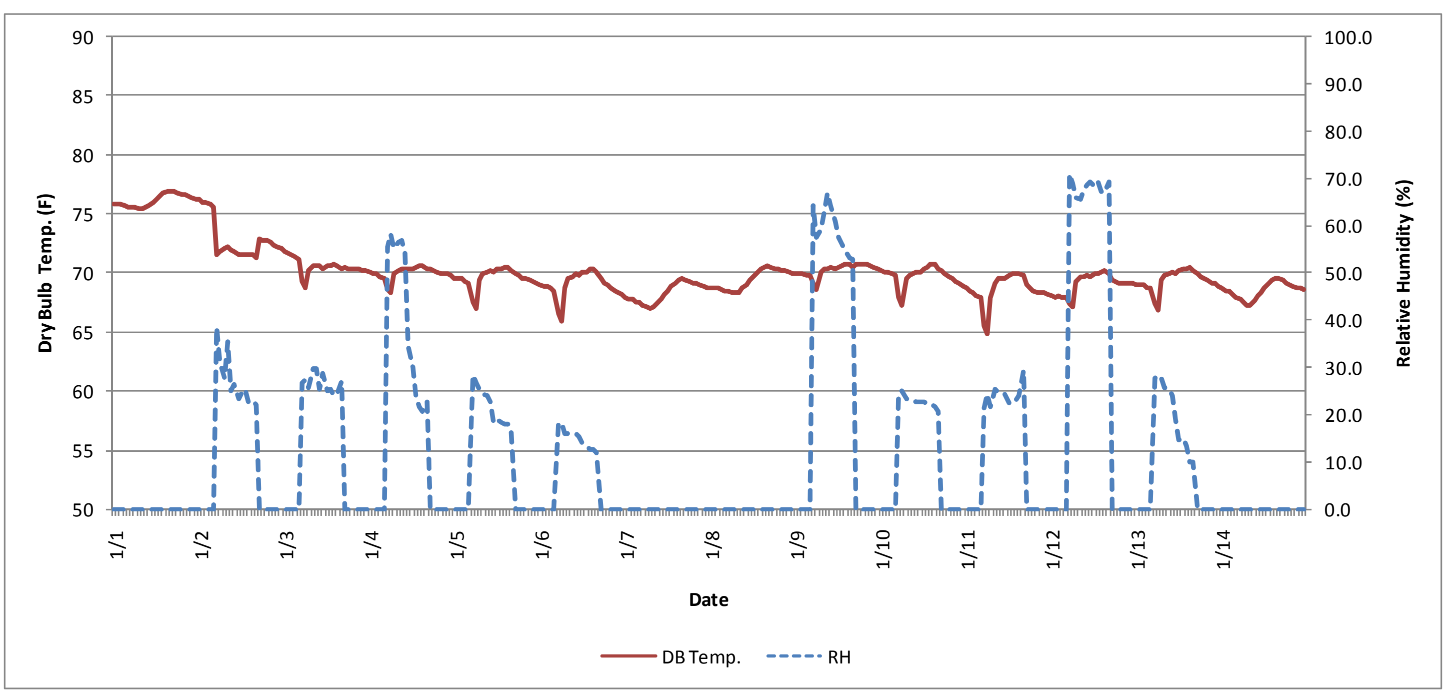


Figure 8.21- Indoor Thermal Comfort for High Performance Measures: Step 10+11





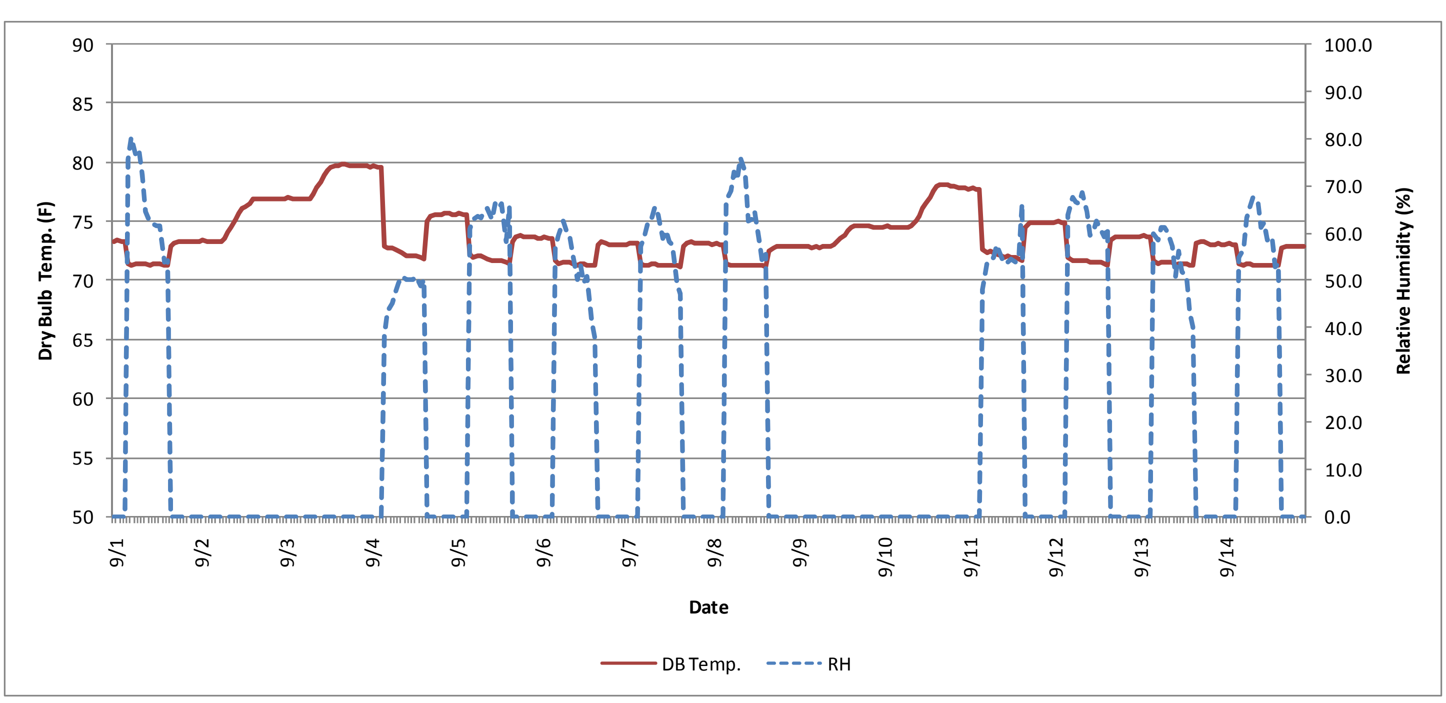


Figure 8.22- Indoor Thermal Comfort for High Performance Measures: Step 11+12

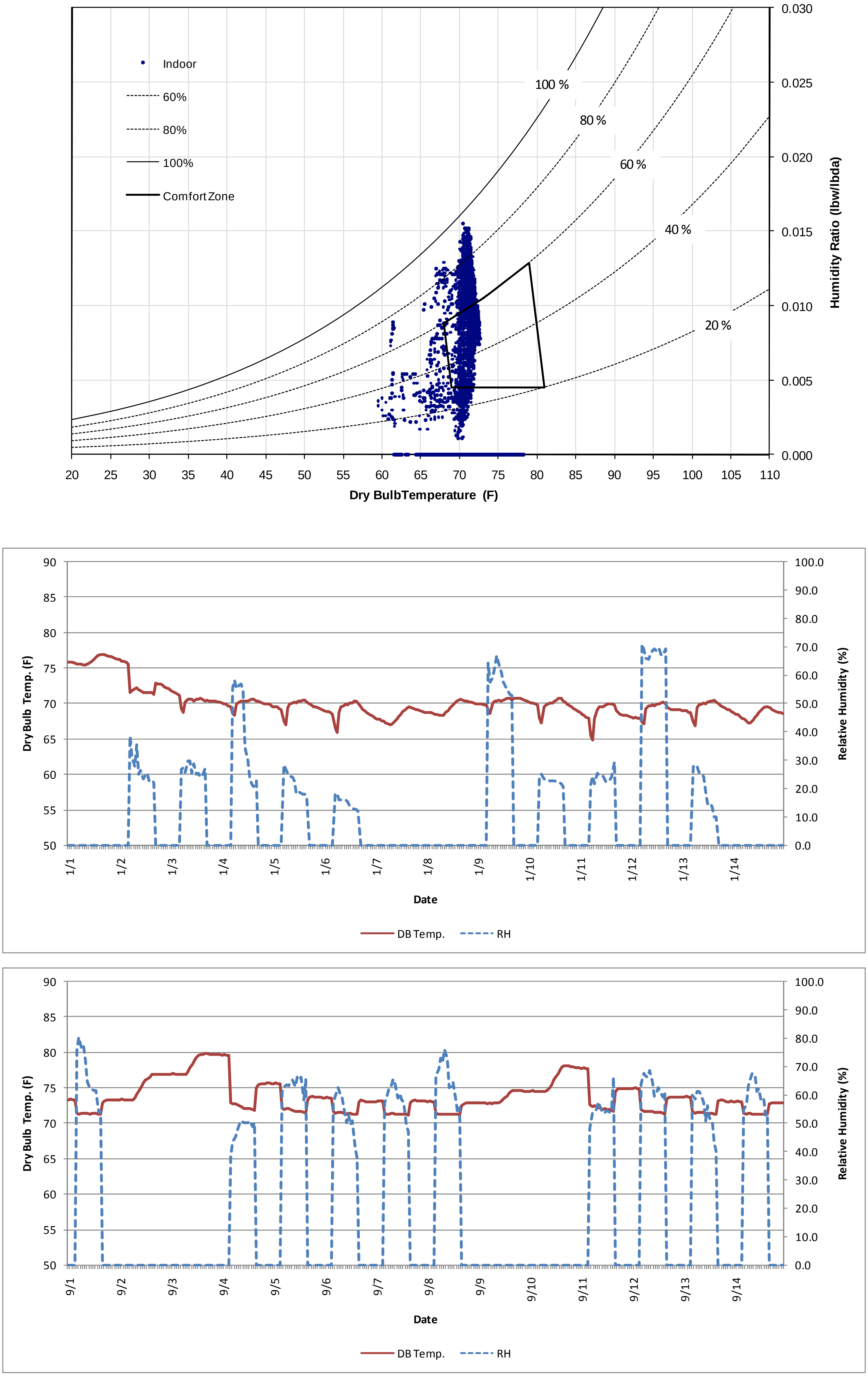


Figure 8.23- Indoor Thermal Comfort for High Performance Measures: Step 12+13

The energy and cost saving over ASHRAE 90.1-1999 compliant school building were then calculated. The simulation result is presented in Table 8.12. As shown, the total annual energy use was reduced from 3,649.9 MMBtu to 3,546.9 MMBtu (i.e., a 2.8% decrease). As expected, the lighting energy use decreased about 11.2% (i.e., from 1,043.3 MMBtu to 926.5 MMBtu). The space heating energy increased (i.e., a 5.0% increase) due to the decreased internal heat gain, and the space cooling energy decreased (i.e., a 0.5% decrease) due to the same reason. The calculated annual cost saving is $3,333 (i.e., a 3.5% decrease).

The final cumulative energy saving by applying the daylighting strategy with the 13 measures previously discussed in this chapter is also presented in this section. As discussed earlier, the final cumulative energy and cost savings over the ASHRAE 90.1-1999 compliant school building by applying all 13 measures were 36.8% and 39.2%, respectively. When the final cumulative simulation input was modified for the daylighting strategy, the cumulative energy savings over the ASHRAE 90.1-1999 compliant school building was increased to 38.6% (i.e., 3,649.9 MMBtu/yr to 2,241.3 MMBtu/yr), and the final cost saving is $38,533, which is a 40.8% annual cost savings. Table 8.13 summarizes the energy and cost savings.

Figure 8.25 shows the thermal comfort condition after applying the daylighting strategy for the selected spaces in the school building.

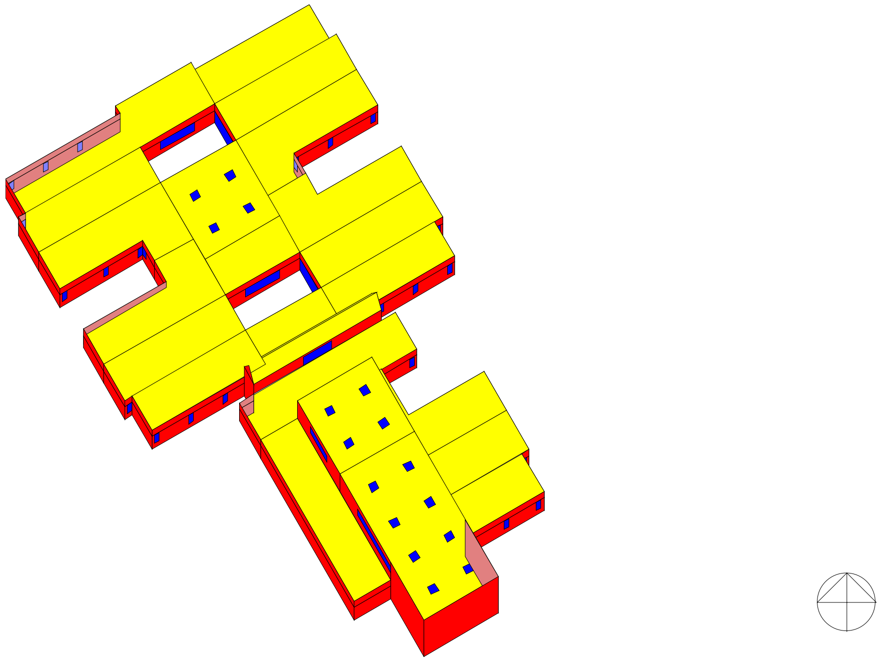


Figure 8.24 - DrawBDL of the School Building with Toplight Application

Table 8.12 - Individual Energy and Cost Savings over ASHRAE 90.1-1999 by Applying the Daylighting Strategy

	Baseline School (ASHRAE 90.1-1999)	Daylighting Strategy	% Diff.
AREA LIGHTS (MMBtu/yr)	1,043.30	926.5	-11.2%
MISC EQUIPMT (MMBtu/yr)	417.3	417.3	0%
SPACE HEAT (MMBtu/yr)	392.6	412.4	5.0%
SPACE COOL (MMBtu/yr)	1,146.00	1140.7	-0.5%
PUMPS & MISC (MMBtu/yr)	4.4	4.5	2.3%
VENT FANS (MMBtu/yr)	434	433.1	-0.2%
DOMHOT WATER (MMBtu/yr)	212.3	212.3	0.0%
TOTAL (MMBtu/yr)	3,649.90	3546.90	-2.8%
% Diff (vs. Baseline)	-	**-2.8%**	
$ Elec.	88,301.00	84,770.98	-4.0%
$ N.G.	6,060.20	6,257.623	3.3%
$ Total	94,361.10	9,1028.61	-3.5%
% Diff (vs. Baseline $)	**-**	**-3.50%**	

Table 8.13 - Cumulative Energy and Cost Savings over ASHRAE 90.1-1999 by Applying 13 Measures and the Daylighting Strategy

	Baseline School (ASHRAE 90.1-1999)	Cumulative Savings (13 Measures + Daylighting)	% Diff.
AREA LIGHTS (MMBtu/yr)	1,043.30	391	-62.52%
MISC EQUIPMT (MMBtu/yr)	417.3	417.3	0.00%
SPACE HEAT (MMBtu/yr)	392.6	295.3	-24.78%
SPACE COOL (MMBtu/yr)	1,146.00	833.7	-27.25%
PUMPS & MISC (MMBtu/yr)	4.4	3	-31.82%
VENT FANS (MMBtu/yr)	434	107.6	-75.21%
DOMHOT WATER (MMBtu/yr)	212.3	193.4	-8.90%
TOTAL (MMBtu/yr)	3,649.90	2241.3	-38.59%
% Diff (vs. Baseline)	**-**	**-38.59%**	
$ Elec.	88,301.00	50,941.12	-42.31%
$ N.G.	6,060.20	4,887.20	-19.36%
$ Total	94,361.10	55,828.32	-40.84%
% Diff (vs. Baseline $)	**-**	**-40.84%**	

8.5. Application of Solar Thermal and PV Systems

After modifying the case-study school to achieve the maximum energy savings by applying the 13 high performance measures and the daylighting, renewable energy sources are considered in this section in order to achieve further energy savings. For renewable energy strategies, in this study, solar thermal and photovoltaic (PV) systems are considered. The choice of the solar PV and solar thermal systems were selected based on the experience and data from the Texas A&M University's 2007 Solar Decathlon (Malhotra et al. 2008). For the analysis, the F-Chart and PV F-Chart program were used for the solar thermal and solar PV systems, respectively. The detailed methodology of analysis was discussed in Chapter IV.

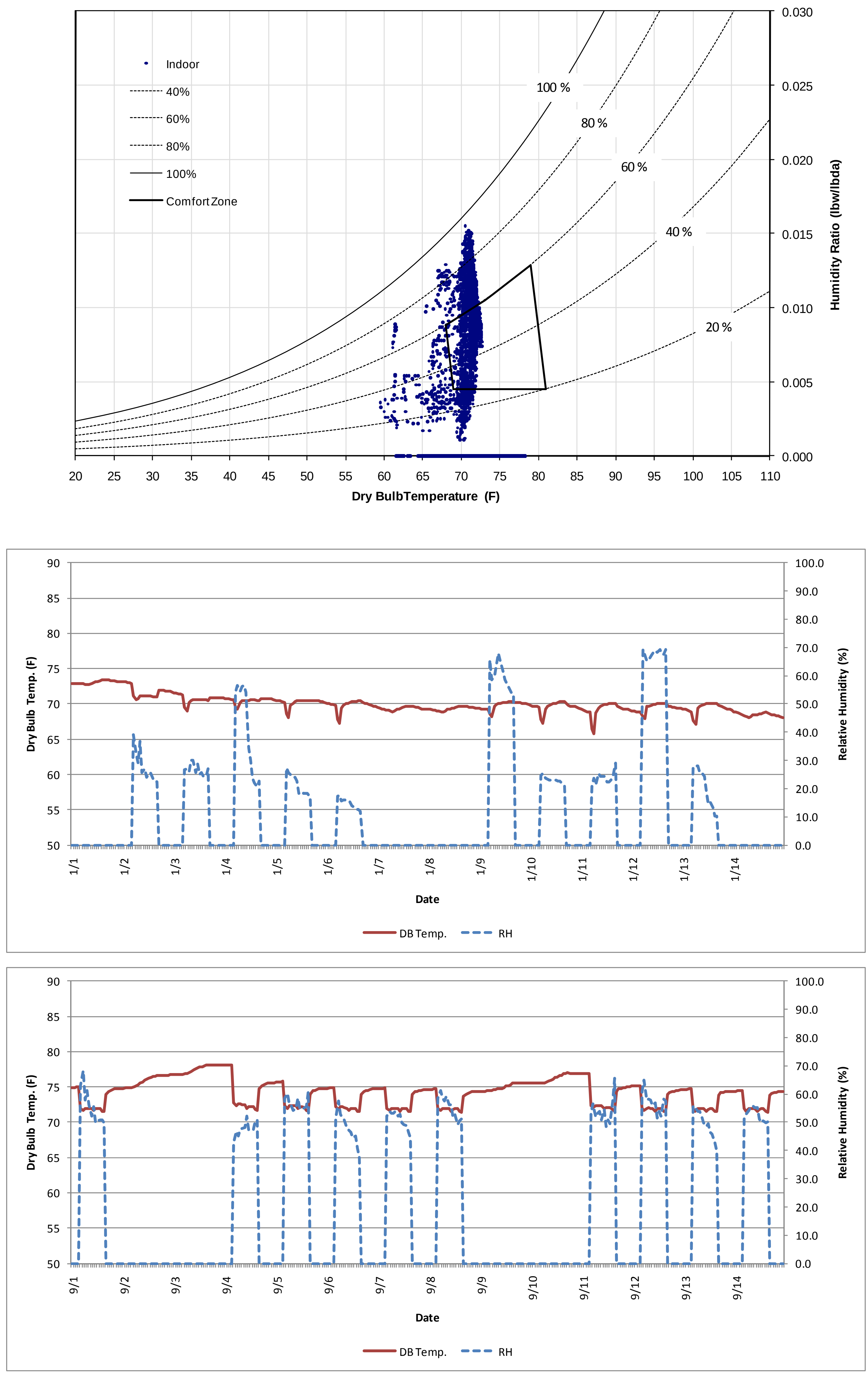


Figure 8.25 - Indoor Thermal Comfort for High Performance Measures: Daylighting Strategy (Cumulative)

8.5.1. Application of Solar Thermal System

The analysis and application of the solar thermal system for the high performance school is discussed in this section. The solar thermal system was designed to provide all or part of service hot water heating and part of the hot water for space heating. As explained in Chapter IV, the monthly space heating and service water heating (SWH) loads from the DOE-2's SYSTEM output were extracted from the DOE-2's SS-A and SS-P reports. These reports were selected because the monthly heating and SWH loads from these reports do not consider the efficiencies for the boiler and water heater (Malhotra et al. 2008). Table 8.14 presents the monthly space heating and the SWH loads from SS-A and SS-P report, respectively. This table also shows the monthly space heating and the SWH loads from PS-E report which shows the final energy consumption. As shown in Table 8.14, the total space heating and SWH load from SS-A and SS-P report are less than the space heating and SWH loads from PS-E report because the values from the PS-E report reflects the efficiencies from the boiler and the SHW heater.

As described in Chapter IV, the F-Chart program requires a building's total heat transfer coefficient (i.e., building UA) and the building's change-point temperature (T_{bal}) as inputs. In order to calculate those values, the space heating loads from the SS-A report were analyzed with ASHRAE's Inverse Modeling Toolkit (IMT). The results are shown in Figure 8.26. Using a three parameter heating model, the calculated building UA value can be determined as the slope (2,861.7 Btu/hr-F) of the buildings' increasing energy use as temperature fall below the change point (71.4 F). These values were then used

Table 8.14 - Monthly Space Heating and SWH Load (SS-A, SS-P, and PS-E Report)

	Monthly Space Heating Load (SS-A) (MMBtu)	Monthly SWH Load (SS-P) (MMBtu)	Monthly Space Heating Load (PS-E) (MMBtu)	Monthly SWH Load (PS-E) (MMBtu)
Jan	49.60	18.15	69.1	23.1
Feb	53.81	17.35	72.8	22
Mar	29.93	16.27	43.2	21.1
Apr	2.43	16.50	3.7	21.2
May	0.55	14.98	0.8	19.5
Jun	0.00	2.42	0.0	5.6
Jul	0.00	2.24	0.0	5.3
Aug	0.00	8.72	0.0	12.2
Sep	0.00	11.90	0.0	15.6
Oct	0.00	13.25	0.0	17.2
Nov	20.84	13.02	29.0	17
Dec	46.16	9.64	64.8	13.6
Total	**203.31**	**144.44**	**283.4**	**193.4**

directly in the F- Chart program.

Before the F-Chart program could be run, the F-Chart weather data needed to be modified as the same values as the 2006 TRY weather file used in the DOE-2 simulation. Table 8.15 shows the modified F-Chart weather input. The monthly weather information (i.e., solar radiation, temperature, humidity, and main water temperature) was extracted from the hourly report of the DOE-2 simulation results using the 2006 TRY file.

There are two input screens in the F-Chart program. One is for the system parameters and the other for the collector parameters. Table 8.16 shows the system parameter inputs. The selected system for the simulation was a water storage and SWH system (See Figure

```
*********************************************
 ASHRAE INVERSE MODELING TOOLKIT (1.9)
*********************************************
   Output file name = IMT.Out
*********************************************
   Input data file name = heating_1.dat
   Model type =            3P Heating
   Grouping column No =     0
   Value for grouping =     0
   Residual mode =          1
   # of X(Indep.) Var =     1
   Y1 column number =       4
   X1 column number =    3
   X2 column number =    0 (unused)
   X3 column number =    0 (unused)
   X4 column number =    0 (unused)
   X5 column number =    0 (unused)
   X6 column number =    0 (unused)
*********************************************
   Regression Results
  --------------------------------------
         N =      12
  --------------------------------------
        R2 =      0.937
  --------------------------------------
     AdjR2 =      0.937
  --------------------------------------
      RMSE =       5.8426
  --------------------------------------
   CV-RMSE =     34.483%
  --------------------------------------
         p =      0.495
  --------------------------------------
        DW =      0.948  (p>0)
  --------------------------------------
        N1 =       6
  --------------------------------------
        N2 =       6
  --------------------------------------
       Ycp =       0.4492  (       2.1653)
  --------------------------------------
        LS =      -2.8617  (       0.2356)
  --------------------------------------
        RS =       0.0000  (       0.0000)
  --------------------------------------
       Xcp =      71.4440  (       0.6360)
  --------------------------------------
```

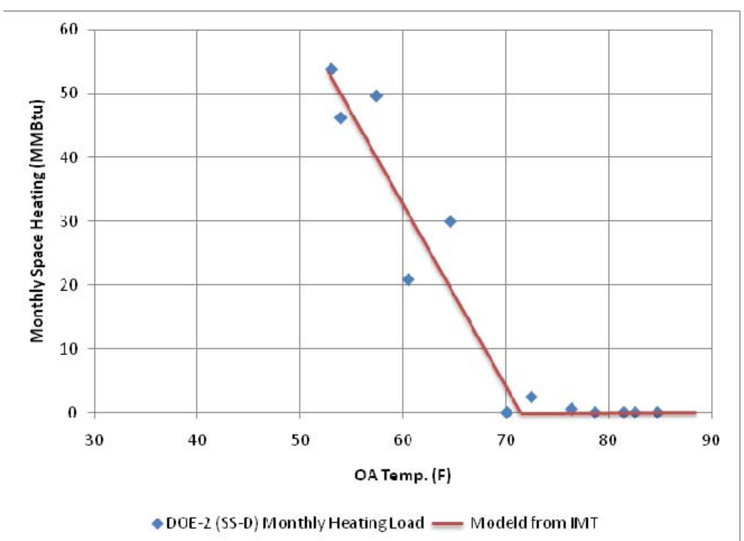


Figure 8.26 - IMT Results for Space Heating

Table 8.15- F-Chart Weather Input

	Solar Rad. (Btu/ft2)	Temp. (F)	Humidity (lb/lb)	Mains (F)	Reflect	Degree-days
Jan	942	57.4	0.0058	64.1	0.2	482
Feb	965	53	0.006	61.7	0.2	572
Mar	1183	64.6	0.0089	61.5	0.2	280
Apr	1668	72.5	0.0118	62.6	0.2	76
May	1830	76.4	0.013	67.3	0.2	26
Jun	2082	81.5	0.0138	71.9	0.2	3
Jul	1892	82.6	0.0169	75.9	0.2	0
Aug	1938	84.8	0.0164	78.4	0.2	0
Sep	1467	78.7	0.0129	78.6	0.2	10
Oct	1217	70.1	0.0112	76.6	0.2	131
Nov	974	60.5	0.0081	72.7	0.2	390
Dec	712	53.9	0.0066	68.2	0.2	605

Table 8.16 - F-Chart: System Parameter Inputs

Input Parameter	Input	Unit
Location	College Station, TX	
Water volume/collector area	2	gallons/ft^2
Building UA (0 if only DHW)	2862	Btu/hr-F
Fuel	Gas	
Efficiency of fuel usage	85	%
Domestic hot water	Yes	
Daily hot water usage	1200	gallons
Water set temperature	110	F
Environmental temperature	69.7	F
UA of auxiliary storage tank	7.6	Btu/hr-F
Pipe heat loss	No	
Inlet pipe UA		Btu/hr-F
Outlet pipe UA		Btu/hr-F
Relative load heat exchanger size	1	
Collector-storage heat exchanger	No	

8.27). The building UA value calculated using the ASHRAE's IMT as previously described. The daily hot water usage for the school was calculated based on the values from the DOE-2 simulation. In the DOE-2 simulation, the SWH use was simulated with: 1) daily SWH use, and a 2) SWH schedule. For the school simulation input in this study, the daily SWH use was 3.5 gallons/min, and there is weekday, weekends, and summer vacation schedules for the SWH use. From this information, the average daily DHW use was calculated as about 1,200 gallons. The water setpoint temperature was the same as the DOE-2 simulation input. The environmental temperature, 69.7 F is the average outdoor temperature calculated from the TRY weather file for College Station, TX.

Table 8.17 shows the collector parameter inputs. The collectors selected were evacuated tube solar collectors. The values shown for the FR*UL (Test Slope) and the FR*TAU*ALPHA (Test Intercept) were obtained from a test result for the evacuated tube collector. As a final step, the values for the number of collector panels, the collector panel area, the collector slope, and the collector azimuth were varied to achieve the optimal results for the solar thermal system design.

The first simulation was performed to provide all the space heating and SWH loads for the school building. With the total installed collector area of 7,434 sqft, the simulation result showed that all the loads can be met by the system (Table 8.17). Although a solar thermal system can be designed to meet all the heating and SWH loads for the school building as demonstrated above, it is not cost effective since there is very little demand during the summer vacation. In order to meet the space heating and SWH load during winter period, the system would be grossly over-designed during the

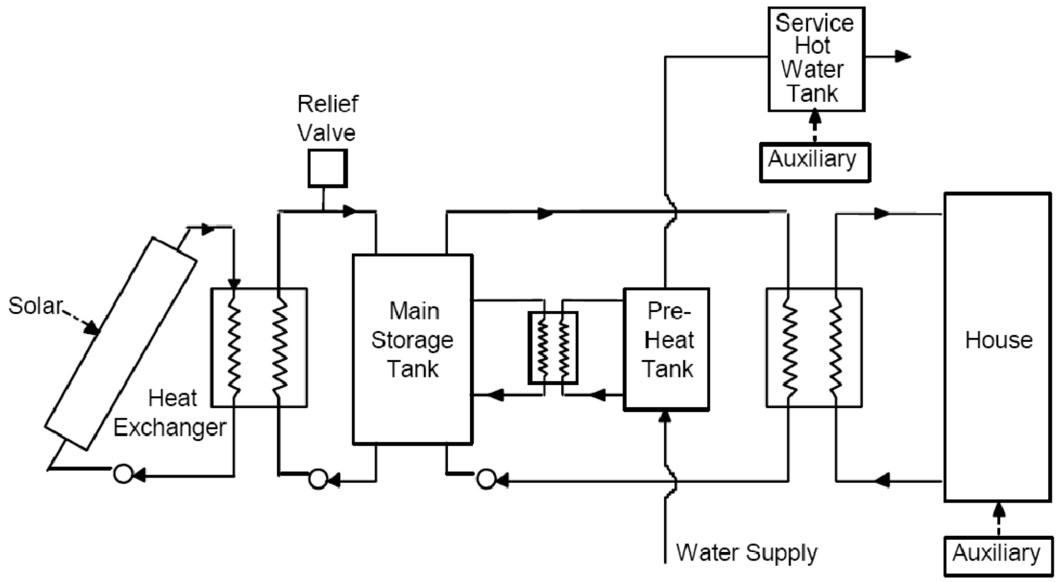


Figure 8.27 – Diagram for Water Storage and DHW System (Source: Klein and Beckman 1983)

Table 8.17 - F-Chart: Collector Parameter Inputs

Input Parameter	**Input**	**Unit**
Number of collector panels	230	
Collector panel area	32.32	ft^2
FR*UL (Test slope)	0.05	Btu/hr-ft^2-F
FR*TAU*ALPHA (Test intercept)	0.42	
Collector slope	50	degrees
Collector azimuth (South = 0)	0	degrees
Receiver orientation	NS	
Incidence angle modifier (Perpendicular)	Ang Dpe	
Incidence angle modifier (Parallel)	Ang Dpe	
Collector flowrate/area	11	lb/hr-ft^2
Collector fluid specific heat	1	Btu/lb-F
Modify test values	No	
Test collector flowrate/area		lb/hr-ft^2
Test fluid specific heat		Btu/lb-F

summer. This would be in contrast to a grid-tied solar PV system which could sell the excess electricity generated from PV array to a utility company during the summer vacation period when the school's electric demand is low. To safely operate a solar thermal system during low summer load, a heat rejection device may be required. Therefore, in this study, a solar thermal system was designed only for service hot water for the school building. Tables 8.18 and 8.19 show the F-Chart results of a solar thermal system for the space heating and SWH load, and only SWH load, respectively. With a total collector area of 1,630 sqft, the entire SHW demand for the school can be met. Therefore, the final annual natural gas consumption would be decreased from the 476.8 MMBtu to 283.45 MMBtu, which excludes the SWH energy use.

Table 8.18 - F-Chart: Simulation Results (Space Heating & SWH)

	Solar [10^6 Btu]	Heat [10^6 Btu]	Dhw [10^6 Btu]	Aux [10^6 Btu]	f [ ]
Jan	415.7	55.80	14.45	0.000	1.000
Feb	316.8	64.11	13.72	0.000	1.000
Mar	369.6	31.42	15.26	0.000	1.000
Apr	443.2	8.50	14.43	0.000	1.000
May	440.9	2.88	13.46	0.000	1.000
Jun	455.2	0.34	11.65	0.000	1.000
Jul	443.6	0.00	10.79	0.000	1.000
Aug	501.6	0.00	10.02	0.000	1.000
Sep	429.1	1.14	9.64	0.000	1.000
Oct	440.6	14.68	10.58	0.000	1.000
Nov	397.1	43.70	11.41	0.000	1.000
Dec	301.6	67.88	13.18	0.000	1.000
Year	4955.0	290.44	148.59	0.000	1.000

Table 8.19 - F-Chart: Simulation Results (SWH Only)

	Solar [10^6 Btu]	Heat [10^6 Btu]	Dhw [10^6 Btu]	Aux [10^6 Btu]	f [ ]
Jan	68.39	0.000	14.45	0.000	1.000
Feb	52.12	0.000	13.72	0.000	1.000
Mar	60.80	0.000	15.26	0.000	1.000
Apr	72.92	0.000	14.43	0.000	1.000
May	72.54	0.000	13.46	0.000	1.000
Jun	74.88	0.000	11.65	0.000	1.000
Jul	72.99	0.000	10.79	0.000	1.000
Aug	82.52	0.000	10.02	0.000	1.000
Sep	70.60	0.000	9.64	0.000	1.000
Oct	72.48	0.000	10.58	0.000	1.000
Nov	65.32	0.000	11.41	0.000	1.000
Dec	49.62	0.000	13.18	0.000	1.000
Year	815.18	0.000	148.59	0.000	1.000

8.5.2. Application of Solar PV System

A solar PV system for the high performance school building was designed and analyzed in this section. The system was purposed to provide part or all of the electricity demand of the school. The selected PV system is a utility feedback or grid-tied system which does not need electrical storage such as a battery bank. In this system, the building's electricity would be provided by the PV system first, and if the electricity from the PV system were not enough for the building's demand, the utility grid will provide the remainder of the electricity demand. On the contrary, if there would be excess electricity from the PV system, it was assumed that the utility company buys the excess electricity from the school's PV system. In general, the electricity generated from the PV system peaks during the summer period. Unfortunately, the school building is usually closed during the summer vacation. Therefore, a relatively large amount of excess electricity during summer period could be sold to the utility company.

As described in Chapter IV, the PV F-Chart program was used to calculate the electricity generated from the PV system for the high performance school building. The selected PV panel for the school is the Suntech STP 180 panel. The specification of this panel is shown in Table 8.20. The efficiency of this panel is about 13.3%. Since the cost effectiveness was not considered in this study, the PV system was designed to provide about half of the electricity consumed in the school building. From several runs with various PV array areas, a 17,864 ft^2 area was chosen for the PV system (i.e., about 1,300 Suntech 180 panels, which cost about $800,000). These panels will cover about 20.9% of the total roof area, and provide about one half of the building electricity needs.

Table 8.20 - Specification of the Selected PV panel

Electrical data	
Nominal output Pmpp:	180 W
Max. power tolerance:	+/- 3 [%]
Max. Voltage system:	1000 [V]
Nominal Voltage Umpp:	36,2 [V]
Nominal current Impp:	4,97 [A]
Panel Efficiency	13.3 [%]
Open circuit voltage Uoc:	45 [V]
Short circuit current Isc:	5,26 [A]

Dimensions	
Length:	1580 [mm]
Breadth:	808 [mm]
Height:	35 [mm]

The inputs for the PV F-Chart program are shown in Table 8.21. All inputs shown here were from the manufacturer's data. Since there were no weather data for College Station, Texas with the PV F-Chart program, the monthly average solar radiation and drybulb temperature were extracted from the 2006 TRY weather file that was used in the DOE-2 and used in the F-Chart program. Table 8.22 shows the weather data replaced.

With the simulation inputs and weather data described above, a PV F-Chart analysis was performed. The results are shown in Figure 8.28 and Table 8.21. As shown, about 49.8% of the total electricity uses could be provided by the PV system. The remainder of the electricity would be provided by the local utility. Since there is still more than 80% of the roof area available for PV panel installation, if one does not consider the cost effectiveness, the entire school building could easily be powered by a PV system, which would also have extra electricity to send back to the utility during the summer days.

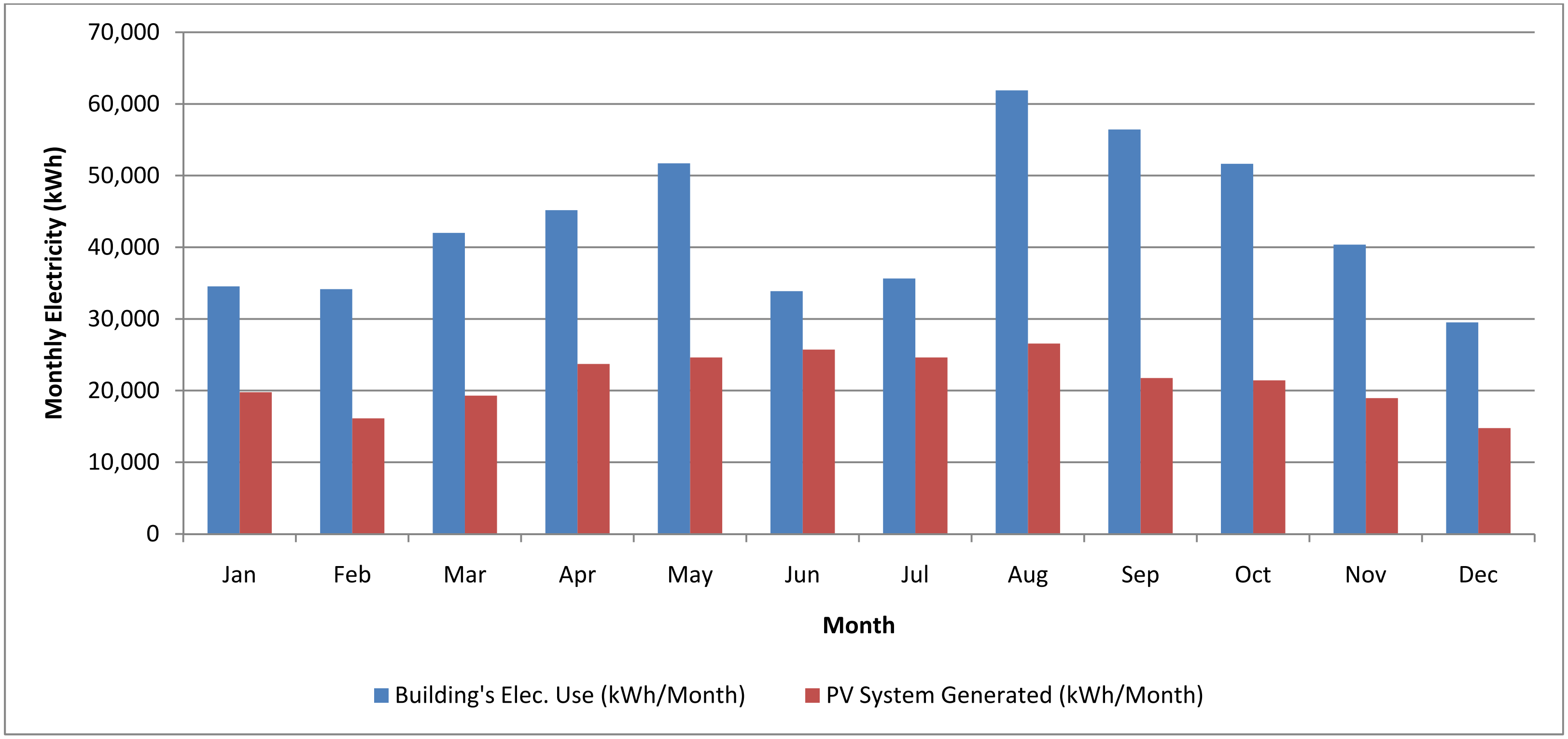
Finally, the annual total electricity use for the high performance school building with solar PV system designed in this section would be decreased from 517,017 kWh to 257,361 kWh. Therefore, with the solar thermal and PV systems designed in this section, the net energy consumption of the final high performance school would be 1,162.1MMBtu, which is corresponding to the 14.9 kBtu/sqft-yr of EUI, which is 68.2% energy savings over the code compliant school building. When this energy savings converted to the energy cost savings, the final school with solar PV and thermal systems would save $65,976 (i.e., 69.9% savings over the code compliant school) annually.

Table 8.21 - Input and Output of PV F-Chart Analysis

	Input					Results		
	Item	IP Unit		SI Unit		Month	Solar kWh	Elec. Generated (kWh)
1	City number for COLLEGE STATION TX................	N/A		N/A		Jan	205,079	19,774
2	Output: 1 for summary, 2 for detailed (Neg: graph)	1		1		Feb	164,691	16,117
3	Cell temperature at NOCT conditions...............	113	F	45	C	Mar	205,184	19,305
4	Array reference efficiency........................	0.15		0.15		Apr	260,549	23,716
5	Array reference temperature.......................	77	F	25	C	May	273,907	24,629
6	Max. power eff. temperature coeff. (times 1000)...	2.5	1/F	4.5	1/C	Jun	291,329	25,715
7	Eff. of maximum power point tracking electronics..	0.9		0.9		Jul	278,788	24,622
8	Efficiency of power conditioning electronics......	0.88		0.88		Aug	303,582	26,575
9	Percent standard deviation of the load...........	0	%	0	%	Sep	242,178	21,752
10	Array area.......................................	17864	ft^2	1659.62	m^2	Oct	232,294	21,425
11	Array slope......................................	30	deg	30	deg	Nov	198,212	18,961
12	Array azimuth (south=0)..........................	0	deg	0	deg	Dec	150,281	14,770
						Yr	**2,806,074**	**257,361**

Table 8.22 - Weather Data for PV F-Chart

	Solar Rad. (kJ/m^2)	Temp (C)	Ground Albedo
Jan	10702	14.1	0.20
Feb	10962	11.7	0.20
Mar	13435	18.1	0.20
Apr	18940	22.5	0.20
May	20787	24.7	0.20
Jun	23650	27.5	0.20
Jul	21484	28.1	0.20
Aug	22012	29.3	0.20
Sep	16655	25.9	0.20
Oct	13822	21.2	0.20
Nov	11064	15.8	0.20
Dec	8081	12.2	0.20



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Building's Elec. Use (kWh/Month)	34,541	34,163	42,003	45,185	51,722	33,885	35,642	61,887	56,441	51,658	40,366	29,524	**517,017**
PV System Generated (kWh/Month)	19,774	16,117	19,305	23,716	24,629	25,715	24,622	26,575	21,752	21,425	18,961	14,770	**257,361**
% Generated from PV System	57.2%	47.2%	46.0%	52.5%	47.6%	75.9%	69.1%	42.9%	38.5%	41.5%	47.0%	50.0%	49.8%

Figure 8.28 - Monthly PV F-Chart Results with DOE-2 Results

8.6. Summary

The energy savings potentials for the ASHRAE 90.1-1999 compliant school building were analyzed in this chapter. For the analysis, first, the calibrated case-study school simulation was modified to be compliant with the ASHRAE 90.1-1999 using the ECB method. The modified simulation result shows that the EUI for the code compliant school is 48.7 kBtu/sq.ft.-yr, while the EUI for the calibrated case-study school is 51.6 kBtu/sq.ft.-yr (i.e., 5.7% decrease). When the energy cost for the code-compliant school was calculated, the case-study school and the code-compliant school costs almost same amount of energy bills (i.e., annually $39 more cost for the case-study school and 0.04% more consumptive).

Next, the ASHRAE AEDG for K-12 schools recommended school measures were simulated to estimate the energy savings potential. After applying eight measures recommended in the AEDG for the K-12 schools, the school consumed 22.8% less energy than the ASHRAE 90.1-1999 compliant school. Of the eight measures, the installation of occupancy sensors and the reduced lighting power density from 1.5 W/sq.ft. to 1.1W/sq.ft were the first and the second most effective energy saving measures, respectively (i.e., 8.7% and 6.7% of total energy savings, respectively).

In order to achieve savings above the AEDG for K-12 schools, more energy efficient measures were applied to the school. After applying 5 measures, the final high performance school building consumed 36.8% less energy than the ASHRAE 90.1-1999 compliant school building. As a result, the EUI for the school was reduced from 48.7

kBtu/sqft-yr to 30.8 kBtu/sqft-yr by applying the all 13 measures (i.e., eight from the AEDG for K-12 schools, and five from from the above AEDG design).

In addition, a daylighting strategy was also applied to the school building to evaluate the energy impact. The gymnasium, cafeteria, and library were modified to include skylights on roof of the model. Then, using the DOE-2 simulation, the available daylighting was calculated each hour and the artificial lights in the spaces were dimmed. The simulation result showed that the application of the skylights for the selected spaces could reduce the total annual energy use by 2.8% compared to the ASHRAE 90.1-1999 compliant school. The final cumulative energy savings from applying the 13 measures and the daylighting strategy were simulated as 38.6% energy savings over the ASHRAE 90.1-1999 compliant school.

As a final section of this chapter, a solar thermal and PV system was designed and applied to the high performance school developed in the previous section to calculate the further energy savings potential. The solar thermal and PV system was designed to provide all needs for the SWH load and half of the school's electricity demand, respectively. The results show that the net energy consumption of the final high performance school with the solar thermal and PV systems would be 1,162.1 MMBtu, which corresponds to the 15.0 kBtu/sqft-yr of EUI. Figure 8.29 shows the final chart of the cumulative energy savings by applying all 15 measures including daylighting, solar PV and solar thermal systems. As shown, the SWH use was eliminated and the electricity use decreased in half in the final cumulative energy use as the solar PV and thermal system provides the SWH and the portion of electricity demand.

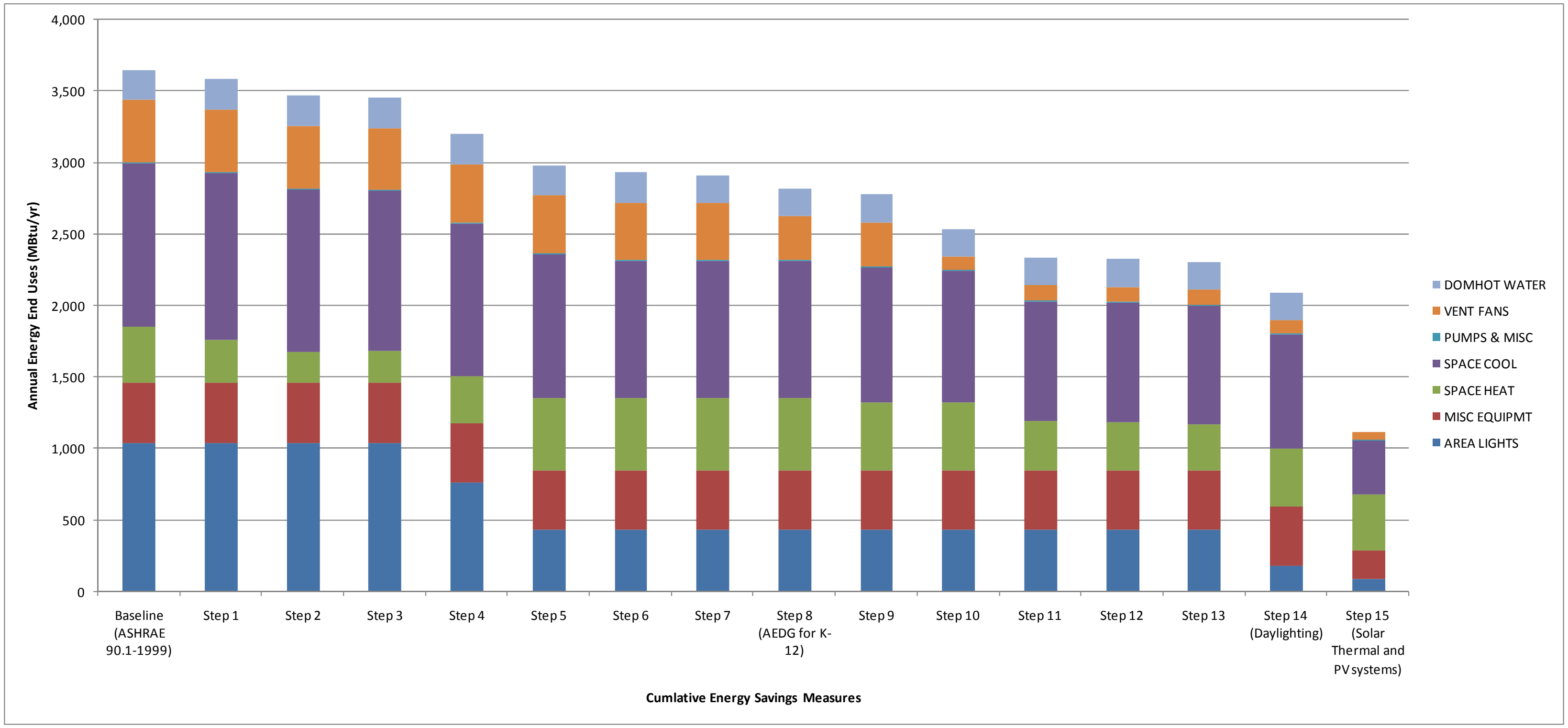


Figure 8.29 – Cumulative Energy Savings by Step

CHAPTER IX

RESULTS: METHODOLOGY FOR DEVELOPMENT OF A SIMPLIFIED SIMULATION TOOLKIT

As a final step of this study, procedures for developing an easy-to-use simplified simulation tool are discussed, including the development of a prototype that performs selected functions. As explained in Chapter IV, in this study, the DOE-2 simulation program would be used for the simulation engine for the final web-based tool. In addition, as described in the limitation of this study, the prototype simulation only performs, selected functions related to the envelope.

9.1. School Building Configuration

As described in Chapter IV, in this section, the most common school building configuration was identified using the satellite views of the schools in two adjacent school districts in Central Texas. Figure 9.1, 9.2 and 9.3 present the survey results. Of the twenty-three K-12 schools in the case-study school districts, the spine school configuration was identified as the most dominant school shape (i.e., 52.2% of total). As for the K-5 schools, the spine school configuration was also identified as the most dominant school shape (i.e., 61% of eighteen K-5 schools surveyed). The centralized resource plan, the courtyard plan, and a spine with single-loaded classroom wings were the next most frequent building shape (i.e., approximately 11% each). Therefore, for this study, the spine plan was used to define the proposed prototype K-5 school geometry.

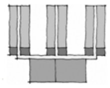
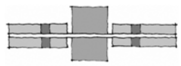
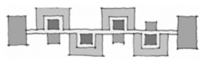
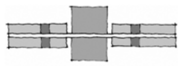
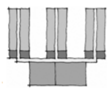
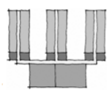
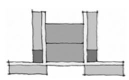
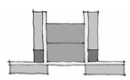
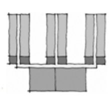
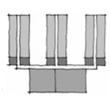
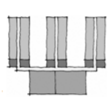
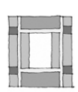
Building Shape	Classification	Classification_Name	DISTNAME
		The spine plan	COLLEGE STATION ISD
		The Centralized resource plan	COLLEGE STATION ISD
		A classroom -clustering model	COLLEGE STATION ISD
		The Centralized resource plan	COLLEGE STATION ISD
		The spine plan	COLLEGE STATION ISD
		The spine plan	BRYAN ISD
		A spine with single-loaded classroom wings	BRYAN ISD
		A spine with single-loaded classroom wings	BRYAN ISD
		The spine plan	BRYAN ISD
		The spine plan	BRYAN ISD
		The spine plan	BRYAN ISD
		The courtyard plan	BRYAN ISD

Figure 9.1 - Survey for the School Building Configuration (Classification Drawings from the Perkins 2001)

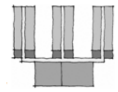
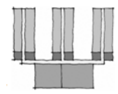
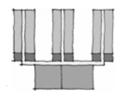
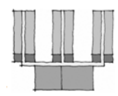
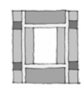
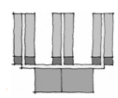
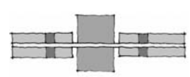
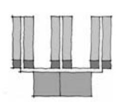
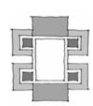
Building Shape	Classification	Classification_Name	DISTNAME
		The spine plan	BRYAN ISD
		The spine plan	BRYAN ISD
		The spine plan	BRYAN ISD
		The spine plan	BRYAN ISD
		The courtyard plan	BRYAN ISD
		The spine plan	BRYAN ISD
	N/A		COLLEGE STATION ISD
		The Centralized resource plan	COLLEGE STATION ISD
		The spine plan	COLLEGE STATION ISD
		A courtyard with classroom-clastering plan	BRYAN ISD
	N/A		BRYAN ISD

Figure 9.1 - Continued

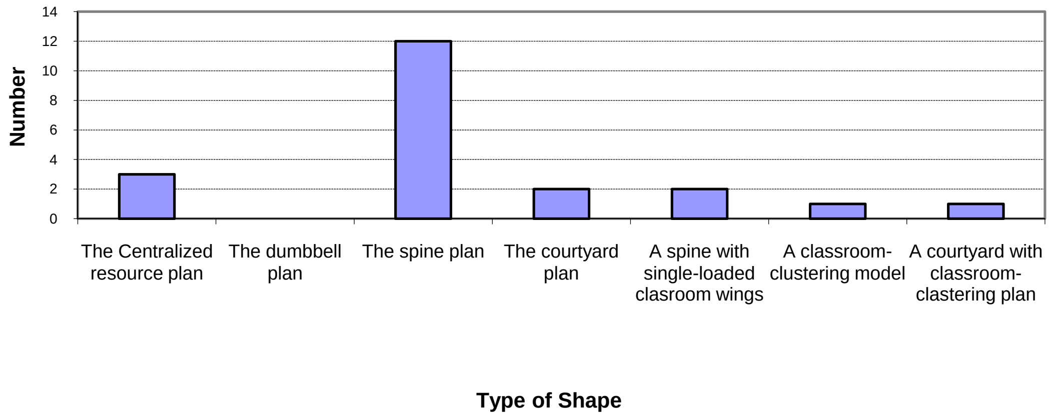


Figure 9.2 - Survey Results for K-12 Schools

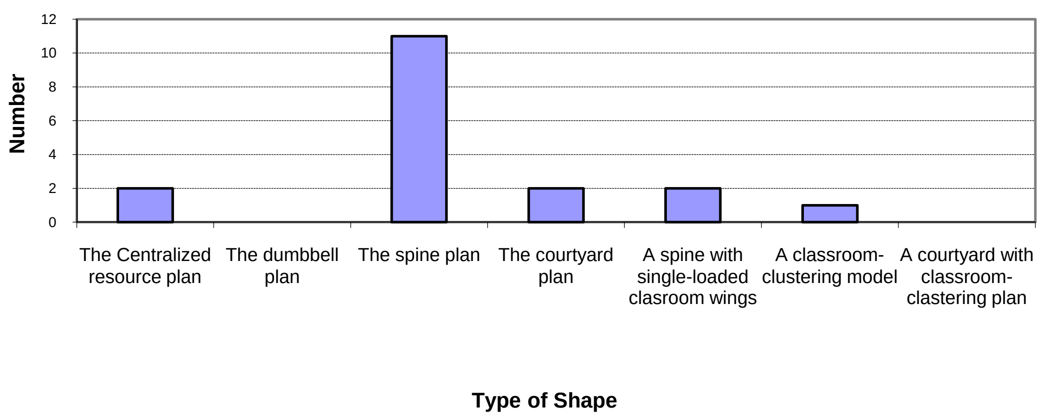


Figure 9.3 - Survey Results for K-5 Schools

9.2. Proposed School Geometry

In the previous section, the most dominant school building shape in the local school district was identified as the spine plan. Since the existing school building shapes surveyed showed the modified spine plan rather than the original spine plan, the original plan configuration was modified as shown in Figure 9.4. In addition, the shared facility space was divided into three major spaces (i.e., gymnasium, cafeteria, and administration office) as defined in Chapter IV. Therefore, the prototype building consists of classroom + library (i.e., blue shaded), physical education (i.e., grey shaded), dining area (i.e, yellow shaded), and administration office (i.e., green shaded).

Figure 9.4 - Simplification Procedure

Next, in order to define the dimension of the simplified geometry, the average dimensions of each space (e.g., dimension of classrooms, width of the corridor, height of the classroom, gymnasium, cafeteria, and office, etc.) were determined from a combination of the case-study school, the North Carolina Public Schools facilities guidelines (Public Schools of North Carolina, 2003), and Perkins (2001). Figure 9.5 shows the resultant prototype building shape.

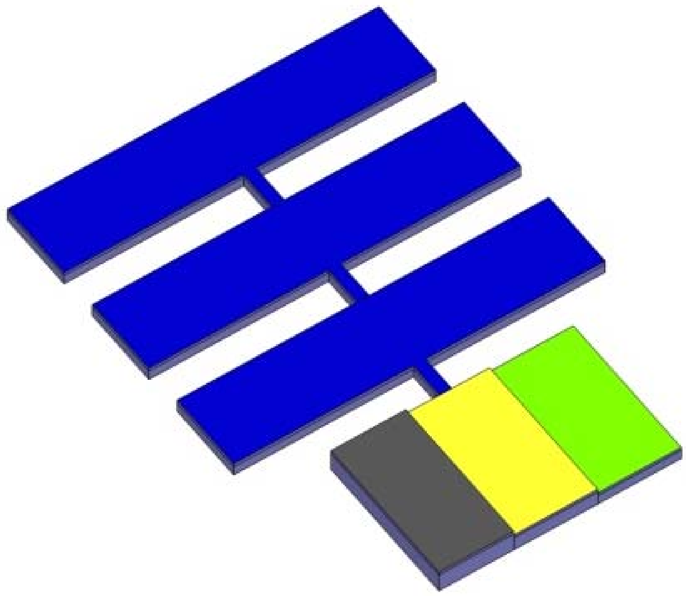


Figure 9.5 - Prototype School Shape

As described in Chapter IV, the size of the total building and each 4 major spaces increases as number of students increases (See Figure 9.6). Since the simulation input was developed using *macro* and *include* commands in DOE-2.1e, the method of changing the geometry was simplified so that the macro input could be concise. Specifically, the vertical length of a classroom wing wasfixed at 66 ft, which is the sum of two classroom widths (i.e., 58 ft) and a corridor width (i.e., 8 ft). In the simulation, the width of classroom wing would grow as the number of students increases as shown in Figure 9.6. As for the shared facilities (i.e., physical education, dining area, and administration office), the widths of three spaces are fixed, and the vertical length of three spaces grows as the number of students increases (also shown in Figure 9.6). In this fashions, the same simulation input file can be used for schools of varuing dimensions, through the use of specific macros or parameters, while the remainder of the input file is fixed.

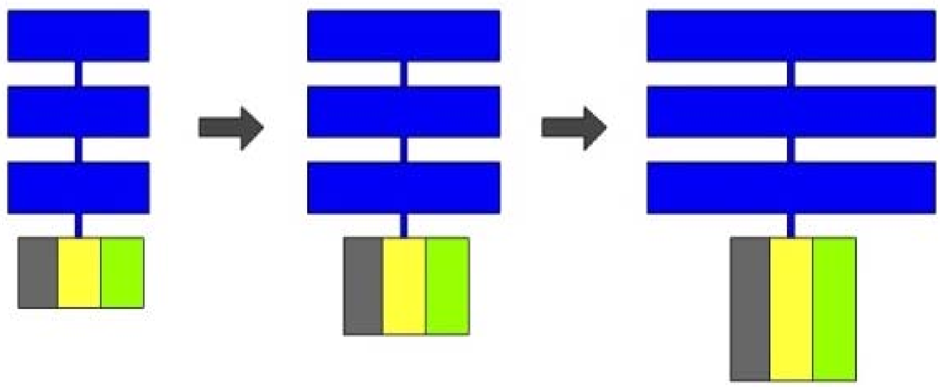


Figure 9.6 - Change of School Geometry as Number of Student Increases

9.3. Input Parameters for the Tool

The limited number of input parameters is one of the key features of the easy-to-use toolkit. With such limited information about a school, users can quickly estimate the energy use for the school in the preliminary design phase of a school. Therefore, the limited input parameters for the toolkit were defined and as shown in Table 9.1. The first group of the input parameter is the general building information such as location, azimuth of building, number of student, etc. Although the floor-to-ceiling height for each space can be varied, those heights are fixed in this version of the pruposed tool. As previously described, the input value of the number of students drives the entire building size and shape.

Table 9.1 - Input Parameters for the Proposed Tool

BLDG1		Default
b01	Thermal Mass mode	Q (Fixed)
b02	County and weather location	Harris
b03	The azimuth of building	0
b04	Number of student	700
b05	Floor to ceiling height for classroom (ft)	Fixed for this versrion (9ft)
b06	Floor to ceiling height for Gym (ft)	Fixed for this verstion (17ft)
b07	Floor to ceiling height for Cafeteria (ft)	Fixed for this verstion (13ft)
b08	Floor to ceiling height for Admin (ft)	Fixed for this version (9ft)
b09	Height for Plenum (ft)	Fixed for this version (3ft)
b10	Run Year	1999
b11 ~ b32	Spare	
CONS1		Default
c01	Roof absorptance	0.89
c02	Roof roughness	0.45
c03	Roof outside emissivity	1
c04	Roof insulation R-value	25
c05	Wall absorptance	0.57
c06	wall roughness	2
c07	Wall outside emissivity	0.9
c08	Wall insulation R-value	13
c09	Ground refelectance	0.24
c10	Percentage of window area (Windo-to-wall Ratio)	30
c11	U-Factor of Glazing	0.45
c12	Solar Heat Gain Coefficient (SHGC)	0.4
c13	Number of pane glazing	2
c14	Spare	
c15	Spare	
c16	Spare	
c17	Floor weight (lb/sq-ft)	11.5
c18	Slab-on-grade floor insulation R-value	A
c20	Ceiling R-value	0.77
c21 ~ c32	Spare parameters	0
SPC01		Default
sp01	Lighting Load	1.2
sp02	Equipment Load	0.6
sp03~sp32	Spare parameters	

The second group of the input paramters is the construction information of the building. In this section, the building's envelope insulation level, window properties (i.e., glazing U-value, SHGC) will be input by the users. If not entered, the default values that are compliant with the ASHRAE 90.1-1999 will be used for the simulation. One of the other input parameters is the window-to-wall ratio. When a user enters the windows-to-wall ratio in the tool, the area of the window will be calculated and evenly distributed across all the walls of the model.

The third group of the input parameters is the lighting and equipment load for the school building. This group defines the power density of lighting and quipement. The default values here are defined as ASHRAE Standard 90.1-1999.

In future versions of the tool, additional input parameters for the HVAC and Plant equipment such as the type of HVAC system, setpoint temperature, type of chillers boilers, efficiencies of the chillers and boilers, etc. will be added.

After defining all the input parameters, as described in Chapter IV, the DOE-2 simulation input would be run using "Input Macro" commands. When each DOE-2 input file is run, the input parameters from the include file (i.e., .inc) is imported into the DOE-2 input file, and the simulation is run. The results will then be generated based on the values in the input parameters. The LOAD part of the DOE-2 input and the sample include file which defines the input parameter values are provided in a separate ESL technical report.

9.4. Validation of the Simplified DOE-2 Simulation Input

After the initial development of the simplified DOE-2 simulation input, the DOE-2 result with the simplified input was compared to the simulation result of the detailed input, which is the ASHRAE Standard 90.1-1999 compliant school building used in the previous chapter. As described above, the current version of the DOE-2 input was developed only for the portion of the LOADS part. Therefore, the results from the LOADS runs were compared with each other. The report LS-D: Building Monthly Loads Summary provides the monthly cooling, heating and electrical energy needed for the building without HVAC system integration. The report LS-D from the detailed and simplified simulation results were retrieved and compared. Table 9.2 and Figures 9.7 through 9.9 present the comparison results. The total annual cooling and heating energy from the simplified LOADS simulation results were 2.1% lower than the cooling and heating energy from the detailed simulation result. The total annual electrical energy from the simplified LOADS simulation results were 1.8% lower than the electrical energy from the detailed simulation result. Therefore, based on this comparison, the simplified LOADS simulation input developed in this section could be used in preliminary design for a school building to estimate the annual energy use of the building, which would be reasonably close to the real building's energy use.

As future work, after developing all parts of the simulation input (i.e., including SYSTEM and PLANT input files), the simplified simulation results with various set of input parameters from real school buildings would need to be compared to the real schools for additional validations. Based on these, the simplified simulation inputs would be needed to be modified to estimate the energy use more accurately.

Table 9.2 -Energy Load Comparison (Detailed vs. Simplified) from LS-D Report

	Detailed Input (ASHRAE 90.1-1999 Compliant)			Simplified Input (ASHRAE 90.1-1999 Compliant)			% Diff.	
Month	Cooling Energy (MBtu)	Heating Energy (MBtu)	Electrical Energy (kWh)	Cooling Energy (MBtu)	Heating Energy (MBtu)	Electrical Energy (kWh)	Cooling + Heating Energy	Electrical Energy
Jan	108.20	9.56	43,311	122.75	8.83	41,457	-11.7%	4.3%
Feb	95.60	16.39	39,244	96.80	12.25	38,413	2.6%	2.1%
Mar	125.31	5.26	39,236	148.75	3.82	40,422	-16.8%	-3.0%
Apr	171.41	0.50	39,671	187.90	0.48	40,707	-9.6%	-2.6%
May	202.34	0.18	39,689	193.91	0.13	36,973	4.2%	6.8%
Jun	134.69	0.01	16,627	130.38	0.00	16,490	3.2%	0.8%
Jul	146.69	0.00	16,458	133.69	0.00	15,979	8.9%	2.9%
Aug	243.17	0.00	36,832	215.14	0.00	34,262	11.5%	7.0%
Sep	233.02	0.08	41,636	217.43	0.07	41,693	6.7%	-0.1%
Oct	196.99	0.97	43,311	173.69	1.27	41,457	11.6%	4.3%
Nov	133.36	5.72	39,574	125.88	7.02	38,736	4.4%	2.1%
Dec	70.19	18.28	32,381	83.92	14.29	33,571	-11.0%	-3.7%
Total	**1860.98**	**56.95**	**427,970**	**1830.25**	**48.17**	**420,161**	**2.1%**	**1.8%**

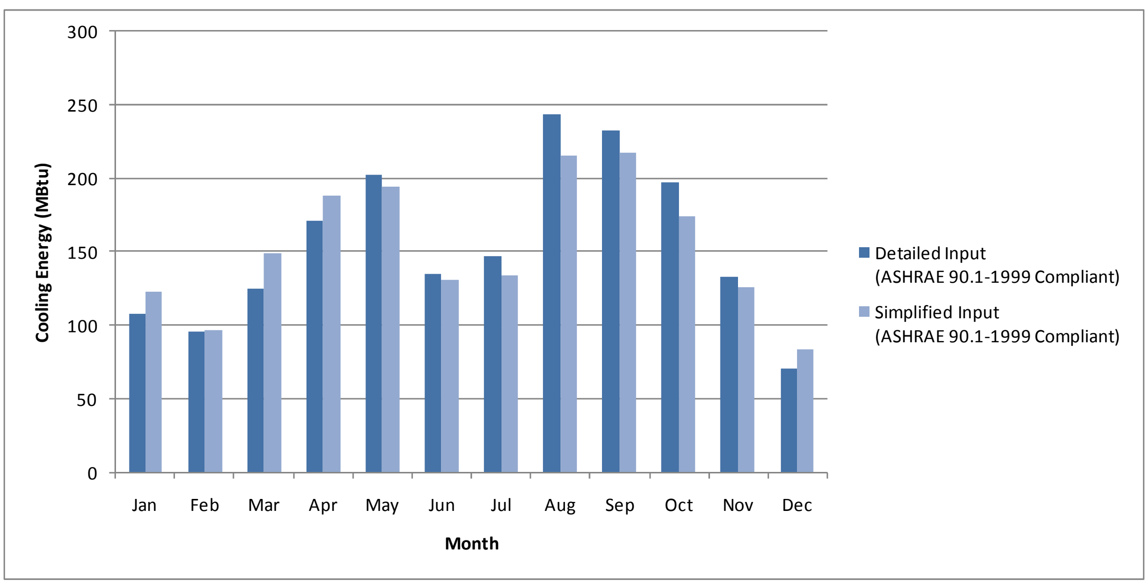


Figure 9.7 -Monthly Cooling Energy Loads Comparison from LS-D Report

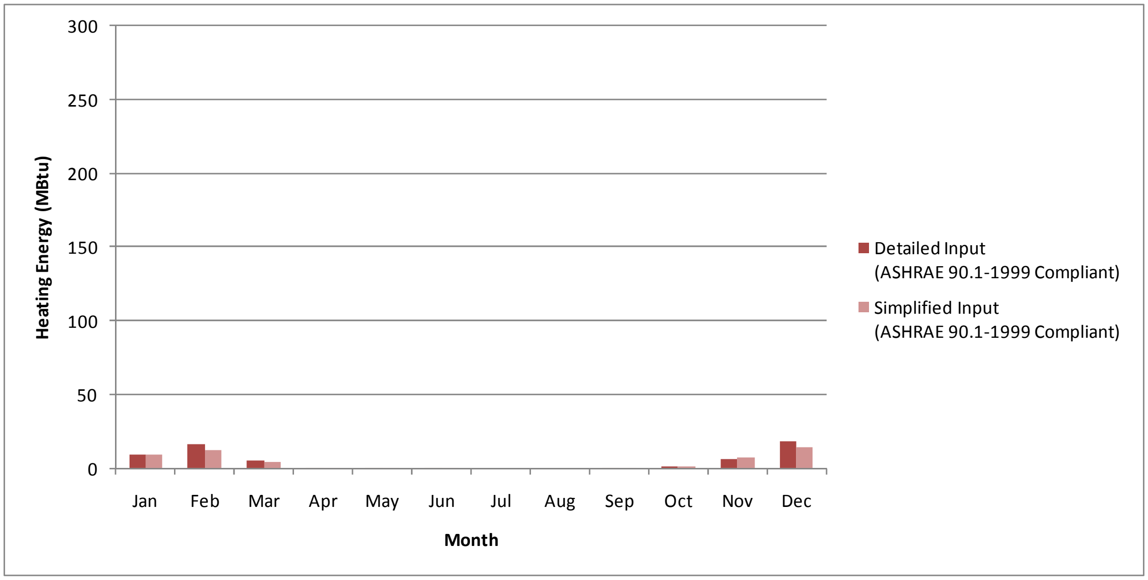


Figure 9.8 - Monthly Heating Energy Loads Comparison from LS-D Report

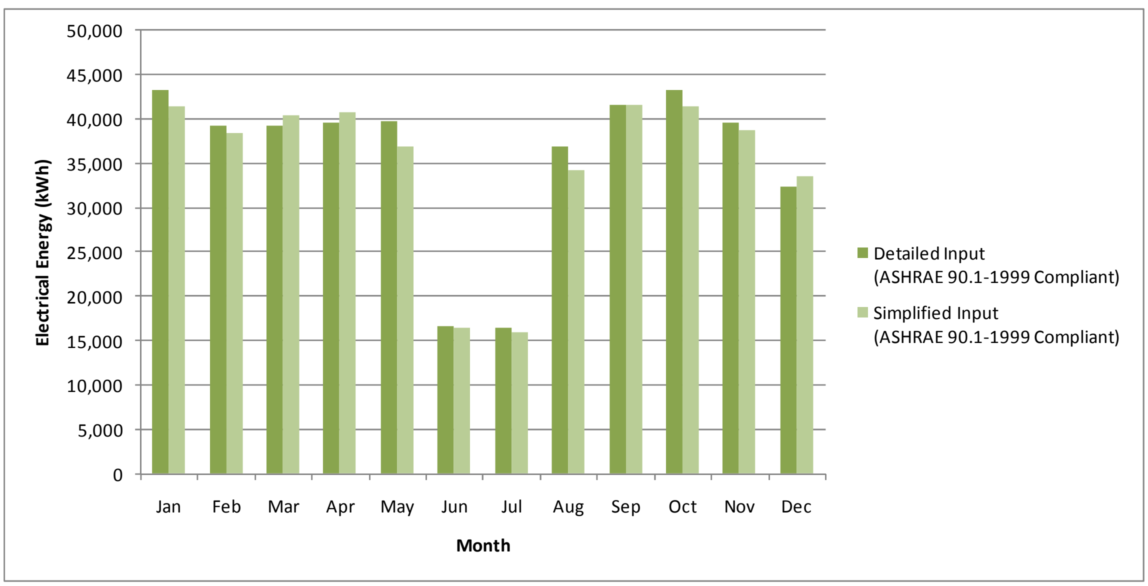


Figure 9.9 - Monthly Electrical Energy Loads Comparison from LS-D Report

9.5. Integration with the Existing eCalc Web-based Simulation

As described in Chapter II, one of the purposes of this study is to provide a functional specification for the K-12 school input extension for the ESL's eCalc engine. As of 2008, the eCalc engine has 3 options (i.e., New building models, Community projects, and Renewables) for the energy and emission savings calculation as shown in Figure 9.10. Of these, the "New Building Models" category has single family, multifamily, office, and retail options. As one of final recommendations of this dissertation, a specification for a school option to be added to eCalc has been developed. Figure 9.11 shows how the simplified school input would be added to the new building models option in the current eCalc engine. This recommendation assumes input screens for the new school option would be similar with other building inputs These include an "express" calculation and "detailed" calculation option. Figure 9.12 shows the current entry screen for eCalc that asks the user for the basic project information. Figure 9.13 shows the example of the proposed express calculation screen.

One of the big differences with other building types in the eCalc is the method of the building geometry input. As described earlier in the proposed new simplified school model, the building geometry will be changed based on the number of students. Therefore, Figure 9.13 only shows the number of students input to determine school's geometry. Other simplified input parameters for the express calculation are roof insulation (i.e., R-value), wall insulation (ie., R-value), windows U-factor, SHGC, window-to-wall ratio (i.e., %) for the envelope category, and economizer type (i.e., none or dry bulb temperature), cooling/heating choices (i.e., all electric, and electric cooling and natural gas heating), cooling and heating efficiency (i.e., COP and %) for the system category. Figures 9.14 through 9.18 show examples of the detailed calculation input screens for Building, Shade, Construction, System, and Plant, respectively.

In the input screen for the Building (See Figure 9.13), the number of students will be asked to determine the building's geometry, the lighting and equipment load (i.e., W/ft^2). For other building information, the orientation of the building and the detailed floor-to-floor and floor-to-ceiling height for each space will be asked.

In the input screen for the Shade (See Figure 9.15), the depth of front, back, left and right shade (i.e., ft) will be asked.

In the input screen for the Construction (See Figure 9.16), the detailed input parameters for each part of the building construction (i.e., roof, wall, windows, and floor) will be asked.

In the input screen for the System (See Figure 9.17), the mode of system (i.e., PVAV with reheat, VAV with reheat, and CV with reheat), economizer type (i.e., none or dry bulb), fan control type (i.e., variable speed drive, inlet vane, constant volume, or discharge dampers), and fan efficiency will be asked.

Finally, in the input screen of the Plant (See Figure 9.18), the type and the efficiency of the cooling, heating and service water heating system will be asked.

9.6. Easy-to-use Toolkit for School Buildings

An important new feature of the easy-to-use simplified simulation toolkit for school buildings is the integrated building simulation with solar PV and thermal systems.

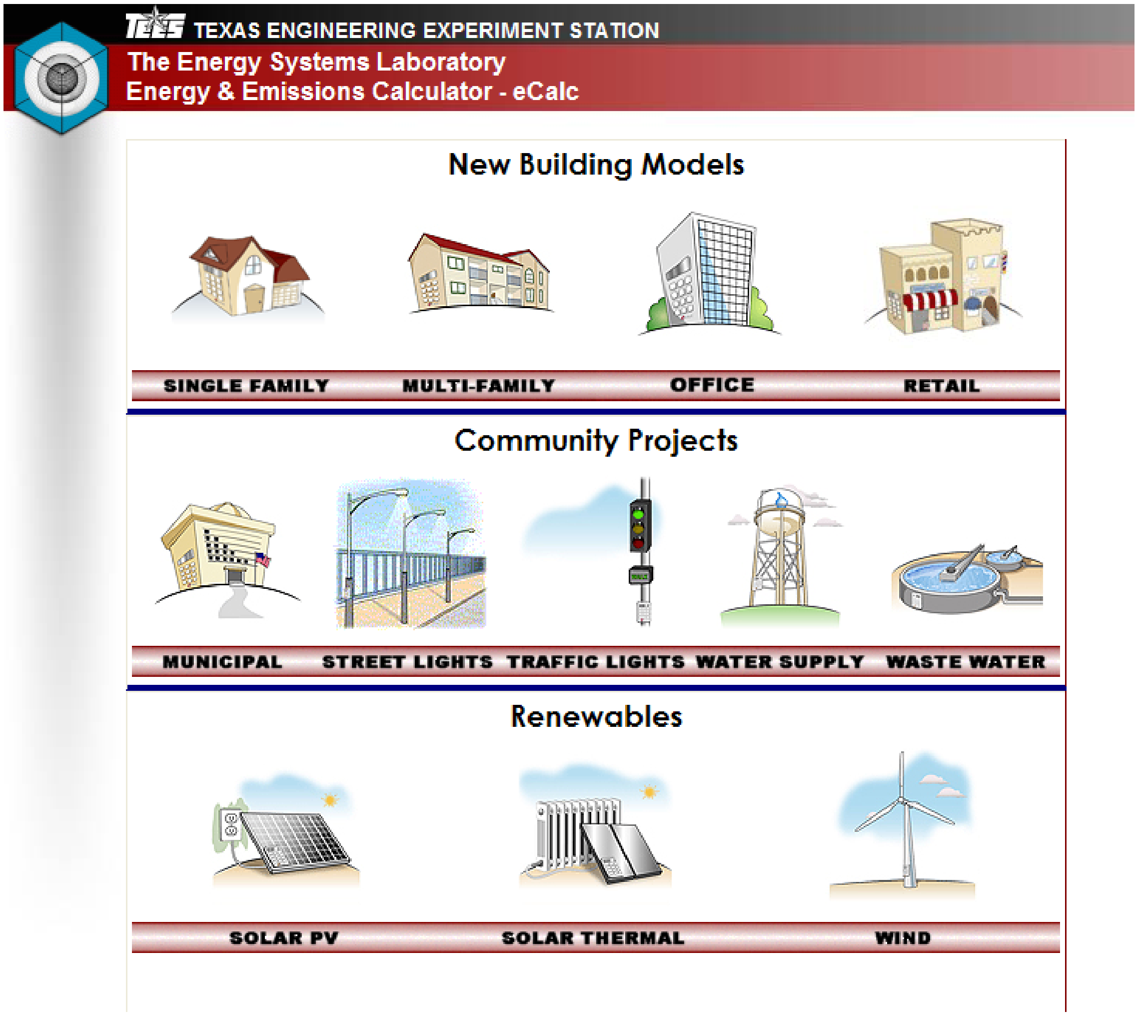


Figure 9.10 – Screenshot of eCalc (http://ecalc.tamu.edu/gui/home/)

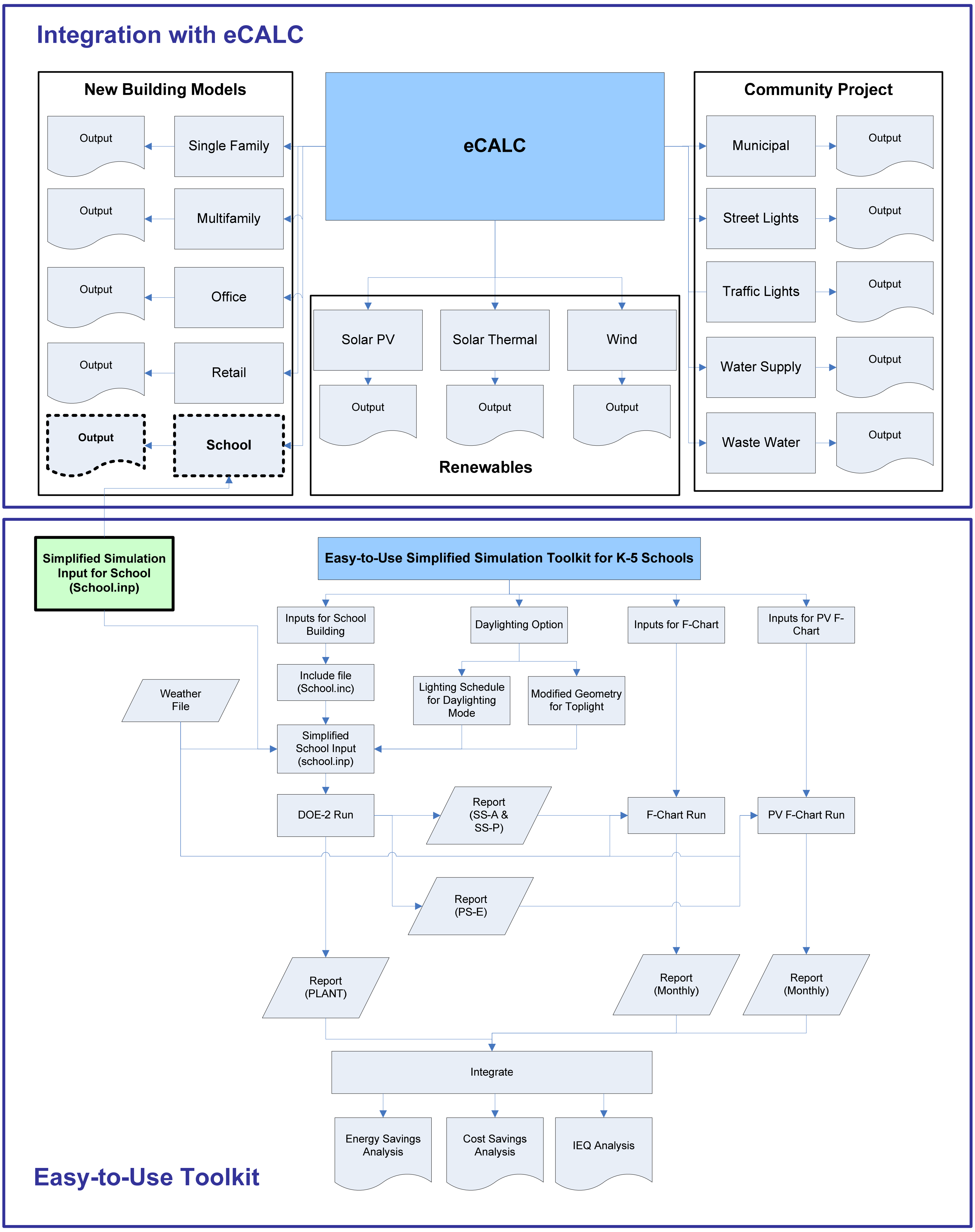


Figure 9.11 – eCalc and Easy-to-use Toolkit

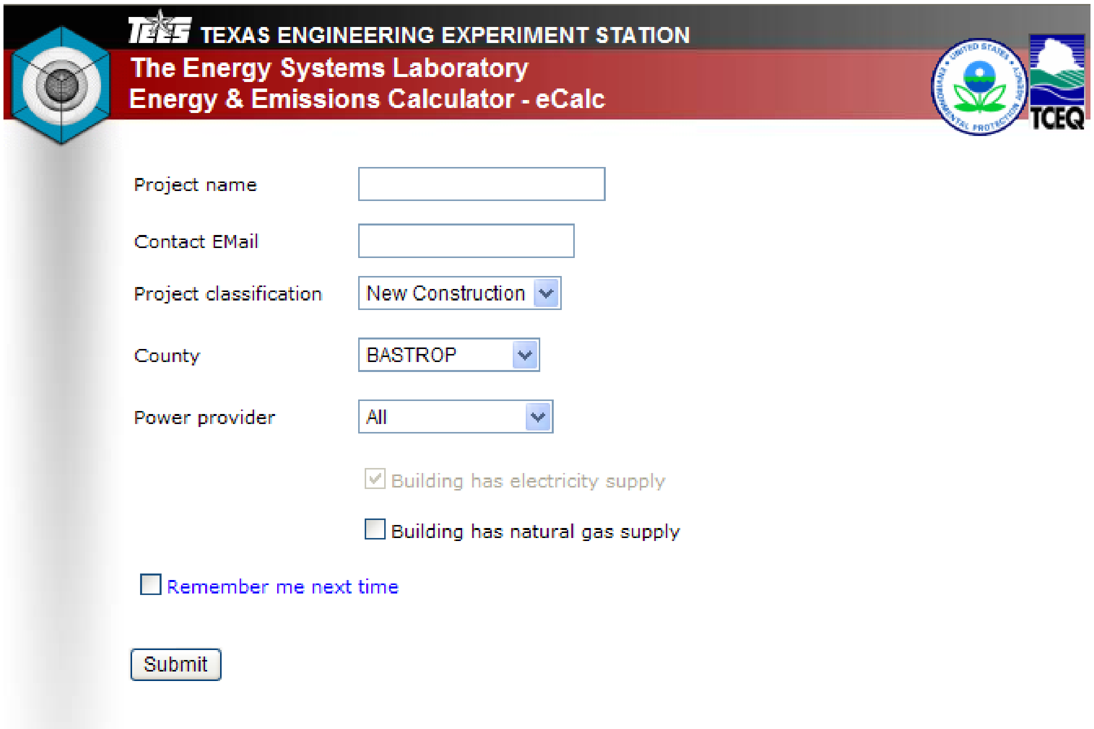


Figure 9.12 – Proposed First Input Screen for eCalc: School Option

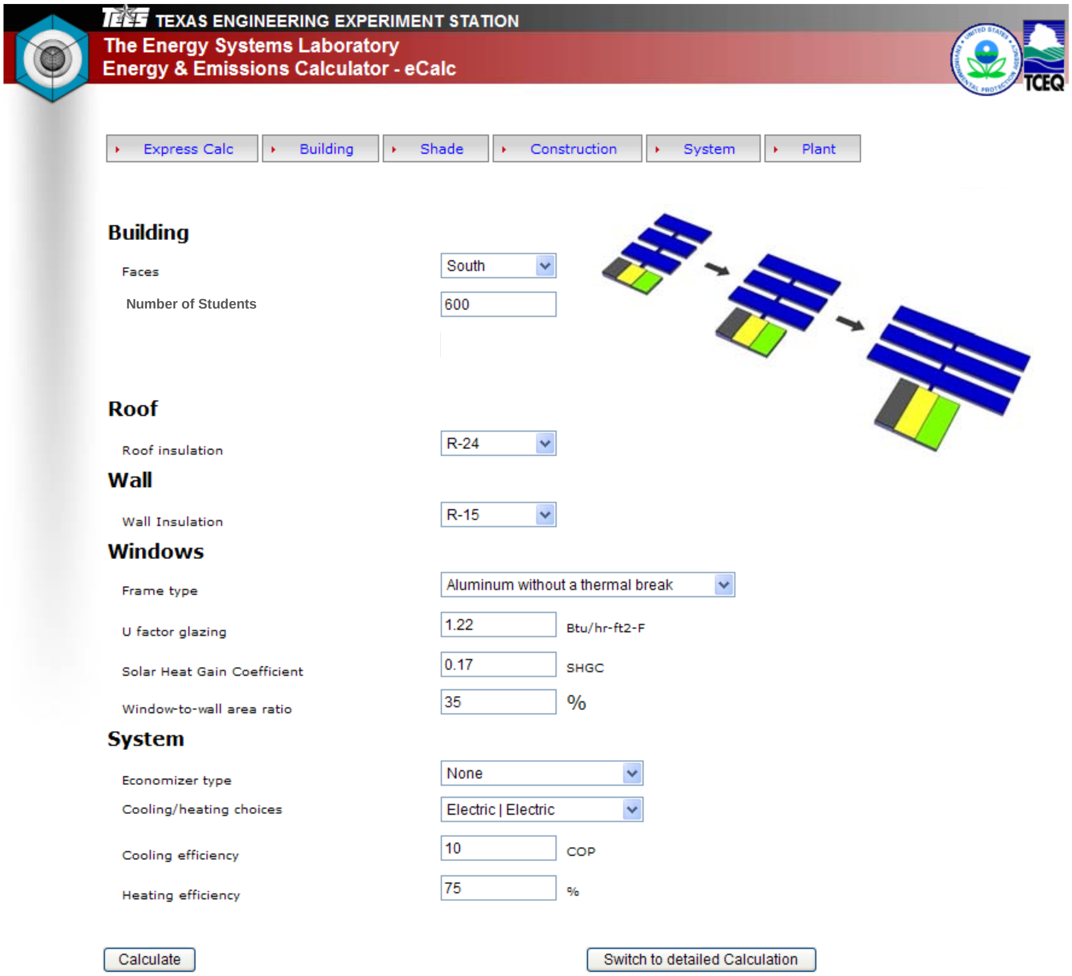


Figure 9.13 – Proposed Screen Shot for Express Calculation

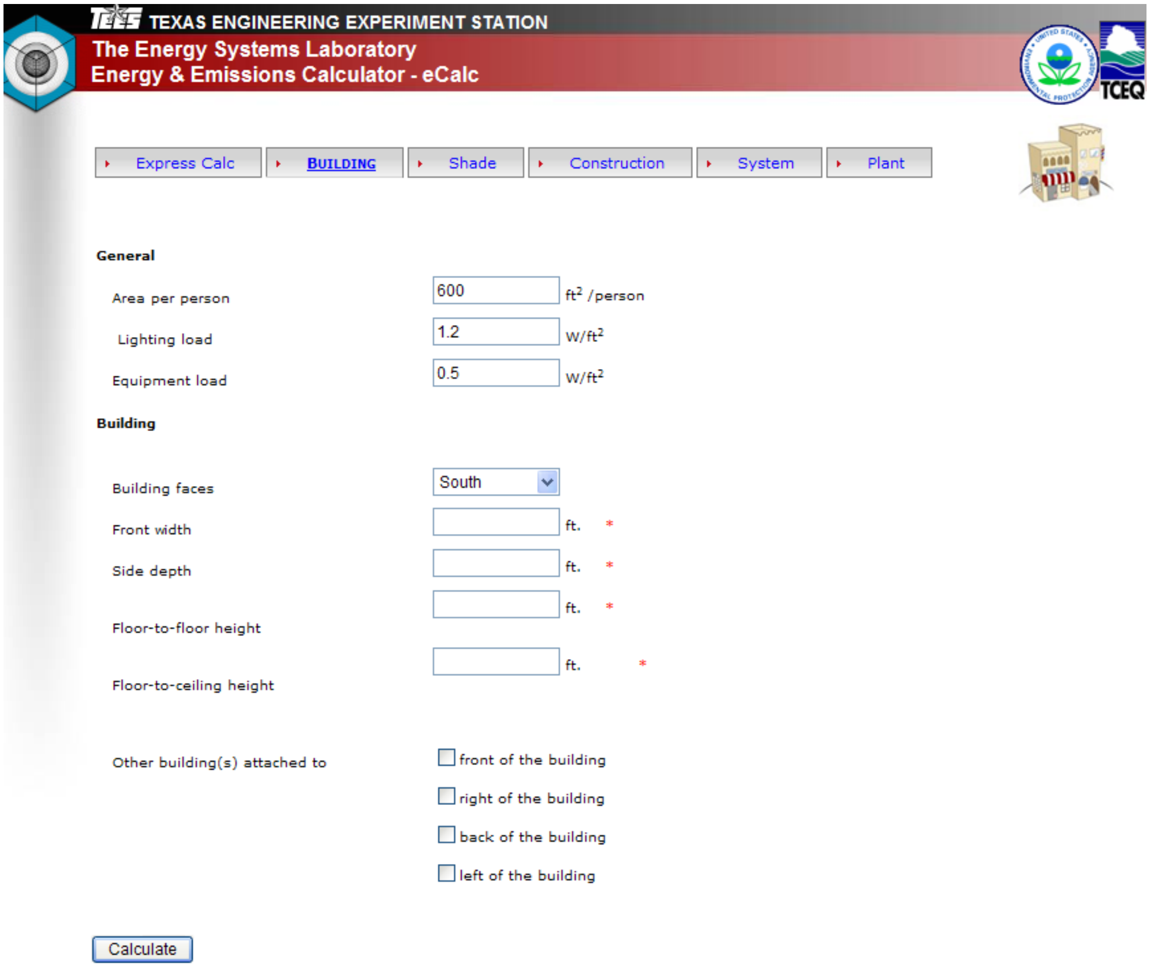


Figure 9.14 – Proposed Screen Shot for Detailed Calculation: Building

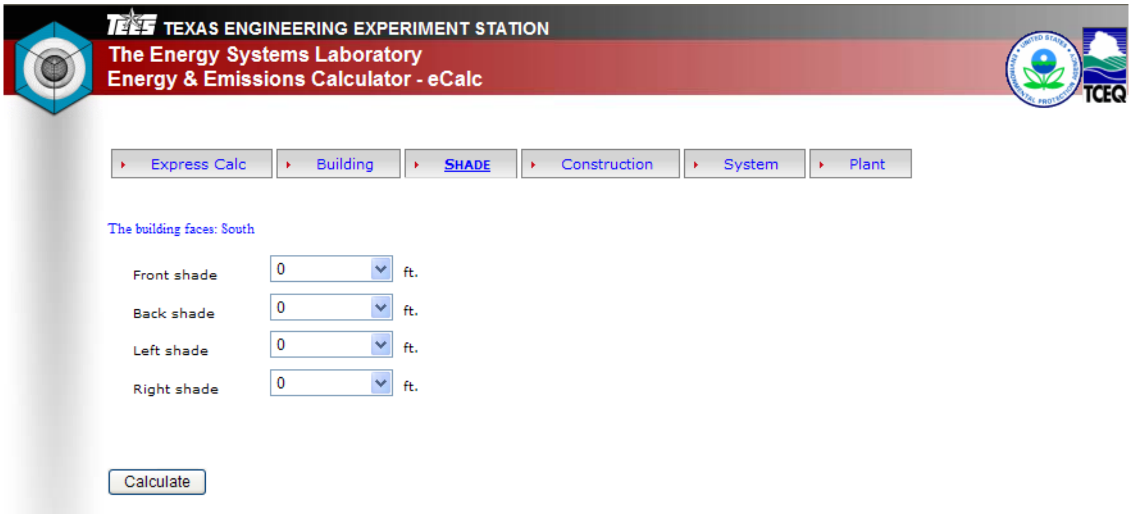


Figure 9.15 – Proposed Screen Shot for Detailed Calculation: Shade

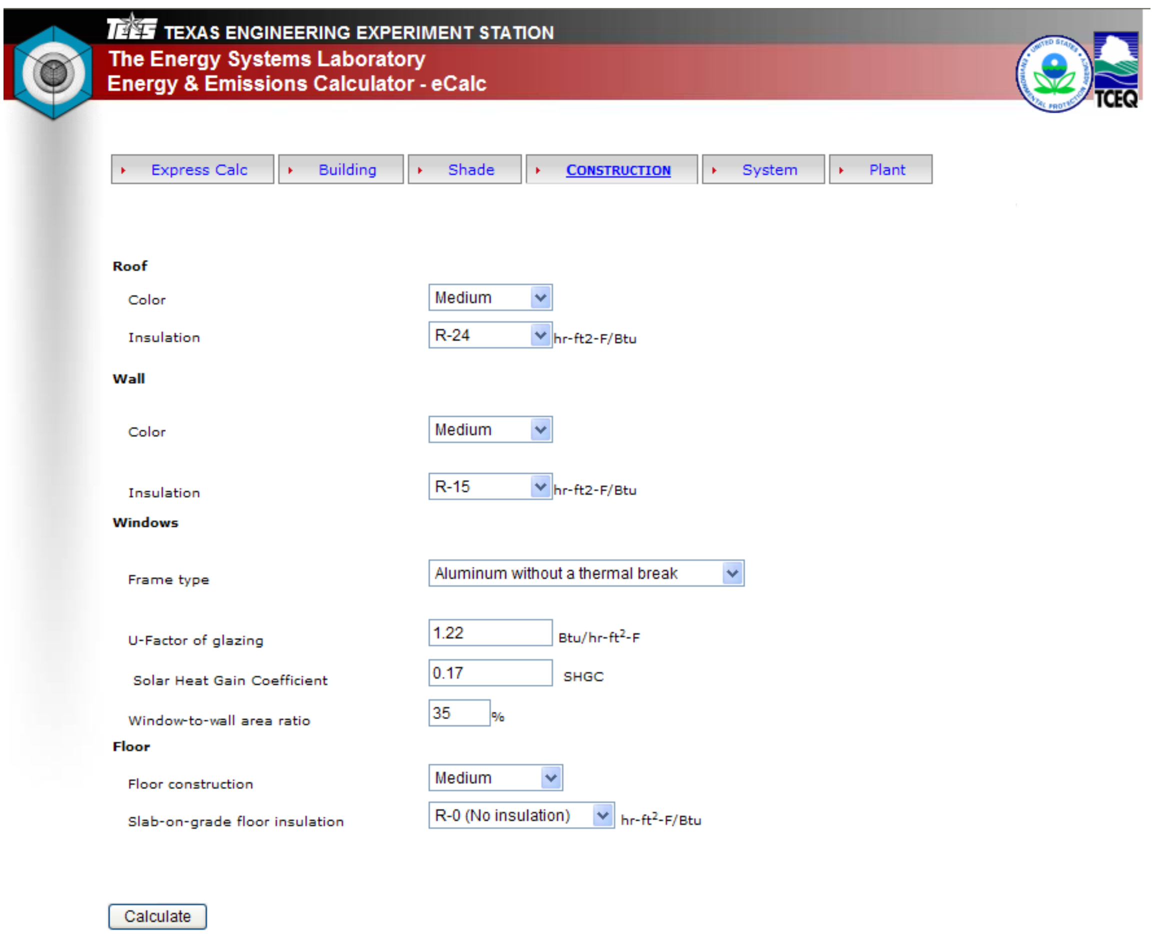


Figure 9.16 – Proposed Screen Shot for Detailed Calculation: Construction

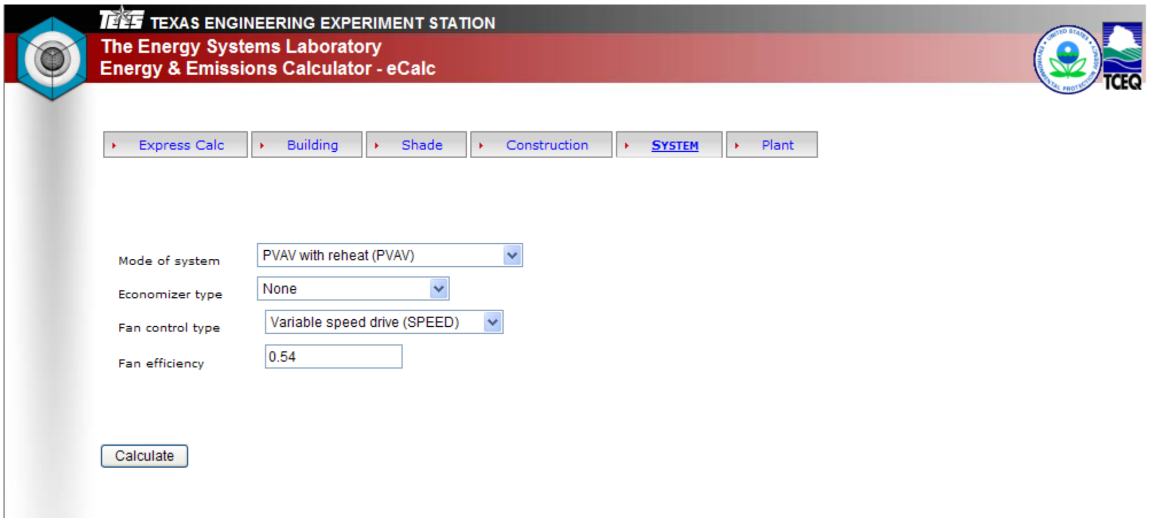


Figure 9.17 – Proposed Screen Shot for Detailed Calculation: System

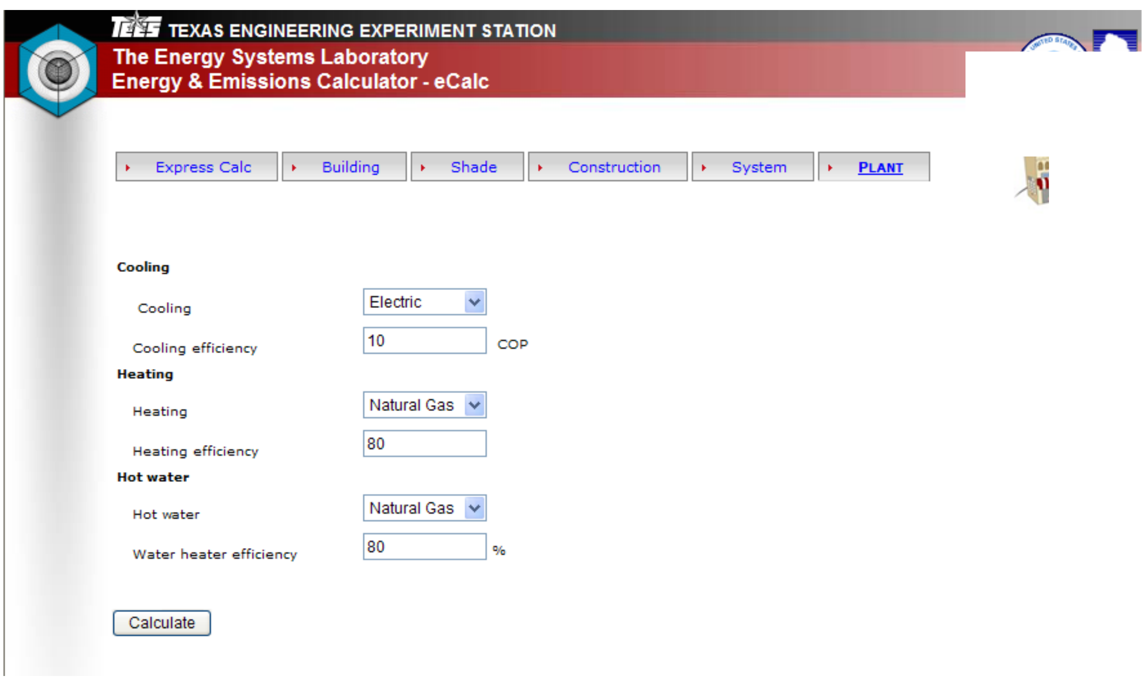


Figure 9.18 – Proposed Screen Shot for Detailed Calculation: Plant

Figure 9.11 (i.e., bottom portion of the flowchart) shows how the simplified school simulation toolkit, including how the solar PV and solar thermal systems will be integrated with the building simulation result. An example of this integration procedure was described in Chapter VIII, including how the hourly reports from the DOE-2 output was used for the F-Chart and PV F-Chart runs.

9.6.1. Mock-Up Screens of the Easy-to-use Toolkit for School

This section provides the mock-up screens of the final toolkit to help describing the intended final function of the toolkit. In similar fashion as the eCalc software, this easy-to-use toolkit has two different options for the simulation: 1) Express calculation and 2) Detailed calculation. In the express calculation option (Figure 9.19), users are asked to enter the limited number of input values to obtain a quick simulation result. In the detailed calculation option (Figures 9.20 through 9.26), users needs to enter additional input parameters for each category. There are seven (7) tabs recommended for the detailed calculation option: 1) Building, 2) Shade, 3) Construction, 4) System, 5) Plant, 6) Daylighting, and 7) Solar. Of these, the final two categories (i.e., daylighting and solar) are new options for the eCalc software. As shown, the input parameters from: 1) Building through 5) Plant are similar with the parameters explained in the eCalc program. Each input screen also provides high performance measures recommended in the AEDG for K-12 or other literatures for several input parameters. Users can replace single or several input parameters based on these high performance measures to estimate the energy savings potential.

In the input screen for the Daylighting (See Figure 9.25), the application of daylighting option will be asked (i.e., Yes or No). If a user select to turn on the daylighting option, the DOE-2 geometry with the selected % of the toplights will replace the original input geometry without the toplights, and the original lighting schedule will be replace with the modified lighting schedule generated from the Radiance simulation.

In the input screen for the Solar (See Figure 9.26), the input parameters for solar PV and solar thermal system will be asked. For the solar PV system, the total PV array area (i.e., sq.ft.), array slope (i.e., degree), solar azimuth (i.e., degree), and array efficiency (i.e., %) will be asked. For the solar thermal system, the total size of collectors (i.e., sq.ft.), collector slope (i.e., degree), and collector azimuth (i.e., degree) will be asked.

Figure 9.27 presents a mock-up screen of a simulation result. When a user simulates a school building, the corresponding ASHRAE 90.1-1999 compliant school building and a high performance school building recommended in the AEDG for K-12 also will be simulated. Then, the simulation results from those three cases (i.e., code-compliant, user input, and high performance school) will be tabulated in the final output screen. The simulation result will provide the total energy use and savings, the energy cost savings, and the building's Indoor Environmental Quality (IEQ) (i.e., Temperature and RH) changes by case. From the result screen, users can identify 1) code-compliant check for the user define school, 2) energy and cost savings compared to the code-compliant building, 3) more energy savings potential from the application of the high performance measures recommended in the toolkit, and 4) the IEQ of the school building defined by the user.

Express Calc	Building	Shade	Construction	System	Plant	Daylight	Solar

Building			**High Performance Option**
Faces	South		
Number of Student	600		
Roof			
Roof Insulation	R-15		*R-25*
Wall			
Wall Insulation	R-11		*R-13*
Windows			
U-Factor of Glazing	1.27	Btu/hr-ft2-F	*0.20*
Solar Heat Gain Coefficient	0.40	SHGC	*0.25*
Window-to-Wall Ratio	35	%	
Daylighting Option	Yes	(Yes or No)	*Yes*
System			
Economizer Type	None		
Cooling/Heating Choices	Electric/natural		
Cooling Efficiency	10.1	EER	*10.6 EER*
Heating Efficiency	80	%	*85%*
Solar			
Total solar PV array area	10,000	sqft	
Total solar thermal collector area	1,000	sqft	
	Calculate		**Switch to Detailed**

Figure 9.19 – Easy-to-use Toolkit: Express Calculation

Express Calc	**Building**	Shade	Construction	System	Plant	Daylight	Solar

General			**High Performance Option**
Number of Student	600		
Lighting Load	1.5	w/sqft	1.1
Equipment Load	0.5	w/sqft	
Occupancy Sensor for Lighting	No		Yes
Building			
Building faces	South		
Classrooms			
Floor-to-roof height	12	ft	
Floor-to-ceiling height	9	ft	
Gymnasium			
Floor-to-roof height	20	ft	
Floor-to-ceiling height	17	ft	
Cafeteria			
Floor-to-roof height	16	ft	
Floor-to-ceiling height	13	ft	
Admin office			
Floor-to-roof height	12	ft	
Floor-to-ceiling height	9	ft	
	Calculate		

Figure 9.20 – Easy-to-use Toolkit: Detailed Calculation - Building

Express Calc	Building	**Shade**	Construction	System	Plant	Daylight	Solar

Overhangs			**High Performance Option**
Front side	0	ft	Projection factor = 0.5
Back side	0	ft	Projection factor = 0.5
Left side	0	ft	Projection factor = 0.5
Right side	0	ft	Projection factor = 0.5
	Calculate		

Figure 9.21 – Easy-to-use Toolkit: Detailed Calculation – Shade

Express Calc	Building	Shade	**Construction**	System	Plant	Daylight	Solar

			High Performance Option
Roof			
Color	Medium		
Insulation	R-15		R-25
Wall			
Color	Medium		
Insulation	R-13		
Windows			
U-Factor of glazing	1.22	Btu/hr-ft2-F	0.20
Solar Heat gain Coefficient	0.25	SHGC	
Window-to-Wall ratio	35	%	
Floor			
Floor construction	Medium		
Slab-on-grade floor insulation	R-0		
	Calculate		

Figure 9.22 – Easy-to-use Toolkit: Detailed Calculation - Construction

Express Calc	Building	Shade	Construction	**System**	Plant	Daylight	Solar

		High Performance Option
Mode of System	PVAV with reheat	
Economizer Type	None	Temperature-Controlled Economizer
Fan control type	Inlet vane	VFD
Fan efficiency	0.61	
Cold deck reset schedule	Constant	Reset
	Calculate	

Figure 9.23 – Easy-to-use Toolkit: Detailed Calculation - System

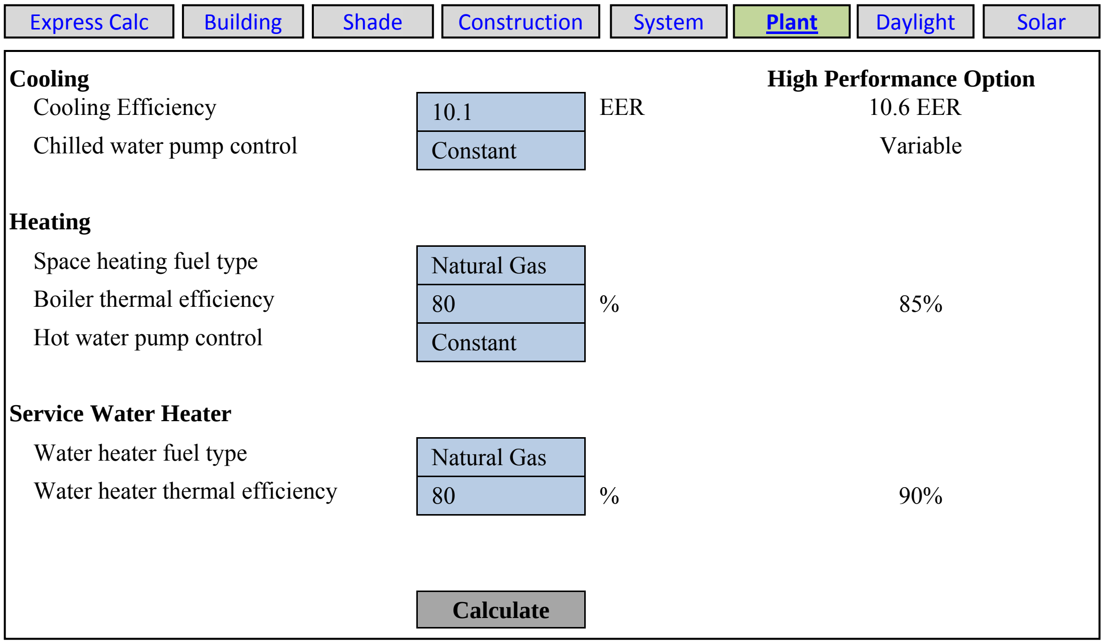


Figure 9.24 – Easy-to-use Toolkit: Detailed Calculation – Plant

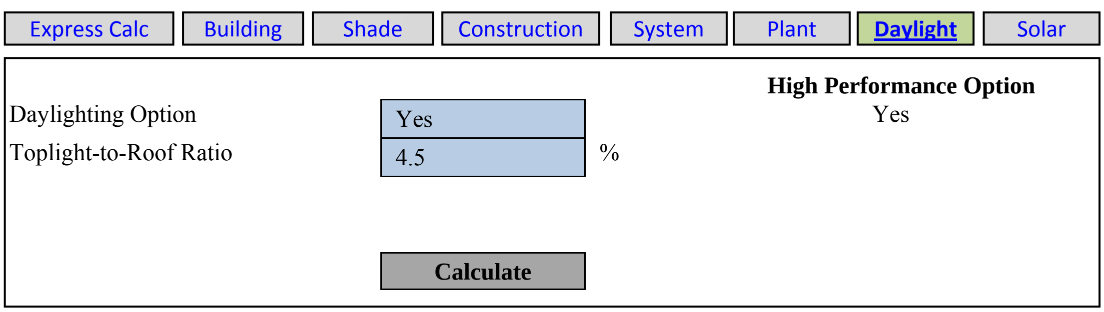


Figure 9.25 – Easy-to-use Toolkit: Detailed Calculation - Daylight

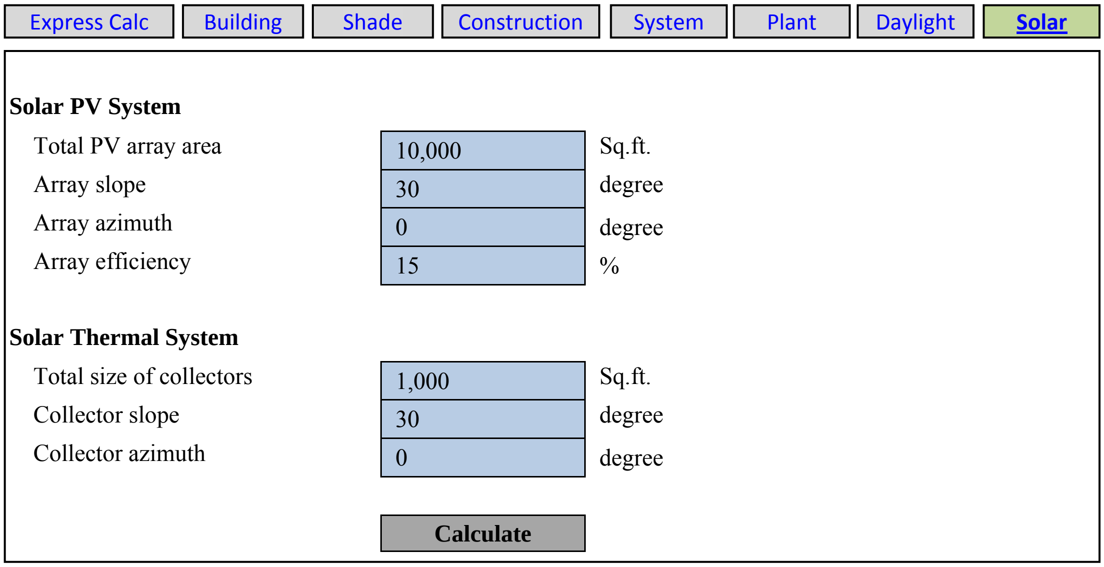


Figure 9.26 – Easy-to-use Toolkit: Detailed Calculation – Solar PV and Thermal System

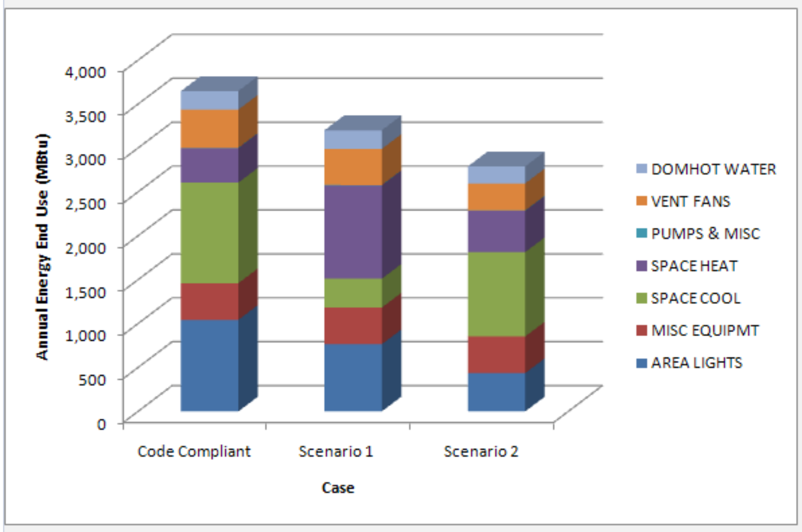
9.7. Summary

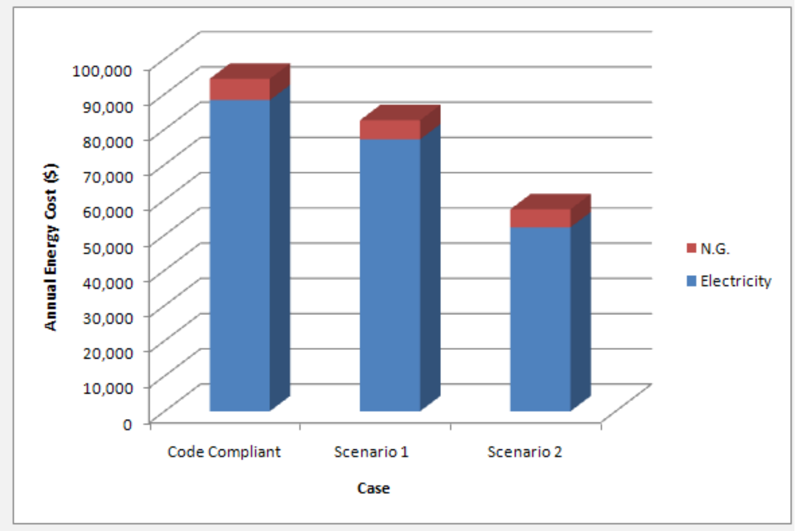
As a final step of this study, the functional specifications for a simplified easy-to-use toolkit were developed. In order to define the most dominant school building shape, a survey using the satellite views was performed, and the modified spine shape was defined as the dominant shape of the K-5 school in hot and humid climates. The four main spaces in the proposed school building are: 1) classrooms and library, 2) gymnasium, 3) cafeteria, and 4) administration office. Based on the number of student, the size of each building space is changed proportionally.

Energy and Cost Report

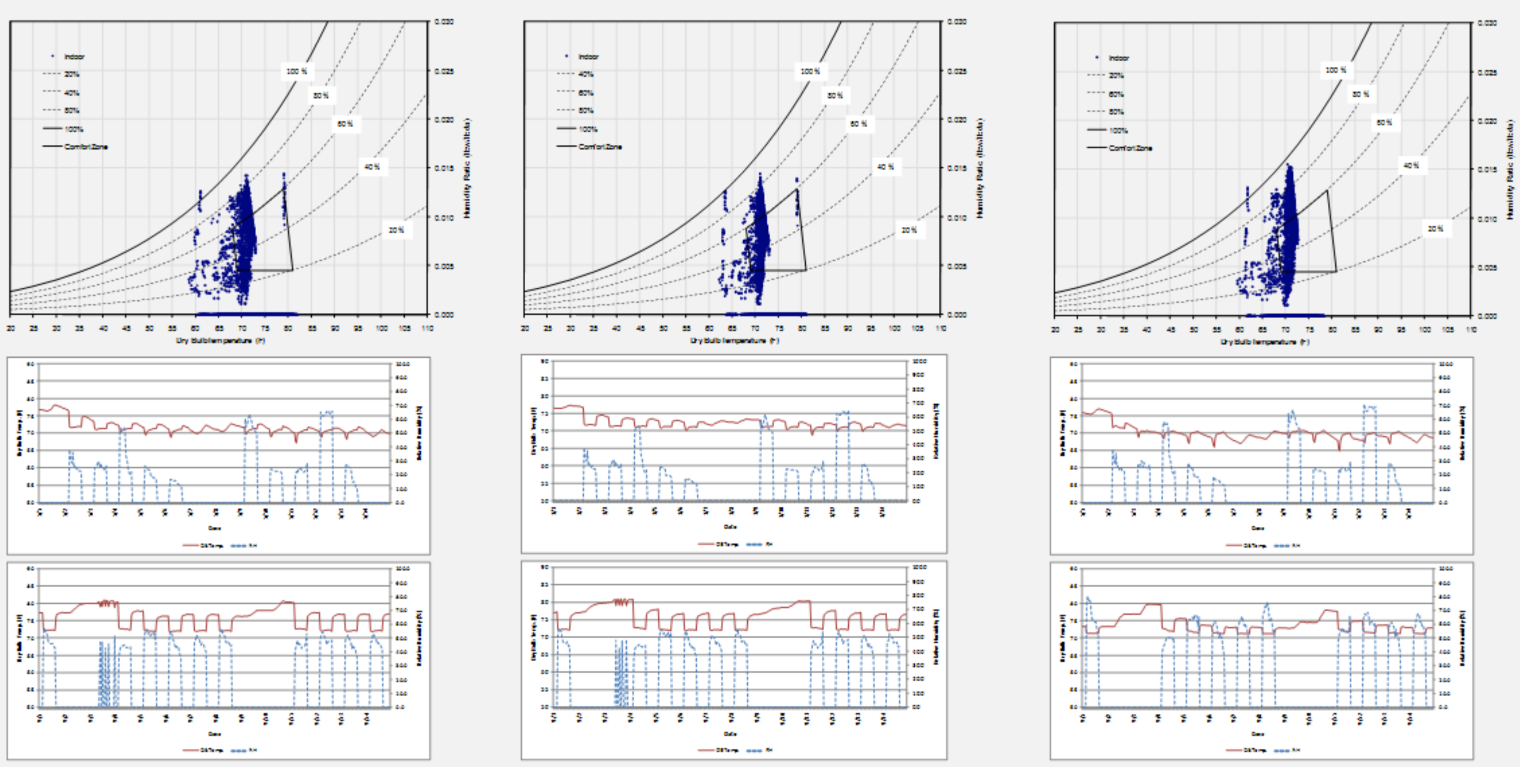
End Use (MBtu)	Code Compliant	Scenario 1	Scenario 2
AREA LIGHTS	1,043	765	437
MISC EQUIPMT	417	417	417
SPACE COOL	1,146	329	961
SPACE HEAT	393	1,063	470
PUMPS & MISC	4	5	5
VENT FANS	434	411	308
DOMHOT WATER	212	212	193
Total	**3,650**	**3,202**	**2,791**
Energy Cost ($)			
Electricity	88,301	77,188	52,215
N.G.	6,060	5,416	5,110
Total	**94,361**	**82,605**	**57,325**

Summary	
Energy Savings	
Scenario 1 vs. Code	12.3%
Scenario 2 vs. Code	23.5%
Scenario 1 vs. Scenario 2	12.9%
Cost Savings	
Scenario 1 vs. Code	12.5%
Scenario 2 vs. Code	39.2%
Scenario 1 vs. Scenario 2	30.6%





Thermal Comfort



Code Compliant	Scenario 1	Scenario 2

Figure 9.27 – Easy-to-use Toolkit: Screenshot of Sample Output

As a next step, the proposed input parameters that will be used as inputs in the final toolkit were defined. In this study, the input parameters for the general building information, building envelope, and lighting and equipment load were defined. Based on the input parameters defined, the LOADS portion of the DOE-2 input file was developed using DOE-2's "Input Macro" command. The new DOE-2 input was then used with the input values that are the same with the ASHRAE 90.1-1999 compliant input for the validation purpose. The comparison result shows that the total annual cooling and heating energy from the simplified simulation result was 2.1% lower than the cooling and heating energy from the detailed simulation result. The total annual electrical energy from the simplified simulation result was 1.8% lower than the electrical energy from the detailed simulation result.

Finally, the specification for a new simplified simulation input to be used with the eCalc software were described. The proposed easy-to-use simulation toolkit will have two options for the input: 1) Express calculation and 2) Detailed calculation. The proposed simulation output screen will provide the total energy use and savings, the energy cost savings, and the building's Indoor Environmental Quality (IEQ) (i.e., temperature and RH) changes of the user input, code-compliant and high performance school building.

CHAPTER X

SUMMARY AND FUTURE WORK

An effort to develop a simplified easy-to-use simulation toolkit for preliminary design of high performance schools in hot and humid climates was presented in this research. The proposed toolkit will allow decision makers without simulation knowledge to easily and accurately evaluate selected energy efficient measures, which would contribute to the accelerated dissemination of energy efficient design in K-12 schools.

10.1. Summary

In order to develop the toolkit, first, an existing case-study building in a hot and humid climate was selected and analyzed to understand the energy use pattern in a school building. This case-study school was then used in the procedure of calibrated simulation. The findings from the analysis of the measured data are as followings.

- Time series and the scatter plots for the hourly whole-building electricity use described that the patterns of the school energy use, including: summer use, and several school holidays. Therefore, different schedules for these periods need to be modeled in the simplified simulation procedure.
- The data measurement from the portable loggers showed that the indoor temperature and relative humidity in the classrooms during occupied hours were within the comfort zone defined in ASHRAE Standard 55-1999.

- The measured HVAC supply temperatures were in the range of 48 to 52 F, which is lower than the supply temperature (i.e., 55F) identified from the interview.
- The measured CO_2 concentration levels showed that the CO_2 concentration levels during a major portion of the occupied hours were above 1,000 ppm, which can be an indication of indoor air quality problems. Inadequate OA ventilation rates would be the main reason for this problem.
- The measured indoor CO_2 levels also revealed that too much OA is being introduced into the building during unoccupied period based on the observation that the indoor CO_2 level dropped rapidly to the ambient levels within a few hours of the time when the occupancy level drops. This may be caused by excessive operation of exhaust fans in bathrooms.

As a next step, an as-built simulation model for the case-study building was developed based on the as-built drawings and interviews with the maintenance personnel. The initial as-built simulation showed a lower electricity uses than the measured use mainly due to the under-estimated lighting and equipment energy use. The whole-building electricity NMBE and the CV(RMSE) for the as-built simulation was 10.2% and 35.5%, respectively. The initial simulation model was then calibrated with the data measured from the building. Five calibration steps were performed to match the simulation results with the measured energy use. The five steps includes: 1) Using an actual 2006 weather file with measured solar radiation, 2) Modifying lighting & equipment schedule using AHSRAE's RP-1093 method, 3) Using a scroll chiller performance curve, 4) Using the Winkelmann's method for the underground floor, and 5) Modifying the HVAC and room setpoint temperature based on the measured data. Through the five calibration steps, the final NMBE and CV(RMSE) for whole building electricity were calculated as 1.4% and 16.6%, respectively, which are considered acceptable.

In this research, a daylighting strategy and an improved simulation of the strategy was discussed as one of the high performance measures. A pilot study of the integration of the daylighting simulation with the DOE-2 simulation was also presented. To accomplish this, a classroom with and without skylights was simulated using the Desktop Radiance program combined with the DOE-2 simulation program. The result shows that the use of daylighting and reduced auxiliary lighting decreased the total annual energy consumption 10.7%, which includes a lighting energy use reduced of 36.7% compared to the original classroom. In addition, the simulation results showed that the addition of toplights increased the space heating energy use due to the decreased heat gain from the reduced lighting load.

In Chapter VIII, the energy savings potentials by applying several high performance measures to the ASHRAE Standard 90.1-1999 compliant school building were analyzed. The high performance measures applied included the recommendations from the ASHRAE AEDG for K-12 and other high performance measures from the literature review as well as the daylighting strategy, solar PV and solar thermal systems. The high performance measures applied in this study included: increased roof R-value, improved glazing U-value, reduced SHGC, adding overhangs, reduced lighting power density, occupancy sensors for lighting, higher cooling COP, higher SWH efficiency, reduced fan power, cold deck reset, variable speed for pumps, higher boiler efficiency, skylights, and the application of solar PV and solar thermal systems.

For the analysis, first, the calibrated case-study school simulation was modified to be compliant with the ASHRAE Standard 90.1-1999 using the ECB method. The modified simulation result showed that the EUI for the code-compliant school is 48.7 kBtu/sq.ft.-yr, while the EUI for the calibrated case-study school is 51.6 kBtu/sq.ft.-yr (i.e., 5.7% decrease). When the energy costs for the code-compliant school were calculated, the case-study school and the code compliant school costs almost same amount of energy bills (i.e., $39 more cost annually for the case-study school, which is 0.04% more consumptive).

Then, the AEDG for K-12 schools recommended school simulation was performed to estimate the energy savings potential from measured in the AEDG for K-12. After applying eight measures recommended in the AEDG for K-12 schools, the school consumed 22.8% less energy than the ASHRAE 90.1-1999 compliant school. Of the eight measures, the installation of occupancy sensors and reducing the lighting power density from 1.5 W/sq.ft. to 1.1W/sq.ft were the first and the second most effective energy saving measures, respectively (i.e., 8.7% and 6.7% of total energy savings, respectively).

In order to achieve above the AEDG for K-12 schools, more energy efficient measures were applied to the school. After applying five measures, the final high performance school building consumes 36.8% less energy than the ASHRAE 90.1-1999 compliant school building. As a result, the EUI for the school was reduced from 48.7 kBtu/sqft-yr to 30.8 kBtu/sqft-yr by applying the all 13 measures (i.e., eight from the AEDG for K-12 schools, and five from above AEDG).

A daylighting strategy was also applied to the school building to evaluate the energy impact. The gymnasium, cafeteria, and library were modified to be installed with skylights on the roof. Based on the available daylights, the artificial lights in the spaces were dimmed. The simulation result shows that the application of the skylights for the selected spaces could reduce a 2.8% of the total annual energy use compared to the ASHRAE 90.1-1999 compliant school. The final cumulative energy savings from applying the 13 measures and the daylighting strategy were simulated as 38.6% energy savings over the ASHRAE 90.1-1999 compliant school.

As the high performance measures, a solar thermal and PV system was designed and applied to the high performance school developed in the previous step to verify the additional energy savings potential. The solar thermal and solar PV system were designed to provide all needs for the service water heating loads and one-half of the school's electricity use, respectively. The results show that the net energy consumption of the final high performance school with the solar thermal and PV systems would be 1,162.1 MMBtu, which corresponds to 15.0 kBtu/sqft-yr of EUI, which is 68.2% energy savings over the code-compliant school building.

As a final step of the research, specifications for a simplified easy-to-use toolkit were developed. In order to define the most dominant school building shape, a survey using Google satellite views was performed. From this survey a modified spine shape was chosen as the shape of the simplified K-5 school in a hot and humid climate. The four main spaces in the proposed school building are: 1) classrooms and library, 2) gymnasium, 3) cafeteria, and 4) administration office. Based on the number of students, the size of each building space is changed proportionally.

As a next step, the proposed input parameters to be used as inputs in the simplified toolkit were defined. In this study, the input parameters for the general building information, building envelope, and lighting and equipment load were defined. Based on these input parameters, the LOADS portion of the DOE-2 input file was demonstrated as a simulation for the final web-based toolkit using DOE-2's "Input Macro" command. The prototype DOE-2 input was then run with the same input values as the ASHRAE Standard 90.1-1999 compliant input for the validation purpose. The comparison result showed that the total annual cooling and heating energy from the simplified simulation result was 2.1% lower than the cooling and heating energy from the detailed simulation result. The total annual electricity use from the simplified simulation result was 1.8% lower than the electricity use from the detailed simulation result.

10.2. Future Work

As described earlier in this dissertation, additional work would help expand and strengthen the results of this research. This includes:

- Research on plug loads for school buildings to identify the energy savings potential by using energy efficient appliances and office equipment.

- Develop additional shape for the prototypical school geometry for the simplified simulation input.
- Develop simulations with improved humidity control for proper thermal comfort condition maintained.
- Survey the most common average school HVAC and plant systems for use as default values in the prototypical school input.
- Develop SYSTEMS and PLANT portions of the simplified simulation input.
- Consider the use of other simulation program that can simulate the more complex high performance systems (i.e., dual path systems, Under Floor Air Distribution (UFAD) systems, heated/cooled slabs with dedicated outside air system, natural ventilation, etc.) available today, such as EnergyPlus or TRNSYS.
- Integrate other renewable systems such as wind energy into the simplified simulation input.
- Add an additional cost analysis for the high performance measures to evaluate the cost effectiveness of the selected high performance systems, including life-cycle cost, maintenance, etc.

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APPENDIX A

SUMMARY TABLE FOR LITERATURE REVIEW

Appendix A provides two summary tables for the energy efficient measures for school buildings surveyed from previous studies and other high performance building database. Table A.1 provides a summary of the selected papers. This table presents the author of paper, the classification of energy efficiency measures, the application of energy efficiency measures, the climate zones where the schools are located, the number of schools analyzed in each study, the total floor area of the school, the method of energy use analysis if any, and finally, the energy savings compared to other conventional schools. Of the sixteen papers reviewed, three papers showed the energy savings from the application of energy efficient building envelope measures such as tight windows, high insulation levels, shading devices, etc (Pletzer et al. 1988, Hunn et al. 1993, and Akbari et al. 1997).

Eleven papers described energy efficient HVAC systems for schools such as ground source heat pumps, an ice-making thermal storage system, and a dual-path air distribution system (Cane and Clemes 1995, Dinse 1998, Goss 1992, Rafferty 1996, Shonder et al. 2000, and Khattar et al. 2003). The total annual energy savings from these studies varies from 1% to 49%.

Table A.2 presents the summary of the high performance school buildings in the High Performance Buildings Database sponsored by the U.S. Department of Energy. In the table, the first six buildings are the existing high performance K-12 schools, and the rest of buildings are the existing high performance colleges/universities. In a similar fashion of Table A.1., this table also provides 1) The study number, 2) Authors, 3) Building name, 4) Climate zone of the building, 5) Location of the building, 6) Building type (i.e., K-12 or higher education), 7) Number of Floors, 8) Total floor area, 8) Baseline to calculate energy savings (e.g., ASHRAE 90.1-1999), 9) Method used for estimating energy savings (i.e., actually measured, simulated, or simple calculations), 10) EUI by percentage, 11) Annual energy savings by percentage, and 12) High performance strategies applied to the building.

Table A.1 - Summary Table for Literature Review

No.	Authors	Classification	Application	Climate Zone	# Bldgs Analyzed	Size (ft2)	Energy Use Analysis*	Energy Savings (%)							Remarks
								10	20	30	40	50	60	70	
S1	Akbari et al. 1997	Envelope	High-albedo Roof	Hot and Dry	2	958	M,S		25 -	35					Cooling Energy Savings
S2	Becker 1990	HVAC System	Four Different Types of Heating and Cooling Systems	Temperate and Mixed Cool and Humid Temperature and Humid	16	62,200, 46,700, 31,293	M,S								
S3	Butala and Novak 1999	Envelope	Tight window, more insulation	Slovenia (Heating dominant)	24	3,422 ~ 287,278	C		20						Heating Energy Savings
S4	Cane and Clemes 1995	HVAC System	Closed-loop ground source heat pump (GSHP)	Ontario, Canada	1	185,000	M,S								Simulation of the performance of a GSHP(compare w/ measured data)
S5	Desideri and Proietti 2002	N/A	Survey existing schools find most efficient school	Central Italy	13		M			38					Heating Energy Savings
S6	Dinse 1998	HVAC System	Geothermal systems	Temperature and Humid	1	160,000	M			34					
S7	Fuller and Luther 2003	HVAC System	Small reverse cycle air conditioner	Australia	4	940	M		20 - 27						Heating Energy Savings
S8	Goss 1992	HVAC System	Direct and indirect use of groundwater	Cool and Dry	1		M			33					This school was an ASHRAE award winner in 1986
S9	Haughey 2003	HVAC System	Ice thermal storage	Cool and Dry	1		M								4.1 years of simple payback
S10	Hunn et al. 1993	Envelope	Shading device	Cold and Humid	1	54,746	S	1							
S11	Khattar et al. 2003	HVAC System	Dual-path, low temperature air -distribution system w/ thermal energy storage (TES)	Hot and Humid	2		M		22						
S12	Montgomery 1998	HVAC System	Ice thermal storage	Hot and Humid	1	103,114, 166,162									1.5 years of simple payback
S13	Rafferty 1996	HVAC System	Groundwater heat pump systems	Temperature and Mixed	2	55,000 56,000	M	1.7 (Cali			49 (Ore				
S14	Santamouris et al. 1994	N/A	Audit and estimate of the potential for energy savings	Greece	23				20						
S15	Shoner et al. 2000	HVAC System	Geothermal Heat Pump	Cool and Humid	1	69,000	M,S		26						Compared to 50 schools around
S16	Stotz and Hanson 1992	HVAC System	Using heat recovery and aquifer wells	Hot and Humid	1	210,000	M								

** Energy Use Analysis*
M: Actual measurement
S: Simulation
U: Utility Bills

Table A.2 - Summary Table for Case Studies

No.	Authors	Building Name	Climate Zone	Location	Bldg Type	Const. Year	Floor(s)	Size (ft2)	Baseline	Energy Use Analysis*	EUI (kBtu/sq-ft)							Energy Savings (%)							High Performance Strategies
											20	40	60	80	100	120	140	10	20	30	40	50	60	70	
SC1	EERE, 2006	Baca/Dlo'ay azhi Community School	Cool and Dry	Prewitt, NM	K-12	2003	1	78,900	ASHRAE 90.1-1999	**S (Using Trane Trace® 700 Software)**	**26.9**								**20**						* Low SHGC (0.52) * T8 fluorescent lamps * Occupancy sensors * Whole-roof R-value of 25 or greater * VAV systems
SC2	EERE, 2006	Clackamas High School	Temperate and Mixed	Clackamas, OR	K-12	2002	2	265,000	ASHRAE 90.1-2000	**S (Using Visual DOE)**	**28.1**										**39**				* Natural ventilation w/ fan coil back up unit * Thermal mass * 90% AFUE boiler * T8& T-5 fluorescent lamps
SC3	EERE, 2006	Clearview Elementary School	Cool and Humid	Hanover, PA	K-12	2002	2	43,600	ASHRAE 90.1-1999	**S (Using Power DOE v.1.17)**	**23.3**										**40**				* Ground source heat pump * Wall R-value of 25 or greater * Windows U-factor less than 0.32 * Heat-recovery ventilation * UFAD systems
SC4	EERE, 2006	Durant Road Middle School	Temperate and Humid	Raleigh, NC	K-12	1995	1	149,000	N/A	N/A	**25**														* Low SHGC (0.52) * T8 fluorescent lamps * Occupancy sensors * Whole-roof R-value of 25 or greater * VAV systems
SC5	EERE, 2006	Hidden Villa Youth Hostel & Summer Camp	Temperate and Mixed	Los Altos Hills, CA	K-12	2001	2	3,370	N/A	**S (Using Energy Scheming Software)**	**9.49**														* Ground-source heat pumps * High internal thermal mass * Evaporative cooling * Photovoltaic (PV) system * Replace incandescent lamps with CFLs
SC6	EERE, 2006	Third Creek Elementary School	Temperate and Humid	Statesville, NC	K-12	2002	1	92,000	N/A	**S (Using Trane Trace 600)**			**59.8**												* R-45 roof, R-22 walls, and low-emissivity windows * AC systems with a high efficiency rating * Windows U-factor less than 0.32 * Heat-recovery ventilation * Occupancy sensors * 97% Boiler efficiency
SC7	EERE, 2006	C. K. Choi Building for the Institute of Asian Research	N/A	Vancouver, Canada	Higher Education	1996		34,400	N/A	**U**		**41.6**													* Natural ventilation (no air conditioning) * Use light colors for surfaces and finishes * High-efficiency luminaires * Occupancy sensors * Achieve a whole-wall R-value of 15 or greater
SC8	EERE, 2006	Environmental Technology Center at Sonoma State University	Temperate and Humid	Rohnert Park, CA	Higher Education	2001		2,200	California's Title 24	**U**				**80**				**2.32**							* Photovoltaic (PV) system * High-efficacy T-5 fluorescent lamps * Direct-gain passive solar heating * Mass-wall passive solar heating
SC9	EERE, 2006	Management Building at Technology Square, Georgia Institute of Technology	Temperate and Humid	Atlanta, GA	Higher Education	2003		248,000	N/A	**S (Using DOE-2.1E Build 133)**			**59.5**												* Use light-colored exterior walls and roofs * Use high-efficacy T8 fluorescent lamps * VAV systems
SC10	EERE, 2006	Adam Joseph Lewis Center for Environmental Studies--Oberlin College	Cool and Humid	Oberlin, OH	Higher Education	2000		13,600	N/A			**30.1**													* Photovoltaic (PV) system * High internal thermal mass building * Windows U-factor less than 0.25 * Occupancy sensors * Roof R-value of 25 or greater * Closed-loop geothermal wells
SC11	EERE, 2006	Rinker Hall at the University of Florida	Hot and Humid	Gainesville, FL	Higher Education	2003		47,300	ASHRAE 90.1-1999	**S (Using DOE-2.1E)**		**30.1**										**57**			* High performance glazing * Occupancy sensor * Enthalpic heat-recovery ventilation * Reflective shade
SC12	EERE, 2006	Smithsonian Tropical Research Institute Research Station	N/A	Bocas del Toro, Panama	Higher Education	2003		7,530	N/A	**U**		**42.6**													* Building-integrated photovoltaics (PV) * High-efficacy T8 fluorescent lamps * Use light colors for surfaces and finishes
SC13	EERE, 2006	Vermont Law School James L. and Evelena S. Oakes Hall	Cold and Humid	South Royalton, VT	Higher Education	1998		23,500	N/A	N/A	**27.2**														* T-8 fluorescent lighting * Triple-glazed, argon-filled units with a single low-e coating (less than 0.25 U) * Enthalpic heat-recovery ventilation

** Energy Use Analysis*
M: Actual measurement
S: Simulation
U: Utilty Bills

APPENDIX B

MONTHLY UTILITY BILLS FOR THE CASE STUDY SCHOOL

Appendix B provides the case-study school building's historical utility bills from 2000 to 2006. Table B.1 to B.7 and Table B.8 to B.14 present the monthly electricity bills and monthly natural gas bills from 2000 to 2006, respectively. Of these, the electricity and natural gas bills in 2006 were used for the calibrated simulation.

Table B.1 – Monthly Electrical Utility Bills for 2006

ELECTRICAL:											
					2006-2007						
BUILDING: Rockprairie Elem											
					On Peak		Off Peak				
2006-2007	KWH	KWH $	KW	KW $	KW	KW $	KW	KW $	P.C.	Security	Total Cost
Sep	77,640	3,529.98			212.40	1,263.78	360.00	1,108.80	388.20		6,290.76
Oct	70,200	3,577.98			220.80	1,468.32	291.60	1,006.02	351.00		6,403.32
Nov	61,680	3,152.83			159.00	1,057.35	278.40	960.48	308.40		5,479.06
Dec	50,640	2,601.94			159.00	1,057.35	238.80	823.86	253.20		4,736.35
Jan											
Feb											
Mar											
Apr											
May											
Jun											
Jul											
Aug											
Total	260,160	12,862.73	0.00	0.00	751.20	4,846.80	1,168.80	3,899.16	1,300.80	0.00	22,909.49

Table B.2 – Monthly Electrical Utility Bills for 2005 -2006

file: ROCKPRA (Rockprairie) Combined files of: ROCKPE, ROCKW

ELECTRICAL:											
					2005-2006						
BUILDING: Rockprairie Elem									Sept Sq. Ft.		0
(Portable added 2/93) 900 sq ft					On Peak		Off Peak				
2005-2006	KWH	KWH $	KW	KW $	KW	KW $	KW	KW $	P.C.	Security	Total Cost
Sep	114,120	4,605.56			256.80	1,527.96	360.00	1,108.80			7,242.32
Oct	79,320	3,604.74			198.00	1,178.10	325.20	1,001.62			5,784.46
Nov	67,560	3,081.42			156.00	928.20	328.80	1,012.70			5,022.32
Dec	64,320	2,937.24			159.60	949.62	244.80	753.98			4,640.84
Jan	57,120	2,616.84	Rachet = 21.60 KW On-Peak		139.20	828.24	303.60	935.09			4,380.17
Feb	59,160	2,707.62			152.40	906.78	259.20	798.34			4,412.74
Mar	63,240	2,889.18			187.20	1,113.84	298.80	920.30	316.20		5,239.52
Apr	74,400	3,385.80			220.80	1,313.76	328.80	1,012.70	372.00		6,084.26
May	87,960	3,989.22			212.40	1,263.78	318.00	979.44	439.80		6,672.24
Jun	62,640	2,862.48			217.20	1,292.34	219.60	676.37	313.20		5,144.39
Jul	67,320	3,070.74			204.00	1,213.80	241.20	742.90	336.60		5,364.04
Aug	100,200	4,533.90			318.00	1,892.10	357.60	1,101.41	501.00		8,028.41
Total	897,360	40,284.74	0.00	0.00	2,421.60	14,408.52	3,585.60	11,043.65	2,278.80	0.00	68,015.71

Table B.3 – Monthly Electrical Utility Bills for 2004 -2005

ELECTRICAL:

2004-2005

BUILDING: Rockprairie Elem — Sept Sq. Ft. 0

(Portable added 2/93) 900 sq ft

2004-2005	KWH	KWH $	KW	KW $	On Peak KW	KW $	Off Peak KW	KW $	P.C.	Security	Total Cost
Sep	112,320	4,534.10			277.20	1,649.34	382.80	1,179.02			7,362.46
Oct	94,680	3,833.80			264.00	1,570.80	372.00	1,145.76			6,550.36
Nov	82,920	3,366.92			229.20	1,363.83	339.60	1,045.97			5,776.72
Dec	68,880	2,809.54			195.60	1,163.82	308.40	949.87			4,923.23
Jan	75,240	3,062.03			177.60	1,056.72	330.00	1,016.40			5,135.15
Feb	75,000	3,052.50			159.60	949.62	298.80	920.30			4,922.42
Mar	71,520	2,914.34			166.80	992.46	343.20	1,057.06			4,963.86
Apr	75,120	3,057.26			193.20	1,149.54	330.00	1,016.40			5,223.20
May	109,680	4,429.30			241.20	1,435.14	331.20	1,020.10			6,884.54
Jun	110,040	4,443.59			187.20	1,113.84	216.00	665.28			6,222.71
Jul	100,200	4,052.94			223.20	1,328.04	206.40	635.71			6,016.69
Aug	118,080	4,762.78			278.40	1,656.48	343.20	1,057.06			7,476.32
Total	1,093,680	44,319.10	0.00	0.00	2,593.20	15,429.63	3,801.60	11,708.93	0.00	0.00	71,457.66

Table B.4 – Monthly Electrical Utility Bills for 2003 -2004

ELECTRICAL:

2003-2004

BUILDING: Rockprairie Elem — Sept Sq. Ft. 0

(Portable added 2/93) 900 sq ft

2003-2004	KWH	KWH $	KW	KW $	On Peak KW	KW $	Off Peak KW	KW $	P.C.	Security	Total Cost
Sep	110,880	4,476.94			274.80	1,635.06	346.80	1,068.14			7,180.14
Oct	93,120	3,771.86			238.80	1,420.86	339.60	1,045.97			6,238.69
Nov	79,200	3,219.24			236.40	1,406.58	342.00	1,053.36			5,679.18
Dec	79,080	3,214.48			194.40	1,156.68	283.20	872.26			5,243.42
Jan	75,600	3,076.32			186.00	1,106.70	284.40	875.95			5,058.97
Feb	77,760	3,162.07			159.60	949.62	253.20	779.86			4,891.55
Mar	88,560	3,590.83			163.20	971.04	301.20	927.70			5,489.57
Apr	87,840	3,562.25			232.80	1,385.16	313.20	964.66			5,912.07
May	99,240	4,014.83			246.00	1,463.70	328.80	1,012.70			6,491.23
Jun	90,480	3,667.06			216.00	1,285.20	225.60	694.85			5,647.11
Jul	103,200	4,172.04			265.20	1,577.94	271.20	835.30			6,585.28
Aug	118,200	4,767.54			284.40	1,692.18	362.40	1,116.19			7,575.91
Total	1,103,160	44,695.46	0.00	0.00	2,697.60	16,050.72	3,651.60	11,246.94	0.00	0.00	71,993.12

Table B.5 – Monthly Electrical Utility Bills for 2002 -2003

ELECTRICAL:

2002-2003

BUILDING: Rockprairie Elem

					On Peak		Off Peak				
2002-2003	KWH	KWH $	KW	KW $	KW	KW $	KW	KW $	P.C.	Security	Total Cost
Sep	103,920	2,745.74			262.80	1,563.66	351.60	1,082.93	1,454.88		6,847.21
Oct	86,040	2,286.23			231.60	1,378.02	340.80	1,049.66	1,204.56		5,918.47
Nov	72,360	1,934.65			218.40	1,299.48	307.20	946.18	1,013.04		5,193.35
Dec	66,000	1,771.20			184.80	1,099.56	284.40	875.95	924.00		4,670.71
Jan	67,440	1,808.21			183.60	1,092.42	279.60	861.17	944.16		4,705.96
Feb	68,400	2,790.48			154.80	921.06	260.40	802.03	0.00		4,513.57
Mar	71,280	2,904.82			159.60	949.62	288.00	887.04	0.00		4,741.48
Apr	81,000	3,290.70			199.20	1,185.24	339.60	1,045.97	0.00		5,521.91
May	99,600	4,029.12			246.00	1,463.70	367.20	1,130.98	0.00		6,623.80
Jun	85,800	3,481.26			254.40	1,513.68	309.60	953.57	0.00		5,948.51
Jul	84,720	3,438.38			230.40	1,370.88	284.40	875.95	0.00		5,685.21
Aug	107,280	4,334.02			304.80	1,813.56	363.60	1,119.89	0.00		7,267.47
Total	993,840	34,814.81	0.00	0.00	2,630.40	15,650.88	3,776.40	11,631.32	5,540.64	0.00	67,637.65

Table B.6 – Monthly Electrical Utility Bills for 2001 -2002

ELECTRICAL:

2001-2002

BUILDING: Rockprairie Elem

					On Peak		Off Peak				
2001-2002	KWH	KWH $	KW	KW $	KW	KW $	KW	KW $	P.C.	Security	Total Cost
Sep	97,080	2,569.96			254.40	1,513.68	361.20	1,112.50	1,359.12		6,555.26
Oct	85,800	2,280.06			158.40	942.48	338.40	1,042.27	1,201.20		5,466.01
Nov	77,520	2,067.26			214.80	1,278.06	334.80	1,031.18	1,085.28		5,461.78
Dec	60,600	1,632.42			156.60	931.77	316.80	975.74	848.40		4,388.33
Jan	70,080	1,876.06			156.60	931.77	284.40	875.95	981.12		4,664.90
Feb	63,600	1,709.52			156.60	931.77	282.00	868.56	890.40		4,400.25
Mar	61,320	1,650.92			231.60	1,378.02	279.60	861.17	858.48		4,748.59
Apr	87,000	2,310.90			223.20	1,328.04	334.80	1,031.18	1,218.00		5,888.12
May	98,880	2,616.22			212.40	1,263.78	370.80	1,142.06	1,384.32		6,406.38
Jun	67,320	1,805.12			190.80	1,135.26	265.20	816.82	942.48		4,699.68
Jul	75,600	2,017.92			189.60	1,128.12	246.00	757.68	1,058.40		4,962.12
Aug	110,040	2,903.03			280.80	1,670.76	339.60	1,045.97	1,540.56		7,160.32
Total	954,840	25,439.39	0.00	0.00	2,425.80	14,433.51	3,753.60	11,561.08	13,367.76	0.00	64,801.74

Table B.7 – Monthly Electrical Utility Bills for 2000 -2001

ELECTRICAL:

2000-2001

BUILDING: Rockprairie Elem

					On Peak		Off Peak				
2000-2001	KWH	KWH $	KW	KW $	KW	KW $	KW	KW $	P.C.	Security	Total Cost
Sep	96,240	2,776.58			266.40	1,585.08	345.60	1,064.45	294.34		5,720.45
Oct	81,480	2,169.04			168.00	999.60	336.00	1,034.88	651.84		4,855.36
Nov	71,400	1,909.98			158.40	942.48	316.80	975.74	571.20		4,399.40
Dec	59,160	1,595.41			154.80	921.06	273.60	842.69	473.28		3,832.44
Jan	64,080	1,721.86			135.00	803.25	238.80	735.50	897.12		4,157.73
Feb	64,080	1,721.86			146.40	871.08	302.40	931.39	1,281.60		4,805.93
Mar	61,800	1,663.26			214.80	1,278.06	271.20	835.30	865.20		4,641.82
Apr	70,680	1,891.48			133.20	792.54	320.40	986.83	989.52		4,660.37
May	89,280	2,369.50			194.40	1,156.68	352.80	1,086.62	1,249.92		5,862.72
Jun	79,440	2,116.61			228.00	1,356.60	270.00	831.60	1,112.16		5,416.97
Jul	95,400	2,526.78			279.60	1,663.62	283.20	872.26	1,335.60		6,398.26
Aug	118,800	3,128.16			313.20	1,863.54	364.80	1,123.58	1,663.20		7,778.48
Total	951,840	25,590.52	0.00	0.00	2,392.20	14,233.59	3,675.60	11,320.84	11,384.98	0.00	62,529.93

Table B.8 – Monthly Natural Gas Utility Bills for 2006 -2007

GAS:

2006-2007

CAMPUS: Rock Prairie

2005-2006	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	255	38.94	192.78		5.08	236.80
Oct	219	36.10	181.54	5.14	4.85	227.63
Nov	673	62.61	551.65	1.41	13.12	628.79
Dec	761	67.36	623.78	3.39	14.79	709.32
Jan						
Feb						
Mar						
Apr						
May						
Jun						
Jul						
Aug						
Total	1,908	205.01	1,549.75	9.94	37.84	1,802.54

Table B.9 – Monthly Natural Gas Utility Bills for 2005 -2006

GAS:

2005-2006

CAMPUS: Rock Prairie

2005-2006	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	857	69.22	844.85		19.80	933.87
Oct	1,058	81.03	1,653.18		144.37	1,878.58
Nov	1,419	100.50	2,217.26		192.97	2,510.73
Dec	2,304	148.24	2,980.92		261.08	3,390.24
Jan	2,187	141.92	2,764.37		242.55	3,148.84
Feb	2,088	137.55	1,680.53		152.78	1,970.86
Mar	1,739	118.73	1,150.28		44.54	1,313.55
Apr	1,164	87.71	653.23		17.07	758.01
May	545	54.33	305.85		8.10	368.28
Jun	114	26.43	63.79		1.99	92.21
Jul	67	22.72	49.59		1.57	73.88
Aug	293	41.94	221.51		5.78	269.23
Total	13,835	1,030.32	14,585.36	0.00	1,092.60	16,708.28

Table B.10 – Monthly Natural Gas Utility Bills for 2004 -2005

GAS:

2004-2005

CAMPUS: Rock Prairie

2004-2005	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	258	35.87	176.00		4.32	216.19
Oct	269	36.73	231.60		5.47	273.80
Nov	398	44.47	342.67		7.89	395.03
Dec	2,862	177.37	2,464.12		53.81	2,695.30
Jan	2,752	171.44	2,379.87		51.97	2,603.28
Feb	3,430	208.01	1,806.86		41.04	2,055.91
Mar	2,262	145.01	1,191.58		27.23	1,363.82
Apr	1,367	96.73	810.29		20.36	927.38
May	846	68.63	556.57		14.25	639.45
Jun	636	57.30	390.76		10.00	458.06
Jul	30	17.87	25.82		0.93	44.62
Aug	710	61.30	635.68		15.18	712.16
Total	15,820	1,120.73	11,011.82	0.00	252.45	12,385.00

Table B.11 – Monthly Natural Gas Utility Bills for 2003 -2004

GAS:

2003-2004

CAMPUS: Rock Prairie

2003-2004	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	269	58.12	176.60	0.00	5.62	240.34
Oct	694	118.59	562.04	-1.38	16.00	695.25
Nov	1,129	176.94	914.32	3.47	25.82	1,120.55
Dec	2,310	335.35	1,870.75	-17.19	44.59	2,233.50
Jan	2,214	322.47	1,302.30	52.40	34.16	1,711.33
Feb	4,257	596.50	2,504.01	-50.97	62.12	3,111.66
Mar	2,076	303.96	847.22	47.08	24.41	1,222.67
Apr	1,381	210.74	697.52	35.74	19.60	963.60
May	905	146.89	457.10	0.00	6.62	610.61
Jun	255	35.63	162.80	0.00	4.04	202.47
Jul	473	48.51	322.66	0.00	7.56	378.73
Aug	811	66.74	553.23	0.00	12.63	632.60
Total	16,774	2,420.44	10,370.55	69.15	263.17	13,123.31

Table B.12 – Monthly Natural Gas Utility Bills for 2002 -2003

GAS:

2002-2003

CAMPUS: Rock Prairie

2002-2003	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	315	50.40	122.80		3.62	176.82
Oct	610	79.09	258.09		7.05	344.23
Nov	1,498	226.43	670.83	-37.17	17.52	877.61
Dec	2,375	344.06	1,063.57	-65.47	27.34	1,369.50
Jan	2,460	355.46	1,108.25	15.33	30.13	1,509.17
Feb	2,733	392.08	1,425.92	-17.81	36.67	1,836.86
Mar	2,439	352.65	1,667.62	-76.97	39.59	1,982.89
Apr	1,644	246.01	1,282.88	-62.34	29.87	1,496.42
May	665	114.70	518.93	26.83	15.52	675.98
Jun	462	86.90	360.52		10.55	457.97
Jul	129	35.11	84.33		2.83	122.27
Aug	18	15.22	11.77		0.61	27.60
Total	15,348	2,298.11	8,575.51	-217.60	221.30	10,877.32

Table B.13 – Monthly Natural Gas Utility Bills for 2001 -2002

GAS:

2001-2002

CAMPUS: Rock Prairie

2001-2002	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	218	96.94	48.90			145.84
Oct	468	183.51	50.87	-5.14		229.24
Nov	1,185	140.96	460.04	-32.26		568.74
Dec	1,596	165.72	619.60	23.62	16.97	825.91
Jan	2,064	206.84	774.95	-23.81	20.15	978.13
Feb	1,856	188.57	696.85	19.23	19.00	923.65
Mar	1,972	198.76	677.34	-55.81	17.31	837.60
Apr	1,201	131.02	376.06	-12.60	10.44	504.92
May	393	58.42	158.34		4.54	221.30
Jun	481	67.47	193.79		5.46	266.72
Jul	43	17.71	17.92		0.74	36.37
Aug	13	13.73	5.07		0.38	19.18
Total	11,490	1,469.65	4,079.73	-86.77	94.99	5,557.60

Table B.14 – Monthly Natural Gas Utility Bills for 2000 -2001

GAS:

2000-2001

CAMPUS: Rock Prairie

2000-2001	CCF	Base Cost	GCA Amt	WNA Amt	Other Chgs	Total Cost
Sep	204	92.06	47.19			139.25
Oct	385	156.47	134.02	-3.91		286.58
Nov	630	240.52	192.38	-6.20		426.70
Dec	1,720	607.24	496.55	-30.41		1,073.38
Jan	2,733	957.31	1,221.24	-40.52		2,138.03
Feb	2,225	785.13	994.24	-6.41		1,772.96
Mar	1,676	598.53	748.92	-73.92	*	1,273.53
Apr	1,213	437.08	376.98	-20.38		793.68
May	559	216.61	173.73	-6.84		383.50
Jun	162	76.41	50.39			126.80
Jul	71	41.38	15.93			57.31
Aug	48	32.61	10.77			43.38
Total	11,626	4,241.35	4,462.34	-188.59	0.00	8,515.10

APPENDIX C

MEASURED DATA FROM THE PORTABLE LOGGERS

Appendix C provides time series plots for the measured temperatures and RHs in six points in a classroom and an AHU mechanical room in the case-study school. The measurement periods in 2006 include: 1) spring semester before summer vacation (i.e., May 3, 2006 to May 23, 2006), 2) summer vacation (May 23, 2006 through July 26, 2006), and 3) fall semester (i.e., August 23, 2006 through November 3, 2006).

Figures C.1 and C.2 present the plots for the spring periods. Figures C.3 and C.4 presents the plots for the summer periods, and Figures C.5 through C.8 presents the plots for the fall periods.

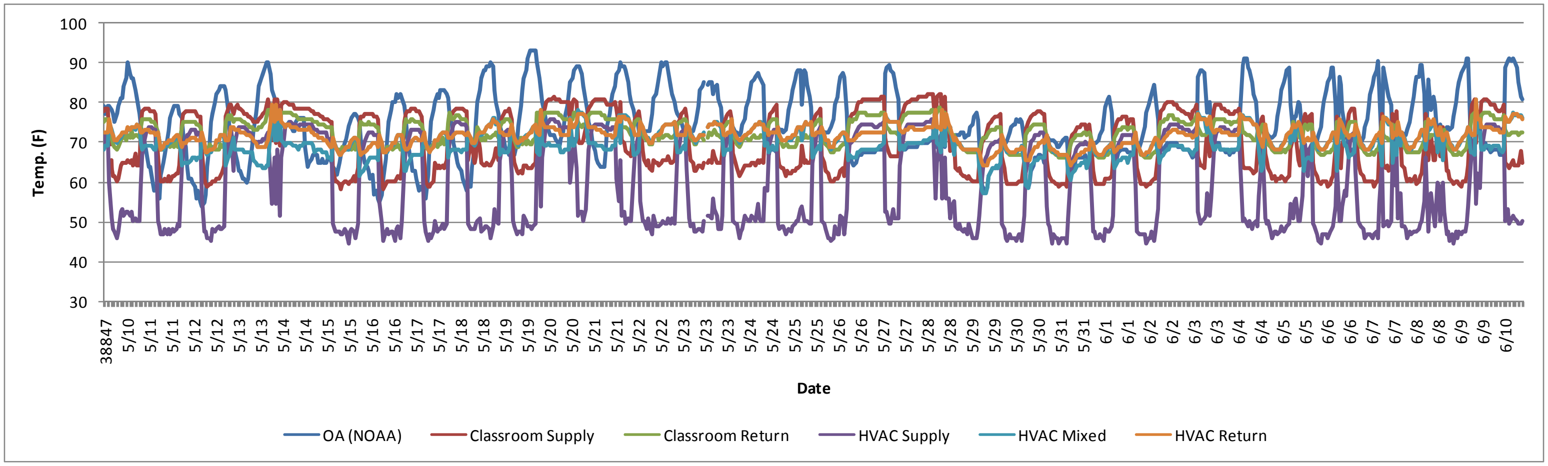

Figure C.1 – Time Series: Hourly Temperature (May 10, 2006 through June 10, 2006)

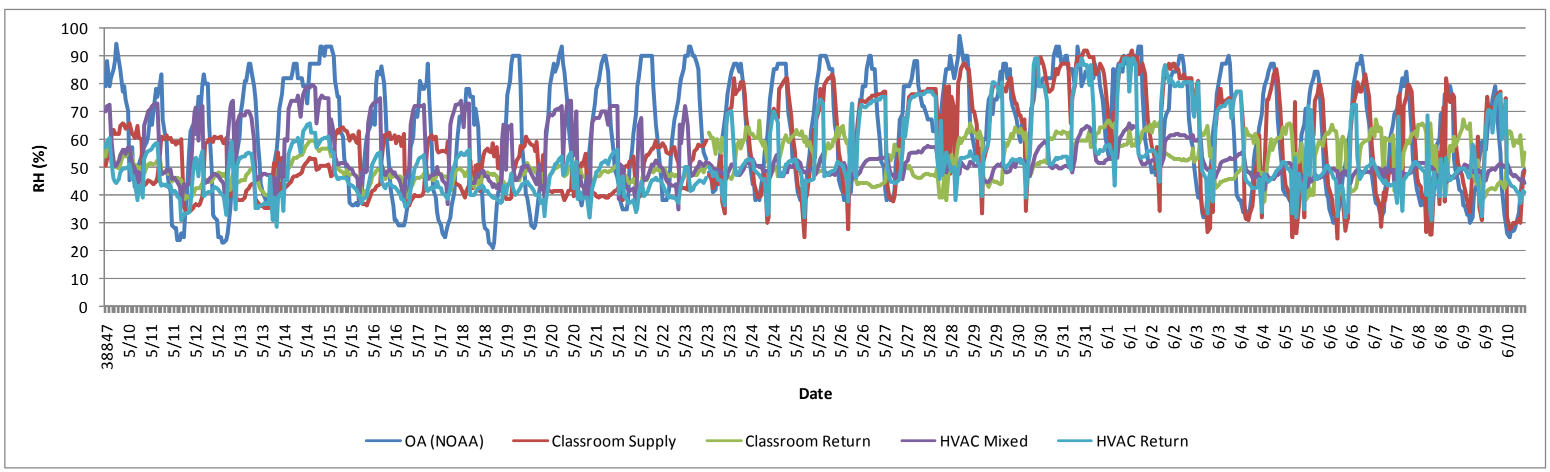

Figure C.2 – Time Series: Hourly RH (May 10, 2006 through June 10, 2006)

Figure C.3 – Time Series: Hourly Temperature (June 17, 2006 through July 23, 2006)

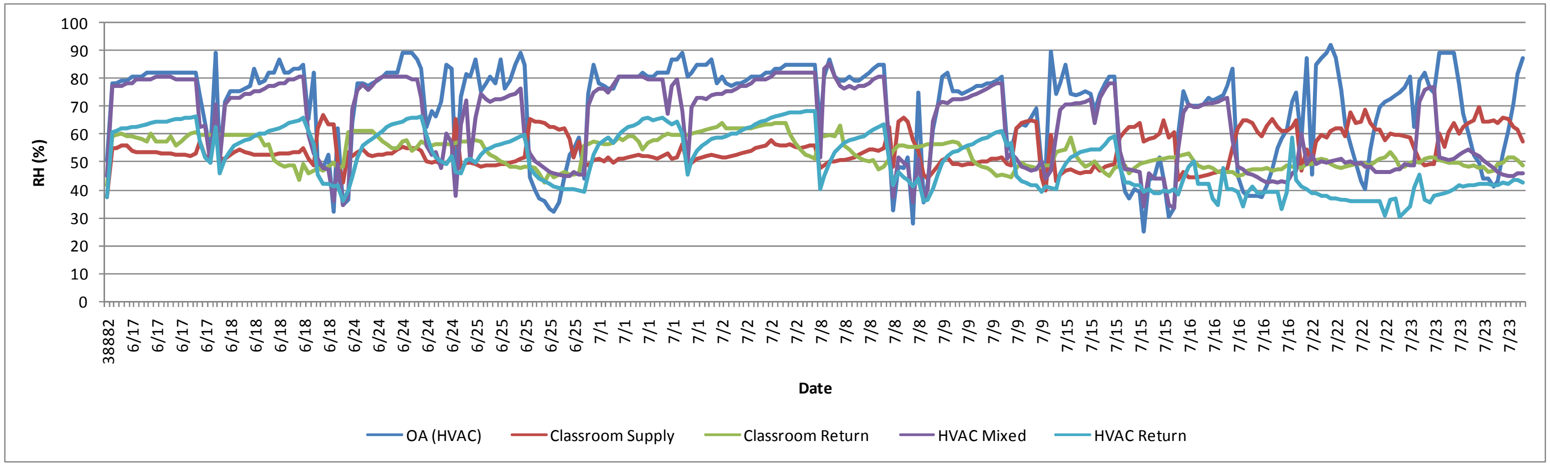

Figure C.4 – Time Series: Hourly RH (June 17, 2006 through July 23, 2006)

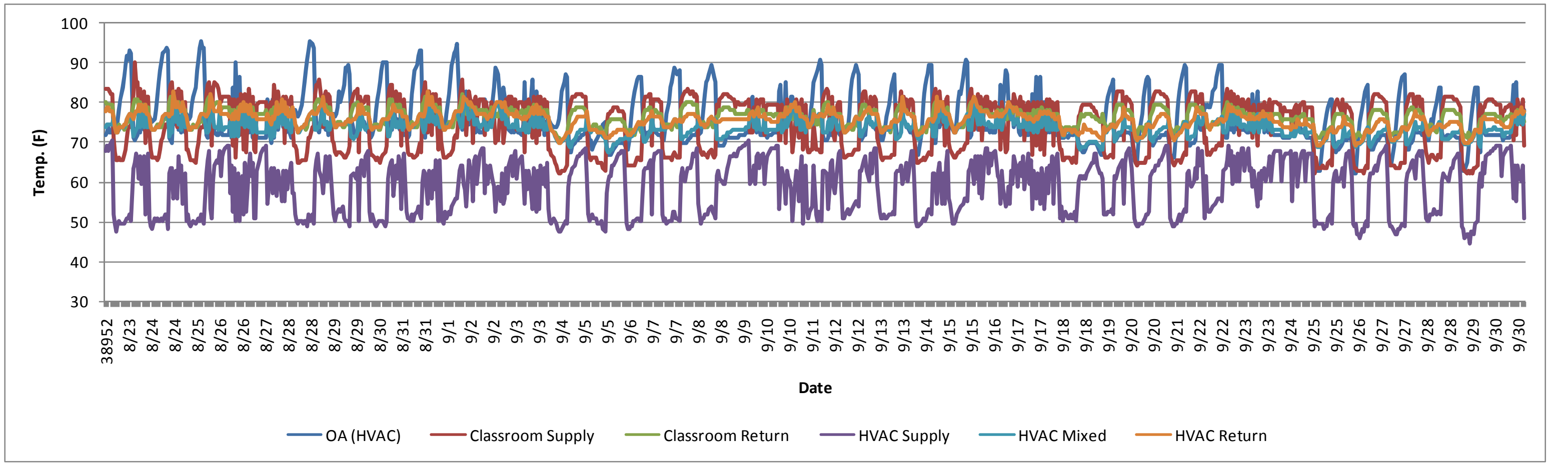

Figure C.5 – Time Series: Hourly Temperature (August 23, 2006 through September 30, 2006)

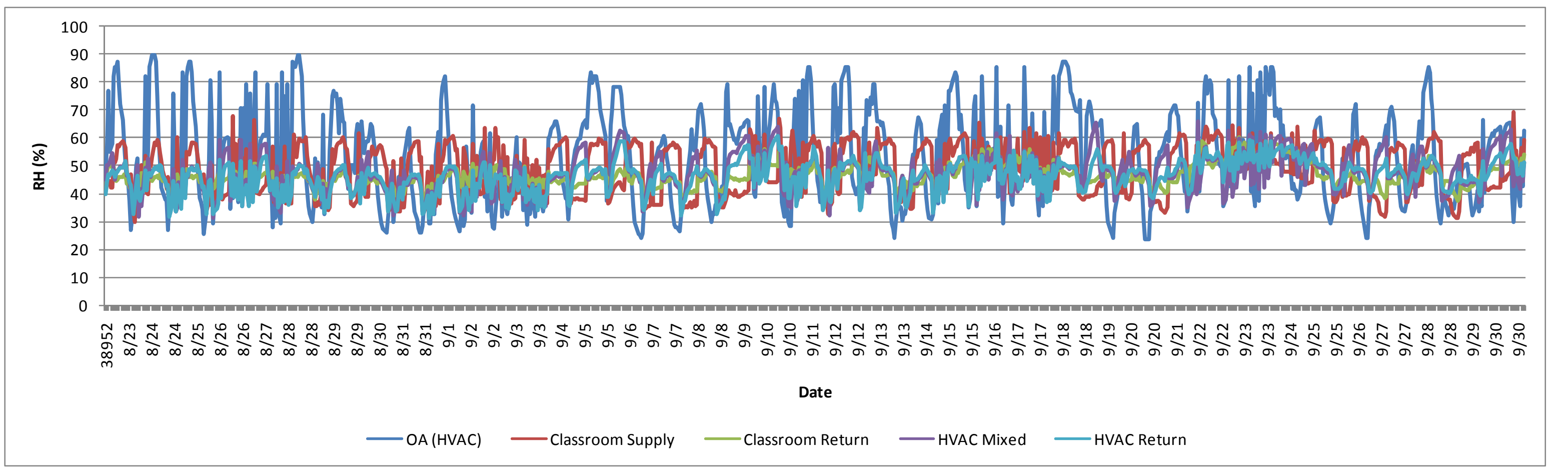

Figure C.6 – Time Series: Hourly RH (August 23, 2006 through September 30, 2006)

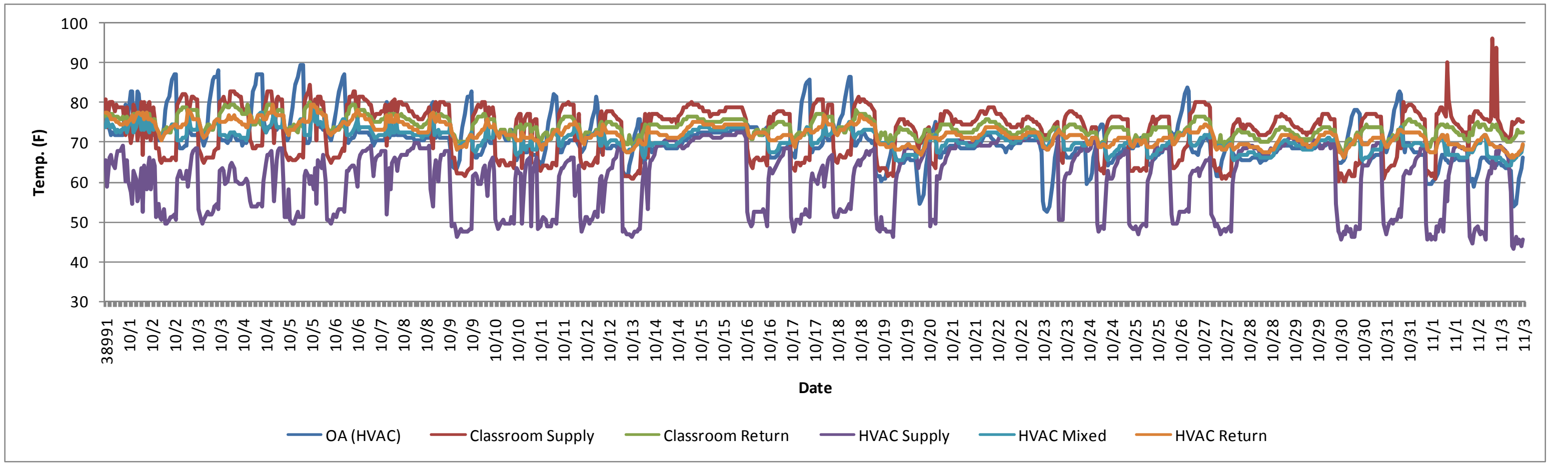

Figure C.7 – Time Series: Hourly Temperature (October 1, 2006 through November 3, 2006)

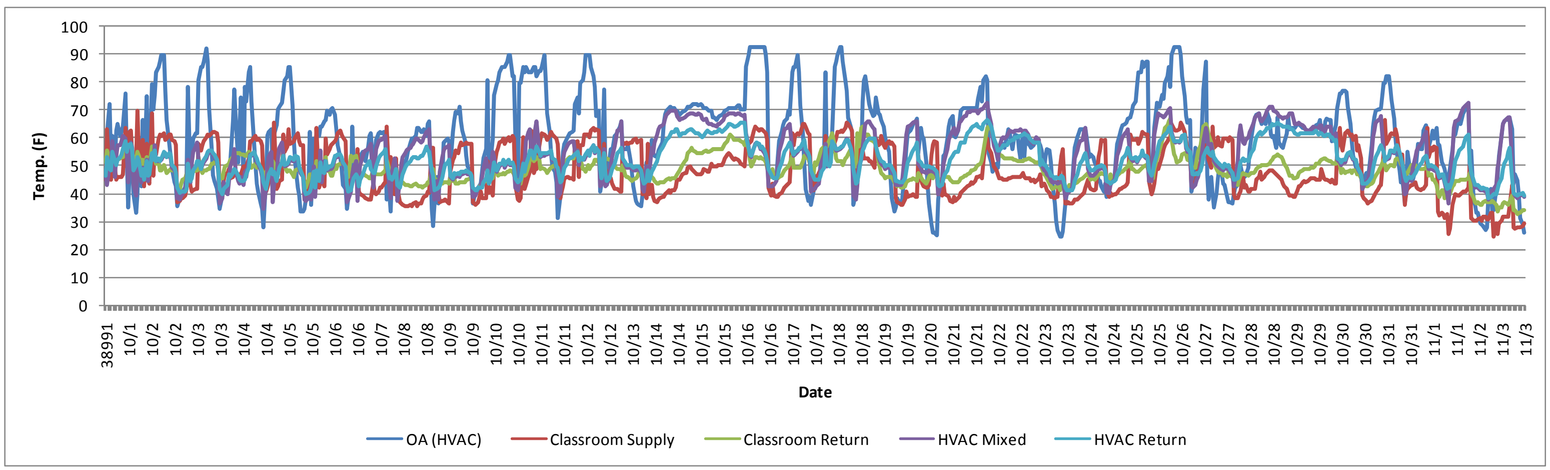

Figure C.8 – Time Series: Hourly RH (October 1, 2006 through November 3, 2006)

APPENDIX D

2006 WEATHER DATA

Appendix D provides the time series plots for the hourly weather data in 2006. The data shown in this appendix were used to pack the 2006 weather file which was used in the calibration procedure. Below is the list of the figures and the corresponding weather data.

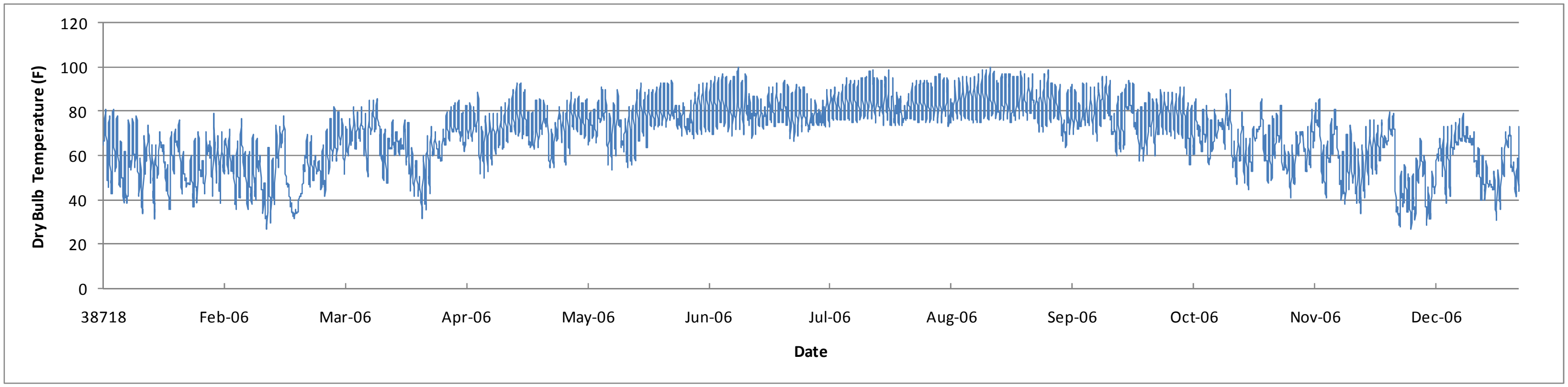

Figure D.1 – Hourly Dry Bulb Temperature in 2006

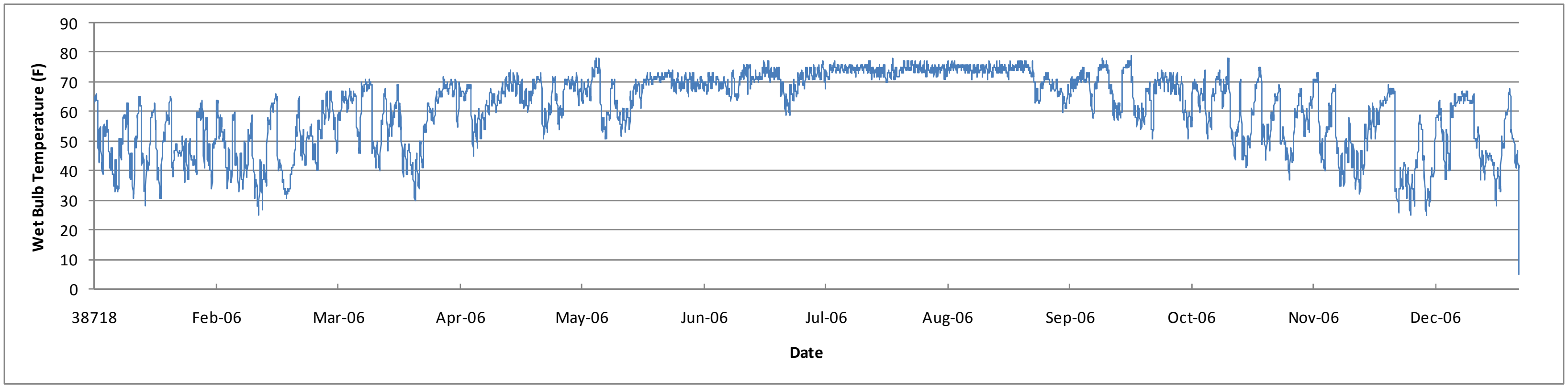

Figure D.2 – Hourly Wet Bulb Temperature in 2006

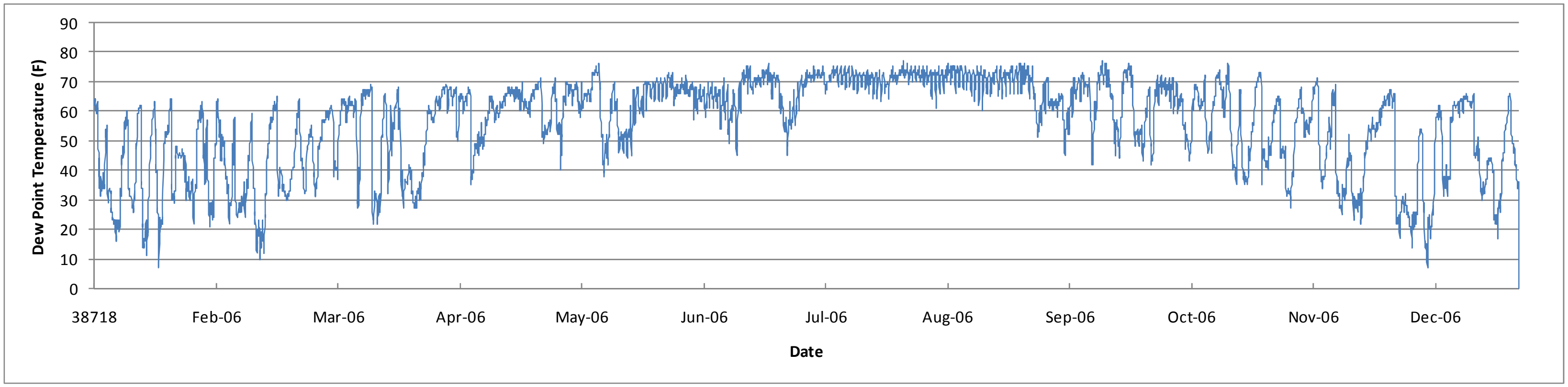

Figure D.3 – Hourly Dew Point Temperature in 2006

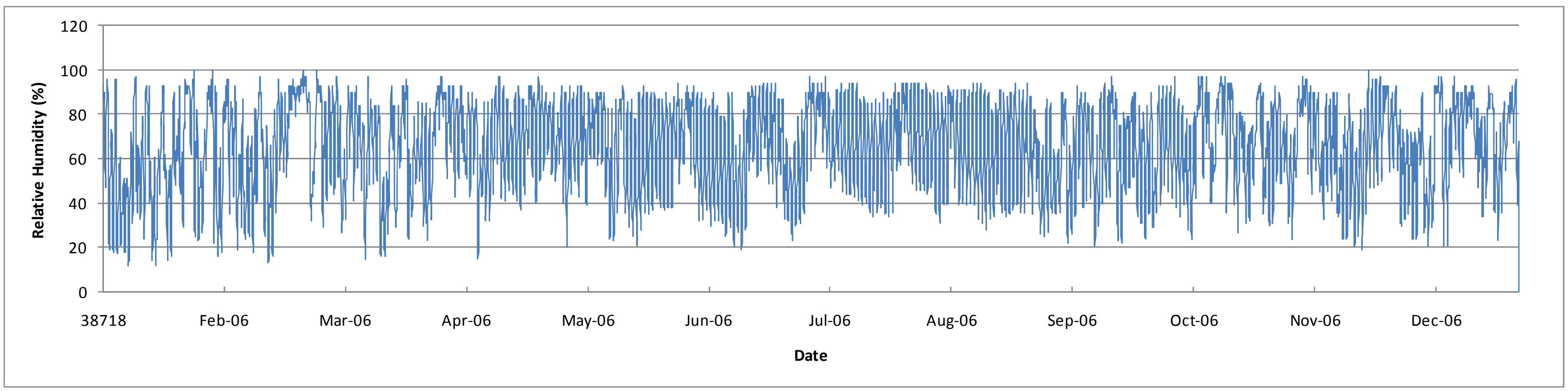

Figure D.4 – Hourly Relative Humidity in 2006

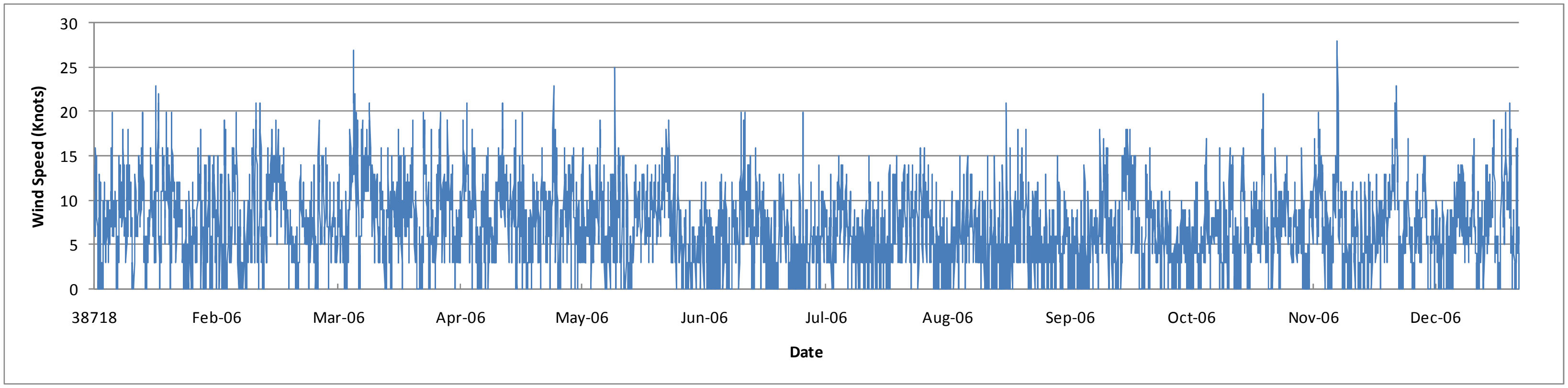

Figure D.5 – Hourly Wind Speed in 2006

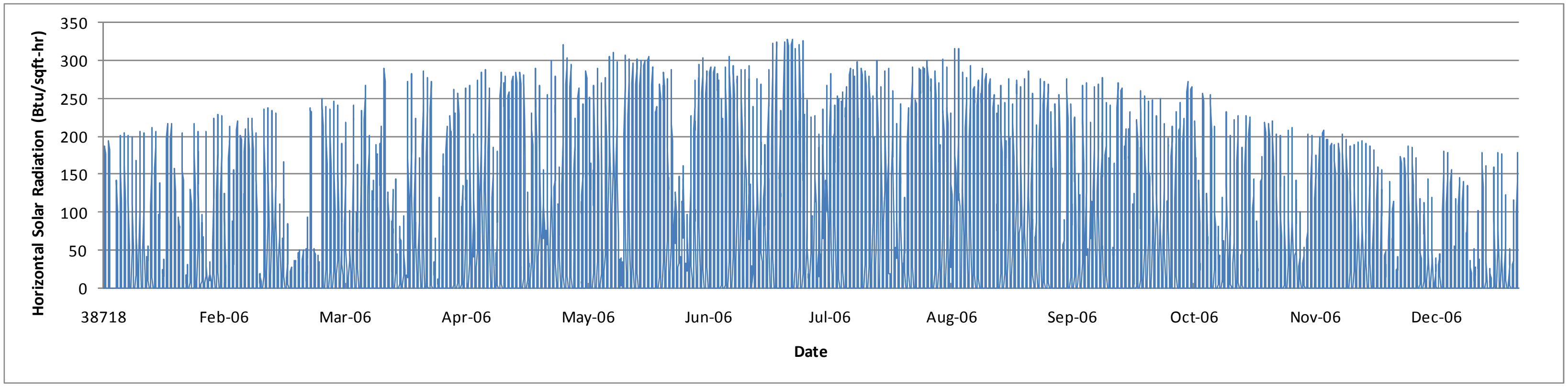

Figure D.6 – Hourly Horizontal Solar Radiation in 2006

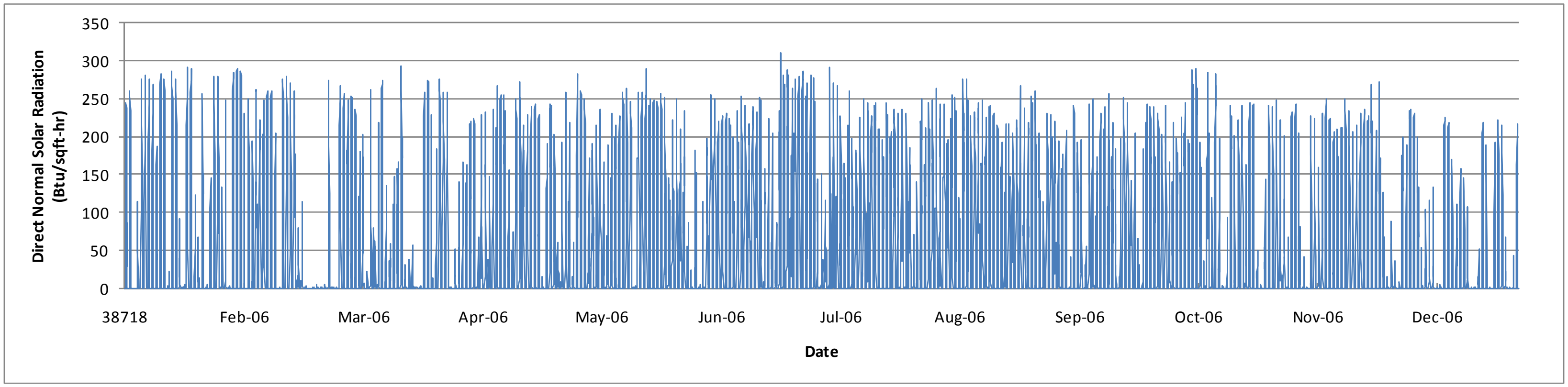

Figure D.7 – Direct Normal Solar Radiation in 2006

VITA

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Renewable Energy
Sustainable Building
Building Energy Simulation