METHODOLOGY TO DEVELOP AND TEST AN EASY-TO-USE PROCEDURE FOR THE PRELIMINARY SELECTION OF HIGH-PERFORMANCE SYSTEMS FOR OFFICE BUILDINGS IN HOT AND HUMID CLIMATES

A Dissertation

by

SOOLYEON CHO

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

August 2009

Major Subject: Architecture

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Approved by:

Chair of Committee,	Jeff S. Haberl
Committee Members,	David E. Claridge
	Charles Culp
	Liliana Beltran
Head of Department,	Glen Mills

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ABSTRACT

Methodology to Develop and Test an Easy-to-use Procedure for the Preliminary Selection of High-performance Systems for Office Buildings in Hot and Humid Climates. (August 2009)

Soolyeon Cho, B.S., University of Ulsan;
M.S., Texas A&M University
Chair of Advisory Committee: Dr. Jeff S. Haberl

A procedure has been developed for the preliminary selection of high-performance systems for office buildings in hot and humid climates. High-performance building systems and components were surveyed for buildings in the U.S., which were applicable for office buildings in hot and humid climates. This research developed a calibrated DOE-2.1e simulation model of a prototypical large office building. In addition, a Simplified Geometry DOE-2.1e (SGDOE-2.1e) model, was also developed, which used a simplified geometry to demonstrate the use of a proposed easy-to-use tool. The calibrated DOE-2.1e simulation model and the SGDOE-2.1e were compared and showed a good match with each.

The SGDOE-2.1e model was then further modified based on the ASHRAE Standard 90.1-1999 commercial building energy code. A code-compliant (ASHRAE Standard 90.1-1999) SGDOE-2.1e simulation model was then used as a baseline for the evaluation of the high-performance measures. A total of 14 high-performance measures

were implemented including the energy savings, while the comfort level was maintained based on the ASHRAE comfort zone. In addition to the 14 high-performance measures, solar thermal and solar PV system analysis were integrated with the SGDOE-2.1e simulation model to further reduce the annual energy use. Finally, specifications of the proposed easy-to-use simulation tool were developed. This tool includes options to choose systems from the 14 high-performance measures and solar systems.

The proposed easy-to-use systems selection tool can be used for new building practitioners and existing building owners as well to evaluate the performance of their new buildings compared to the ASHRAE Standard 90.1-1999 code-compliant building, and to assess the feasibility of implementing high-performance measures to their existing buildings in terms of energy and cost savings.

DEDICATION

To

My Loving Wife and Children

ACKNOWLEDGEMENTS

I would like to express my sincerest appreciation to the chair of my advisory committee, Dr. Jeff S. Haberl, for guiding my research with his profound knowledge and expertise. His dedicated attention and support made it possible to achieve my academic goals.

Also, I would like to greatly acknowledge my advisory committee members; Dr. David Claridge, Dr. Charles Culp, and Dr. Liliana Beltran. I was fortunate to have these professionals as my committee. Their comments and assistance enriched my knowledge and broaden my research ideas.

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This research was partially supported by the Energy Systems Laboratory through the Texas Senate Bill 5 project and by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) through a Grant-In-Aid program.

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CHAPTER I

INTRODUCTION

1.1 Background

In the United States, buildings consume more than one-third of the total energy and more than two-thirds of the total electricity use. Fossil fuels (petroleum, natural gas, and coal) are the main sources (90%) of energy in the U.S. These energy sources, however, will be eventually exhausted in about 50 years (for petroleum and natural gas) and in about 250 years (for coal) based on proven reserves (EIA, 2004). It is, therefore, important to design buildings that consume much less energy than existing buildings. In recent years, some owners and designers have achieved great advances in changing the energy consumption patterns of buildings.

Currently, there is a lot of discussion about sustainability, green buildings, high-performance buildings, and/or energy efficient buildings. Although these terms are different, the main concepts are the same. In general, high-performance buildings are substantially more efficient buildings than conventional buildings in terms of energy, economic, and environmental performance (EERE, 2006). A number of buildings already have been publicly reported as high-performance buildings in many different publications.

This dissertation follows the style of *ASHRAE Transactions.*

However, it was revealed from a detailed literature survey (Cho and Haberl, 2006) that the reported high-performance buildings included only partial descriptions of the characteristics of high-performance systems. Also, there were only a few high-performance buildings identified and reported in hot and humid climates. Consequently, there is a need to show how to design and construct high-performance buildings using high-performance environmental systems and components for hot and humid climates. In addition, even for the technologies applicable in hot and humid climates, a demonstration and analysis are needed for designers and engineers to learn from, so they can implement them into their target buildings with confidence.

To date, there are a lack of tools that can easily evaluate the energy performance of office buildings using high-performance, energy-efficient, and renewable energy systems. The development of these tools is necessary for high-performance building designers and engineers who do not have the budget or expertise to run complex simulation programs. Therefore, in this research, procedures that lead can to a simplified tool were developed to analyze the high-performance characteristics that have been reviewed in the literature survey. This tool includes the use of the DOE-2.1e program (LBNL, 1981) along with other solar energy analysis tools such as F-Chart (Beckman et al., 1977) and PV F-Chart (Klein and Beckman, 1983) without requiring specialized knowledge by the user.

1.2 Purpose and Objectives

The purpose of the research is:

> To demonstrate how the energy performance of office buildings in hot and humid climates can be improved.

The objectives are:

(1) To investigate and identify high-performance (energy-efficient) environmental systems and components that are applicable to office buildings in hot and humid climates,

(2) To develop a prototype high-performance office building model by simulating the high-performance features using the calibrated simulation of a case-study building, and

(3) To develop procedures that will lead to the development of a proposed easy-to-use energy performance evaluation tool for the selection of high-performance components for office buildings in hot and humid climates.

The analysis in this research was primarily focused on energy efficiency, even though the comprehensive definition of high-performance buildings includes not only energy conservation, but also other aspects such as water conservation, thermal comfort, indoor air quality, sustainable materials, and waste management.

CHAPTER II

LITERATURE REVIEW

In order to develop the research, five categories of the existing literature have been reviewed, including: (1) case studies of high-performance buildings, (2) high-performance systems and components, (3) building energy simulation programs, (4) calibrated simulation, and (5) easy-to-use energy performance evaluation tools. To carry out the literature survey, many sources of literature were reviewed, including the Energy Efficiency and Renewable Energy (EERE, 2008) database sponsored by the United States Department of Energy (USDOE), publications of American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2008), the Journal of Energy and Buildings (JEB, 2008), the publications of the American Council for an Energy Efficient Economy (ACEEE, 2008), the Journal of Solar Energy Engineering (JSEE, 2008), the proceedings of the International Building Performance Simulation Association (IBPSA, 2008), and the proceedings of the Symposium on Improving Building Systems in Hot and Humid Climates (H&H, 2008).

Also, reviewed were reports from the national laboratories such as the Lawrence Berkeley National Laboratory (LBNL, 2008a), the National Renewable Energy Laboratory (NREL, 2008), the Oak Ridge National Laboratory (ORNL, 2008a); and the Energy Systems Laboratory (ESL, 2008) at Texas A&M University.

2.1 Case Studies of High-performance Buildings

High performance buildings have been reported in a number of different climates. In this review, a total of 35 high-performance building case studies were selected and reviewed in detail. Table 2.1.1 summarizes the characteristics of high-performance buildings, high-performance strategies, Energy Use Indices (EUIs), and energy savings. Climate zones in which the buildings were located are included according to the map (USDOE, 2002) in Figure 2.1.1. Findings from the selected case studies of high-performance buildings are as follows.

2.1.1 Energy Use Indices (EUIs) of High-performance Buildings

Of the 35 case studies, 32 were suitable to review for Energy Use Indices (EUIs). As shown in Figure 2.1.2, five (16%) of the case studies had EUIs less than 30 kBtu/ft2-yr, eleven studies (34%) had EUIs between 30-50 kBtu/ft2-yr, three studies (9%) had EUIs between 50-70 kBtu/ft2-yr, six studies (19%) had EUIs between 70-90 kBtu/ft2-yr, three studies (9%) had EUIs between 90-110 kBtu/ft2-yr, and four studies (13%) had EUIs greater than 140 kBtu/ft2-yr. Most of these EUIs were much lower than those of prototype office buildings (Huang and Franconi, 1999), which ranged from 93 kBtu/sf-yr to 131 kBtu/sf-yr. Specifically, 78% of the high-performance buildings showed lower EUIs when compared to the average EUIs of prototype conventional buildings (Huang and Franconi, 1999).

Table 2.1.1 Literature Summary of High-performance Building Case Studies.

No.	Authors	Building Name	Climate Zone	Const. Date	Floor(s)	Size (sq. ft.)	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	
1	Deru et al. (2005)	Pennsylvania Department of Environmental Protection's Cambria Office	Cool & Humid	2000	2	36,000	ASHRAE 90.1 - 2001	DOE-2 Simulation		37									40				Wall Insulation, Ground-coupled Systems, Daylighting for Energy Efficiency, Photovoltaics, Lamp Ballasts, High-performance Windows and Doors, Ventilation Systems, Lighting Controls, Roof Insulation, PV providing 28% of total energy use
2	Deru et al. (2005)	BigHorn Home Improvement Center	Cool & Dry	2000	1	44,400	ASHRAE 90.1 - 2001	DOE-2 Simulation		40								35					Wall Insulation, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Interior Design for Light, Photovoltaics, Foundation Insulation, High-performance Windows and Doors, Heating Systems, Lighting Controls, Roof Insulation, PV providing 5-10% of total energy
3	Griffith et al. (2005)	The Chesapeake Bay Foundation's Philip Merrill Environmental Center	Cool & Humid	2000	2	32,000	ASHRAE 90.1 - 2001	EnergyPlus Simulation		40							25						Wall Insulation, Ground-coupled Systems, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Water Heaters, Cooling Systems, Photovoltaics, Heating Loads, Lamp Ballasts, High-performance Windows and Doors, Lighting Controls, HVAC Controls and Zoning, Roof Insulation
4	Torcellini et al. (2005)	Zion National Park Visitors Center	Cool & Dry	2000	1	8,800 & 2,756	Federal Energy Code 10 CFR 435 (Based on ASHRAE 90.1 - 1989)	DOE-2 Simulation	27												62		Daylighting, Natural Ventilation, Cooltowers, Passive Solar Heating, Solar Load Control with Engineered Overhangs, Computerized Building Controls, Uninterrupted Power Supply System Intergrated with PV System
5	Torcellini et al. (2005)	Thermal Test Facility at the National Renewable Energy Laboratory	Cool & Dry	1996	3	10,000	Federal Energy Code 10 CFR 435 (Based on ASHRAE 90.1 - 1989)	DOE-2 Simulation	29										42				Daylighting through High Clerestory Windows, Two-Stage Evaporative Cooling, Overhangs, T-8 Lamps, Instantaneous Hot-Water Heater, Well-Insulated Thermal Envelope
6	Stein & Taylor (2005)	Electric Arts Phase II Building	Temperate & Mixed	2002	4	350,000	CEC Title 24 Standards	DOE-2 Simulation											40				UFAD System, Primary-only Variable Flow, High-Efficiency Chillers, High-Efficiency Cooling Towers with VAV Fans, High Chilled Water Delta T
7	Blaevoet (2005)	Hamilton Landing Project (A Retrofit of a 70-year-old Air Force Base Hanger)	Temperate & Mixed	1998	2	58,000 / Hanger	CEC Title 24 Standards	n/a										30					UFAD System
8	Callaway et al. (1998)	General Services Administration's (GSA) Chet Holifield Building	Hot & Dry	1974	6	915,320	Energy Use of 1993 - 1994	Utility Bills										29					Energy Efficient Chillers, AHUs, Lighting, and EMCS
9	EPA (2001)	U.S. EPA Research Triangle Park Campus	Temperate & Humid	2001	Multiple Bldgs	1,170,000	Conventional Construction	Carrier Hourly Analysis Program							281					52 -	-64		Solar Cooling Loads,Daylighting for Energy Efficiency, Hot Water Loads, Lamp Ballasts, High-performance Windows and Doors, Ventilation Systems, Lighting Controls
10	EPA (2001)	EPA Research Triangle Park Campus, Typical Office Wing	Temperate & Humid	2001	7% of a 3-story building	73,000	Conventional Construction	DOE-2 Simulation	28											52 -	-64		Solar Cooling Loads, Daylighting for Energy Efficiency, Lamp Ballasts, Lighting Controls
11	EERE (2006)	National Wildlife Federation New Headquarters Office Building	Cool & Humid	2000	3	95,000	n/a	Utility Bills			61												Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Water Heaters, Cooling Systems, Light Levels, Standby Heat Loss, Light Sources, Lighting Controls, HVAC Controls and Zoning
12	EERE (2006)	The Nature Conservancy New Headquarters Building	Cool & Humid	1999	8	172,000	n/a	Utility Bills				80											Light Sources, Heating Systems, HVAC Controls and Zoning
13	Lippe (1997)	The Conde Nast Building at Four Times Square (4 Times Square)	Cool & Humid	2000	48	1,600,000	n/a	DOE-2 Simulation			64												Daylighting for Energy Efficiency, Hot Water Loads, Cooling Systems, Light Levels, Photovoltaics, Light Sources, Motors, High-performance Windows and Doors, Ventilation Systems, Lighting Controls, HVAC Controls and Zoning
14	EERE (2006)	PNC Firstside Center	Cool & Humid	2000	5	647,000	n/a	Utility Bills					100										HVAC Distribution Systems - Hybrid air-distribution system
15	EERE (2006)	South Central Regional Office Building	Cool & Humid	1998	3	73,000	n/a	Simulation / GBTool 2000				75											Non-solar Cooling Loads, Interior Design for Light, Cooling Systems, Light Levels, Light Sources, Lamp Ballasts, Ventilation Systems, Lighting Controls
16	EERE (2006)	The Plaza at PPL Center	Cool & Humid	2003	8	280,000	ASHRAE 90.1-1999	DOE-2 Simulation				70						30					Solar Cooling Loads, Daylighting for Energy Efficiency, Cooling Systems, High-performance Windows and Doors, Ventilation Systems, Lighting Controls, HVAC Controls and Zoning
17	EERE (2006)	NOAA's Weather Forecast Office	Cold & Humid	2002	1	8,380	ASHRAE 90.1-1999	DOE-2 Simulation							141			32					Wall Insulation, Ground-coupled Systems, Daylighting for Energy Efficiency, Light Sources, High-performance Windows and Doors
18	EERE (2006)	Society for the Protection of New Hampshire Forests--French Wing	Cold & Humid	2001	2	11,600	n/a	Energysmiths					96										Wall Insulation, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Energy from Biomass, Lighting Controls, Refrigerators and Freezers, Roof Insulation

Table 2.1.1 continued.

19	Miller (1997)	Wampanoag Tribal Headquarters	Cool & Humid	1994	2	8,700	n/a	Utility Bills		30													Wall Insulation, Daylighting for Energy Efficiency, Interior Design for Light, Water Heaters, High-performance Windows and Doors, Heating Systems, Air Infiltration, Ventilation Systems, Lighting Controls, Roof Insulation
20	EERE (2006)	The Brewery Blocks--Brewery Block 4	Temperate & Mixed	2003	10	241,000	ASHRAE 90.1-1999	DOE-2 Simulation				71					24						Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Cooling Systems, Photovoltaics, High-performance Windows and Doors, HVAC Distribution Systems
21	EERE (2006)	NBVC Port Hueneme Energy and Sustainability Showcase Building	Temperate & Mixed	2001	1	17,000	CEC Title 24 Standards	DOE-2 Simulation		40										55			Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Water Heaters, Cooling Systems, Light Levels, Photovoltaics, Light Sources, High-performance Windows and Doors, Lighting Controls, PV providing 68% of total energy
22	EERE (2006)	Energy Resource Center	Hot & Dry	1995	2	123,000	CEC Title 24 Standards	Utility Bills			68								40				Solar Cooling Loads, Daylighting for Energy Efficiency, Cooling Systems, High-performance Windows and Doors, Lighting Controls, HVAC Controls and Zoning, Roof Insulation
23	EERE (2006)	Pierce County Environmental Services Building	Temperate & Mixed	2002	2	50,000	Washington State Energy Code	DOE-2 Simulation				82					15						Daylighting for Energy Efficiency, Cooling Systems, Light Levels, HVAC Distribution Systems
24	Froeschle (1998)	Ridgehaven Office Building	Hot & Dry	1995	1	78,000	Conventional Construction & CEC Title 24 Standards	DOE-2 Simulation	24											50	60		Solar Cooling Loads, Non-solar Cooling Loads, Cooling Systems, Light Sources, HVAC Controls and Zoning, Computers and office Equipment
25	EERE (2006)	Thoreau Center for Sustainability	Temperate & Mixed	1996	2	73,000	n/a	Utility Bills / DOE-2 Simulation		41													Daylighting for Energy Efficiency, Non-solar Cooling Loads, Light Levels, Photovoltaics, Light Sources, Lamp Ballasts, Heating Systems, Ventilation Systems Lighting Controls
26	EERE (2006)	NREL Wind Site Entrance Building	Cool & Dry	2002	1	160	n/a	Metered Data		45												80	Daylighting for Energy Efficiency, Photovoltaics, Light Sources, High-performance Windows and Doors, Heating Systems, Computers and office Equipment
27	Kamin (2002)	Chicago Center for Green Technology	Cool & Humid	2003	2	40,000	ASHRAE 90.1-1999	DOE-2 Simulation		33									40				Ground-coupled Systems, Solar Cooling Loads, Daylighting for Energy Efficiency, High-performance Windows and Doors, Lighting Controls, HVAC Controls and Zoning, PV providing 20% of total energy
28	EERE (2006)	Herman Miller MarketPlace	Cold & Humid	2002	2	95,000	ASHRAE 90.1-1999	Utility Bills					100						40				Daylighting for Energy Efficiency, Use large exterior windows and high ceilings to increase daylighting, Interior Design for Light, Cooling Systems, Light Levels, Light Sources, High-performance Windows and Doors, Heating Systems, HVAC Controls and Zoning, Computers and office Equipment, Roof Insulation
29	EERE (2006)	C. K. Choi Building for the Institute of Asian Research	Temperate & Mixed	1996	3	34,400	n/a	Utility Bills		42													Wall Insulation, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Interior Design for Light, Light Levels, Luminaires, Lighting Controls
30	EERE (2006)	The Barn at Fallingwater	Cool & Humid	2004 (Renovation)	2	13,000	ASHRAE 90.1-1999	Utility Bills		35									38				Wall Insulation, Ground-coupled Systems, Non-Solar Cooling Loads, Light Sources, Ventilation Systems, Lighting Controls, HVAC Controls and Zoning
31	EERE (2006)	Natural Lands Trust Headquarters Renovation and Expansion	Cool & Humid	2001	2	16,500	n/a	eQUEST		31													Ground-coupled Systems, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-Solar Cooling Loads, Heating Loads, Lighting Controls
32	Miller (1997)	Norm Thompson Corporate Headquarters	Temperate & Mixed	1995	2	54,500	n/a	Utility Bills			60												Wall Insulation, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-Solar Cooling Loads, Cooling Systems, Light Levels, Light Sources, High-performance Windows and Doors, Ventilation Systems, Lighting Controls, HVAC Controls and Zoning
33	EERE (2006)	ORNL East Campus Private Development	Temperate & Humid	2003	4 3-Story Bldgs	Total 376,000	Conventional Construction	Utility Bills							263		23						Wall Insulation, Cooling Systems, Motors, High-performance Windows and Doors, Heating Systems, Air Infiltration, Lighting Controls, HVAC Distribution Systems, HVAC Controls and Zoning, Computers and Office Equipment, Refrigerators and Freezers, Roof Insulation
34	EERE (2006)	Woods Hole Research Center	Cool & Humid	2003	3	19,200	ASHRAE-Compliant Building	Metered Data	16													83	Wall Insulation, Ground-coupled Systems, Solar Cooling Loads, Daylighting for Energy Efficiency, Water Heaters, Photovoltaics, High-performance Windows and Doors, Heating Systems, Ventilation Systems, Lighting Controls, HVAC Controls and Zoning
35	Sylvester et al. (2002)	Robert E. Johnson State Ofice Building	Hot & Humid	1998	6	303,389	Conventional Construction	DOE-2 Simulation							148				45				Low-e Window Glazing, Motion Sensors for Lighting Control, Daylighting Dimming Systems with Light Shelves, High-Albedo Roof, Dual-Duct Aariable Air Volume System, Enthalpy Heat Recovery System, High-Efficiency Low NOx Boiler, High-Efficiency Centrifugal Chiller, Primary-Secondary Chilled Water Loops, Variable Frequency Drive (VFD) on the Secondary Loop, Oversized Cooling Tower, Low Head Pump

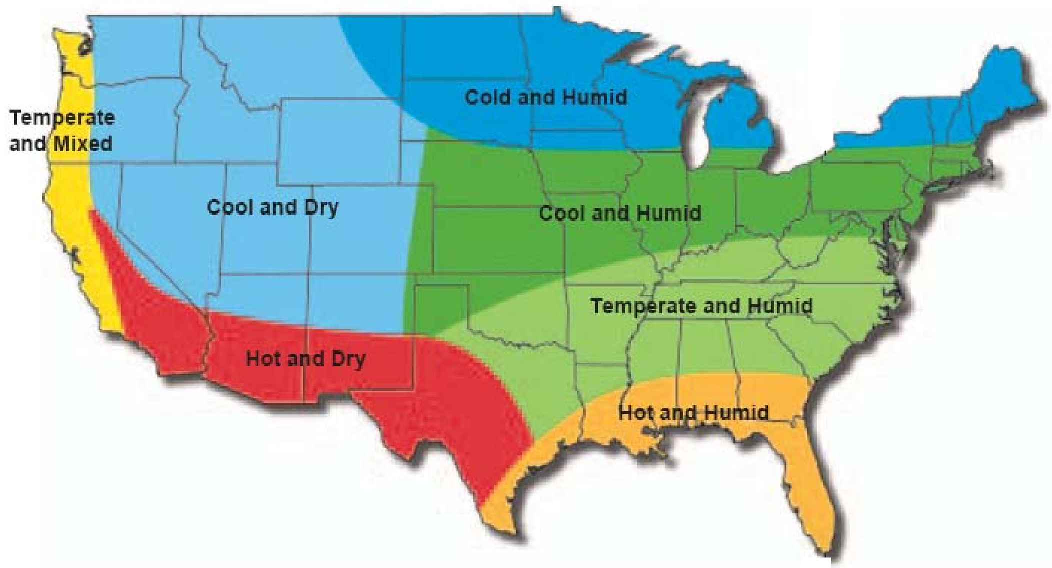

Figure 2.1.1 Map of the Climate Zones in the United States (USDOE, 2002).

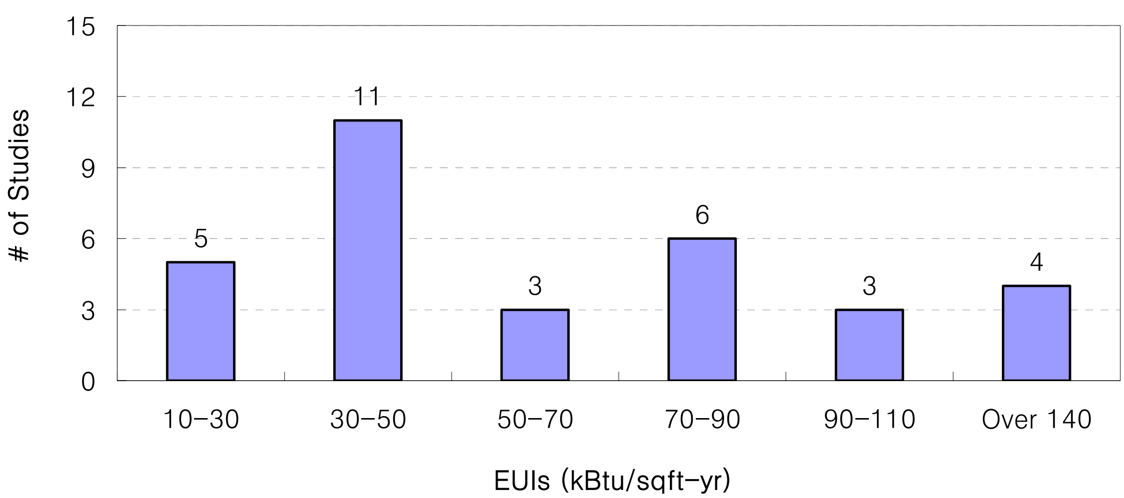

Figure 2.1.2 Energy Use Indices (EUIs) of High-performance Buildings.

2.1.2 Energy Savings of High-performance Buildings

The percentage of energy savings of high-performance buildings were also reported in comparison with several different baselines. When building energy use comparisons were made with conventional buildings, savings of 52-64% were reported. Savings of 24-40% were reported for buildings that were compared to ASHRAE Standard 90.1-2001 (ASHRAE, 2001) compliant buildings. In addition, savings of 40-50% were reported for buildings that were compared to California's Title 24 Standards (CEC, 2001). Although the baselines were minimum code requirements, the energy savings from the high-performance buildings were substantial, which means that many of these buildings are operating at substantially less energy use levels.

2.1.3 Evaluation Tools of Energy Savings of High-performance Buildings

The energy savings of these case-study buildings were calculated mainly with DOE-2.1e (LBNL, 1981) simulations (17 case studies) and its derivative such as eQUEST (eQUEST, 2008) and utility bill comparisons (12 case studies). Only a few studies had metered data comparisons (2 studies). From the review it was clear that the DOE-2.1e building energy simulation program was the most commonly used tool to evaluate the building energy performances. However, very few of the studies provided enough details so that future efforts could be made to replicate the studies.

2.1.4 High-performance Buildings in Hot and Humid Climates

Interestingly enough, as shown in Table 2.1.1 and Table 2.2.1, only a few high-performance buildings were identified in hot and humid climates such as the Robert E. Johnson (REJ) building in Austin, TX (Song, 2006; Sylvester et al., 2002) and the Florida Solar Energy Center (FSEC) building (Parker et al., 1997). In the REJ building analysis, Song developed a baseline simulation model calibrated to the measured whole-building energy consumption to determine the independent and combined effects of the efficient components installed in the building. In this study it was shown that the energy savings resulting from the new design reduced the energy use by 46% when compared to similar state office buildings (Sylvester et al., 2002). Also, it was reported that this building was 21% and 2% more energy-efficient than the ASHRAE Standard Standard 90.1-1989 and 90.1-2001 models, respectively (Song, 2006). This study seems to indicate that there is significant potential to save energy in office buildings in hot and humid climates. This study implied that it is necessary to design and construct high-performance buildings using high-performance HVAC systems and components, which are best optimized for hot and humid climates.

2.1.5 Summary of High-performance Buildings

The high-performance buildings reviewed showed substantially lower EUI values compared to those of the conventional buildings. In these buildings, the energy savings of high-performance buildings were significant, ranging from 24% to 64% compared to energy code-compliant baselines. The EUIs and energy savings numbers from the high-performance buildings reviewed were referenced for developing the high-performance building model for the current study. The DOE-2.1e simulation program was utilized as one of several programs to develop a methodology for an energy performance evaluation tool for the selection of high-performance components.

2.2 High-performance Systems and Components

High-performance systems and system components were reported in a number of different climates. In the survey of high-performance systems and components, a total of 17 papers or reports were selected and reviewed. Table 2.2.1 summarizes the literature and shows system types, applications, climate zones, and energy savings obtained from using high-performance systems or components. The climate zones were indicated using the map of Figure 2.1.1. In this section, the high-performance systems and components, which are at the source of a high-performance building, are introduced based on the literature survey. Of the 17 papers, Torcellini et al. (2004) and Parker et al. (1997) are significant papers showing high-performance building systems and components.

2.2.1 Analysis of Six High-performance Buildings (Torcellini et al., 2004)

In this study, the authors analyzed the performance of six high-performance buildings.

Table 2.2.1 Literature Summary of High-performance Building Systems and Components.

No.	Authors	Classification	Application	Climate Zone	Location	# Bldgs Analyzed	Size (ft2)	Energy Use Analysis	Energy Savings (%)							Remarks
									10	20	30	40				
1	Stein & Taylor (2005)	HVAC System	UFAD System	Temperate & mixed	San Francisco, CA	1	350,000	DOE-2 Simulation				40				UFAD System, Primary-only Variable Flow, High-Efficiency Chillers, High-Eficiency Cooling Towers with VAV Fans, High Chilled Water Delta T
2	Blaevoet (2005)	HVAC System	UFAD System	Temperate & mixed	California	1	58,000 / Hanger	n/a			30					UFAD System
3	Callaway et al. (1998)	HVAC System	High Efficient Chillers	Hot & Dry	Laguna Niguel, CA	1	915,320	Utility Bills			29					Energy Efficient Chillers, AHUs, Lighting, and EMCS
4	Deru et al. (2005)	HVAC System	Ground Source Heat Pump	Cool & Humid	Ebensburg, PA	1	36,000	DOE-2 Simulation				40				Wall Insulation, Ground-coupled Systems, Daylighting for Energy Efficiency, Photovoltaics, Lamp Ballasts, High-performance Windows and Doors, Ventilation Systems, Lighting Controls, Roof Insulation, PV providing 28% of total energy use
5	Deru et al. (2005)	Envelope	Daylighting, Roof Insulation	Cool & Dry	Silverthorne, CO	1	44,400	DOE-2 Simulation			35					Wall Insulation, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Interior Design for Light, Photovoltaics, Foundation Insulation, High-performance Windows and Doors, Heating Systems, Lighting Controls, Roof Insulation, PV providing 5-10% of total energy
6	Griffith et al. (2005)	HVAC System / Envelope	Natural Ventilation	Cool & Humid	Annapolis, MD	1	32,000	EnergyPlus Simulation		25						Wall Insulation, Ground-coupled Systems, Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Water Heaters, Cooling Systems, Photovoltaics, Heating Loads, Lamp Ballasts, High-performance Windows and Doors, Lighting Controls, HVAC Controls and Zoning, Roof Insulation
7	Torcellini et al. (2005)	HVAC System / Envelope	Natural Ventilation, Cool Towers / Daylighting, Overhangs	Cool & Dry	Springdale, UT	1	8,800 & 2,756	DOE-2 Simulation						62		Daylighting, Natural Ventilation, Cooltowers, Passive Solar Heating, Solar Load Control with Engineered Overhangs, Computerized Building Controls, Uninterrupted Power Supply System Intergrated with PV System
8	Torcellini et al. (2005)	Envelope	Daylighting, Overhangs, Thermal Envelope	Cool & Dry	Golden, CO	1	10,000	DOE-2 Simulation				42				Daylighting through High Clerestory Windows, Two-Stage Evaporative Cooling, Overhangs, T-8 Lamps, Instantaneous Hot-Water Heater, Well-Insulated Thermal Envelope
9	Parker et al. (1997)	HVAC System / Envelope	Daylighting / Helical-Rotary Screw Chillers	Hot & Humid	Cocoa, FL	1	41,000	DOE-2 Simulation						62		T-8 Fluorescent Lamps, High-Performance Windows, Reflective Roof, Daylighting, High-Efficiency Chillers, Central Fresh Air Unit with Heat Pipe Heat Exchanger, VAV System
10	Khattar et al. (2003)	HVAC System	Dual-Path & Thermal Storage Systems	Hot & Humid	Rockledge, FL	1	86,000	Utility Bills		22						Dual-Path System, Ice Storage System,
11	Lippe (1997)	HVAC System / Envelope	Daylighting / PV Systems	Cool & Humid	New York, NY	1	1,600,000	DOE-2 Simulation								Daylighting for Energy Efficiency, Hot Water Loads, Cooling Systems, Light Levels, Photovoltaics, Light Sources, Motors, High-performance Windows and Doors, Ventilation Systems, Lighting Controls, HVAC Controls and Zoning
12	EERE (2006)	HVAC System	Hybrid Air Distribution System	Cool & Humid	Pittsburgh, PA	1	647,000	Utility Bills								HVAC Distribution Systems - Hybrid air-distribution system
13	EERE (2006)	HVAC System	Ground Coupled System	Cold & Humid	Caribou, ME	1	8,380	DOE-2 Simulation			32					Wall Insulation, Ground-coupled Systems, Daylighting for Energy Efficiency, Light Sources, High-performance Windows and Doors
14	EERE (2006)	HVAC System / Envelope	Daylighting / PV System	Temperate & Mixed	Port Hueneme, CA	1	17,000	DOE-2 Simulation						55		Solar Cooling Loads, Daylighting for Energy Efficiency, Non-solar Cooling Loads, Water Heaters, Cooling Systems, Light Levels, Photovoltaics, Light Sources, High-performance Windows and Doors, Lighting Controls, PV providing 68% of total energy
15	EERE (2006)	HVAC System / Envelope	Daylighting / PV System	Temperate & Mixed	San Francisco, CA	1	73,000	Utility Bills / DOE-2 Simulation								Daylighting for Energy Efficiency, Non-solar Cooling Loads, Light Levels, Photovoltaics, Light Sources, Lamp Ballasts, Heating Systems, Ventilation Systems Lighting Controls
16	EERE (2006)	HVAC System / Envelope	Daylighting / PV System	Cool & Dry	Golden, CO	1	160	Metered Data							80	Daylighting for Energy Efficiency, Photovoltaics, Light Sources, High-performance Windows and Doors, Heating Systems, Computers and office Equipment
17	Kamin (2002)	HVAC System / Envelope	Daylighting / PV System, Ground Coupled System	Cool & Humid	Chicago, IL	1	40,000	DOE-2 Simulation				40				Ground-coupled Systems, Solar Cooling Loads, Daylighting for Energy Efficiency, High-performance Windows and Doors, Lighting Controls, HVAC Controls and Zoning, PV providing 20% of total energy

These buildings were originally built with goals of energy efficiency and sustainability without compromising environmental elements. To achieve these goals, high-performance systems were implemented in the buildings, which included improved thermal envelopes, daylighting, radiant heating, natural ventilation, mixed-mode ventilation, ground source heat pumps, photovoltaic, and passive solar systems.

The authors used computer simulation tools (DOE-2.1e for five buildings and EnergyPlus for one building) to evaluate the energy performance of the buildings. The results showed that all buildings performed significantly better than the minimum code requirements (i.e., energy cost savings from 44% to 67% compared to ASHRAE Standard 90.1-2001 or the Federal Energy Code 10 CFR 435). The high-performance features, identified from the previous research, were investigated and evaluated to see if they are appropriate for implementation in this research.

2.2.2 Florida Solar Energy Center Building (Parker et al., 1997)

The study presented the energy performance of the new Florida Solar Energy Center (FSEC) building using the DOE-2.1e simulation program. The FSEC's building was designed to be a maximum energy efficient building in Florida's hot and humid climate. The DOE-2.1e simulation program calculated the building energy consumption using ten high-performance systems, which included lighting, glazing, daylighting, HVAC (Heating, Ventilating, and Air-Conditioning) system, humidity control, Energy Star equipment, a reflective roof, variable-speed fans and pumps, demand controlled ventilation, and an Energy Management System (EMS). Because of the regional characteristics (hot and humid), careful attention was given to the humidity control. Overall, the optimized building with the implementation of the ten high-performance systems showed an energy reduction of 62% (EUIs reduction from 71 kBtu/ft2-yr to 27 kBtu/ft2-yr) and cooling capacity decrease by 52% compared to the energy use of the base-case building that has conventional commercial building characteristics for Florida. The base-case building was simulated using the DOE-2.1e program and had an EUI of 71 kBtu/ft2-yr, with a cooling capacity of 128 tons (i.e., 320 ft2/ton). The ten high-performance systems, which contributed the energy savings to the FSEC project, were included as options for the development of the high-performance building model in this research.

2.2.3 USDOE's Commercial Building DOAS Study (Roth et al., 2002)

The authors reported fifteen high-performance commercial building systems and components in the study 'Energy Consumption Characteristics of Commercial Building HVAC Systems'. This study included a detailed evaluation for each of the fifteen technologies. Five of the fifteen technologies, for example, were: dedicated outdoor systems (or dual-path systems), displacement ventilation, enthalpy/energy recovery heat exchangers, liquid desiccant systems, and/or radiant ceiling cooling systems. Roth et al. also showed energy savings potentials from these technologies, including: 15-20%

savings of space cooling energy from Dedicated Outdoor Air Systems (DOAS) compared to conventional VAV systems, 9-69% savings of cooling energy use from Displacement Ventilation (DV) systems implemented in office buildings in five U.S. cities (Albuquerque-23%, Chicago-21%, Fort Worth-9%, New York-23%, and San Francisco-69%) compared to conventional VAV systems, 35% savings of annual heating and cooling energy consumption from enthalpy/energy recovery heat exchangers applied in a New York office building, 20-25% savings of outdoor air cooling energy from liquid desiccant systems (in combination with a DOAS) compared to conventional systems, and 15-20% of space cooling energy from radiant ceiling cooling systems (in combination with a DOAS) compared to conventional VAV systems.

2.2.4 Summary of High-performance Systems and Components

In summary, the major systems or components implemented in the high-performance studies, including technologies not only from the above three studies but also from other case studies, were high-performance glazing, occupancy sensors, HVAC controls, energy-efficient chillers and boilers, solar energy systems, Dedicated Outdoor Air Systems (DOAS), Under Floor Air Distribution (UFAD) systems, Ground Source Heat Pump (GSHP) systems, natural ventilation systems, and daylighting systems. These high-performance systems and components were analyzed to develop high-performance simulation model.

2.3 Building Energy Simulation Programs

A number of building energy simulation programs are currently available from public domain and private sources. Building energy simulation programs have become a required building design and performance evaluation tool for high-performance buildings. General-purpose public domain energy simulation programs in the U.S. include DOE-2.1e (LBNL, 1981), BLAST (BSO, 1993), TRNSYS (Klein et al., 1973), and EnergyPlus (DOE, 2001).

In addition to the general-purpose simulation programs, special purpose programs have been developed over the years for calculating solar energy availability such as F-Chart (Beckman et al., 1977), PV F-Chart (Klein and Beckman, 1983), T*SOL (Valentin, 2008), PV*SOL (Valentin, 2008), PVSYST (CUEPE, 2008), and PVWatts (Energy Grid, 2008). For this research, the DOE-2.1e simulation program and the solar energy analysis tools, F-Chart and PV F-Chart, were used to develop an energy performance evaluation tool for the selection of high-performance components in office buildings in hot and humid climates. The following are descriptions and accuracies of the programs.

2.3.1 DOE-2.1e Simulation Program

DOE-2.1e, developed by the Lawrence Berkeley Laboratory, is a public-domain general-purpose building energy simulation program. The DOE-2.1e program calculates hourly building energy consumption and the energy costs based on the inputs of hourly weather data, building description, Heating, Ventilating, and Air-Conditioning (HVAC) system information, schedules, and plant information. This program is capable of modeling the thermal performance of buildings as well as analyzing the daylight behavior of selected windows with the aid of the Window 5 program (LBNL, 2001), which calculates the thermal performance of windows adopting the National Federation Rating Council (NFRC) procedures.

The reported uncertainty of the DOE-2.1e program was reviewed by Haberl and Cho (2004a) where it was found that DOE-2.1e simulations versus measured data (Empirical Validation) were shown to be within 10% in 33 of 47 studies and within 26% in 14 of 47 studies. DOE-2.1e simulations versus simulations by other programs (Comparative Test) showed agreement in the 1% to 30% range (1% to 15% when weighted). DOE-2.1e simulations versus analytical calculations (Analytical Verification) were shown to vary from 0% to 5%. Sensitivity tests revealed that DOE-2.1e versus analytical calculation was shown to be within 0.2% to 18.7%. Even though there are some limitations on using the DOE-2.1e program regarding the daylighting calculations such as light shelves (Baker, 1990; LBNL, 1993), the DOE-2.1e program is considered one of the most accurate energy simulation programs for the research in terms of capabilities and reliabilities.

2.3.2 F-Chart Solar Thermal Systems Analysis Program

The F-Chart Method, developed at the University of Wisconsin, is a correlation based on simulations that is useful for the design of active and passive solar heating systems, especially for selecting the size and type of solar collectors supplying the hot water and space heating loads. The F-Chart method consists of correlations of the results of a large number of detailed simulations using TRNSYS, a transient systems simulation program by Klein et al. (1976). The main parameters that the F-Chart method requires are two values to describe the solar collector thermal performance: the solar collector thermal performance curve slope (FRUL, Btu/hr-ft2-F) and intercept (FR(τα), %) from standard collector tests. These parameters include the FR (Collector Efficiency Factor), UL (Collector Overall Energy Loss Coefficient) and τα (Transmittance-Absorptance Product). F-Chart estimates the long-term average performance of the solar thermal systems, by calculating average monthly, daily energy performance.

Haberl and Cho (2004b) also reviewed the reported accuracy of the F-Chart method by reviewing the related accuracy of TRNSYS simulations versus measured data, F-Chart predictions versus measured data, F-Chart predictions versus TRNSYS simulations, and F-Chart predictions versus other methods. Hourly TRNSYS simulations versus measured data were shown to be within 5 to 6%, F-Chart predictions versus measured data showed agreement in the 2 to 15% range, and F-Chart predictions versus TRNSYS simulations were shown to vary from 1.1% to 4.7%. A significant number of studies used F-Chart to assess the accuracy of newly developed methods. In these studies agreement varied from 2.5% to 9%. The F-Chart method was therefore used to design solar thermal systems for hot water use and space heating and the results were integrated into the DOE-2.1e simulation model in this research.

2.3.3 PV F-Chart Solar PV Systems Analysis Program

The PV F-Chart Method is an analysis that is useful for the design of photovoltaic (PV) systems and for the estimation of the long term average performance of PV systems with direct utility connection, battery storage systems, and stand-alone systems without batteries. The PV F-Chart method consists of a combination of correlations and fundamental expressions for the hourly calculations of solar radiation at a given location. It uses long-term monthly average solar radiation and ambient temperature to predict the annual performance of a photovoltaic array.

Haberl and Cho (2004c) reviewed the reported uncertainty of the PV F-Chart analysis method by reviewing the published related accuracy of PV F-Chart analysis versus measured data, PV F-Chart predictions versus other methods, and PV F-Chart predictions versus TRNSYS simulations. It was found that hourly PV F-Chart analysis versus measured data were shown to be within 4% of on-site measurement, and PV F-Chart predictions versus TRNSYS simulations and another graphical method were also within 4% of annual values. Therefore, PV F-Chart method was be utilized to design the photovoltaic systems for this research.

2.3.4 Summary of Simulation Programs

In summary, the thermal energy analysis of the case-study building was performed using the DOE-2.1e simulation program that offers a wide capability for simulating design features. In addition, the solar system analysis tools, F-Chart and PV F-Chart, were used along with the DOE-2.1e simulation model for the development of an energy performance evaluation tool for the selection of high-performance components, which can be used for the construction of high-performance buildings in hot and humid climates.

2.4 Calibrated Simulation

There have been a number of studies to calibrate simulations to measured data from existing commercial buildings using the DOE-2.1e simulation program. These include studies using monthly utility billing data (Diamond and Hunn, 1981; McLain et al., 1994), using hourly measured data (Hsieh, 1988; Hinchey, 1991; Kaplan et al., 1990a and 1992; Bronson et al., 1992; Huang, 1994; Haberl et al., 1995; Huang and Crawley, 1996; Haberl and Bou-Saada, 1998; Abushakra et al., 2001; Reddy, 2004; Song, 2006; Kim, 2006; Kootin-Sanwu, 2004; Rasisuttha, 2005;), and using in-situ measurement data from equipment (Phelan et al., 1997a and 1997b; Haberl et al., 1997; Liu et al., 2002).

The calibrated simulation methodologies can also be categorized into three groups such as manual and iterative calibrations (Diamond and Hunn, 1981; TRC, 1984; Hsieh, 1988; Kaplan et al., 1990a & 1990b; Hunn et al., 1992; Bronson, 1992; Reddy et al., 1994; Norford et al., 1994; Haberl et al., 1995; Lunneberg, 1999; FEMP, 2000; Abushakra et al., 2001; IPMVP, 2002; ASHRAE, 2002; Pedrini et al., 2002; Sylvester, 2002; Yoon et al., 2003; Kootin-Sanwu, 2004; Kim, 2006; and Pan et al., 2006), graphical and statistical analysis (Kreider and Haberl, 1994a & 1994b; Haberl and Thamilseran, 1996; Bou-Saada and Haberl, 1995; Haberl et al., 1996; Haberl and Abbas, 1998; Haberl and Bou-Saada, 1998; FEMP, 2000; IPMVP, 2002; and ASHRAE, 2002), and signature analysis (Katipamula, 1993; Liu and Claridge, 1998; Wei et al., 1998; Liu et al, 2003 & 2004; and Song, 2006). In the sections that follow descriptions of each method of calibrated simulation are provided.

2.4.1 Manual and Iterative Calibration

The manual and iterative calibration has been the most popular approach. Figure 2.4.1 and **Error! Reference source not found.** show the history of the manual and iterative calibration methods. In general these methods involve utility data comparison, walk-through audits, and short-term monitoring.

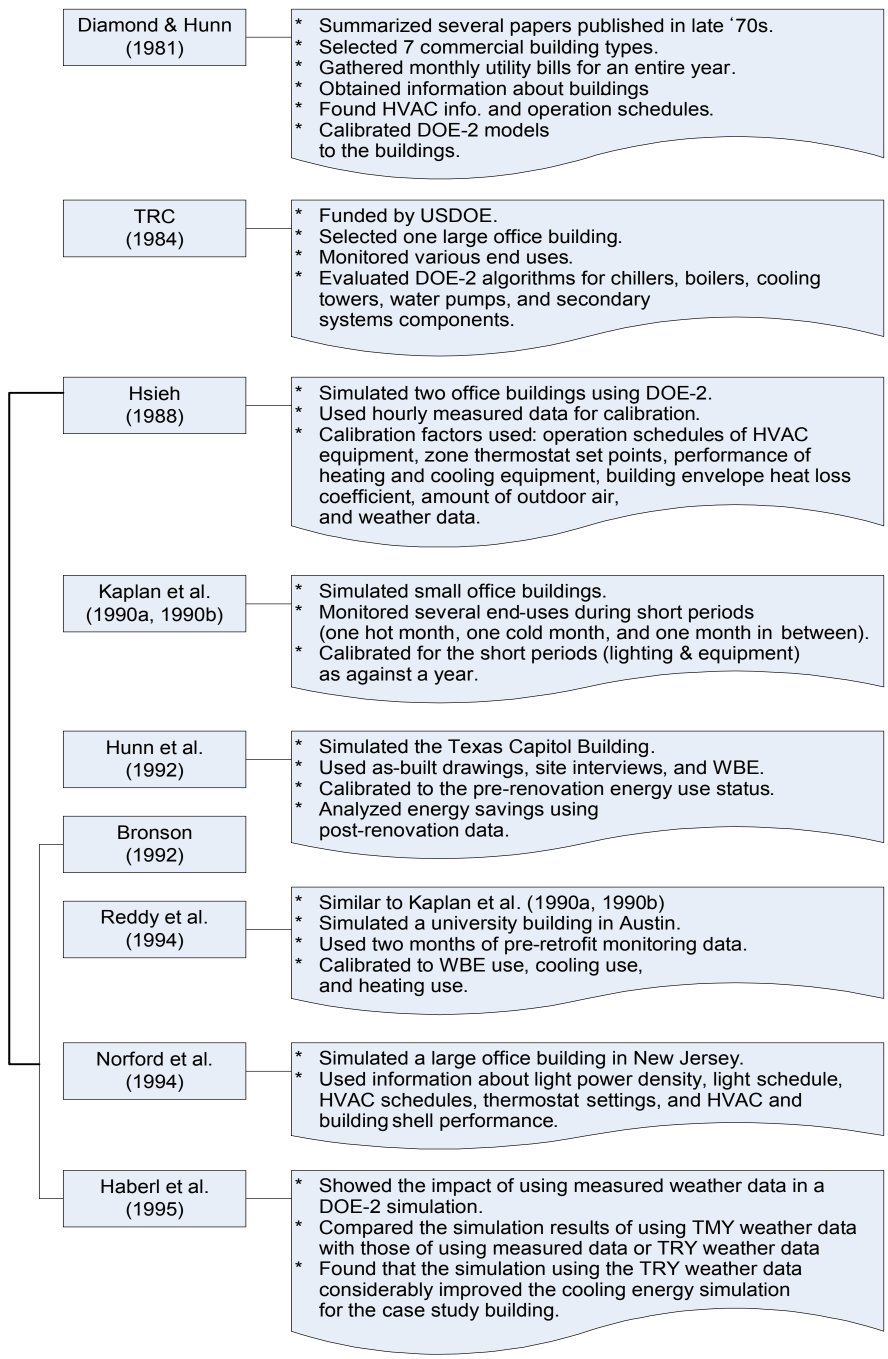

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Figure 2.4.1 Literature Review on Calibrated Simulation – Manual and Iterative Method (1981-1995).

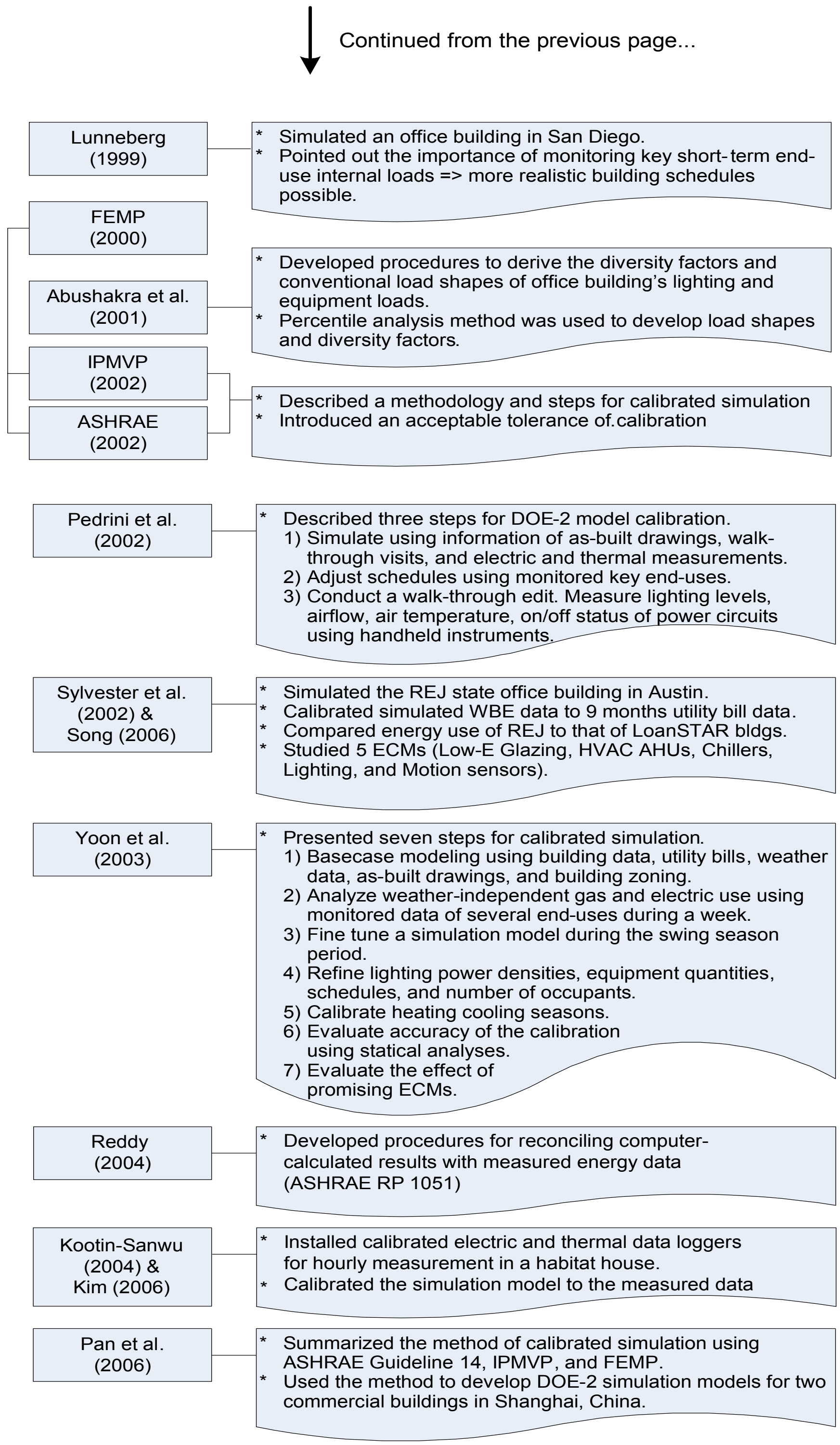


Figure 2.4.2 Literature Review on Calibrated Simulation – Manual and Iterative Method (1999-2008).

To obtain a calibrated simulation model, the procedures were applied in an iterative fashion using heuristics or rules-of-thumb to determine how much to adjust the simulation when differences were observed.

Diamond and Hunn (1981) first summarized several reports written in late 1970's about the calibration of detailed building simulation programs. In this paper, they showed the results from seven commercial building types. They gathered monthly utility bills for an entire year, obtained information about the buildings, HVAC information and operating schedules, and then calibrated the DOE-2.1e simulation models to the buildings by adjusting the simulation inputs until the output from the simulation matched the measured data.

Next, Hsieh (1988) developed a general calibration procedure using DOE-2.1e simulation of two office buildings. The calibration factors that Hsieh used were the operation schedule of the HVAC equipment, zone thermostat set points, variations in the efficiencies of heating and cooling equipment, a building envelope heat loss coefficient, variations in the amount of outside air, and different types of weather data. Hourly measured data were extensively used in Hsieh's. Haberl et al. (1995) also showed the impact of using measured weather data in a DOE-2.1e simulation. They compared the simulation results of using the Typical Meteorological Year (TMY) weather data with those of using measured data or Test Reference Year (TRY) weather data. It was found that the simulation using the TRY weather data considerably improved the cooling energy simulation for their case-study building.

Abushakra et al. (2001) developed procedures to derive the diversity factors and conventional load shapes of office building lighting and equipment loads. In their study, a percentile analysis method was used to develop load shapes and diversity factors. This is an improvement over earlier studies that calibrated the lighting and equipment data input into the DOE-2.1e simulation, such as Kaplan et al. (1990a and 1990b) who showed how to incorporate monitored lighting and equipment data into the DOE-2.1e default values, but did not provide statistical tools for accomplishing the feat. In 2006, Pan et al. summarized the method of calibrated simulation using ASHRAE Guideline 14-2002 (ASHRAE, 2002), IPMVP (IPMVP, 2002), and FEMP (FEMP, 2000). Pan et al. used the method to develop DOE-2.1e simulation models for two commercial buildings in Shanghai, China. In summary, many important calibration factors were identified from the previous studies on manual and iterative calibrations. These calibration features were utilized for the calibration of the case-study building of this study.

2.4.2 Graphical and Statistical Analysis

The second analysis procedure involves the use of both graphical and statistical analysis methods. The graphical and statistical analysis is a method to highlight differences between measured and simulated results with certain types of visual graphs.

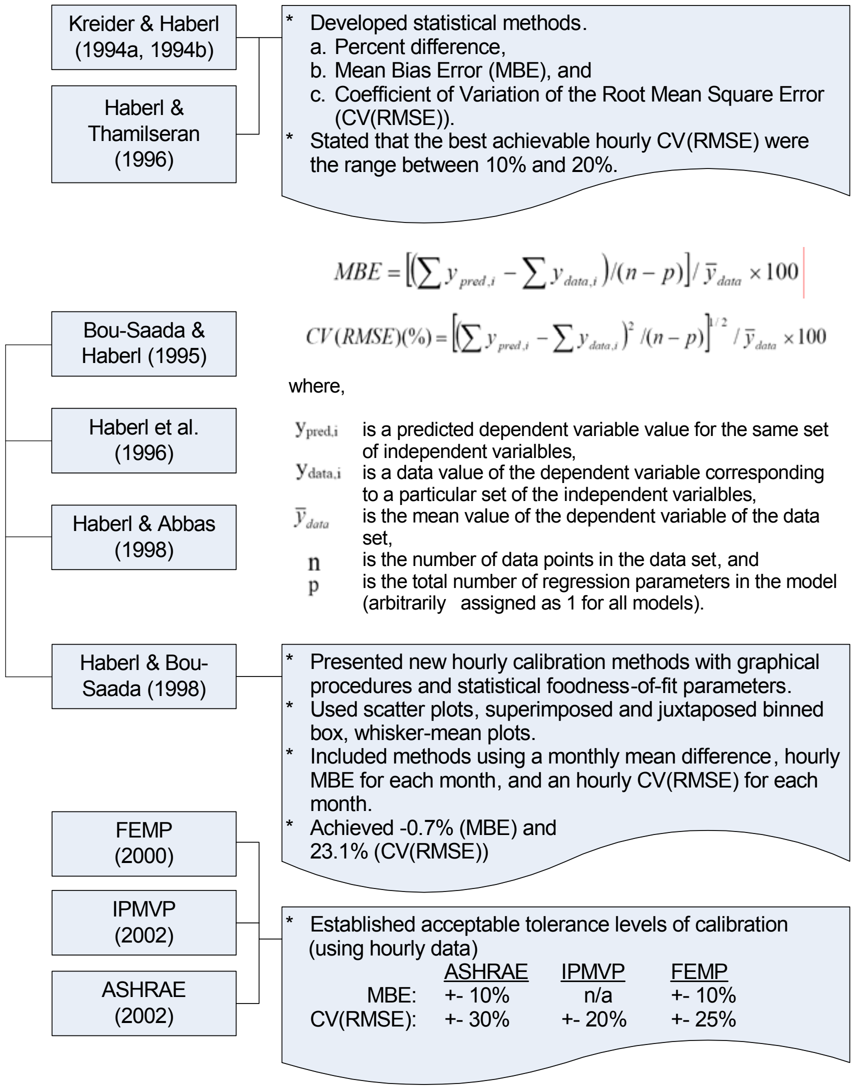


Figure 2.4.3 Literature Review on Calibrated Simulation – Graphical and Statistical Analysis.

Figure 2.4.3 shows the history of this analysis. This is a very useful technique to help decide which parameters need to be calibrated for the next iteration. In addition to graphical techniques, Kreider and Haberl (1994a & 1994b) and Haberl and Thamilseran

(1996) used statistical methods such as percent difference, Mean Biased Error (MBE), and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) to assist with quantifying the progress of the calibration.

In these reports, it was claimed that the best achievable hourly CV(RMSE) was in the range between 10% and 20%. In 1998, Haberl and Bou-Saada (Haberl and Bou-Saada, 1998) presented new hourly calibration methods with graphical procedures and statistical goodness-of-fit parameters.

They used scatter plots, superimposed and juxtaposed binned box and whisker-mean plots. Also included were methods using a monthly mean difference, hourly MBE for each month, and an hourly CV(RMSE) for each month. They achieved an hourly MBE of -0.7% and the CV(RMSE) of 23.1%. Later, as shown in Figure 2.4.3, the allowable tolerance of the MBE and CV(RMSE) using hourly data has been published in several places (FEMP, 2000; IPMVP, 2002; and ASHRAE, 2002); e.g., CV(RMSE) of +-30% (ASHRAE), +-20% (IPMVP), and +-25% (FEMP). This graphical and statistical methods were utilized for the calibration of the case-study building model.

2.4.3 Signature Analysis

Third, a signature analysis was developed as an approach for calibrated simulation. Figure 2.4.4 shows the history of the signature analysis method. Calibration signatures,

Katipamula & Claridge (1993)

* Developed in an effort to improve operation and control schedules, to diagnose malfunction of HVAC components, to predict the effect of different control changes primarily to the secondary equipment of large buildings, and to optimize their control settings.
* Calibrated against measured data of WBE, MCC, heating loads, and cooling loads on an hourly basis.

Liu & Claridge (1998)

* Extended and described the previous work in detail.
* Simplified several things:
  a. Assumed to be a two-zone building (one interior or core zone and one perimeter zone).
  b. Used average daily data and steady-state models for the calibrated simulation and analysis.
  c. One large air-handling unit (AHU) is substituted for the numerous smaller ones for each zone for similar types of AHUs.
* Presented modeling equations.
* Described calibration procedure.
* Explained the use of this approach to identify control changes.
* Important to have heating and cooling thermal load data available for this approach for robust calibration.

Wei et al. (1998)

* Developed calibration signatures that represent graphical deviation between measured and simulated energy use as a function of average dry bulb temperature.
* Energy consumption values can be whole building or system consumption.
* Energy use type can be electric (kWh) or thermal (CHW or HW use in MMBtu).

$$\textit{Calibrated signature} = \frac{\textit{- Residual}}{\textit{Maximum measured energy}} \times 100\%$$

where

Residual = Simulated consumption - Measured consumption

* The denominator is the maximum measured cooling/heating consumption: a cooling/heating calibration signature. The maximum measured energy is determined over the entire range of outside air temperatures contained in the data file being used.

Liu et al. (2003, 2004)

* Included characteristic signatures that represent a sensitivity analysis in each parameter for a building and system level.
* Charateristic signatures provide a predictable shape according to changing an input parameter by a certain amount of value based on the calibration signatures.
* Performed calibrated energy simulations of large buildings with various secondary systems:
  a. Single duct CAV b. Single duct VAV
  c. Dual duct CAV d. Dual duct VAV
* Applied to three California climates (Pasadena, Sacramento, and Oakland)

$$\textit{Characteristic signature} = \frac{\textit{Change in energy consumption}}{\textit{Maximum energy consumption}} \times 100\%$$

* Characteristic calibration signatures can be calculated using simulation programs.
* This is done by simulating the building with one value for an input parameter, then changing that input parameter by a given amount and rerunning the simulation.
* The "residuals" between these two simulations are calculated, normalized, and plotted versus outdoor air temperature
* The numerator is taken as the cooling/heating energy consumption value from the simulation with the changed input minus the baseline value at the same temperature.
* The denominator is the maximum baseline cooling/heating consumption.
* This definition then shows all changes in terms of the percent change relative to the maximum value of the cooling/heating required in the baseline case for the cooling/heating characteristic signature.
* These signatures also represent a parametric sensitivity analysis for the building and system of interest.

Song (2006)

* Used the signature analysis for the calibration of his case study building DOE-2 model.
* Statistically analyzed the characteristic signatures.

Figure 2.4.4 Literature Review on Calibrated Simulation – Signature Analysis.

which represent graphical deviations between measured and simulated energy use as a function of average dry bulb temperature, were shown to be useful for calibrating a simulation model.

Wei et al. (1998) developed the calibration signatures based on the previous efforts from Liu and Claridge (1998) and Katipamula and Claridge (1993). Liu et al. (2003 & 2004) added characteristic signatures, which represent a sensitivity analysis in each parameter for a building and system level. The characteristic signatures provide a predictable shape according to changing an input parameter by a certain amount based on the calibration signatures. Also, developed in this study were calibrated energy simulations of large buildings with various secondary systems such as single duct Constant Air Volume (CAV) system, single duct Variable Air Volume (VAV) system, dual duct CAV system, and dual duct VAV system. They applied these to three California climates.

In 2006, Song (2006) used the signature analysis method for the calibration of the case-study building in his Ph.D. dissertation, and added a statistical index to the characteristic graphical signatures that allowed for the quantification of the progress of the calibration.

In the current research, Song's signature analysis method was applied along with a graphical analysis for the calibrated simulation of the case-study building.

2.5 Easy-to-use Energy Performance Evaluation Tools

For the evaluation of building energy performance, several popular simulation programs can be used such as DOE-2.1e, BLAST, and EnergyPlus. However, these programs require significant time, money, and expertise to develop a simulation model. Currently, there are simplified and easy-to-use tools available on the internet; i.e., Energy IQ (LBNL, 2008b), BCHP Screener (ORNL, 2008b), COMCheck-web (PNNL, 2006), and eCALC (Haberl et al., 2004), which require only simple inputs and basic knowledge of building science.

EnergyIQ is a prototype web-based tool that users can benchmark existing or design-stage buildings compared to wide range of energy-related metrics for other buildings (LBNL, 2008b). This program is still under development and is available for demonstration purposes only. Three interactive internet web pages, which are Benchmarking, Actions, and MyIQ web pages, are working interfaces for users of this program. The Benchmarking web page deals with the matters in which a user finds his/her interests and benchmarks them. In the Action web page, a user can select his/her energy-efficiency opportunities among qualitative indications. The MyIQ web page manages a user's case comparing with other buildings. This program gives users good ideas of comparing their buildings' energy performance to other buildings' and allows to selecting energy efficiency measures for their buildings. However, EnergIQ does not include IAQ evaluation functions.

BCHP (Building Cooling, Heating, and Power) Screener is a tool that uses the DOE-2.1e simulation program as the main engine for evaluations of combined cooling, heating, and power in commercial buildings. This tool has a graphic user interface, so that users can easily access to the program and choose options from a computer screen. It calculates building cooling, heating, hot water, and electrical loads. In addition, the cost of site energy is calculated such as power and natural gas. Energy cost savings can be calculated for time of day rates (ORNL, 2008b). The main purpose of this tool is to assess the energy performance of existing commercial facilities. Users of this tool are to collect data from their existing facilities and set a target for energy efficiency or energy savings of their buildings.

The BCHP Screener helps users develop simulation models of their commercial buildings and evaluate energy performance and calculate energy costs. Then, users can implement Energy Conservation Measures (ECMs) into the simulation models of their buildings. This tool runs the DOE-2.1e simulation program, retrieves results from output files, and compares results between as-is simulation model and simulation model with ECMs. BCHP Screener does evaluate the indoor air quality of buildings.

ECOTECT is an environmental design tool that combines a 3-D modeling interface (Autodesk, 2008a). This tool includes solar, thermal, lighting, acoustic, and cost analysis functions. Users can play with design ideas at the conceptual design stages. As designed and developed by architects, the main focus of this tool is to help design easily and graphically as one of the most visual and interactive tools. This tool includes functions interfacing with Radiance, EnrgyPlus, and many other analysis tools such as AutoCAD DXF, ESP-r, and XML. ECOTECT does not include the analyses for indoor air quality.

The COMCheck-web program runs on the internet and provides a simple check of the code compliance of a commercial building. As intended, however, this program only deals with typical features of commercial buildings to test code compliances, so that many high-performance systems and renewable energy systems cannot be simulated. Also, this is not a performance evaluation tool but a code-compliance assessment tool only for envelope and lighting, not simulating building systems. Also, there is no function for the evaluation of indoor air quality in COMCheck-web.

In contrast to the COMCheck-web program, eCALC (Haberl et al., 2004) includes multiple functions and applications. eCALC is a web-based emissions and energy calculator developed by the Energy Systems Laboratory (ESL) at Texas A&M University. eCALC is a compilation of several legacy programs, including the DOE-2.1e program for building energy simulation analysis, the F-Chart program for solar thermal analysis, the PV F-Chart program for solar photovoltaic analysis, ASHRAE's Inverse Model Toolkit (IMT) (Kissock et al., 2002) for monthly utility billing analysis, and specifically created programs for traffic light, street light, water, waste water, and wind energy analysis. These legacy programs are categorized into three groups of models, including new building models, community projects and renewables. Once users interact with the eCALC's web interface choosing their intended analysis, the calculator directs the user to one of the legacy models.

Currently, however, the eCALC program has limited functions for modeling large office buildings. As commercial office buildings have many different environmental system types, it is necessary to have functions for systems that can improve the building energy performance. Along with the energy efficiency, the indoor air quality needs not to be compromised at the same time. The integration of solar energy analysis is also important for the building energy performance evaluation. For this research, the methodology for an integrated and easy-to-use evaluation tool was developed for the selection of high-performance components, by modifying the existing eCALC program to include several new high-performance functions. Table 2.5.1 summarizes different functionalities between easy-to-use simulation programs.

All programs include Graphic User Interfaces (GUIs). Three programs are web-based tools (i.e., eCALC, COMCheck-web, and Energy IQ) and the other three are not web-based (i.e., eQUEST, BCHP Screener, and ECOTECT). These tools mainly focus on the analysis of new buildings except two programs (i.e., BCHP Screener and Energy IQ) that deal with existing buildings. As one can easily see in the table, however, there are no tools that can provide advice about Indoor Air Quality (IAQ).

Table 2.5.1 Comparison of Internet Web-based Easy-to-use Simulation Tools.

Tools	Author	Year Develop.	Graphic User Interface	Web-Based Tool	New Building Simulation	Existing Building Simulation	Indoor Air Quality
eQUEST	Hirsch	2003	Yes	No	Yes	No	No
eCALC	Haberl et al.	2004	Yes	Yes	Yes	No	No
COMCheck-web	PNNL	2006	Yes	Yes	Yes	No	No
BCHP Screener	ORNL	2008	Yes	No	No	Yes	No
Energy IQ	LBNL	Under Develop.	Yes	Yes	No	Yes	No
ECOTECT	Autodesk	2008	Yes	No	Yes	No	No

2.6 Summary of Literature Review

This literature review presented an overview of the publicly reported high-performance buildings, high-performance environmental systems, building energy simulation tools, and the easy-to-use simulation tools. Many high-performance buildings reported in the United States showed substantially less energy usage than conventional buildings or code-compliant buildings did. In these buildings, the energy savings of high-performance buildings were significant, ranging from 24% to 64% compared to energy code-compliant baselines. The EUIs and energy savings numbers from the high-performance buildings reviewed were referenced for developing the high-performance building model for the current study. The DOE-2.1e simulation program was utilized as one of several programs to develop a methodology for an energy performance evaluation tool for the selection of high-performance components. However, there were very few high-performance buildings reported in hot and humid climates; e.g., the Robert E. Johnson building and the FSEC's headquarters building. It was indicated from the review that there was a high demand for the design and construction of high-performance buildings in hot and humid climates.

The systems implemented in the high-performance buildings were identified. The major systems or components implemented in the high-performance studies, including technologies not only from the above three studies but also from other case studies, were high-performance glazing, occupancy sensors, HVAC controls, energy-efficient chillers and boilers, solar energy systems, Dedicated Outdoor Air Systems (DOAS), Under Floor Air Distribution (UFAD) systems, Ground Source Heat Pump (GSHP) systems, natural ventilation systems, and daylighting systems. These systems were thoroughly investigated and then applied for the research to develop the high-performance building model for the case-study building.

Building energy analysis tools (DOE-2.1e, F-Chart, and PV F-Chart) were introduced and described for the use of this research. The thermal energy analysis of the case-study building was performed using the DOE-2.1e simulation program that offers a wide capability for simulating design features. In addition, the solar system analysis tools, F-Chart and PV F-Chart, were used along with the DOE-2.1e simulation model for the development of an energy performance evaluation tool for the selection of high-performance components, which can be used for the design of high-performance buildings in hot and humid climates.

Three different calibrated simulation methodologies were presented. These calibration methods were used to calibrate the case-study building simulation model. First, the manual and iterative calibration procedure has been the most popular approach. This method involves a utility data comparison, walk-through audits, and short-term monitoring. To obtain a calibrated simulation model, the procedure is applied in an iterative fashion using heuristics or rules-of-thumb. These calibration procedures were utilized for the calibration of the case study building in this study. Second, procedures were identified that used graphical and statistical analysis to highlight differences between measured and simulated results with certain types of visual graphs. These can be very useful techniques to help decide which parameters need to be calibrated for the next iteration. It was decided that graphical and statistical methods would be used for the calibration of the case-study building model along with the statistical MBE and CV(RMSE) guidelines published in the ASHRAE literature. Third, a signature analysis has been developed as an approach for calibrated simulation.

Calibration signatures, which represent graphical deviations between measured and simulated energy use as a function of average dry bulb temperature, were shown to be useful to calibrate a simulation model. The characteristic signatures provide a predictable shape according to changes of an input parameter by a certain amount based on the calibration signatures. These three calibrated simulation methodologies were used for the calibration of the case-study building to measured data of this study.

Finally, the easy-to-use energy simulation tools were reviewed and compared. These tools were eQUEST, eCALC, COMCheck-web, BCHP Screener, and Energy IQ. All these programs included the graphic user interface (GUI) for users to easily develop simulation models and see the results. Three programs (eCALC, COMCheck, and Energy IQ) were web-based tools and two (eQUEST and BCHP Screener) were not web-based tools. Some tools (eQUEST, eCALC, and COMCheck-web) were designed to focus on the evaluation of new buildings and others (BCHP Screener and Energy IQ) were intended to use for existing building analysis. However, there was no tool that analyzes indoor air quality. In this study, a methodology was presented to develop an easy-to-use tool that could include GUI and work on the internet web site, providing analysis functions for both new buildings and existing building. Also, the proposed easy-to-use tool would include an analysis function to check the indoor air quality.

CHAPTER III

SIGNIFICANCE OF THE STUDY

3.1 Significance of the Work

This research proposes to develop procedures that can be used to develop an easy-to-use tool for selecting high-performance systems for use in office buildings in hot humid climates. This research uses a case-study approach to identify appropriate high-performance systems for office buildings, and then identifies changes to the existing eCALC program to allow for the development of a web-based program. As revealed from the literature review, there is a demand for the construction of high-performance buildings in hot and humid climates. This research will benefit designers and engineers who need to select high-performance components in office buildings, so that they can construct high-performance buildings using a simplified tool that provides quick access for the evaluation of energy performance of building components. Such a tool would help planners choose high-performance building components with a minimum effort and only a basic knowledge of building science.

3.2 Limitations of the Work

In this research, there are some limitations. In the current work, the building energy simulations are limited to systems that DOE-2.1e can simulate, and the solar photovoltaic and thermal system analyses are limited to systems that F-Chart and PV F-Chart programs can evaluate. Finally, the methodology for the systems selection tool has been developed only for office buildings in hot and humid climates.

CHAPTER IV

METHODOLOGY

4.1 Overview

This chapter describes steps for the development of a methodology that can be used to develop an easy-to-use tool. There are four phases associated with the methodology development. In the first phase, a calibrated DOE-2.1e simulation model was developed for a case-study building, the John B. Connally Building in College Station, TX. This building is a typical office building with the conditioned space of 124,000 square feet. After the calibrated DOE-2.1e simulation model was developed for the case-study building, a modified-eCALC DOE-2.1e simulation model was developed and calibrated to the case-study building, which runs with a simple parameter input method or BDI (Batch DOE-2.1e Input) used by the eCALC program. The BDI program runs the DOE-2.1e program using a predefined input program with varying parameters. In the third phase, the modified-eCALC DOE-2.1e model was used as a baseline simulation model for the development of an energy performance evaluation tool for the selection of high-performance components for office buildings in hot and humid climates. In the final phase, specifications for the proposed easy-to-use tool are described. Figure 4.1.1 shows a flow diagram for the first three phases involved in the research. The following sections describe the major tasks in the individual phases including the Phase IV for the specifications of the proposed easy-to-use tool.

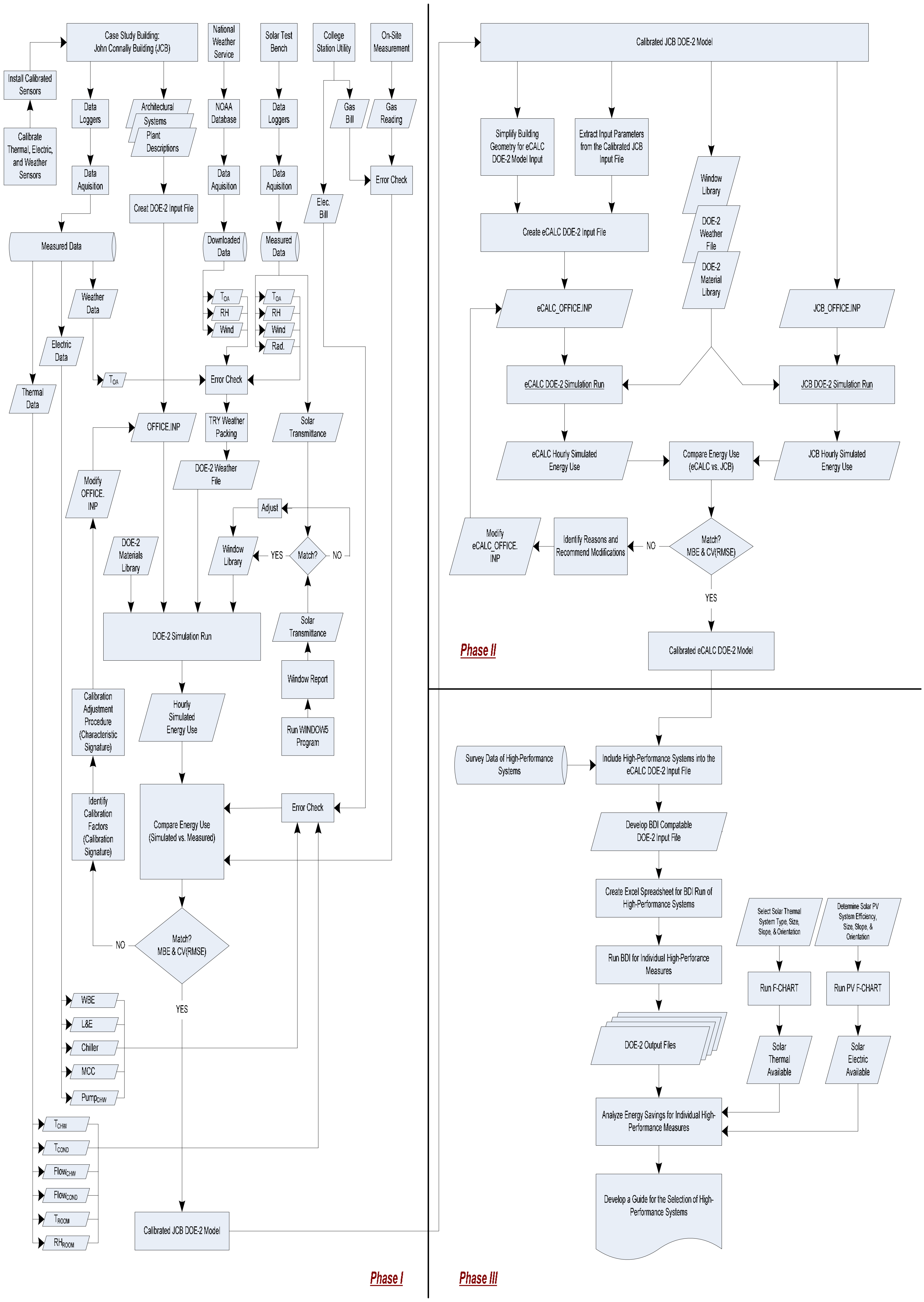


Figure 4.1.1 Schematic Diagram of the Research Procedure.

4.2 Calibrated Simulation Model – Phase I

4.2.1 Identification of High-performance Features

A thorough investigation was performed to find out which environmental systems are high-performance systems that work properly in hot and humid climates. Also, due to the limitations of the DOE-2.1e simulation program, the identified high-performance systems were sorted as either simulatable or non-simulatable by the DOE-2.1e program.

4.2.2 Site Visits and Measurement

This research was conducted using a case-study building, the John B. Connally building, which is located in College Station, Texas. For the energy consumption and the Indoor Environmental Quality (IEQ) measurements of the building, metering equipment was installed, and thermal, electrical, and IEQ data were monitored. All other necessary data and documents such as occupancy profiles, construction drawings, and photographs were gathered and incorporated into the calibrated as-built simulation.

4.2.3 Calibrated Simulation of the As-built Model

Figure 4.2.1 shows a flow diagram of the calibration procedure. To obtain thermal data from the case-study building (i.e., upper left of the diagram), thermal sensors such as temperature sensors, humidity sensors, and flow meters were installed. To obtain electricity consumption data, electricity measurement equipment such as Current Transducers (CTs) and Watthour Transducers (WTs) were installed. These sensors and equipment were calibrated before the hourly data were retrieved from the data loggers. Hourly measured data were retrieved from data loggers weekly for the entire year of 2006. The measured electric data were then compared with the utility electricity bill from the city of College Station for error check. The measured thermal data were used to evaluate the chiller performance comparing the thermal chilled water output of the chiller to the electric input.

Weather information was obtained from several sources and compared to create the 2006 Test Reference Year (TRY) file of the simulation. The weather data available were: ambient dry-bulb temperature from the data logger installed in the case-study building; dry-bulb temperature, relative humidity, and solar radiation from the solar test bench installed on the roof of the Langford Architecture building at Texas A&M; and dry-bulb temperature, relative humidity, wind speed, and solar radiation from the National Weather Service (NWS) database. The measured solar transmittance data from the Texas A&M solar test bench were compared with those from the Windows program report for the glazing property library of simulation.

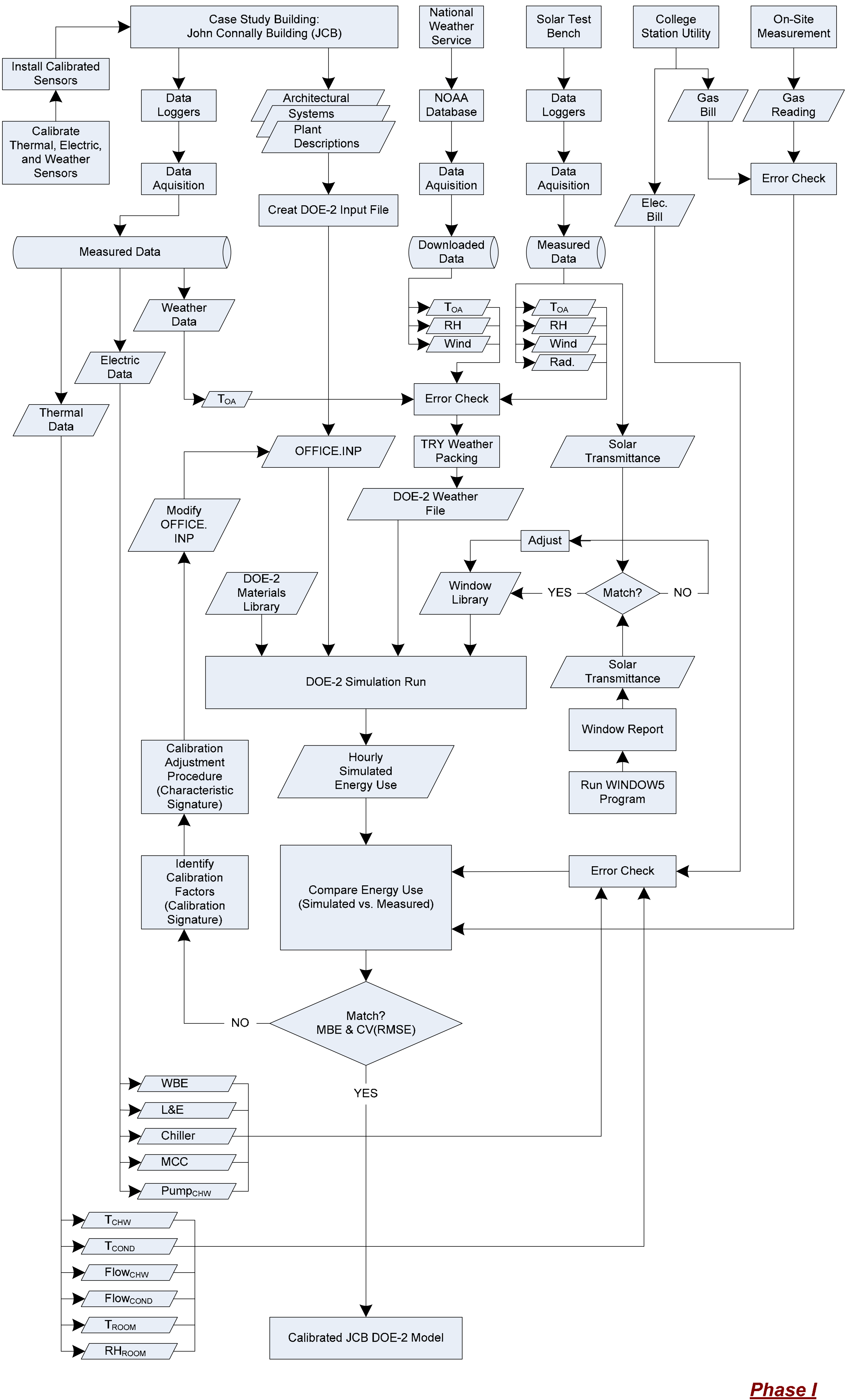


Figure 4.2.1 Schematic Diagram of the Research Procedure – Phase I.

The College Station weather station for NWS database was located in the Eastwood Airport in College Station. These weather data were compared for error check and packed as TRY weather data format for simulation. For the building's natural gas use, manual readings were taken and compared against the monthly utility bills.

Additional information to create the DOE-2.1e input file of the case-study building was gathered from several sources such as architectural drawings, mechanical drawings, construction drawings, and electrical drawings. The DOE-2.1e simulation was then run using the information gathered into the input file, along with the measured TRY weather file, and DOE-2.1e's material and windows library files. The hourly output of the DOE-2.1e simulation was then compared to the measured data for calibration. When the simulation results did not match the measured data, selected inputs were adjusted and the simulation was rerun. This process was repeated until the error ranges were within the tolerance range that the ASHRAE Guideline 14-2002 recommended. This calibrated simulation was then used to represent the existing conditions of the case-study building.

4.3 Modified eCALC DOE-2.1e Simulation Model – Phase II

Unlike the building geometry used for the calibrated simulation of the case-study building in the Phase I, which represents the real building shape, dimensions, and orientation, another DOE-2.1e simulation model was created that represents a modified eCALC simulation that uses a simplified, box-shaped geometry. Figure 4.3.1 shows the process of developing the simplified geometry for the eCALC DOE-2.1e simulation model.

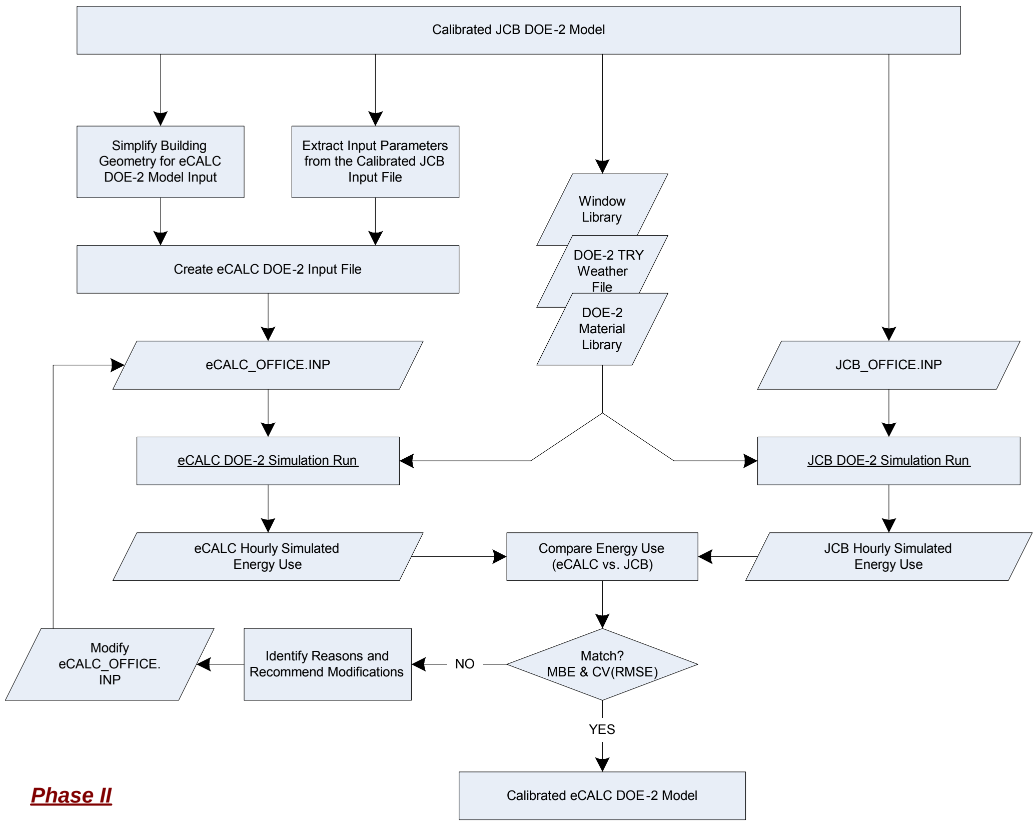


Figure 4.3.1 Schematic Diagram of the Research Procedure – Phase II.

In the eCALC simulation, many of the input parameters used in the calibrated DOE-2.1e simulation model were also utilized in the modified eCALC DOE-2.1e simulation model. In addition, since the eCALC DOE-2.1e input file includes its own input procedures, certain modifications were made in order to use the same input parameters used in the as-built simulation for the case-study building. Also, the building geometry was simplified from the geometry of the real building. Simulation results from the modified eCALC DOE-2.1e model were then compared to those of the calibrated as-built DOE-2.1e model until a suitable match was obtained.

To match the results between the DOE-2.1e simulation model and the modified-eCALC DOE-2.1e simulation model, certain modifications and adjustments were necessary. Geometry adjustment factors were specifically addressed to show how to develop a simplified building shape using parameters such as building width and length, window-to-wall ratio, and aspect ratio. A comparison was then performed and adjustments made until the results from both models agreed within an acceptable tolerance range.

4.4 High-performance Building Simulation Model – Phase III

After the calibrated, modified eCALC DOE-2.1e simulation model was constructed, a high-performance building model was developed, which is applicable for hot and humid climates. The high-performance building simulation model is an enhanced modified-eCALC DOE-2.1e model, consisting of those high-performance features that were identified from the previous investigation. In addition, as shown in Figure 4.5.1, the high-performance modified-eCALC DOE-2.1e model combines the results of the implementation of solar system evaluations using the F-Chart and PV F-Chart programs.

4.5 Specifications for the Proposed Easy-to-use Tool – Phase IV

The prototype work frame for an easy-to-use tool consists of four major components: 1) An "Easy-to-use" processor, 2) A Simplified-Geometry DOE-2.1e (SGDOE-2.1e) program, 3) A linkage to the F-Chart program, and 4) A linkage to the PV F-Chart program. These components were also used as sub-programs of the eCALC program, which is a compilation of 12 individual programs, as shown in Figure 4.5.2.

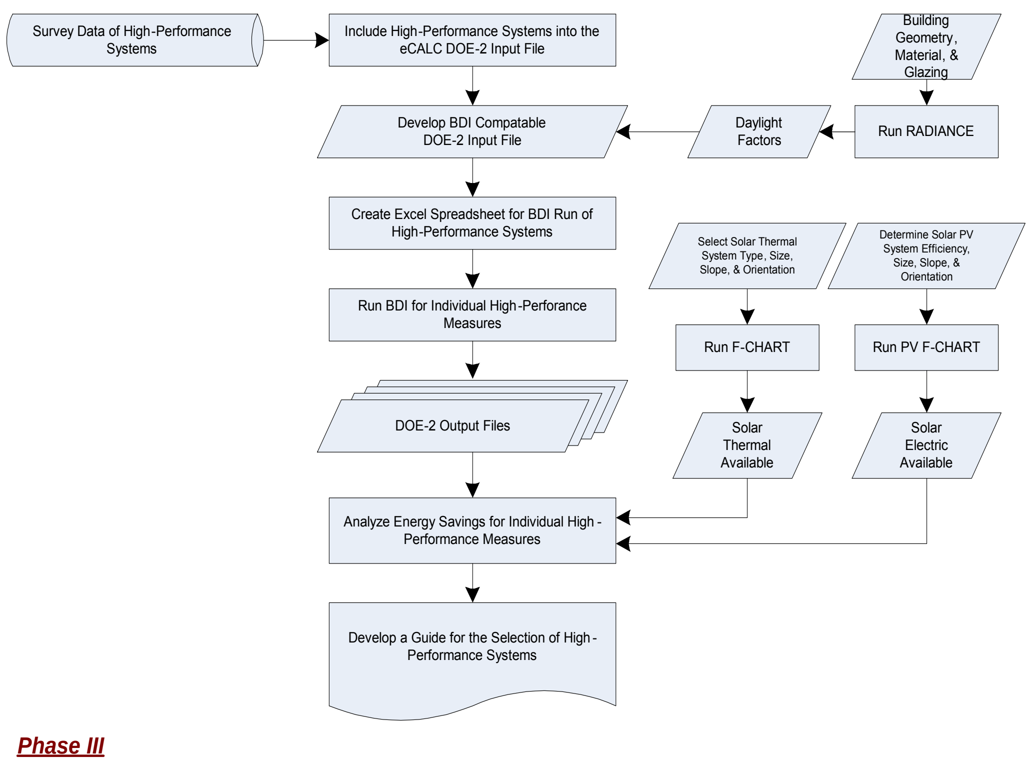


Figure 4.5.1 Schematic Diagram of the Research Procedure – Phase III.

eCALC consists of three project groups: 1) community projects, 2) new buildings projects, and 3) renewable projects. The community projects include five areas, which are municipal, street lights, traffic lights, water supply, and waste water. The new buildings projects include single family, multi family, office, and retail sectors. The renewables projects include solar thermal, solar PV, and wind. These individual projects are executed by the eCALC processor independently and show their own results without inter-connections with any other programs in the eCALC program.

In contrast to eCALC, the proposed easy-to-use tool only contains three components, which are the “Office”, “Solar Thermal”, and “Solar PV” models. Each component uses its own computer program. The DOE-2.1e simulation program was used for the “Office” project, F-Chart program for the “solar thermal” project, and PV F-Chart program for the “solar PV” project.

Figure 4.5.3 shows the differences graphically between eCALC and the proposed easy-to-use tool. The eCALC program was designed for new buildings projects only, so that new office building designers can quickly obtain energy efficiency information about their building. The proposed easy-to-use tool is, however, intended for use in new buildings and existing office buildings. In addition, as shown in Figure 4.5.3 (b), the proposed easy-to-use tool is an integrated tool that combines three programs together, while eCALC runs each program independently (i.e., either the input or the output results are shared with another program). In the proposed easy-to-use tool, the F-Chart and PV F-Chart programs receive outputs from the SGDOE-2.1e module to analyze the solar energy availability for space heating, service water heating, and electricity generation. The proposed easy-to-use tool then runs these programs, gathers the outputs from all three programs and displays the results of energy and cost savings and indoor air conditions as well.

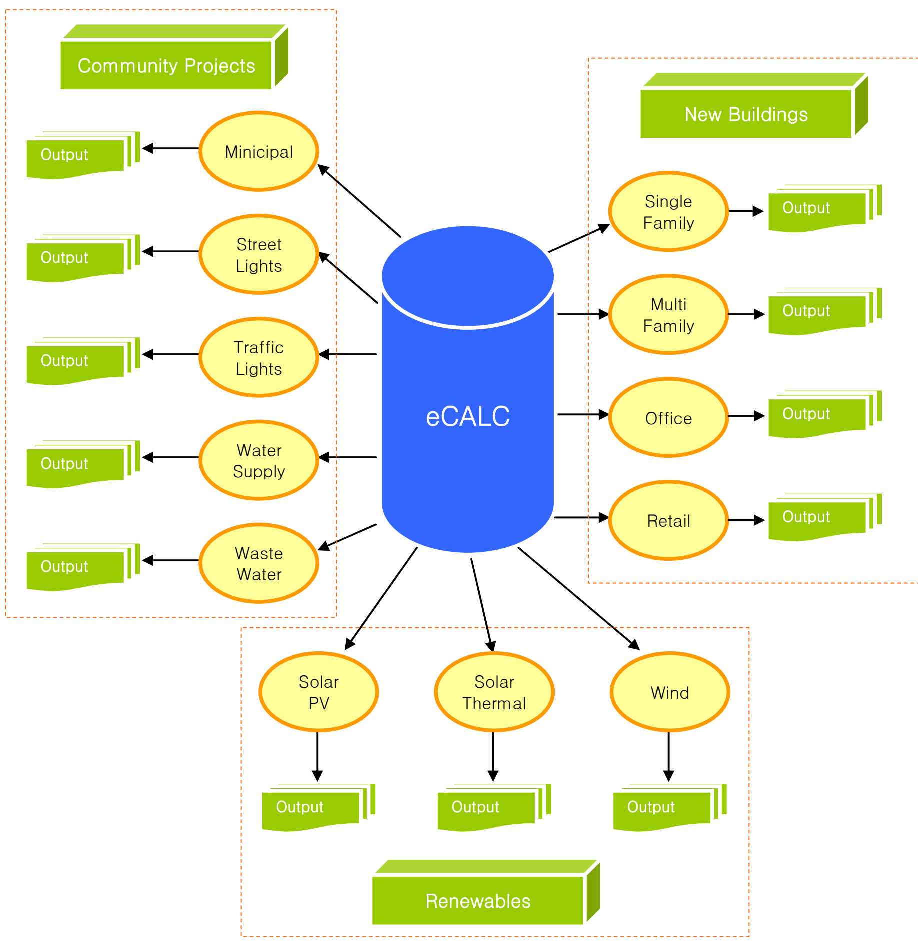
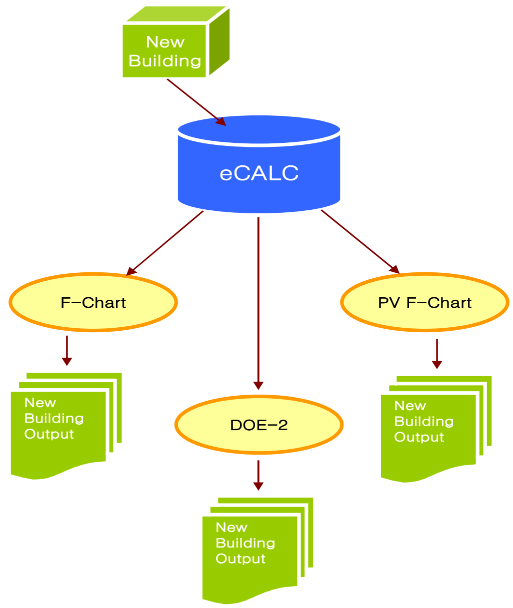
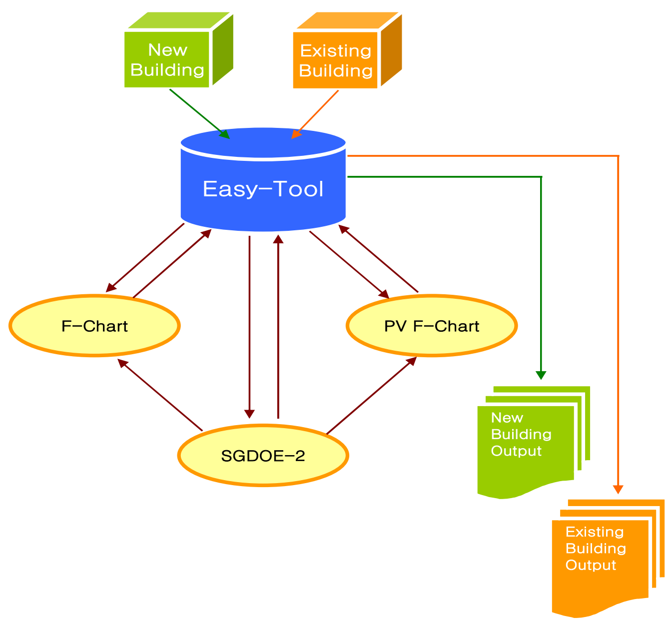


Figure 4.5.2 Schematic Diagram of the eCALC Program.



(a)



(b)

Figure 4.5.3 Schematic Diagrams Comparing the Proposed Easy-to-use Tool with eCALC: (a) eCALC Daigram and (b) Proposed Easy-to-use Tool Diagram.

The internal data flow of eCALC for the “Office” project is shown in Figure 4.5.4. When a user accesses the program via the internet, the BDI (Batch DOE-2.1e Input) program calls an Excel (.XLS) spreadsheet to create a specified DOE-2.1e Include (.INC) file, which contains input parameters that are needed by the the DOE-2.1e input (.INP) files. Then, BDI runs the DOE-2.1e simulation program with the other necessary files such as the materials library file and the weather file appropriate for the user’s location, and then displays the results.

The proposed frame work of the easy-to-use tool is shown in Figure 4.5.5. The proposed easy-to-use tool would include similar algorithms as eCALC up to the “DOE-2.1e” run, which would be replace with the “SGDOE-2.1e” run since the DOE-2.1e input file would be modified for the proposed easy-to-use tool. After the SGDOE-2.1e simulation is run, two DOE-2.1e SYSTEMS output files (SS-A and SS-E) would be extracted and used as input for the F-Chart run for the solar thermal systems analysis. At the same time, the DOE-2.1e PLANT output file (PS-E) would also be extracted and used as input for the PV F-Chart program for the solar PV systems analysis. The proposed easy-to-use tool would then execute the F-Chart and PV F-Chart programs and returns the monthly available solar thermal energy and electricity generation to be reintegrated with the DOE-2.1e results.

The proposed easy-to-use processor takes outputs from all three programs and calculates total energy savings and cost savings, and evaluates the indoor air conditions.

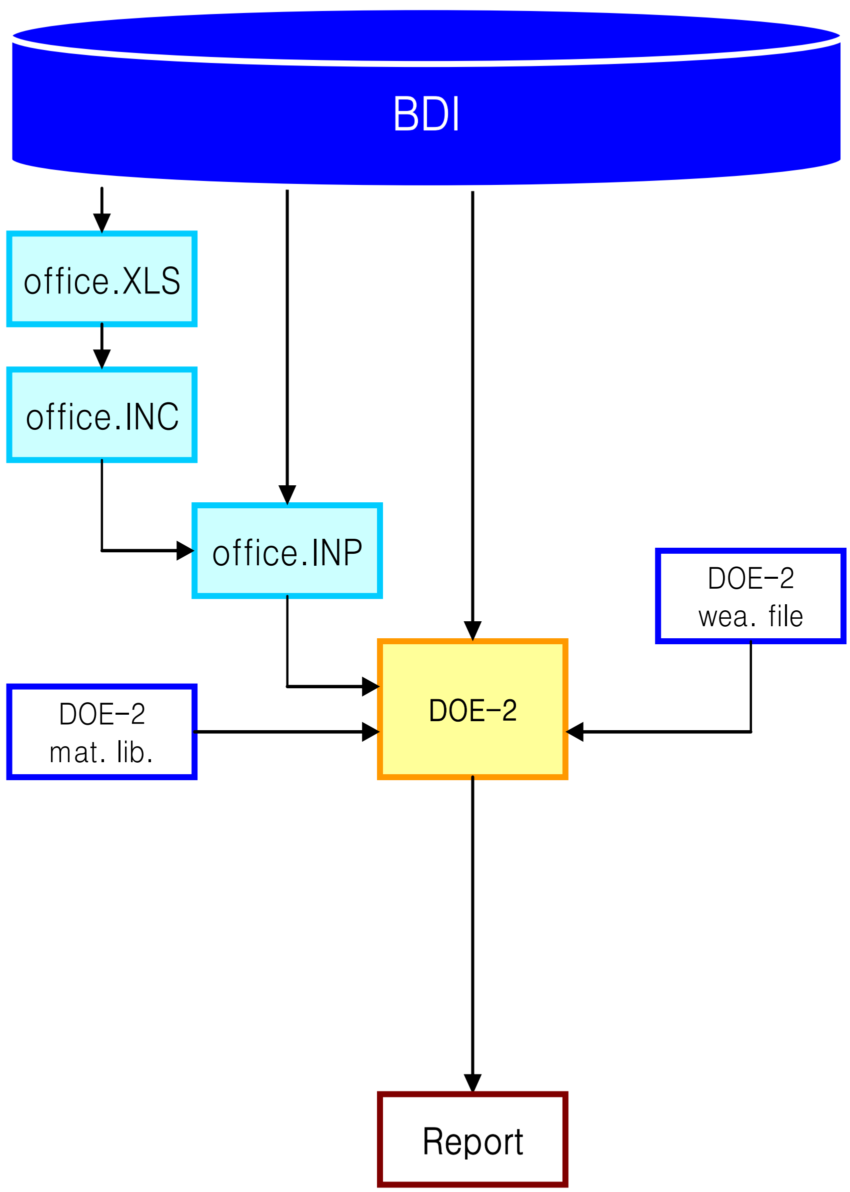


Figure 4.5.4 Internal Data Flow of the eCALC Program for the "Office" Project.

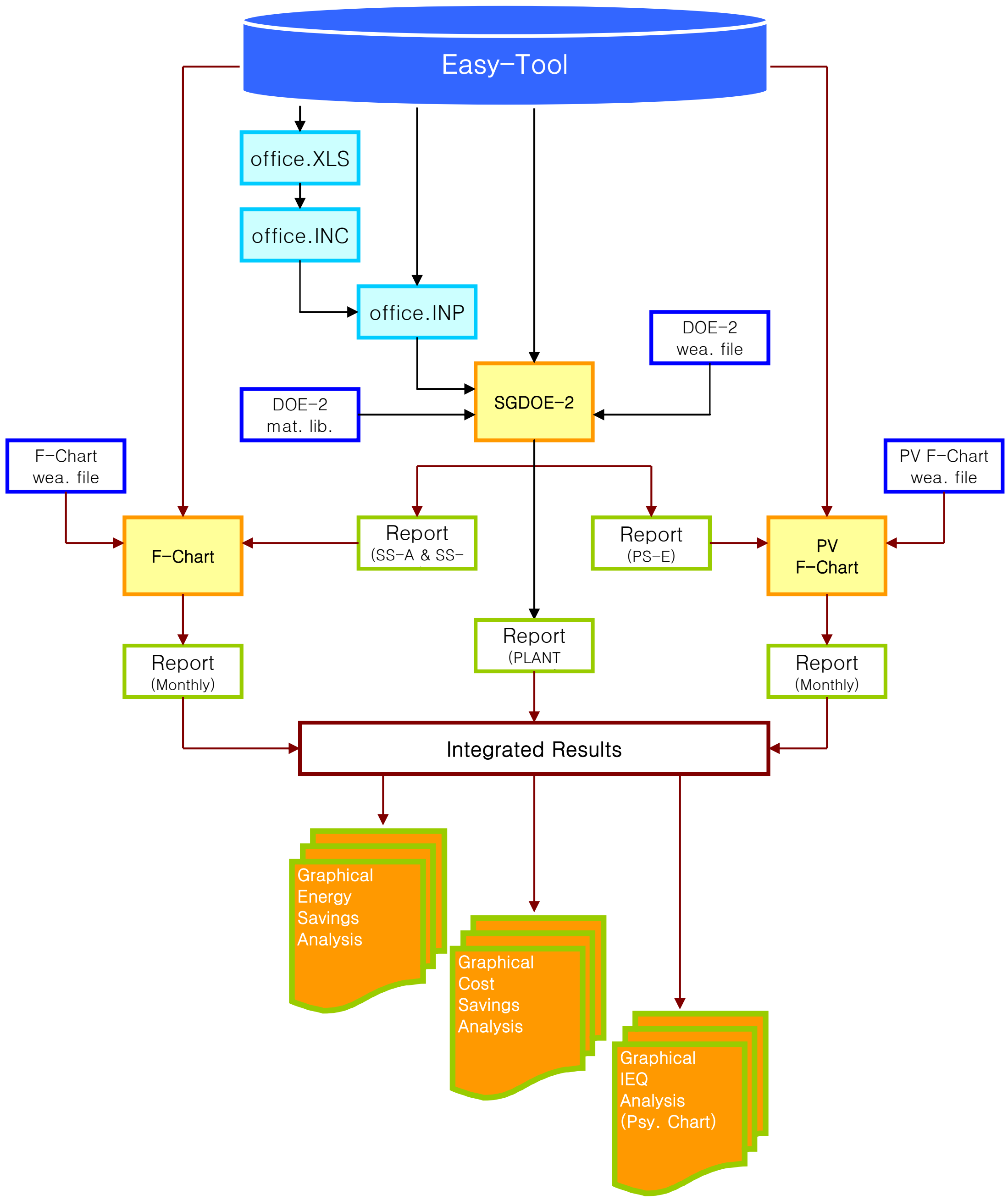


Figure 4.5.5 Internal Algorithm of the Proposed Easy-to-use Tool.

CHAPTER V

PHASE I: CALIBRATED SIMULATION MODEL

5.1 Case-study Building (John B. Connally Building) Description

In this research, a calibrated DOE-2.1e simulation model of a case-study building, the John B. Connally Building in College Station, TX was developed. The John B. Connally (JBC) building is one of the Texas A&M University facilities in College Station, Texas. It is located north of the main campus. As shown in Figure 5.1.1, originally, this building was used as the State Headquarters for the Texas A&M University System, but now is occupied by several departments of Texas A&M. A DrawBDL (Huang, 1994) output of DOE-2.1e input file for the case-study building is also shown in Figure 5.1.1.

This building consists of 124,000 square feet of conditioned space with seven stories and a thermal plant, which is detached from the building. This building is used for offices and conference rooms. The JBC building has a window-to-wall ratio of 40%. Windows are double pane, tinted glazing.

5.1.1 AHU Systems in the John B. Connally Building

There are a total of nineteen (19) Air Handling Units (AHUs) of which seventeen are Single-Duct, Variable Air Volume (SDVAV) AHUs with Variable Frequency Drives

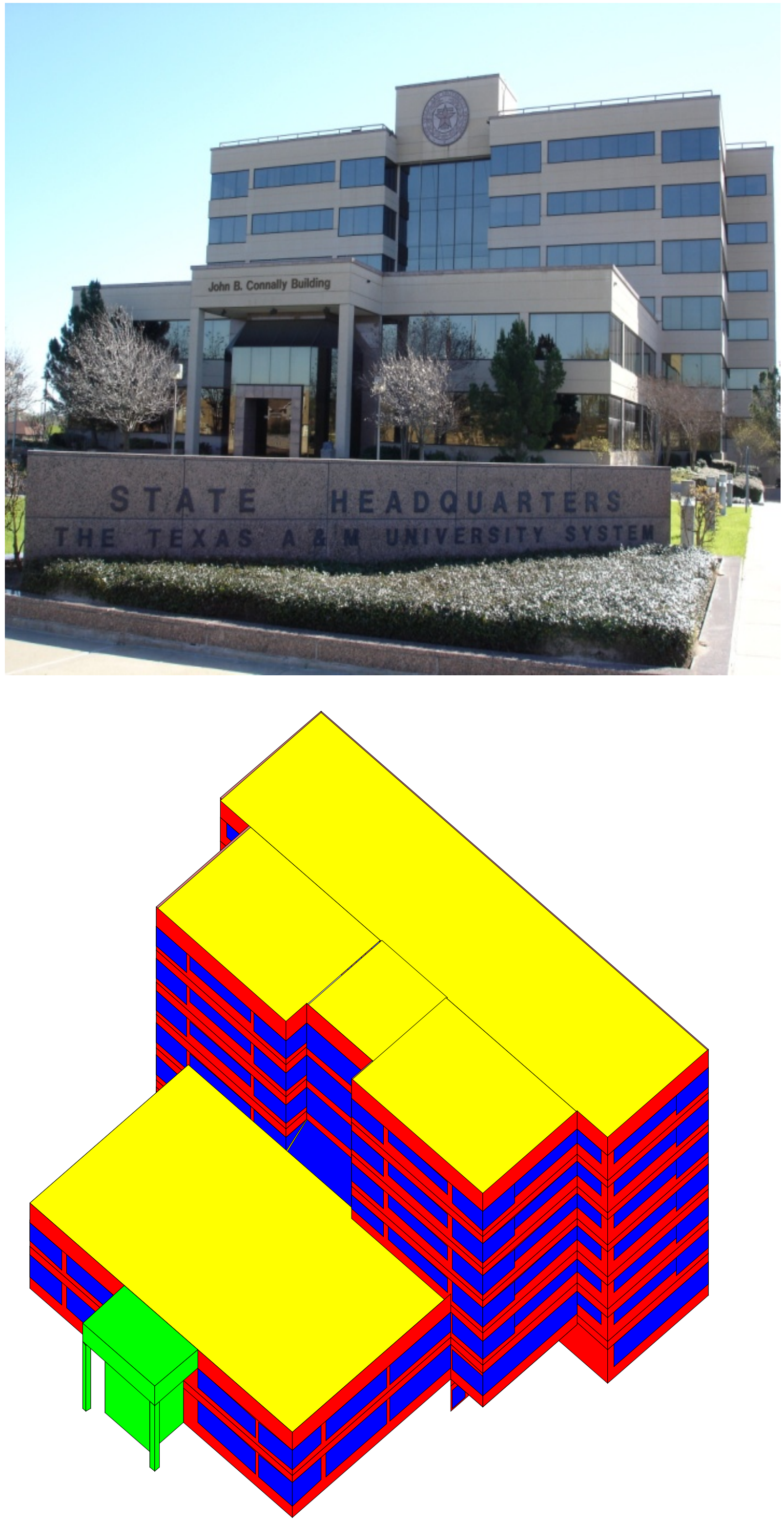


Figure 5.1.1   Case-study Building: John B. Connally Building.

(VFDs) and two (2) AHUs are SDVAV 100% outside AHUs, which provide the seventeen SDVAV AHUs with fresh outdoor air. The two outside air AHUs are located on the roof of the building. The SDVAVs, as shown in Figure 5.1.2, are equipped with a cooling coil and a draw-through supply air fan. The mechanical rooms are used as mixing chambers. Return air comes through plenums on each floor into the mechanical rooms.

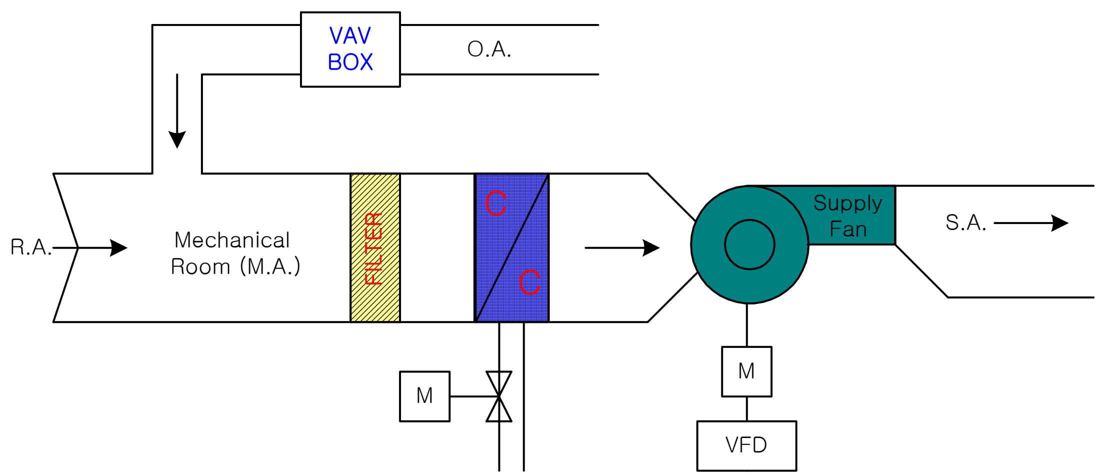


Figure 5.1.2 AHU System Diagram in the JBC Building.

The return air is mixed with the outside air, which comes into the mechanical room through ducts from the OAHUs on the roof. The mixed air in the mechanical rooms comes into the AHUs and passes through the cooling coils. In the building, there are 230 terminal-VAV boxes, which have hot water reheat coils and supply air dampers that are run by Direct Digital Control (DDCs) systems. Also, there are nine (9) fan coil cooling units in selected places such as the electrical room and the mechanical penthouses. Table 5.1.1 specifies the design conditions of the seventeen (17) SDVAV AHUs and two (2) 100% Outside AHUs (OAHUs) in each service area, which was obtained from the JBC building drawings. Table 5.1.1, the fan efficiencies are shown for each AHU, which were calculated from the parameters such as design supply CFM (Cubic Feet per Minute), pressure (inWG), and HP (Horse Power) (Kreider and Rabl, 1994).

Table 5.1.1 Design Conditions of 17 SDVAV AHUs and 2 100% OAHUs.

AHU Schedule								
#	**AHU ID**	**Total CFM**	**OA CFM**	**SP (inWG)**	**HP**	**Unit Location**	**Area Served**	**Air Flow**
1	AHU 1-1	7610	500	2.5	7.5	1st Floor	1st FL North	VAV
2	AHU 1-2	10445	1725	2.5	7.5		1st FL South	
3	AHU 1-3	9385	1565	2.5	7.5		1st FL West	
4	AHU 2-1	8000	500	2.5	7.5	2nd Floor	2nd FL North	VAV
5	AHU 2-2	8535	535	2.5	7.5		2nd FL South	
6	AHU 2-3	12170	670	2.5	10.0		2nd FL West	
7	AHU 3-1	6855	475	2.5	7.5	3rd Floor	3rd FL North	VAV
8	AHU 3-2	10775	575	2.5	10.0		3rd FL South	
9	AHU 3-3	8935	500	2.5	7.5		3rd FL West	
10	AHU 4-1	9520	560	2.5	7.5	4th Floor	4th FL North	VAV
11	AHU 4-2	9850	560	2.5	10.0		4th FL South	
12	AHU 5-1	9520	560	2.5	7.5	5th Floor	5th FL North	VAV
13	AHU 5-2	9850	560	2.5	10.0		5th FL South	
14	AHU 6-1	9520	560	2.5	7.5	6th Floor	6th FL North	VAV
15	AHU 6-2	9850	560	2.5	10.0		6th FL South	
16	AHU 7-1	10560	560	2.5	10.0	7th Floor	7th FL North	VAV
17	AHU 7-2	10620	560	2.5	10.0		7th FL South	
18	OA AHU-1	4215	4215	1.0	3.0	Roof	Outside Air	VAV
19	OA AHU-2	5075	5075	1.0	3.0		Outside Air	

5.1.2 JCB Building's Thermal Plant

The thermal plant is detached from the JBC building, as shown in Figure 5.1.3. The separate thermal plant has two chillers providing chilled water for space cooling, two boilers proving hot water for space heating, and one water heater for service water heating. The two centrifugal chillers have a capacity of 280-tons each. Normally, the JBC building only needs one 280-ton chiller to meet the building's maximum cooling loads during occupied hours. The chillers are sequenced to allow both to run equal amounts each year. There are two 20 HP constant-speed, chilled water pumps. These pumps operate only when their corresponding chillers are running.

Figure 5.1.3 Thermal Plant and Cooling Towers of the John B. Connally Building.

Two cooling towers are located right next to the thermal plant, which have a condensing water flow of 840 gallons per minute each. Each cooling tower has a 15 HP fan, which is a draw-through fan installed on the top of the cooling tower and is controlled by a VFD. In a similar fashion as the chilled water pumps operate, these cooling towers also work when their associated chillers are running.

The plant also contains two gas-fired hot water boilers with an input capacity of 2,000,000 Btu/hr and output capacity of 1,800,000 Btu/hr. Table 5.1.2 summarizes the JBC building's plant information with design conditions for chillers, boilers, cooling towers, pumps, and service water heater.

Table 5.1.2 Thermal Plant Summary of the JBC Building.

Boilers	Fuel Type	GPM	EWT (F)	LWT (F)	HP	Input (MMBtu)	Output (MMBtu)	Remarks
B-1	N.G.	80	150	190	1	2,000	1,600	460V, 3Phase Blower Motor
B-2	N.G.	80	150	190	1	2,000	1,600	Cleaver Brooks Model M4W-2000
Chillers	Tons	Chiller Data				Input	Eff.	Remarks
		GPM	EWT (F)	LWT (F)	Delta-P	(kW)	(kW/ton)	
CH-1	280	560	54	42	15	190	0.68	York Centrifugal Chiller
CH-2	280	560	54	42	15	190	0.68	Model: YT E1 E3 C1-CK FS
Cooling Towers	Condenser Data			Amb. Twb	Fan data			Remarks
	GPM	EWT (F)	LWT (F)	(F)	HP	Volts	Phase	
CT-1	840	96	86	80	15	460	3	VFD
CT-2	840	96	86	80	15	460	3	
Pumps	GPM	Head Ft.	Min. Eff.	HP	Volts	Phase	RPM	Remarks
CHWP-1	560	90	75	20	460	3	1750	Aurora Series 410
CHWP-2	560	90	75	20	460	3	1750	Aurora Series 410
CTWP-1	840	40	81	15	460	3	1750	Aurora Series 1110
CTWP-2	840	40	81	15	460	3	1750	Aurora Series 1110
HWP-1	80	80	60	5	460	3	1750	Aurora Series 360
HWP-2	80	80	60	5	460	3	1750	Aurora Series 360

5.2 Measured Energy Use

5.2.1 Electric Energy Consumption

The case-study building's electricity consumption data were retrieved from the Synergistic data loggers (Synergistics, 1994) installed in the JBC building for one entire year in 2006. The electric data points were Whole-Building Electricity (WBE), Lighting & Equipment (L&E), Chiller, and CHW Pump. Figure 5.2.1 shows a schematic diagram of the electric monitoring system for the JBC building. Whole-Building Electric is the main metering of the total electricity usage of the case-study building. The office building electricity channel (ch4364) is one of the sub-metering channels, which is a digital (D1) channel and reads hourly electricity use of the building's lighting and equipment loads. Chiller 1&2 (ch4365) also use a digital channel (D2) to read the hourly electricity use of the two chillers in the building. There are two analog channels (CT0 and CT21) for the two chilled water pumps (ch4347 and ch4348), which read each chilled water pump's hourly electricity use.

Figure 5.2.2 shows the daily electricity use for the WBE, L&E, and Chiller loads, which was created by summing the hourly energy use data and plotting against the average daily temperature. The WBE is the sum of both L&E and Chiller. There are two discrete electric energy use patterns shown in the L&E use: the upper pattern indicates weekday electricity use and the lower pattern indicates the weekend and holiday electricity use.

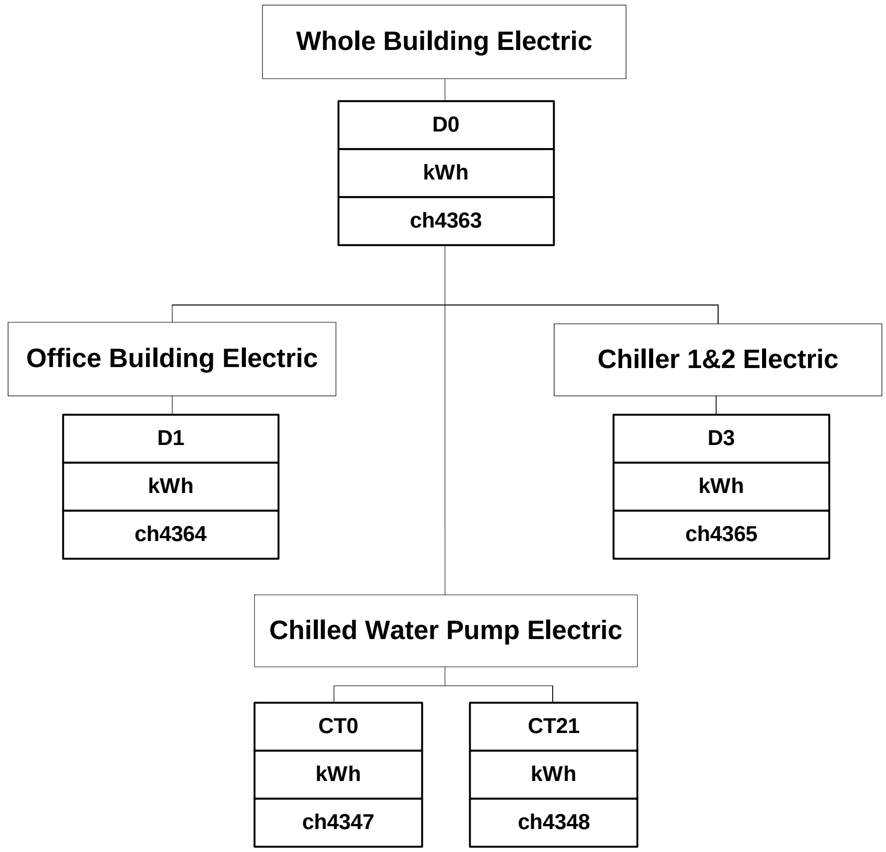


Figure 5.2.1 JBC Building Electric Monitoring Diagram.

To verify the measured electric data, utility bills were obtained from the College Station Utility Services Department. Figure 5.2.3 shows the monthly WBE use comparison for measured versus billed data. For the entire period, the billed WBE was 2,700 MWh/yr and the measured WBE was 2,676 MWh/yr, which is 0.89% lower than the billed. The comparison shows that the measured data were acceptable to be used for the calibrated simulation of the case-study building.

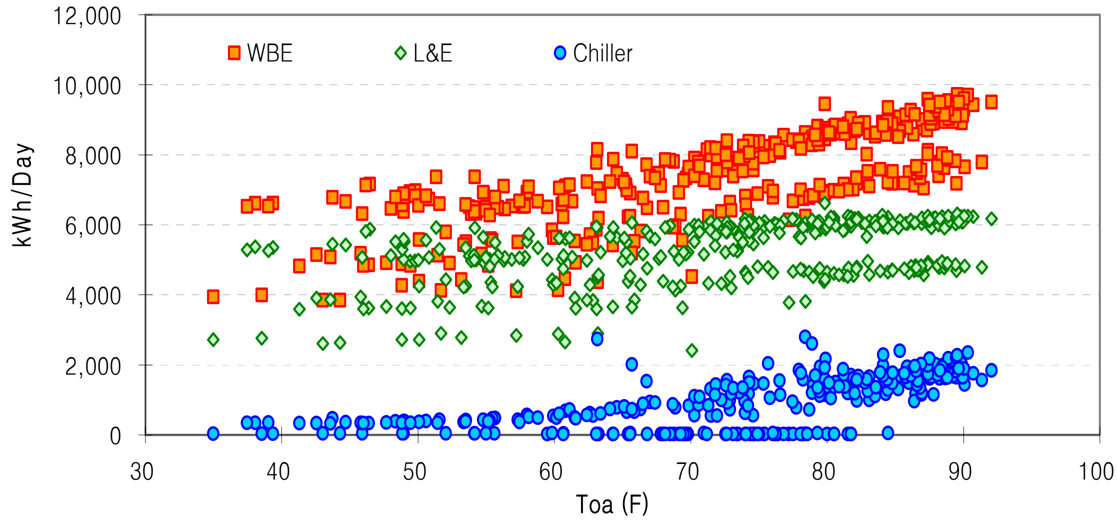


Figure 5.2.2 Measured Electricity Use for the WBE, L&E, and Chiller Loads in 2006.

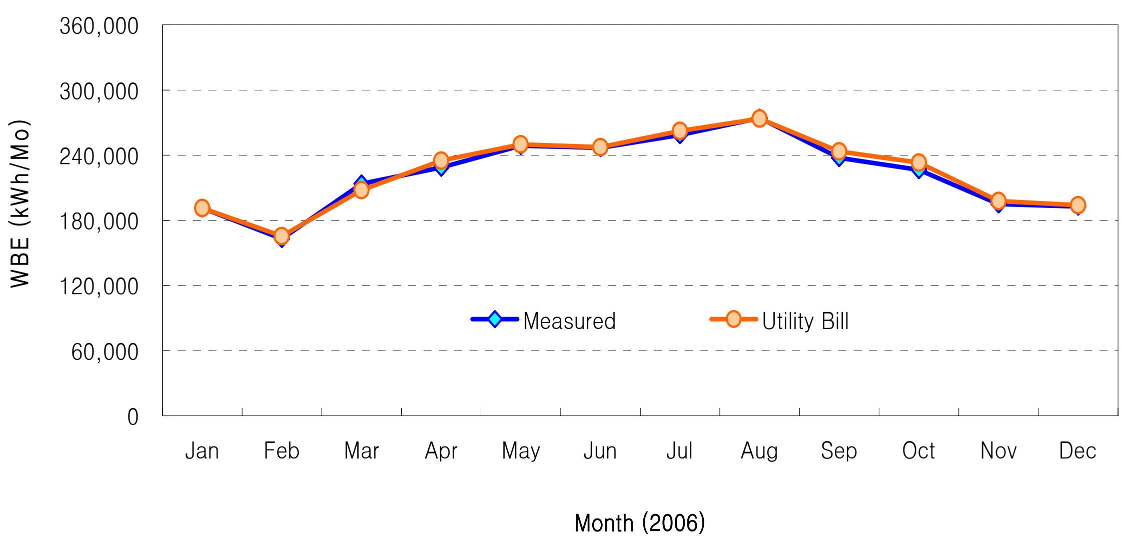


Figure 5.2.3 Whole Building Electric Use Comparison Between Measured and Utility Bill Data in 2006.

5.2.2 Natural Gas Consumption

The Natural Gas (N.G.) consumption of the JBC building was obtained from the utility provider. Unfortunately, there was no hourly N.G. metering equipment installed in the JBC building for this study. So the gas meter on site was read weekly for the period from June 2006 to October 2006 as shown in Table 5.2.1. The total N.G. consumption of the JBC building was 8,171 therms in 2006. As shown in Figure 5.2.4, manual readings were performed for four months. These readings for four months were then compared to the utility bills month-by-month. The figure shows that the utility bills were reasonable close to the measured weekly data.

Table 5.2.1 JBC Building Natural Gas Manual Consumption Readings.

JBC Building Gas Meter Manual Readings					
Reading Date	Meter Reading (Cubic Feet)	# of Days	Average Daily Use		Monthly Use (Therm)
			Cubic Feet	Therm	
6/10/2006 10:30	8,163,158	-	-	-	Jun.: 582
6/17/2006 12:00	8,176,176	7.1	1843.3	18.4	
6/24/2006 22:00	8,190,056	7.4	1871.5	18.7	
7/4/2006 15:20	8,208,738	9.7	1921.6	19.2	Jul.: 586
7/9/2006 16:30	8,218,469	5.0	1927.5	19.3	
7/15/2006 10:10	8,228,980	5.7	1832.4	18.3	
7/22/2006 10:40	8,241,815	7.0	1828.1	18.3	
7/31/2006 21:30	8,259,206	9.5	1840.0	18.4	
8/7/2006 20:40	8,271,436	7.0	1755.9	17.6	Aug.: 559
8/14/06 17:20	8,283,848	6.9	1809.0	18.1	
8/21/2006 14:00	8,296,260	6.9	1809.0	18.1	
8/28/2006 18:00	8,308,898	7.2	1763.4	17.6	
9/5/2006 22:15	8,322,373	8.2	1647.9	16.5	Sep.: 498
9/11/2006 14:40	8,331,620	5.7	1626.8	16.3	
9/17/2006 20:30	8,339,833	6.2	1315.5	13.2	
9/24/2006 21:50	8,352,348	7.1	1773.8	17.7	
10/1/2006 21:10	8,364,702	7.0	1771.9	17.7	

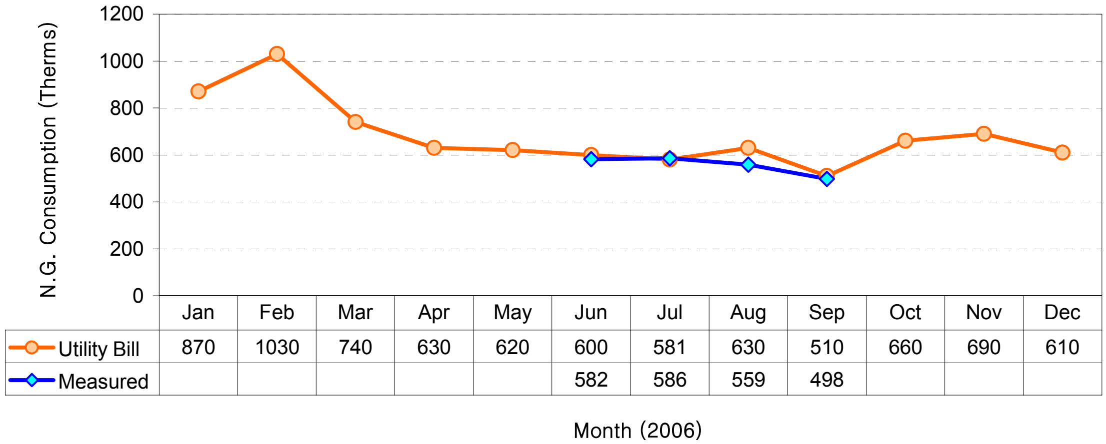


Figure 5.2.4 JBC Building Natural Gas Consumption Measurement (Monthly Billed Data vs. Manual Reading Data).

5.2.3 Comparison of the Energy Use Indices (EUIs)

Energy Use Indices (EUIs) were used as an indicator of energy efficiency for quick comparisons with other similar buildings. The annual total energy use per square foot of conditioned space is the most frequently used method for EUIs. The JBC building consumed 2,676 MWh of electricity (EUI of 21.58 kWh/sqft-yr) and 8,171 therms of N.G. (EUI of 6.59 kBtu/sqft-yr) in 2006. This total energy use is divided by the total building's conditioned space of 124,000 sq-ft. The EUI of the JCB building is 80.2 kBtu/sqft-yr. To have a snap shot of the JBC building's energy performance, the EUI of the JBC building was compared with ones from similar buildings in Austin, Texas. Table 5.2.2 shows the John Connally building's EUI along with other six buildings (Haberl et al., 2001), which are similar building types (offices) and have similar building areas (102,000 – 183,000 sq-ft). As shown in Figure 5.2.5, the JBC building's energy performance is better than the average, which is 27.3 kWh/sqft-yr from the six Austin buildings, in terms of total electric consumption (WBE + Cooling Energy).

In addition, the JBC building went through a Continuous Commissioning (CC®) process in 2003 by engineers in the Energy Systems Laboratory at Texas A&M. Continuous Commissioning (CC®) is a registered mark of Texas Engineering Experiment Station (TEES) and Energy Systems Laboratory (ESL). Before the commissioning, the building consumed 2,879 MWh of electricity (EUI of 23.22 kWh/sqft-yr) and 40,960 therms (EUI of 33.03 kBtu/sqft-yr). After the commissioning process, the JBC building's electric consumption dropped by 10%.

Table 5.2.2 Energy Use Indices (EUIs) Comparison Between the John Connally Building and Six Similar Buildings in Austin, Texas.

Building Category: Large Buildings				EUI of WBE (L&E + Cooling)
Bldg I.D.	Building Name	Location	Building Area (ft^2)	kWh/ft^2-yr
208	Archives Building 1	Austin, TX	120,000	17.0
JBC	*John B. Connally Building*	*College Station, TX*	*140,000*	*21.6*
229	Tom C. Clark Building	Austin, TX	121,654	21.9
228	Price Daniels Building 1	Austin, TX	151,620	24.4
203	John H. Reagan	Austin, TX	169,746	28.1
206	Insurance Building 1	Austin, TX	102,000	36.1
201	Sam Houston Building 1	Austin, TX	182,961	36.5

However, as shown in Figure 5.2.6, the N.G. use dropped to less than half of the 2004 use. Additional changes were made in 2005 and 2006 that reduced this further. One major change during the commissioning of the natural gas boilers was to reset the constant boiler temperature, which was 180 F year round (Chen, 2003). The supply hot water temperature was set to 180 F for the outdoor temperature of 20 F or lower, to 100 F for the outdoor temperature of 80 or higher, and from 180 F to 100 F, linearly decreasing as the outdoor temperature increases from 20 F to 80 F.

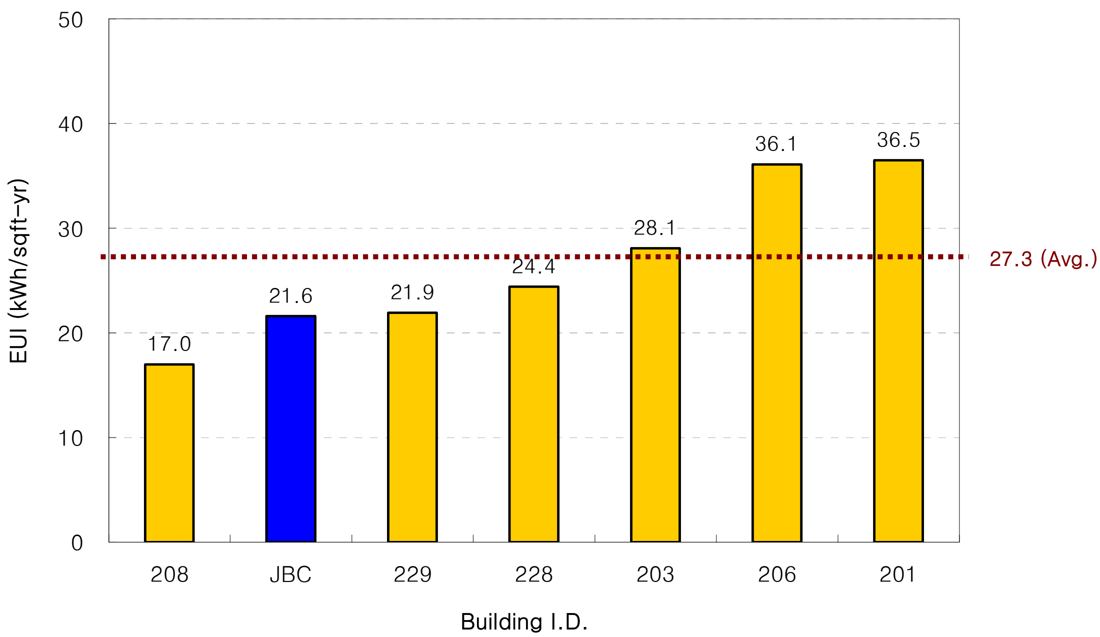
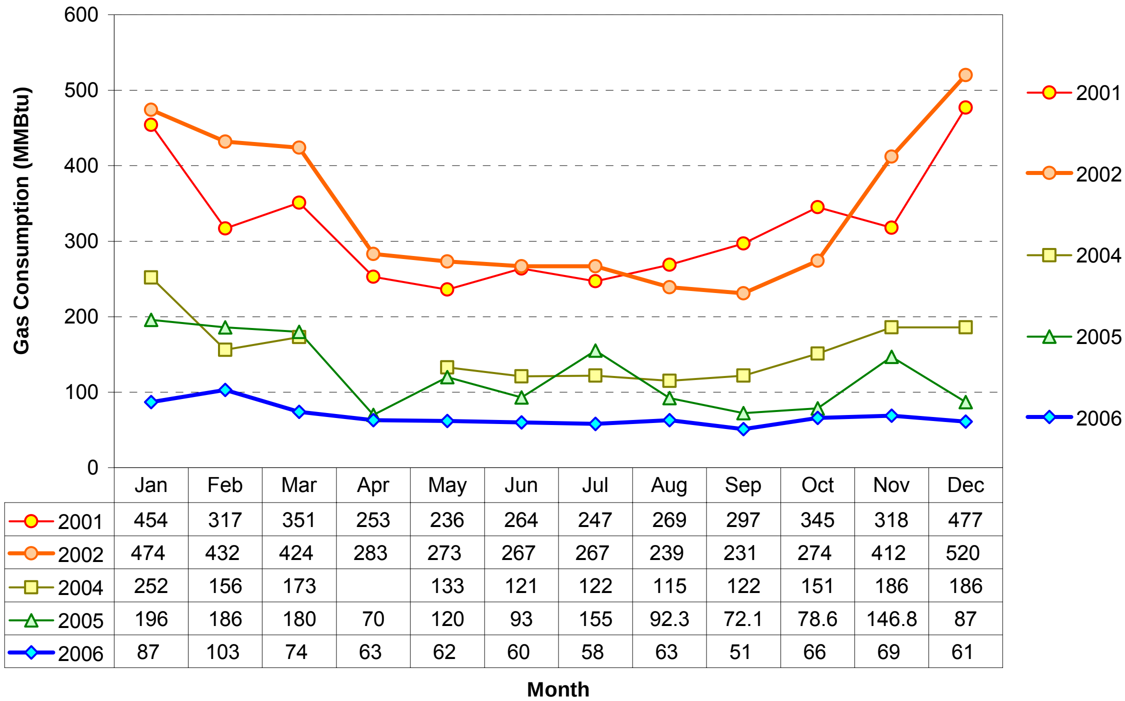


Figure 5.2.5 Comparison of EUIs (JBC Bldg. vs. Other Bldgs. in Austin, TX) – (Source: Haberl et al., 2001).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	454	317	351	253	236	264	247	269	297	345	318	477
2002	474	432	424	283	273	267	267	239	231	274	412	520
2004	252	156	173		133	121	122	115	122	151	186	186
2005	196	186	180	70	120	93	155	92.3	72.1	78.6	146.8	87
2006	87	103	74	63	62	60	58	63	51	66	69	61

Figure 5.2.6 N.G. Consumption Changes of the JBC Building Before and After Commissioning.

5.3 Measured Data Analysis for the Calibrated Simulation

5.3.1 Weather Data

The DOE-2.1e simulation program includes weather files for cities in the United States. These weather files are formatted as TMY2, which is Typical Meteorological Year derived from 1961-1990 National Solar Radiation Data Base (NSRDB) (NREL, 1995). The earlier version of weather files, TMY, was derived from the 1952-1975 weather data base (NOAA, 2008). One of the TMY2 weather files that is closest to the location where the case-study building is Houston TMY2 weather file. However, the Houston TMY2 weather file does not exactly represent the weather conditions in the City of College Station where the case-study building is located since the two cities are about 100 miles away from each other. Also, the TMY2 files are not for a specific year but are typical weather conditions for locations that are averaged from the 30 years of weather data.

For example, the Heating Degree Days of 65 F ($HDD_{65\ F}$) from the TMY2 weather data were 1,552 for Houston, but the $HDD_{65\ F}$ were 1,258 for College Station in 2006, which is 294 HDDs less than Houston. Also, the Cooling Degree Days base 50 F ($CDD_{50\ F}$) from the TMY2 weather data were 7,062 for Houston, but $CDD_{50\ F}$ were 7,492 for College Station in 2006, which is 430 more CDDs in College Station than in Houston. Therefore, the calibrated simulation was performed using measured 2006 energy consumption data and measured 2006 weather data.

For the calibrated simulation of the case-study building, a Test Reference Year (TRY) weather file was created. The DOE-2.1e program also includes a weather packing processor, so that users can create their own weather files for specific locations and for specific years. In this study, a TRY weather file for College Station was created for measured data for 2006. To create or pack the TRY weather file, several weather variables are required, including temperatures (dry-bulb_Tdb, wet-bulb_Twb, and dew-point_Tdp), wind (speed and direction_w), station pressure (p), and solar radiation (global horizontal total radiation and direct normal radiation_In). These hourly variables were obtained from two sources, which are the National Weather Service (NWS) for the weather data (Tdb, Twb, Tdp, w, p) and National Renewable Energy laboratory (NREL) for solar data.

A detailed TRY weather packing process for the 2006 College Station weather condition is included in Appendix A. Figure 5.3.1 through Figure 5.3.4 show both the hourly and daily average weather data for College Station, TX in 2006, which are dry-bulb temperature, wet-bulb temperature, dew-point temperature, and wind speed, respectively. Figure 5.3.5 and Figure 5.3.6 show the hourly solar data for College Station, Texas in 2006; hourly global horizontal solar radiation and hourly direct normal solar radiation. The hourly direct normal solar radiation data were calculated using the hourly global solar radiation data and the routine (Erbs, 1982).

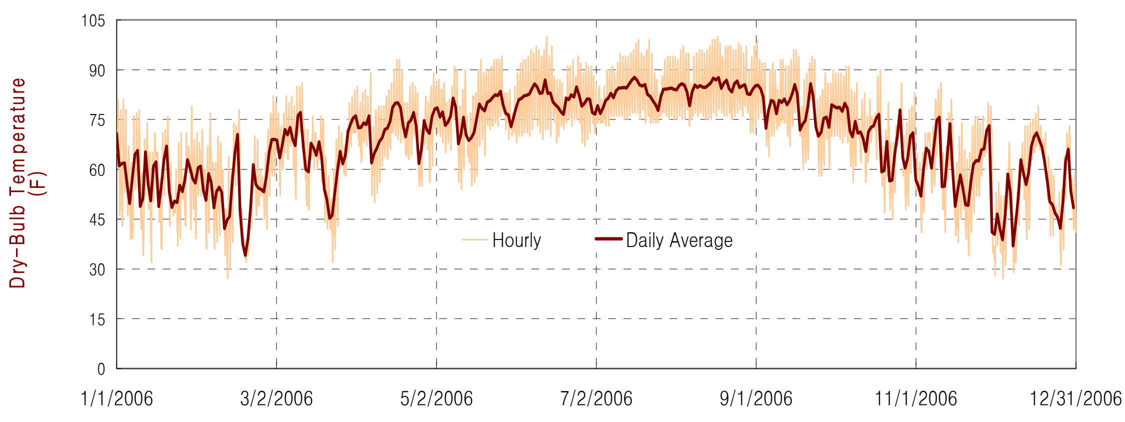


Figure 5.3.1 Hourly and Daily Dry-Bulb Temperature for College Station, TX in 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

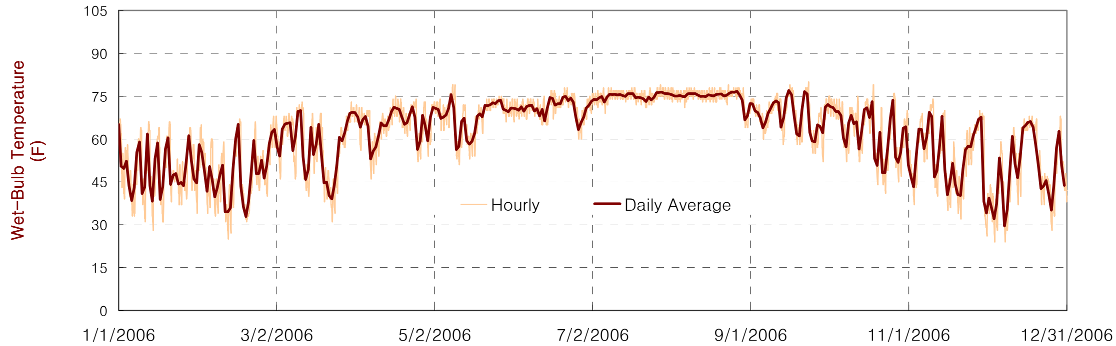


Figure 5.3.2 Hourly and Daily Wet-Bulb Temperature for College Station, TX in 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

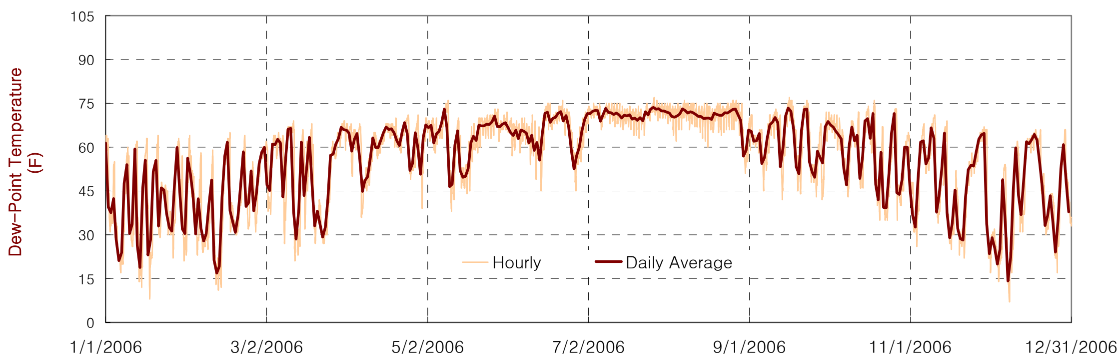


Figure 5.3.3 Hourly and Daily Dew-Point Temperature for College Station, TX in 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

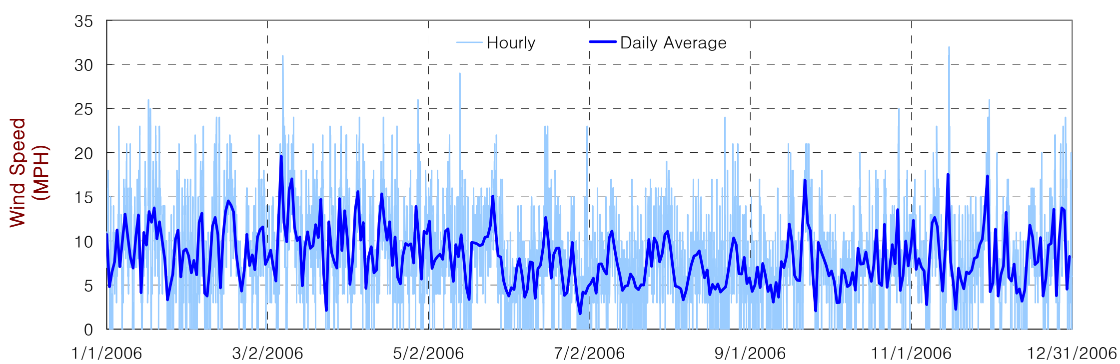


Figure 5.3.4 Hourly and Daily Wind Speed for College Station, TX in 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

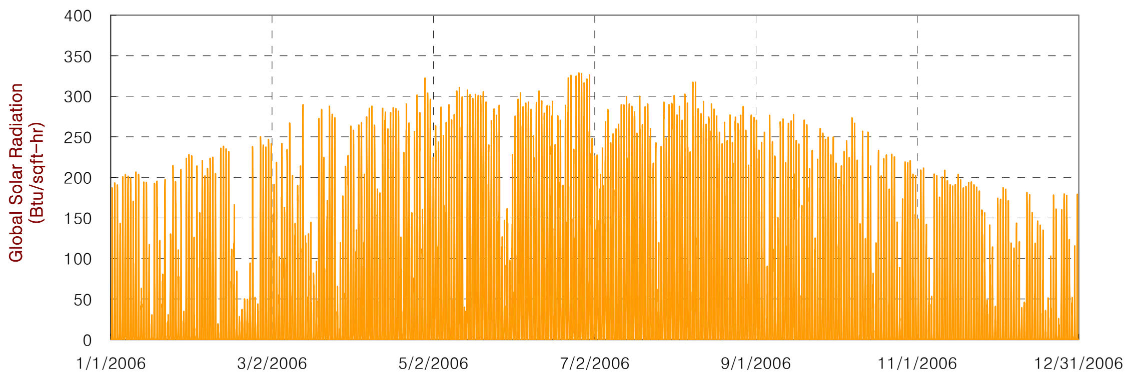


Figure 5.3.5 Hourly Global Horizontal Solar Radiation for College Station, TX in 2006 Obtained from the National Renewable Energy Laboratory (NREL) Data Base (NREL, 2007).

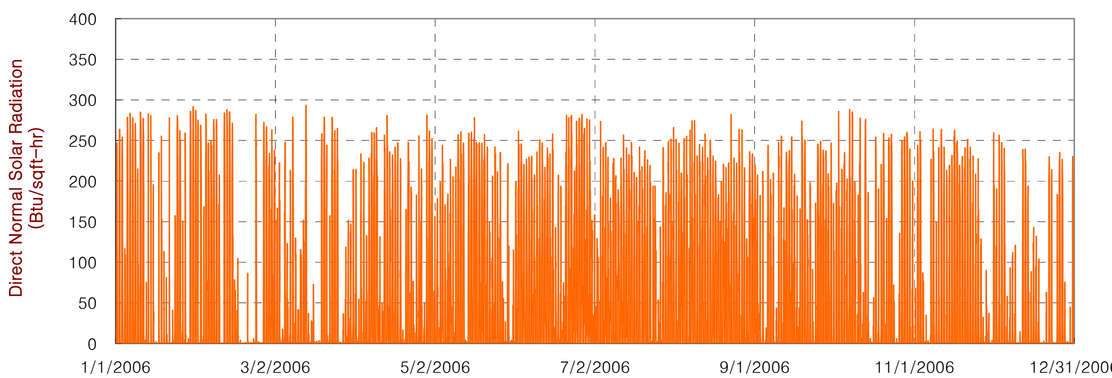


Figure 5.3.6 Hourly Direct Normal Solar Radiation for College Station, TX in 2006 Calculated Based on the Hourly Global Solar Radiation Data.

For the calculation of the direct normal radiation (I_{DN}), the solar beam radiation component (I_B) and its incidence angle (θ) are used because the I_{DN} is dependent on the intensity of I_B and θ. The relationships between these values are:

$$\mathbf{I_{DN} = I_B / \cos(\theta)} \qquad \textit{Equation 1}$$

Where the beam radiation, I_B, can be calculated using the Erb's correlation method (Erbs et al., 1982), which is:

$$\mathbf{I_B} = (1 - (\mathbf{I_D/I})_{\mathbf{Erbs}}) / \mathbf{I} \qquad \textit{Equation 2}$$

Where the global solar radiation (I) is the measured value and the Erb's correlation $(I_D/I)_{Erbs}$ is:

$$(\mathbf{I_D/I})_{\mathbf{Erbs}} = 1.0 - 0.09\ \mathbf{K_t} \qquad \textit{For } \mathbf{K_t} \leq 0.22 \qquad \textit{Equation 3}$$

$$(\mathbf{I_D/I})_{\mathbf{Erbs}} = 0.9511 - 0.1604 * \mathbf{K_t} + 4.388 * \mathbf{K_t}^{2} - 16.638 * \mathbf{K_t}^{3} + 12.336 * \mathbf{K_t}^{4}$$

$$\textit{For } 0.22 \leq \mathbf{K_t} \leq 0.8 \qquad \textit{Equation 4}$$

$$(\mathbf{I_D/I})_{\mathbf{Erbs}} = 0.165 \qquad \textit{For } \mathbf{K_t} > 0.8 \qquad \textit{Equation 5}$$

Where I_D is the diffuse radiation and clearness index, K_t, is a relationship between the global solar radiation (I) and the extraterrestrial solar radiation (I_o) (Duffie and Beckman, 2006).

The clearness index can be calculated from the measured horizontal surface radiation by dividing by the extraterrestrial radiation calculated over the same period. The following equation is used to calculate the integrated extraterrestrial radiation on a horizontal surface (Duffie and Beckman, 2006).

$$\mathbf{K_t = I / I_o} \qquad \textbf{\textit{Equation 6}}$$

Where "**I**" is the hourly measured solar radiation for College Station, Texas, and "$\mathbf{I_o}$" is extraterrestrial radiation. It is calculated by the following equation.

$$\mathbf{I_o = Gsc\left(1 + 0.033\cos\frac{360N}{365}\right)(\cos\Phi\cos\delta\cos h_w + \sin\Phi\sin\delta)} \qquad \textbf{\textit{Equation 7}}$$

Where, **Gsc** is solar constant (1,367 W/m^2), "**N**" is day of year, "**Φ"** is the local latitude, "**δ**" is the solar declination, and "$\mathbf{h_w}$" is sunset angle. The declination (**δ**) and sunset angle ($\mathbf{h_w}$) are:

$$\mathbf{\delta = 23.45\sin[360*(284+N)/365]} \qquad \textbf{\textit{Equation 8}}$$

$$\mathbf{h_w = (solar\ time\ -12)*15} \qquad \textbf{\textit{Equation 9}}$$

And the incidence angle, **cos(*θ*)**, from ***Equation 1*** is:

$$\boldsymbol{\cos(\theta) = [\cos(\Phi)\cos(\delta)\cos(h_w) + \sin(\Phi)\sin(\delta)]} \qquad \textbf{\textit{Equation 10}}$$

The calculation of global radiation on a tilted surface (**I_T**) using global horizontal radiation and diffuse radiation (Duffie and Beckman, 2006) is:

$$\mathbf{I_T = r_{b,t}(I - I_D) + I_D(r_{d,t}) + I * \rho(r_{r,t})}$$ ***Equation 11***

where,

$$\mathbf{r_{d,t} = (\frac{1 + cos\beta}{2})}$$ ***Equation 12***

$$\mathbf{r_{r,t} = (\frac{1 - cos\beta}{2})}$$ ***Equation 13***

Where "**I_D**" is the isotropic diffuse radiation, "**β**" is the solar collector tilt angle, "**ρ**" is the ground reflectance, and "**$r_{b,t}$**" is a tilt factor for the beam radiation.

The above equation can be rearranged to:

$$\mathbf{\frac{I_T}{I} = r_{b,t} - (I_D/I)_{Erbs}\left(r_{b,t} - \frac{1}{2} - \frac{cos\beta}{2}\right) + \rho(\frac{1 - cos\beta}{2})}$$ ***Equation 14***

Since only **I_T** is known, ***Equation 14*** can be used to solve the value of **$(I_D/I)_{Erbs}$** by iteration, guessing the value of **K_t** in ***Equation 3***, ***Equation 4***, and ***Equation 5***.

For the calculation of the clearness index, **K_t**, a value is assumed to calculate **$(I_D/I)_{Erbs}$**. The estimated value is renamed as **$K_{t,est}$** to avoid confusion with the calculated **K_t**. The initial guess for **K_t** is randomly chosen at 0.1 and then it is augmented automatically with a step function between 0 and 1. As each step with an arbitrary $\mathbf{K_t}$ gives a value for $\mathbf{(I_D/I)_{Erbs}}$, this value can be plugged in to ***Equation 14***, which solves for $\mathbf{I_T/I}$. Now, "**I**" can be calculated since $\mathbf{I_T}$ is known (measured value). Next step is to verify the estimated value, $\mathbf{K_{t,est}}$. By dividing **I** by $\mathbf{I_o}$ from ***Equation 6***, $\mathbf{K_t}$ can be calculated. This calculated $\mathbf{K_t}$ is compared with estimated $\mathbf{K_{t,est}}$. If these two values agree within a small error range, which is an arbitrary range set to 2.5%, the calculated solar radiation, **I**, is accepted. If the error is out of tolerance range of 2.5%, $\mathbf{K_{t,est}}$ is increased by the step function until it is reached within the tolerance range.

After all the necessary weather information was gathered and created, a TRY weather file for College Station of 2006 was made using the DOE-2.1e weather processor.

5.3.2 Lighting and Equipment Data

To develop typical load shapes of lighting and equipment loads, the ASHRAE RP-1093 (Abushakra et al., 2001) method was used. This method uses 10th, 25th, 75th, and 90th percentiles for each hour of the day by daytype such as weekday and weekend. The 50th percentiles are recommended to be used for the diversity factors for lighting and equipment. And the 90th percentile values are used for the peak load calculation. The maximum W/sqft values are calculated, and then these values were used to normalize the hourly data, which is expressed as values between 0 and 1. DOE-2.1e input schedules are compatible with these values. Figure 5.3.7 and Figure 5.3.8 show the weekday and weekend electric use patterns for the JBC building, respectively. These electric use patterns were then divided by the maximum hourly electric consumption number to be expressed as 0 to 1 index. Figure 5.3.9 and Figure 5.3.10 show the diversity factors as 0 to 1 index for the JBC building.

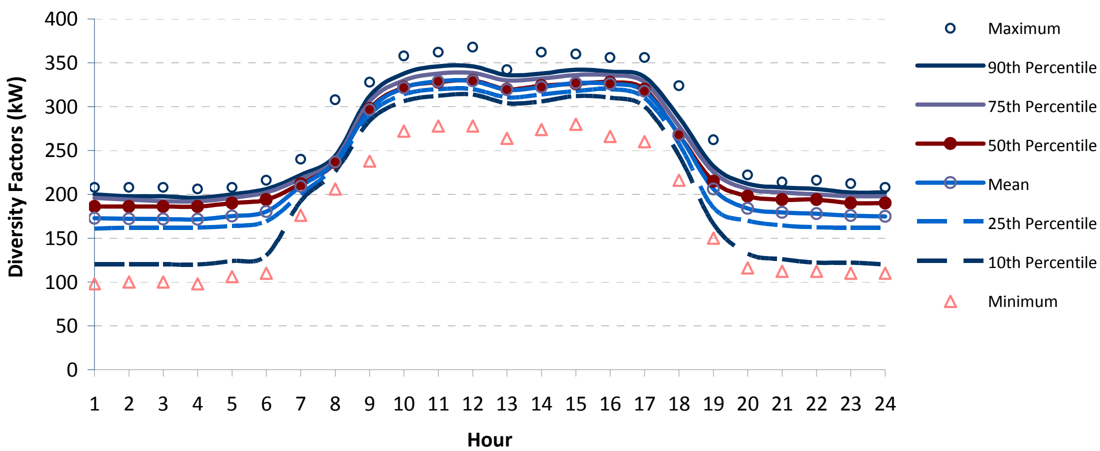


Figure 5.3.7 The JBC Building Diversity Factors of Lighting and Equipment for Weekdays.

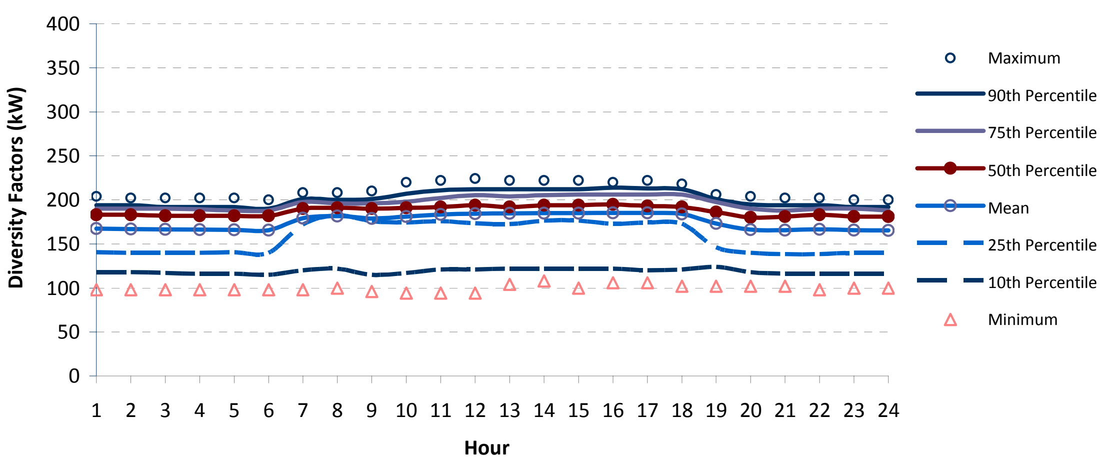


Figure 5.3.8 The JBC Building Diversity Factors of Lighting and Equipment for Weekends and Holidays.

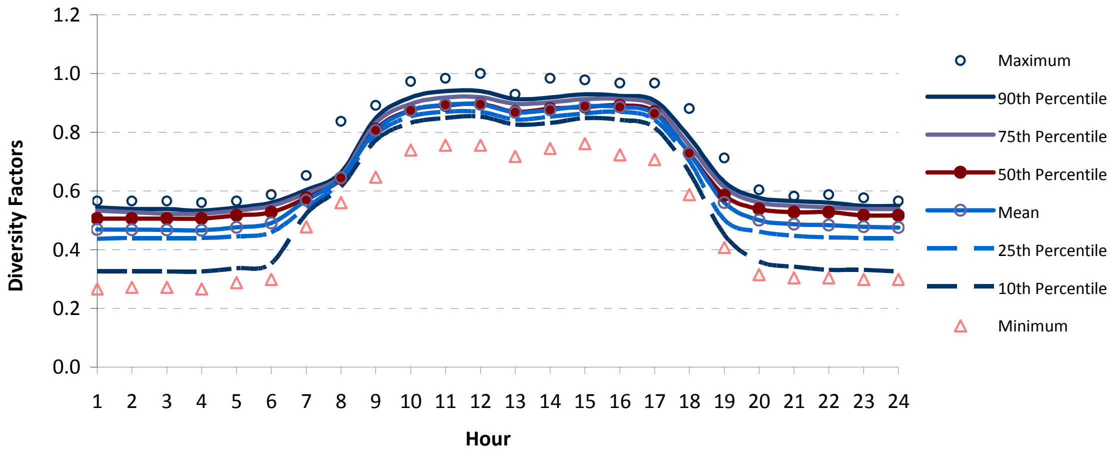


Figure 5.3.9 The JBC Building Diversity Factors of Lighting and Equipment for Weekdays Expressed as 0 to 1 Scale.

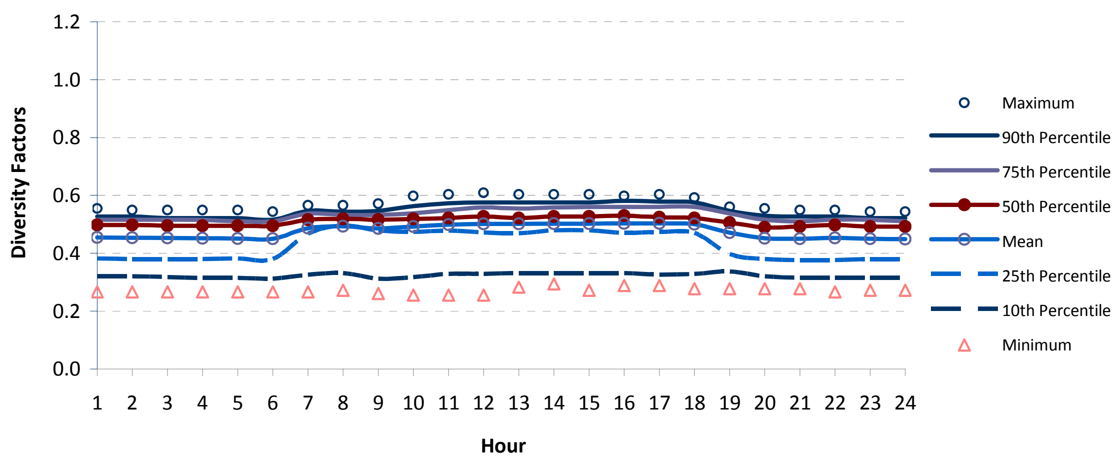


Figure 5.3.10 The JBC Building Diversity Factors of Lighting and Equipment for Weekdays Expressed as 0 to 1 Scale.

For the DOE-2.1e simulation, the 50th percentile numbers from the diversity factors were used, which are, as shown in Table 5.3.1:

For weekdays,

1am to 8am: 0.51 0.51 0.51 0.51 0.52 0.53 0.58 0.64

9am to 4pm:	0.81	0.88	0.89	0.90	0.87	0.88	0.89	0.89
5pm to 0am:	0.87	0.73	0.58	0.54	0.53	0.53	0.52	0.52

For weekends,

1am to 8am:	0.50	0.50	0.49	0.49	0.49	0.49	0.52	0.52
9am to 4pm:	0.52	0.52	0.52	0.53	0.52	0.53	0.53	0.53
5pm to 0am:	0.52	0.52	0.51	0.49	0.49	0.50	0.49	0.49

These diversity factors were used for the calibration of simulation model as schedules for lighting and equipment of the JBC building.

Table 5.3.1 The JBC Building Diversity Factors of Lighting and Equipment for Weekdays and Weekends Expressed as 0 to 1 Scale.

Weekdays Profiles																								
Mean	0.47	0.47	0.47	0.47	0.48	0.49	0.57	0.64	0.81	0.87	0.89	0.90	0.87	0.88	0.89	0.89	0.86	0.73	0.56	0.50	0.49	0.48	0.48	0.48
10th Percentile	0.33	0.33	0.33	0.33	0.34	0.35	0.52	0.61	0.77	0.83	0.85	0.85	0.83	0.83	0.85	0.84	0.82	0.66	0.45	0.36	0.34	0.33	0.33	0.33
25th Percentile	0.44	0.44	0.44	0.44	0.45	0.46	0.54	0.63	0.79	0.85	0.87	0.87	0.84	0.85	0.86	0.87	0.84	0.70	0.50	0.46	0.45	0.44	0.44	0.44
50th Percentile	**0.51**	**0.51**	**0.51**	**0.51**	**0.52**	**0.53**	**0.58**	**0.64**	**0.81**	**0.88**	**0.89**	**0.90**	**0.87**	**0.88**	**0.89**	**0.89**	**0.87**	**0.73**	**0.58**	**0.54**	**0.53**	**0.53**	**0.52**	**0.52**
75th Percentile	0.53	0.53	0.52	0.52	0.53	0.55	0.59	0.65	0.83	0.90	0.92	0.92	0.90	0.90	0.91	0.91	0.89	0.76	0.61	0.56	0.55	0.54	0.54	0.54
90th Percentile	0.54	0.54	0.54	0.53	0.54	0.56	0.60	0.66	0.85	0.92	0.94	0.94	0.91	0.92	0.93	0.92	0.91	0.78	0.63	0.58	0.57	0.56	0.55	0.55
Maximum	0.57	0.57	0.57	0.56	0.57	0.59	0.65	0.84	0.89	0.97	0.98	1.00	0.93	0.98	0.98	0.97	0.97	0.88	0.71	0.60	0.58	0.59	0.58	0.57
Minimum	0.27	0.27	0.27	0.27	0.29	0.30	0.48	0.56	0.65	0.74	0.76	0.76	0.72	0.74	0.76	0.72	0.71	0.59	0.41	0.32	0.30	0.30	0.30	0.30
Weekends Profiles																								
Mean	0.45	0.45	0.45	0.45	0.45	0.45	0.49	0.49	0.49	0.49	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.47	0.45	0.45	0.45	0.45	0.45
10th Percentile	0.32	0.32	0.32	0.32	0.32	0.31	0.33	0.33	0.31	0.32	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.34	0.32	0.32	0.32	0.32	0.32
25th Percentile	0.38	0.38	0.38	0.38	0.38	0.38	0.47	0.50	0.48	0.47	0.48	0.47	0.47	0.48	0.48	0.47	0.47	0.47	0.40	0.38	0.38	0.38	0.38	0.38
50th Percentile	**0.50**	**0.50**	**0.49**	**0.49**	**0.49**	**0.49**	**0.52**	**0.52**	**0.52**	**0.52**	**0.52**	**0.53**	**0.52**	**0.53**	**0.53**	**0.53**	**0.52**	**0.52**	**0.51**	**0.49**	**0.49**	**0.50**	**0.49**	**0.49**
75th Percentile	0.52	0.52	0.52	0.51	0.51	0.51	0.54	0.53	0.53	0.54	0.55	0.56	0.55	0.56	0.56	0.56	0.56	0.56	0.54	0.52	0.51	0.52	0.52	0.51
90th Percentile	0.53	0.53	0.52	0.52	0.52	0.52	0.55	0.54	0.55	0.56	0.57	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.55	0.53	0.53	0.53	0.52	0.52
Maximum	0.55	0.55	0.55	0.55	0.55	0.54	0.57	0.57	0.57	0.60	0.60	0.61	0.60	0.60	0.60	0.60	0.60	0.59	0.56	0.55	0.55	0.55	0.54	0.54
Minimum	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.28	0.29	0.27	0.29	0.29	0.28	0.28	0.28	0.28	0.27	0.27	0.27

5.3.3 Typical AHU (SDVAV) Operation Data

Several thermal data points were measured to verify the real AHUs operation status of the JBC building. Portable data loggers were installed in several places such as mechanical rooms and offices. Before the installation of the portable loggers, the loggers were individually calibrated to obtain correct thermal information from the JBC building. Appendix B includes detailed information about the calibration of the portable data loggers. The portable loggers were then installed in the return air duct, outside air duct, and inside an AHU in the mechanical room on the 5th floor. Figure 5.3.11 is the photo of the mechanical room on the 5th floor of the JBC building. In the mechanical room, there are two air ducts, one for the return air and the other for outside air. There is no mixed air duct, because the mechanical room is used as a mixing chamber. The mixed air in the mechanical room passes through the air filter mounted on the outside the AHU as shown in the photo. After the air filter, the mixed air goes through cooling coil. The cooled air is pulled in by a draw-through fan. This AHU is a single duct system, which has only a cold duct. Cold air is then reheated in the terminal box to meet the zone load. Figure 5.3.12 and Figure 5.3.13 show the installation of the portable loggers for the measurement of cooling coil leaving temperature or supply air temperature and return air temperature.

Figure 5.3.14 shows the hourly measured cold deck temperature or cooling coil leaving temperature (Tcc) from both AHUs located in the south and north mechanical rooms.

There are two AHUs on the floor; one provides conditioned air to the south area and the other to the north area. Figure 5.3.15 shows the return air temperature (Tra) against the outdoor air temperature Toa). The return air temperature was 74 F in average, which also agreed to the value of the JBC's energy management system. These measured temperatures were used for the calibration of the JBC simulation model.

Figure 5.3.11 Air Handling Unit in the 5th Floor of the JBC Building.

Figure 5.3.12 Installation of a Portable Logger to Measure the Cooling Coil Leaving Temperature of an AHU on the 5th Floor.

Figure 5.3.13 Installation of a Portable Logger to Measure the Return Air Temperature of an AHU on the 5th Floor.

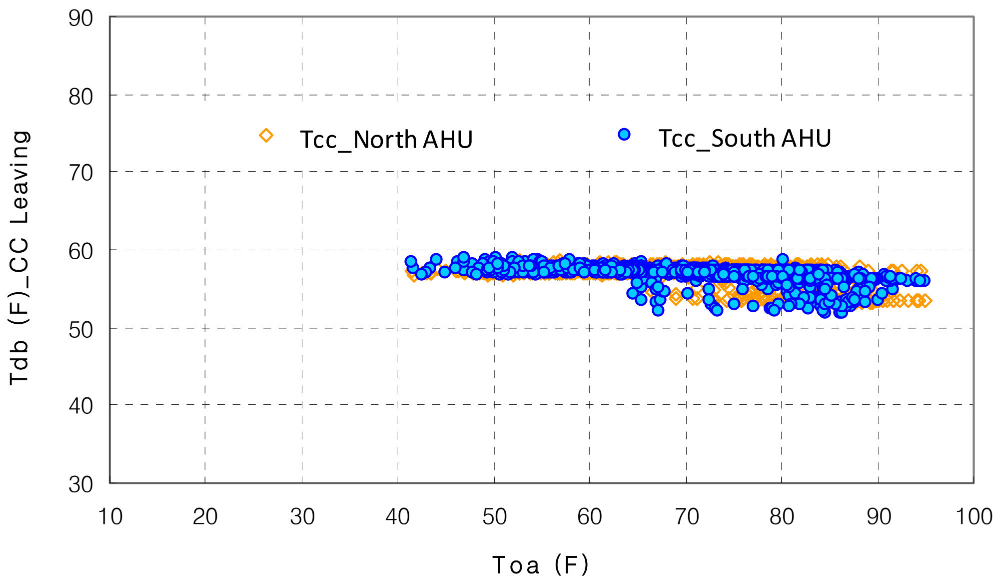


Figure 5.3.14 Cold Deck Air Temperature versus Outdoor Dry-Bulb Temperature of the 5th Floor AHUs.

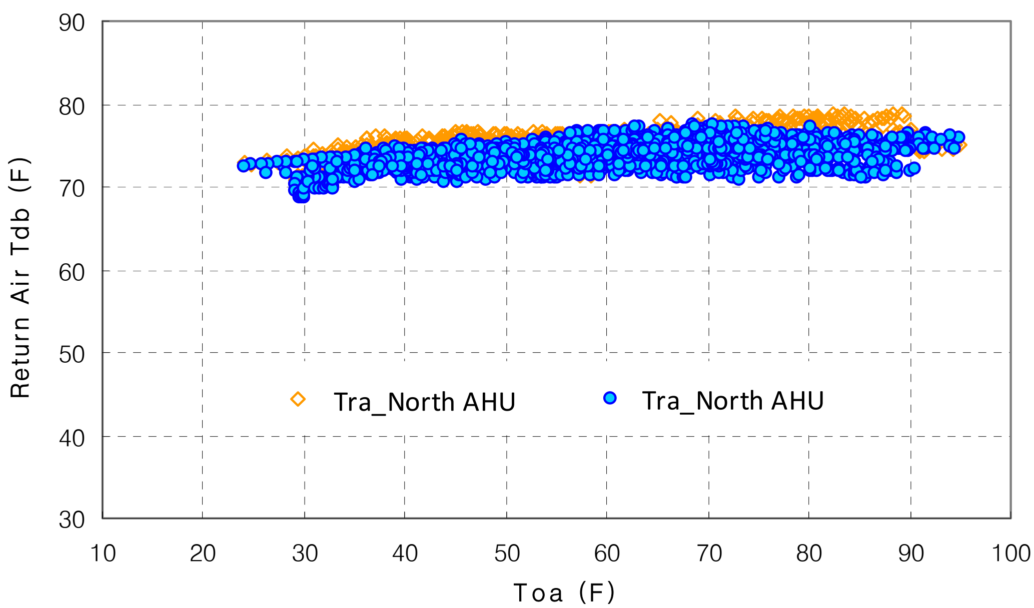


Figure 5.3.15 Return Air Temperature versus Outdoor Dry-Bulb Temperature of the 5th Floor AHUs.

5.3.4 Chiller Data

Thermal data were also retrieved from the permanently installed water flow meters (Figure 5.3.16) and temperature sensors (Figure 5.3.17). The data points include water flow and supply and return water temperatures for both chilled water and condenser water loops. Figure 5.3.19 is the JBC building's thermal plant diagram. In the thermal plant, there are two natural gas hot water boilers (Figure 5.3.18) for the space heating of the JBC building. The hot water runs through the terminal boxes where the supply air is reheated by the heating coil. Two hot water pumps (Figure 5.3.20) run when the corresponding boilers are turned on. There are also two chillers (Figure 5.3.21) with two chilled water pumps (Figure 5.3.22). The cooling system has two water cooled towers (Figure 5.3.23).

The cooling towers cool the condensing water that is used as a heat sink for the chiller. Two condenser pumps (Figure 5.3.24) draw the water from the cooling tower and push it into the heat exchanger. There are temperature sensors installed (Figure 5.3.25) before and after the equipment to measure the temperature differences of the condenser water. Flow meters were also installed (Figure 5.3.26) after the pumps to measure the flow rate. These temperature differences and flow rate are used to calculate the thermal energy, by which equipment efficiencies are calculated comparing with the fuel or electricity inputs. Electric meters are installed in the two chilled water pumps to measure the electricity consumptions of the pumps.

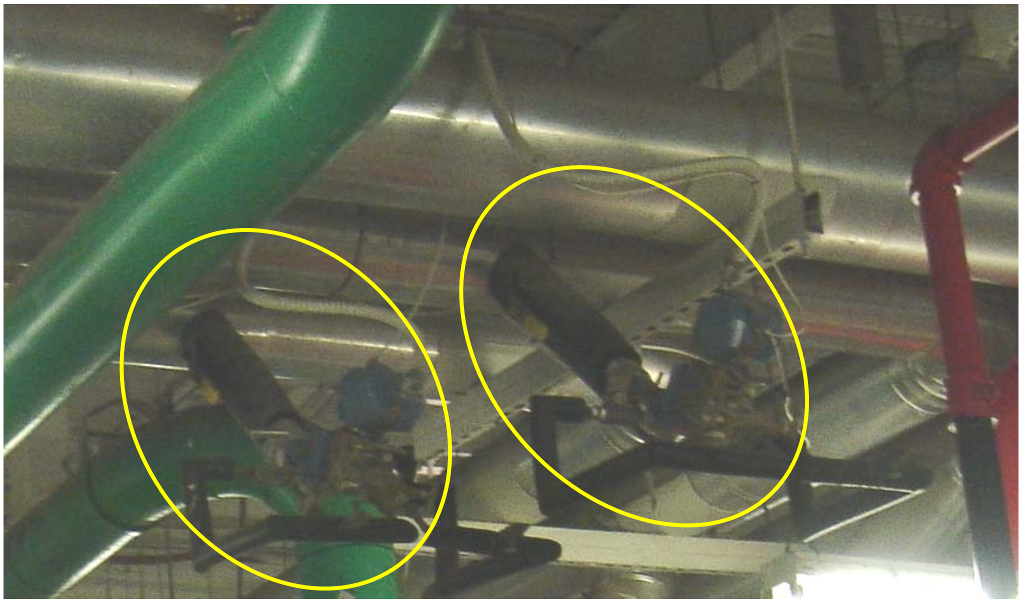


Figure 5.3.16 Photo of Flow Meters Permanently Installed in the Chilled Water Pipes.

Figure 5.3.17 Photo of a Temperature Sensor Permanently Installed in a Chilled Water Pipe.

Figure 5.3.18 Photo of a Natural Gas Hot Water Boiler.

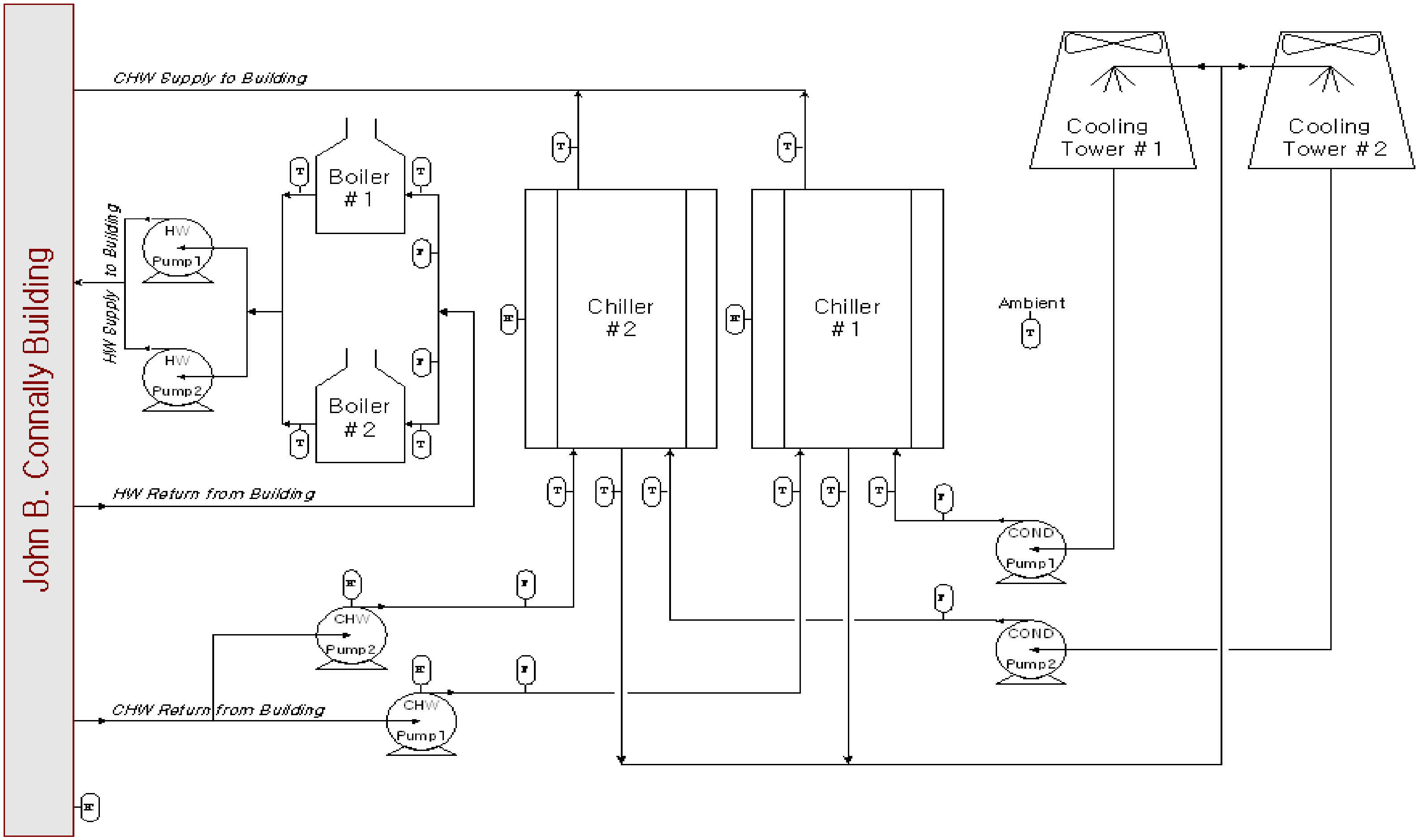


Figure 5.3.19 The JBC Building's Thermal Plant Diagram.

Figure 5.3.20 Photo of a Hot Water Pump in the Thermal Plant of the JBC Building.

Figure 5.3.21 Photo of the Two Identical Centrifugal Chillers in the Thermal Plant of the JBC Building.

Figure 5.3.22 Photo of a Chilled Water Pump in the Thermal Plant of the JBC Building.

Figure 5.3.23 Photo of the Two Cooling Towers outside the Thermal Plant of the JBC Building.

Figure 5.3.24 Photo of the Two Condenser Water Pumps in the Thermal Plant of the JBC Building.

Figure 5.3.25 Photo of a RTD Temperature Sensor Installed in a Condenser Water Pipe in the Thermal Plant of the JBC Building.

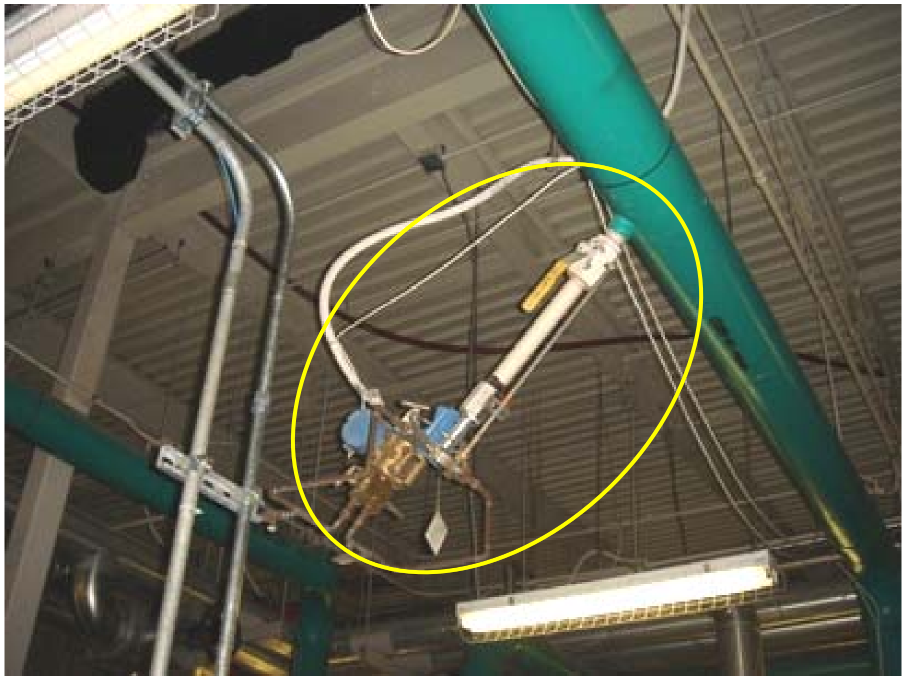


Figure 5.3.26 Photo of a Flow Meter Permanently Installed in a Condenser Water Pipe in the Thermal Plant of the JBC Building.

Figure 5.3.27 shows the performance of the chillers calculated using measured data. The chiller performance was compared against the manufacturer's curve for the chiller (Peraza, 2006). There are two different performance patterns in the graph. One pattern, which was from the chiller-1, appears little bit above the manufacturer's data line, and the other pattern, which was from the chiller-2, little bit below the line for the part load range between 60 tons and 160 tons. Although the two chillers were identical and had 280-tons each with same rated efficiencies, there were differences in the actual performances measured.

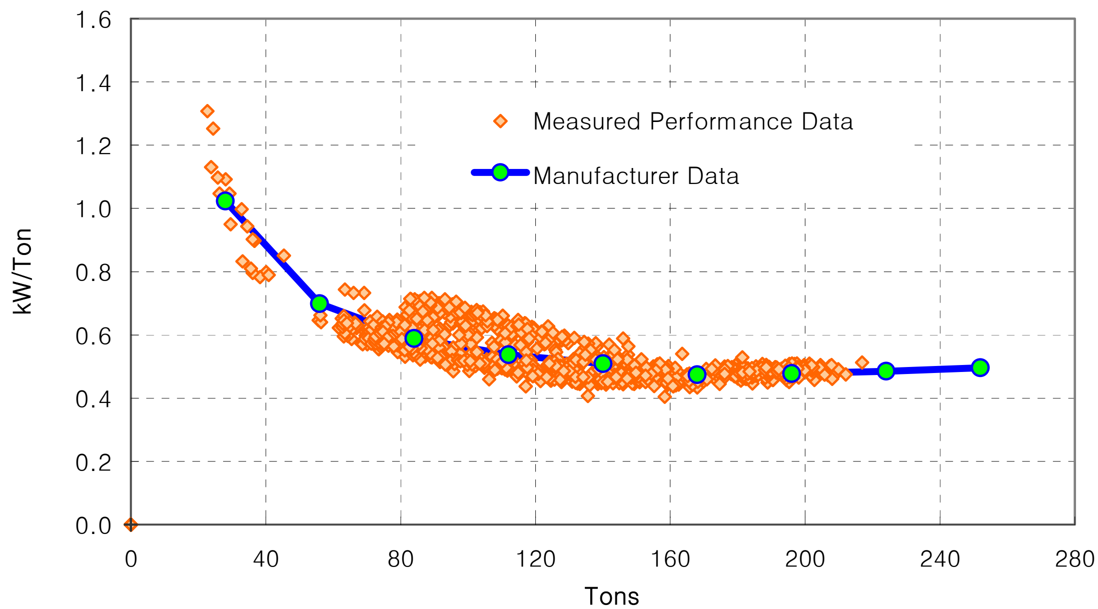


Figure 5.3.27 The JBC Building's Chiller Performance (Measured vs. Manufacture data Comparison).

5.4 DOE-2.1e Simulation Model Development

5.4.1 DOE-2.1e LOADS Input

This section describes the DOE-2.1e keywords and input values used for the DOE-2.1e LOADS simulation of the case-study building. Table 5.4.1 shows the inputs for the building location. The front of the JBC building faces west (see Figure 5.1.1). The location information was obtained from the National Oceanic and Atmospheric Administration (NOAA) data base website for College Station, Texas (NOAA, 2007).

Table 5.4.1 Building Location of the JBC Building.

DOE-2 Keywords	DOE-2 Values	Description
Latitude	30.35 N	College Station Weather Station (from NOAA)
Longitude	96.22 W	College Station Weather Station (from NOAA)
Altitude	326 ft	College Station Weather Station (from NOAA)
Time Zone	6	Central Time Zone
Azimuth	90 Degree	Facing West
Holiday	Yes	TAMU Holidays
Daylight-Savings	Yes	Daylight Savings Time
Ground Temperature	No	Monthly ground temperatures are automatically calculated, using the method of Kusuda and Achenbach (1965) by DOE-2 weather processor (Buhl, 1999).

The JBC building is a seven-story building with a total conditioned space of 124,000 square feet. The interior zones of the first three floors (1st through 3rd) consist of an atrium and exterior office zones. The remainder of the floors (4th through 7th) consist of offices in both interior and exterior zone locations. This building is used by three departments of the Texas A&M University. Table 5.4.2 shows details of the construction materials of the JBC building. For the calculation of the exterior wall R-value, a batt insulation of R-13 and a metal frame wall of R-0.61 were combined to be an R-value of R-4.91. The calculation was based on 27% framing factor (16" o.c. steel frame), which is consistent with Syed and Kosny (2006).

About 40% of the JBC building is covered with windows. The glazing information of the JBC building was obtained from the manufacturer (ACME, 2006). Table 5.4.3 is a summary of the manufacturer's data. It is double-pane glazing with a half inch air gap

Table 5.4.2 Material and R-values (U-values) of the JBC Building Construction.

Items	Materials	Values	Units
Roof	Outside Air Film	0.17	Hr-Sqft-F/Btu (R-value)
	Gravel Ballast	0.05	Hr-Sqft-F/Btu (R-value)
	Urethane 4" Minimum	25.00	Hr-Sqft-F/Btu (R-value)
	Concrete (Light-80lb)	3.20	Hr-Sqft-F/Btu (R-value)
	Inside Film Resistance	0.61	Hr-Sqft-F/Btu (R-value)
	Roof Total R-value	***29.03***	***Hr-Sqft-F/Btu (R-value)***
	Roof Total U-value	***0.034***	***Btu/Hr-Sqft-F (U-value)***
Exterior Wall	Outside Air Film	0.17	Hr-Sqft-F/Btu (R-value)
	Concrete (Light-80lb)	3.2	Hr-Sqft-F/Btu (R-value)
	Batt Insulation (R-13)	4.91	Hr-Sqft-F/Btu (R-value)
	Wall Metal Frame (R-0.61)		
	5/8" Gypsum Board	0.56	Hr-Sqft-F/Btu (R-value)
	Inside Film Resistance	0.68	Hr-Sqft-F/Btu (R-value)
	Exterior Wall Total R-value	9.52	Hr-Sqft-F/Btu (R-value)
	Exterior Wall Total U-value	***0.105***	***Btu/Hr-Sqft-F (U-value)***
Floor	Inside Air Film	0.77	Hr-Sqft-F/Btu (R-value)
	Concrete (Light-80lb)	2.80	Hr-Sqft-F/Btu (R-value)
	Inside Air Film	0.77	Hr-Sqft-F/Btu (R-value)
	Floor Total R-value	4.34	Hr-Sqft-F/Btu (R-value)
	Floor Total U-value	***0.230***	***Btu/Hr-Sqft-F (U-value)***
Ceiling	Inside Air Film	0.61	Hr-Sqft-F/Btu (R-value)
	5/8" Gypsum Board	0.56	Hr-Sqft-F/Btu (R-value)
	Inside Air Film	0.61	Hr-Sqft-F/Btu (R-value)
	Ceiling Total R-value	1.78	Hr-Sqft-F/Btu (R-value)
	Ceiling Total U-value	***0.562***	***Btu/Hr-Sqft-F (U-value)***
Interior Wall	Inside Air Film	0.61	Hr-Sqft-F/Btu (R-value)
	5/8" Gypsum Board	0.56	Hr-Sqft-F/Btu (R-value)
	Wall Metal Frame	0.61	Hr-Sqft-F/Btu (R-value)
	5/8" Gypsum Board	0.56	Hr-Sqft-F/Btu (R-value)
	Inside Air Film	0.61	Hr-Sqft-F/Btu (R-value)
	Interior Wall Total R-value	2.95	Hr-Sqft-F/Btu (R-value)
	Interior Wall Total U-value	***0.339***	***Btu/Hr-Sqft-F (U-value)***

between panes. The inside pane is one quarter inch clear glass. The outside pane is one quarter inch bronze tinted glass. The value is 0.50 Btu/hr-sqft-F for summer and 0.48 Btu/hr-sqft-F for winter and has a Solar Heat Gain Coefficient (SHGC) of 0.34 (ACME, 2006).

Table 5.4.3 Glazing Thermal Properties of the JBC Building Obtained from the Manufacturer Data.

Glazing Properties	Manufacturer Values	Description
Layer	Exterier Lite	1/4" PPG Solarcool Bronze Reflective #2
	1/2" Cavity	1/2" Air
	Interior Lite	1/4" Clear Glass
U-values	0.50	Summer Daytime (Btu/hr-sf-F)
	0.48	Winter Nighttime (Btu/hr-sf-F)
SHGC	0.34	Solar Heat Gain Coefficient
Tvis	0.19	Visible Light Transmittance
Rvis	0.14	Visible Light Reflectance (Outside)
	0.38	Visible Light Reflectance (Inside)
Ttot	0.21	Total Solar Transmittance
Rtot	0.12	Total Solar Reflectance (Outside)

The zoning of the JBC building spaces used interior and exterior zones based on the JBC building architecture drawings. Figure 5.4.1 shows the zoning of the JBC building and Figure 5.4.2 shows the schematic floor plans for both lower levels (1st through 3rd floors) and upper levels (4th through 7th floors). The JBC building has three AHUs for each floor from the 1st to 3rd floors and two AHUs for each floor from 4th to 7th floors. Figure 5.4.3 is a floor plan of the 5th floor in which there are two AHUs, one serving south area and the other serving north area. The line between south and north area in Figure 5.4.3 is a fictitious line dividing the area into two zone for the two AHUs. Each AHU supplies conditioned air to both interior and exterior zones in either south or north area of the JBC building.

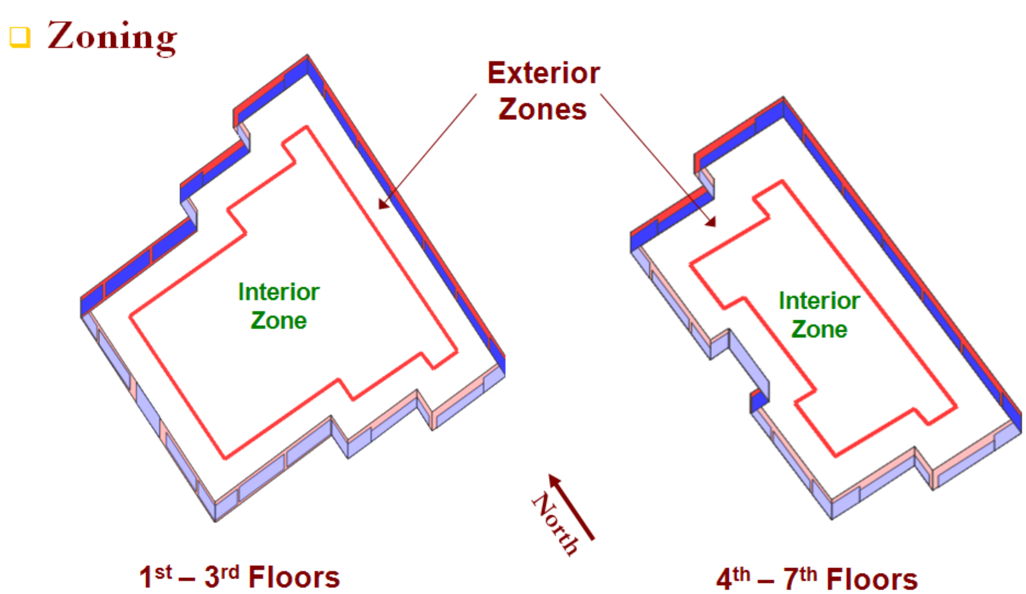


Figure 5.4.1 Zoning of the JBC Building.

The information about the space condition of the JBC building for the DOE-2.1e simulation input was mainly obtained from measured data. Table 5.4.4 shows a summary of the DOE-2.1e space condition input. An average space temperature of 74 F was observed from the measured return air temperature as shown in Figure 5.3.15. The lighting and equipment power densities and schedules were retrieved from measured electric data using the methodology presented in the ASHRAE RP-1093 toolkit

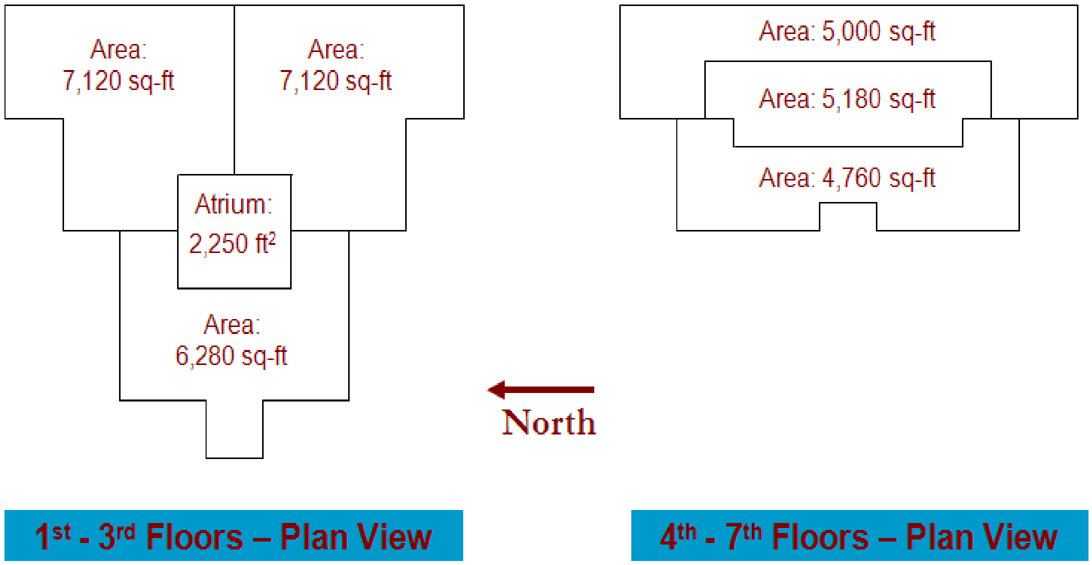


Figure 5.4.2 Schematic Floor Plans of the JBC Building.

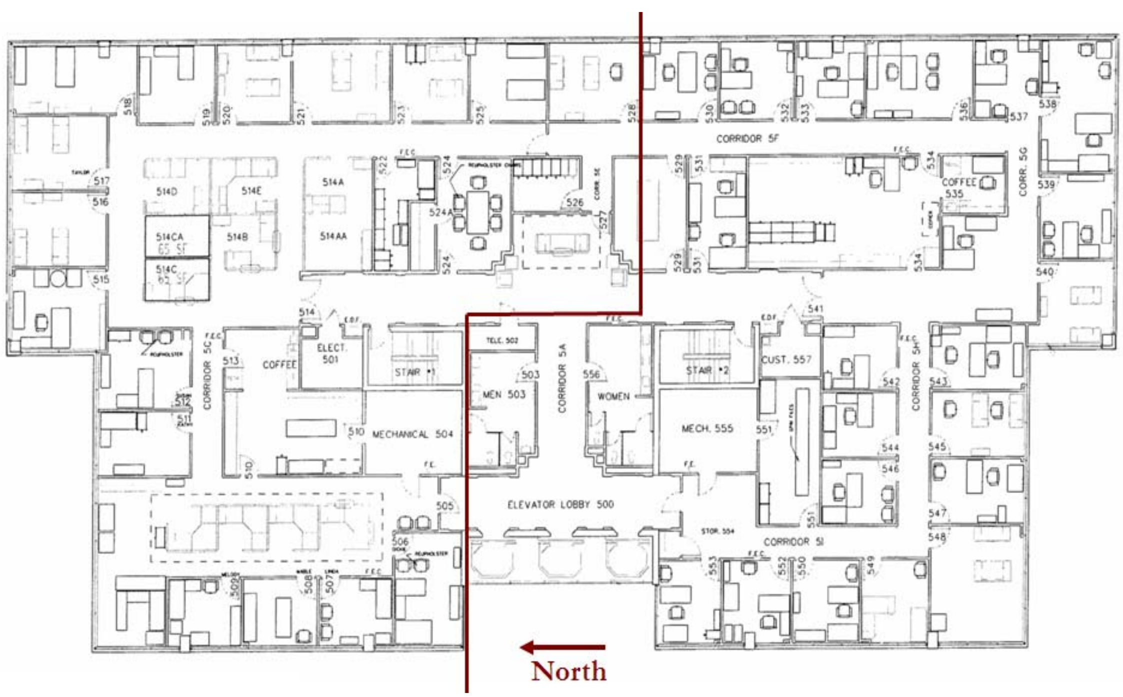


Figure 5.4.3 A Typical Floor Plan of the JBC Building (5th Floor).

(Abushakra et al., 2001). No air infiltration was assumed because the HVAC systems are always on in the building and the building is slightly pressurized.

Table 5.4.4 Space Conditions Input for DOE-2.1e Simulation.

DOE2 Key Words	Inputs	Descriptions
TEMP	74 F	Average of Measured Value
AREA/PERSON	492	124,000 sqft / 252 People
PEOPLE-HG-SENS	245 Btu/Hr	ASHRAE Fundamental 1997 - Office seated very light work
PEOPLE-HG-LAT	155 Btu/Hr	ASHRAE Fundamental 1997 - Office seated very light work
LIGHTING-TYPE	REC-FLUOR-RV	Recessed Fluorescent Vented to Return Air
LIGHTING-W/SQFT	1.90	Measured
LIGHTING-SCHEDULE	LIGHTS-1	Measured (RP-1093)
LIGHT-TO-SPACE	0.80	DOE2 Default for REC-FLUOR-RV
EQUIPMENT-W/SQFT	1.07	Measured
EQUIP-SCHEDULE	EQUIP-1	Measured (RP-1093)
INF-METHOD	AIR-CHANGE	
AIR-CHANGE/HR	0	HVAC always ON
INF-SCHEDULE	INFIL-SCH	
FLOOR-WEIGHT	70 LB/SQFT	DOE2 Default for Medium Construction

5.4.2 DOE-2.1e SYSTEMS Input

The JBC building has a total of 17 AHUs, which are all Single Duct Variable Air Volume (SDVAV) systems with terminal reheat. All units use the plenum above the drop ceiling as the return air path to the units without return fan. The main draw-through fans in each AHU run to circulate the conditioned air in the building. After the air passes through each zone, the return air comes back to the mechanical rooms through plenums located above the drop ceiling. In each unit a portion of the return air is exhausted to the outside and fresh air is added to the return air in the mechanical rooms to meet the indoor air quality requirements by two outside air handling units.

Figure 5.4.4 shows a typical AHU system schematic diagram of the JBC building. The outdoor fresh air is supplied by two 100% Outside Air Variable Air Volume (OAVAV) AHUs, each serving either the south or north AHUs on each floor. The two OAVAV AHUs are located on the roof of the JBC building, as shown in Figure 5.4.5. These OA units do not have cooling coils or heating coils. They only supply each AHU with unconditioned fresh air.

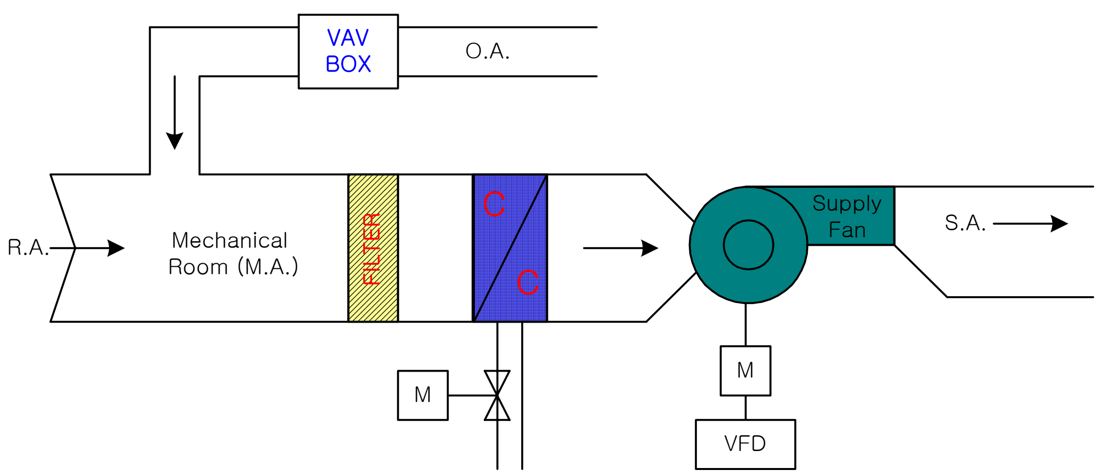


Figure 5.4.4 JBC Building AHU System Schematic Diagram.

For the DOE-2.1e simulation of the JBC building, a VAV system type was selected, which the DOE-2.1e program closely matches the JBC building's AHU system type. Figure 5.4.6 shows VAVS system diagram. In the system diagram, the components in the dotted boxes are optional, so that users can add or delete them in their simulation. For the JBC building AHU systems simulation, no optional system components were used except the reheat coil, RH/C in the diagram. Also, there were no preheat or heating coils in the JBC building's AHUs. The conditioned air is only reheated in the reheat coil in the terminal boxes.

Figure 5.4.5 JBC Building 100% Outside Air Variable Air Volume AHU.

Table 5.4.5 shows the summary of the SYSTEMS input for the initial JBC building DOE-2.1e simulation. The cooling and heating setpoints were 74 F based on the measured return air temperature. To model the VAV system, reverse action type thermostats were used for thermostat types. The minimum supply temperature was observed as 53 F by measurements. The cold deck supply air temperature was scheduled based on the outdoor temperature condition. The outside air was assigned to each zone as designed in the as-built mechanical drawings. The AHU fans are always on and the supply static pressure is 2.0 inH_2O.

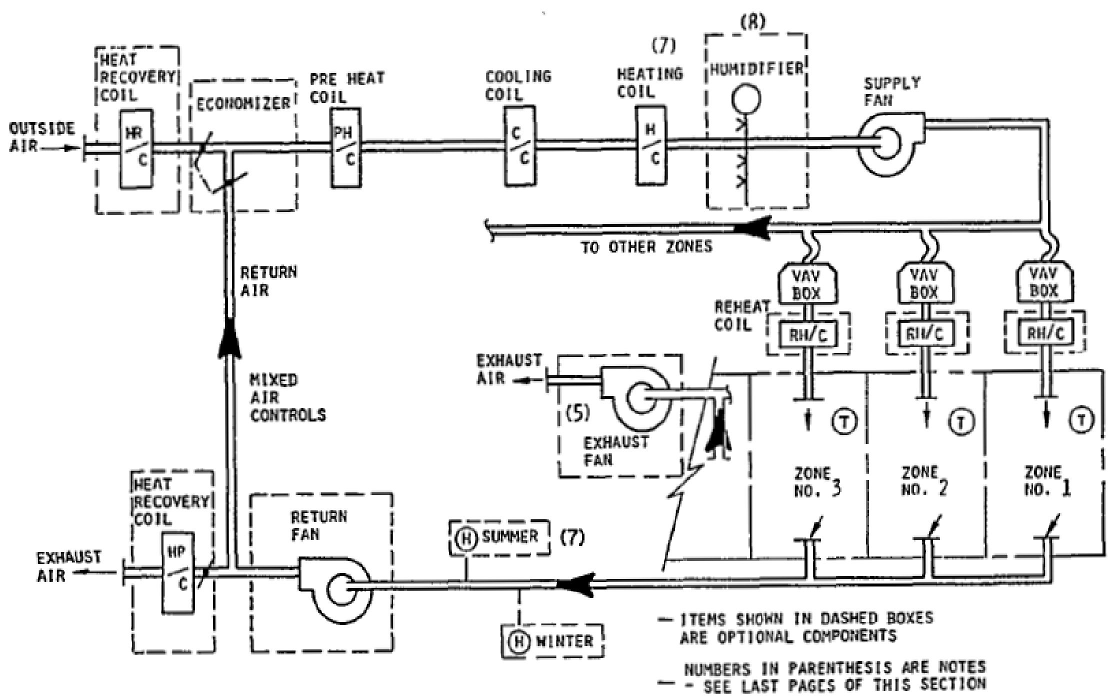


Figure 5.4.6 DOE-2.1e System Diagram of the Variable Air Volume Fan System w/ Optional Reheat (VAVS) (LBNL, 1981).

Table 5.4.5 SYSTEMS Input Summary.

Item	DOE2 Key Words	DOE2 Model	Descriptions
ZONE-CONTROL	HEAT-TEMP-SCHEDULE	HEAT-SCHED	74 F
	COOL-TEMP-SCHEDULE	COOL-SCHED	74 F
	THERMOSTAT-TYPE	REVERSE-ACTION	VAV System
SYSTEM	SYSTEM-TYPE	VAVS	Variable Air Volume System
	RETURN-AIR-PATH	PLENUM-ZONES	Through Plenums
SYSTEM-CONTROL	MIN-SUPPLY-TEMP	53 F	Measured
	COOL-CONTROL	RESET	Reset Schedule
	COOL-RESET-SCH	SAT-RESET	Supply Air Temp. Reset
	MAX-SUPPLY-TEMP	105 F	DOE-2 Default
	HEAT-SET-TEMP	105 F	DOE-2 Default
	PREHEAT-TEMP	NO PREHEAT	No Preheating
SYSTEM-AIR	MIN-OUTSIDE-AIR	Assigned to each zone	From Drawing
	OA-CONTROL	Assigned to each zone	From Drawing
SYSTEM-FAN	FAN-SCHEDULE	FAN-SCHED	Always ON
	SUPPLY-STATIC	2.5 inH_2O	From DOE-2 Sample File
	SUPPLY-EFF	0.41	From Drawing
	MOTOR-PLACEMENT	IN-AIRFLOW	Installed in Airflow
	FAN-CONTROL	SPEED	Variable-speed
SYSTEM-TERMINAL	MIN-CFM-RATIO	30%	DOE-2 Default
	REHEAT-DELTA-T	48 F	DOE-2 Default

5.4.3 DOE-2.1e PLANT Input

Table 5.4.6 shows the summary of the PLANT input in the DOE-2.1e simulation. There are two boilers installed in the thermal plant. However, only one boiler runs at a time and is sequenced to switch with other boiler regularly.

Table 5.4.6 PLANT Input Summary.

	Items	DOE2 Model	Descriptions
BOILER	TYPE	HW Boiler	Conventional Boiler
	SIZE	1.2	1.2 MMBtu/Hr
	INSTALL NUMBER	2	Running One Boiler at a Time
	HW-BOILER-HIR	1.25	Input (2000) / Output (1600)
	HCIRC-PUMP-TYPE	VARIABLE-SPEED	Variable-speed Hot Water Pump
CHILLER	SIZE	3.36 (280 TON)	3.36 MMBtu/Hr
	INSTALL NUMBER	2	Running One Chiller at a Time
	ELEC-INPUT-RATIO	0.143	0.5 kW/Ton
	TYPE	OPEN-TWR	York Chiller
COOLING TOWER	SIZE	4.2	Mbtu/Hr
	INSTALL NUMBER	2	Running One Condenser at a Time
	TWR-CAP-CTRL	VARIABLE-SPEED-FAN	Variable-speed Control
	CCIRC-PUMP-TYPE	VARIABLE-SPEED	Variable-speed Chilled Water Pump

Each boiler has a capacity of 1.2 MMBtu/hr with the thermal efficiency of 80%. Two York open centrifugal chillers are installed in the JBC building. One chiller is enough to meet the peak cooling load. The chillers are also sequenced to run every other time. The electric draw is 190 kW for each chiller and chiller cooling capacity is 280 tons (3.36 MMBtu/hr). Two cooling towers were installed, one for each chiller. Two variable-speed draw-through fans were installed, one for each cooling tower. The cooling towers were sized to be 4.2 MMBtu/hr each. Hot water pumps and chilled water pumps are all variable-speed.

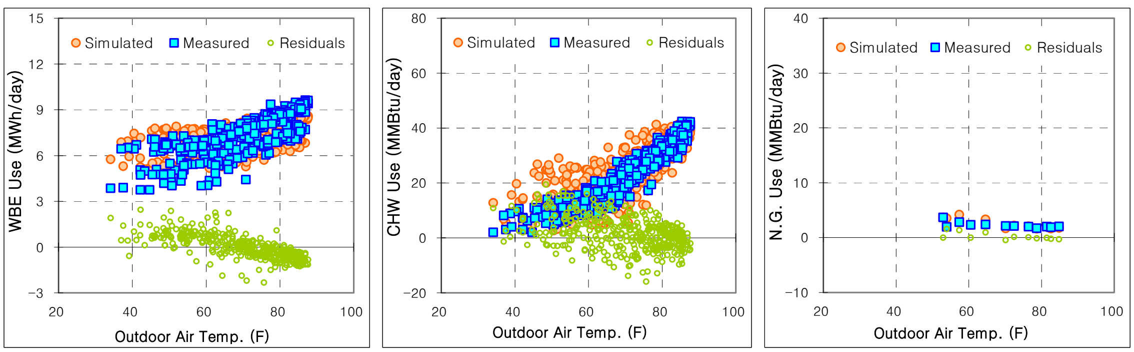
5.5 Simulation Results

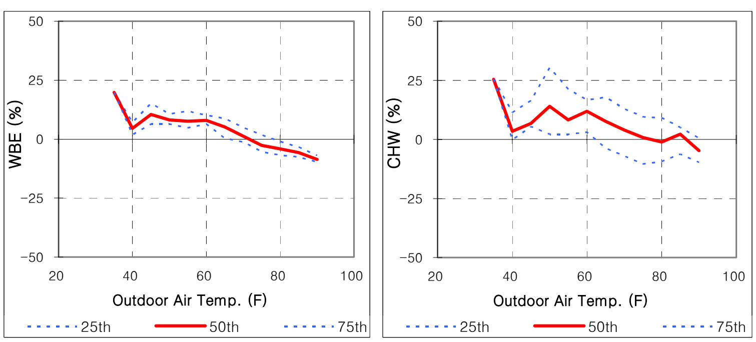
The baseline simulation results are reported in this section. The initial simulation was used to determine the basic energy consumption patterns of the JBC building using the Houston TMY2 weather file. A series of simulation calibration steps followed after the initial simulation. The calibration used the measured data and equipment manufacturer data to make changes to the input file. For the cases where no appropriate measured or manufacturer data were available, DOE-2.1e default values were used. Special cases are noted as needed.

5.5.1 Initial Simulation Results

The initial simulation was performed using design data available from the building drawings and TMY2 Houston weather data. The hourly simulation results from HVAC systems, lightings, equipment, and other building energy systems were summed up to the daily energy consumption. These daily energy use data were then divided into cooling, heating, and whole-building electricity use to compare these with measured energy consumption.

Figure ***5.5.1*** shows the initial simulation results and comparison with measured data.





Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	817
Initial Simulation	**2,666**	**9,035**	**904**
Difference (Sim. - Measured)	-4	546	87

Uncertainty	WBE	CHW	N.G.
MBE (%)	-0.1	6.4	10.6
CVRMSE (%)	10.6	26.0	31.0

Figure 5.5.1 Initial Simulation Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

The uncertainties of the initial simulation were a CV(RMSE) of 10.6% (WBE), 26.0% (CHW), and 31.0% (N.G.). The discrepancies between the measured and simulated energy usages can easily be seen in the figures. The top three plots show the Whole

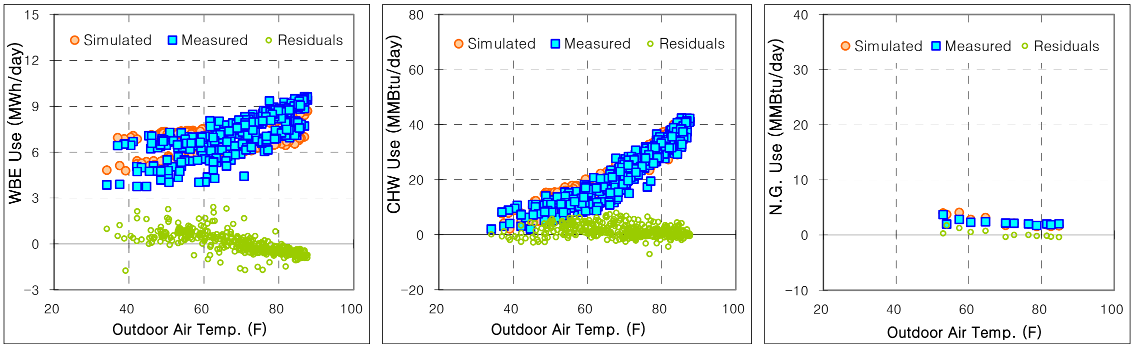
Building Electric (WBE) use, cooling energy use, and Natural Gas (N.G.) use. The other two plots in the lower part of the figure show calibration signatures for WBE and CHW. The N.G. usage was not able to be evaluated using an hourly basis since only monthly bills were available for the JBC building. Therefore, the N.G. use calibration was performed on monthly consumption basis.

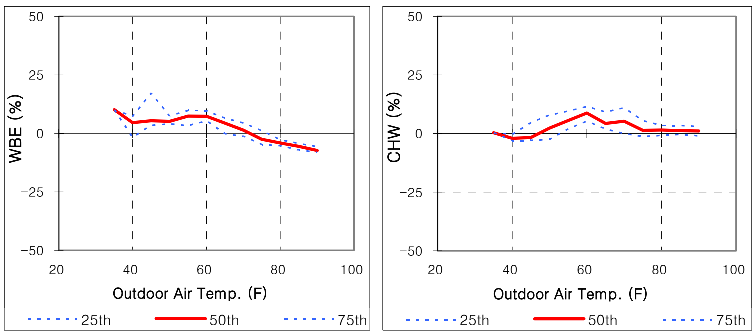
5.5.2 Calibration 1: Weather File (TMY2 to Measured Data Using TRY Format)

In this calibration, the TMY2 Houston, TX weather file has been replaced with a specially prepared or "packed" 2006 TRY weather file for College Station, TX. As shown in Figure 5.5.2, after replacing the weather file, the simulated cooling energy improved significantly, so that the CV(RMSE) of the cooling energy reduced to 11.3% from 26.0%, while that of WBE changed to 9.5% from -0.2% and N.G. to 32.1% from 12.0%.

5.5.3 Calibration 2: Diversity Factor for Lighting and Equipment

In this calibration, the lighting and equipment schedule was changed to the measured data using the methodology of the ASHRAE RP-1093 (Abushakra et al., 2001). As shown in Figure 5.5.3, the hourly measured L&E electric data were rearranged for weekday and weekend profiles using the ASHRAE RP-1093 method. The lighting and equipment power densities were initially used from typical values for large office buildings developed in the RP-1093 project (Figure 5.5.4).



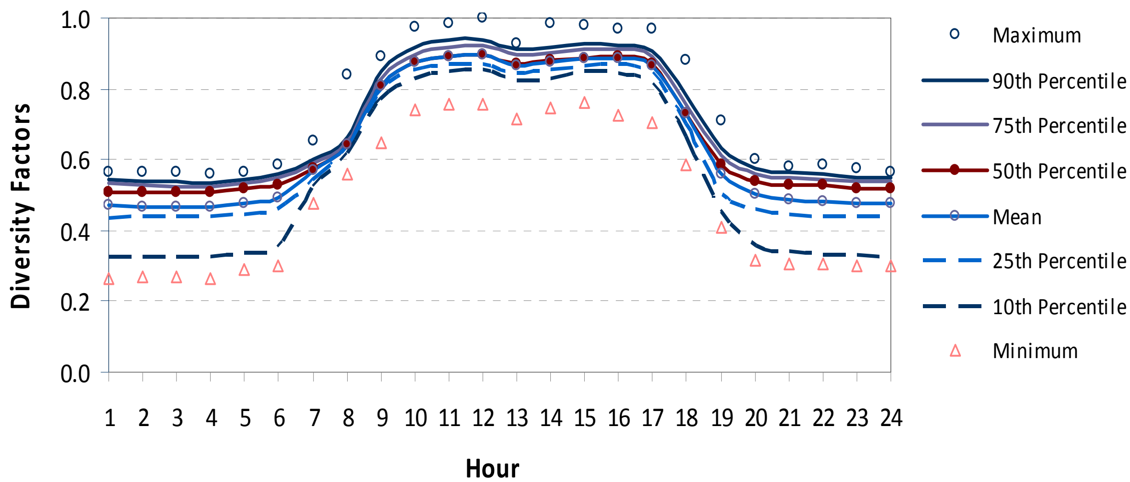


Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	817
Previous Calibration	2,666	9,035	904
Calibration	**2,663**	**8,995**	**915**
Difference (Cali. - Measured)	-6	506	98
Difference (Cali. - Prev. Cali.)	-3	-40	11

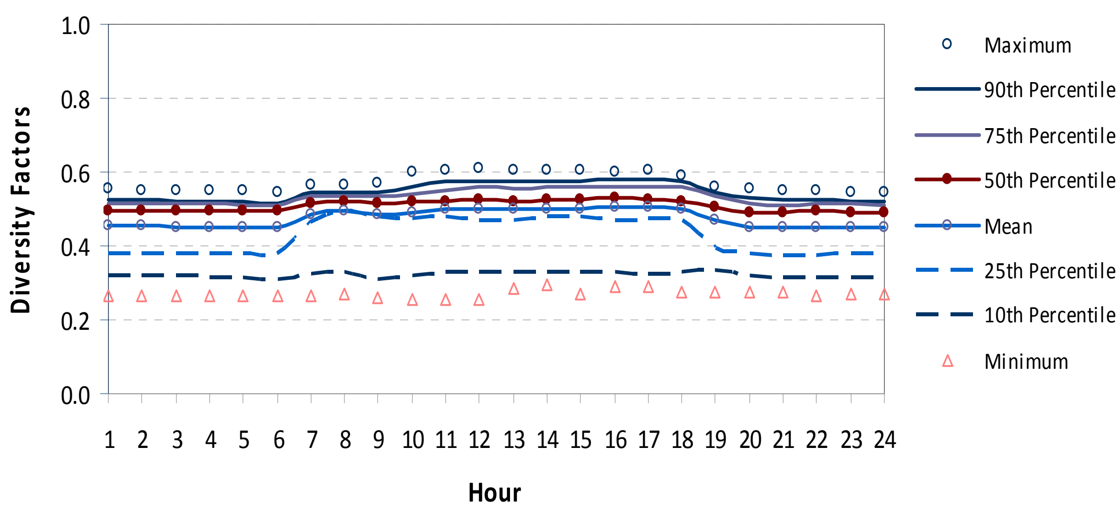
Uncertainty	WBE	CHW	N.G.
MBE (%)	**-0.2**	**6.0**	**12.0**
CVRMSE (%)	**9.5**	**11.3**	**32.1**

Figure 5.5.2 First Calibration Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

The resultant weekday and weekend diversity factors, which are based on the JBC building's measured data were incorporated into the simulation with the results shown in Figure 5.5.5. The diversity factors with the measured data for the JBC building improved the simulation results, increasing both cooling and WBE energy consumption. Statistical analysis showed that the CV(RMSE) of the WBE was improved from 9.5% to 7.8%, while the cooling energy CV(RMSE) increased from 11.3% to 12.0%. The N.G. increased slightly from 32.1% to 32.5%. The detailed diversity factors impacted the simulation changing the energy consumption patterns substantially.



(a)



(b)

Figure 5.5.3 JBC Building L&E Weekday and Weekend Profiles: (a) Weekday Profile and (b) Weekend Profile.

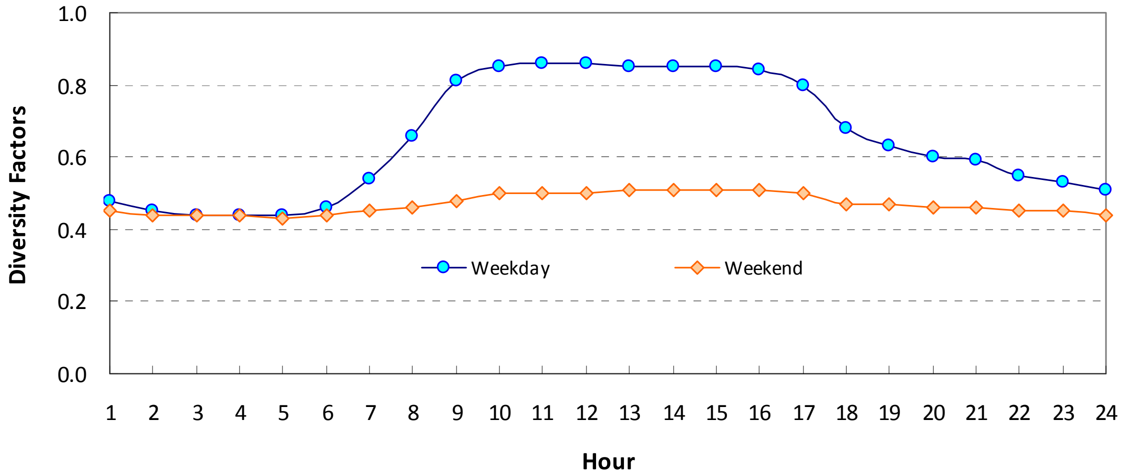
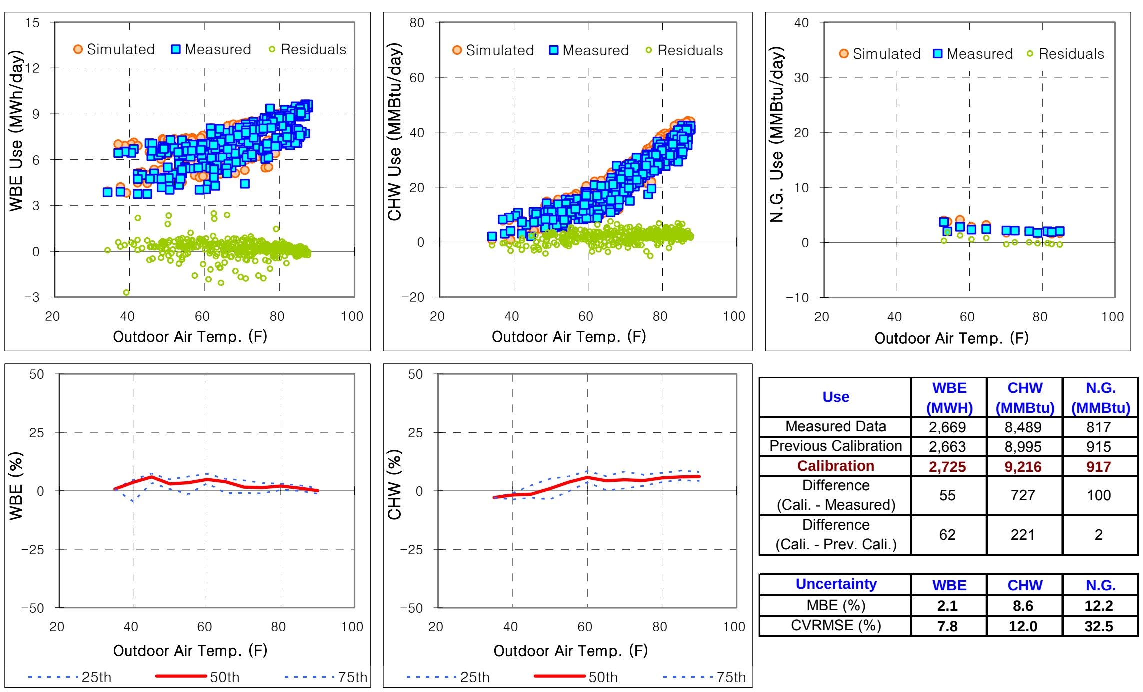


Figure 5.5.4 Weekday and Weekend Lighting & Equipment Profiles for Large Office Building Referenced from the ASHRAE RP-1093 (Abushakra et al., 2001).



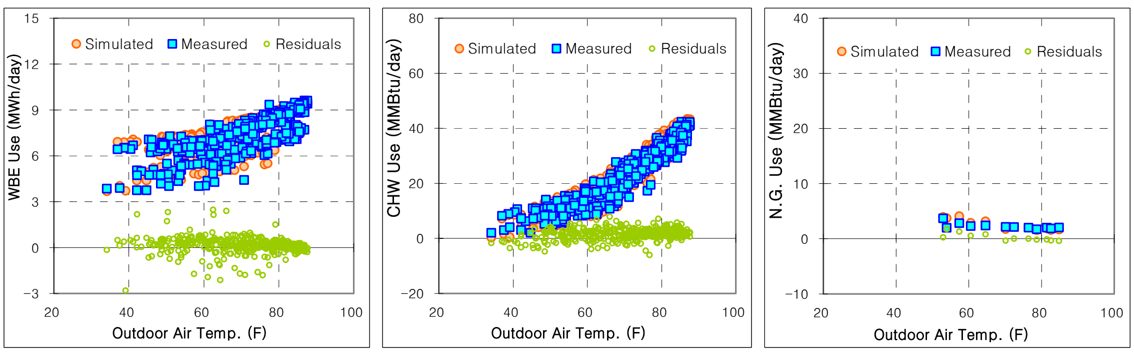
Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	817
Previous Calibration	2,663	8,995	915
Calibration	**2,725**	**9,216**	**917**
Difference (Cali. - Measured)	55	727	100
Difference (Cali. - Prev. Cali.)	62	221	2

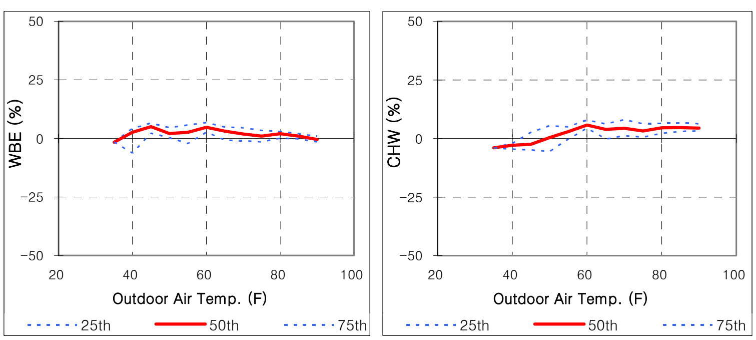
Uncertainty	WBE	CHW	N.G.
MBE (%)	**2.1**	**8.6**	**12.2**
CVRMSE (%)	**7.8**	**12.0**	**32.5**

Figure 5.5.5 Second Calibration Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

5.5.4 Calibration 3: Thermal Mass Effect

In the next calibration, the thermal mass effect was adjusted using the DOE-2.1e Custom Weighting Factor (CWF) method. To accomplish this, FLOOR-WEIGHT was set to “0” and the furniture fractions, type, and weight were activated. After the CWF was turned on, as shown in Figure 5.5.6, the CHW CV(RMSE) decreased to 10.9% from 12.0%.





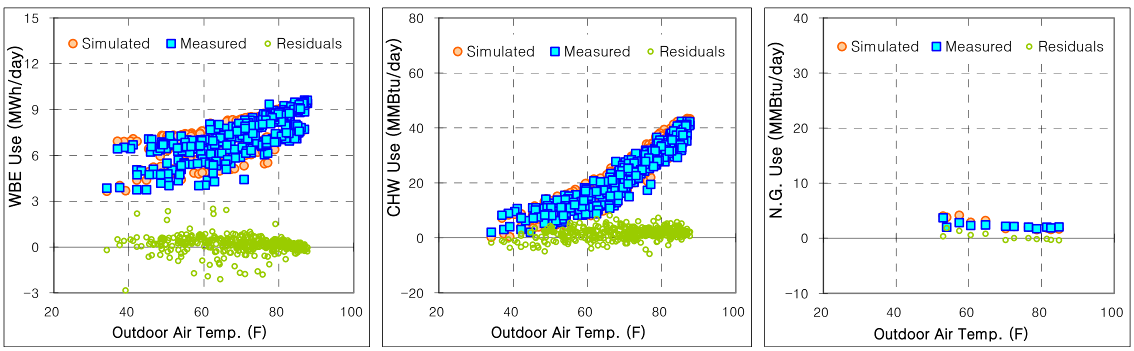
Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	817
Previous Calibration	2,725	9,216	917
Calibration	**2,716**	**9,050**	**917**
Difference (Cali. - Measured)	47	561	99
Difference (Cali. - Prev. Cali.)	-9	-166	0

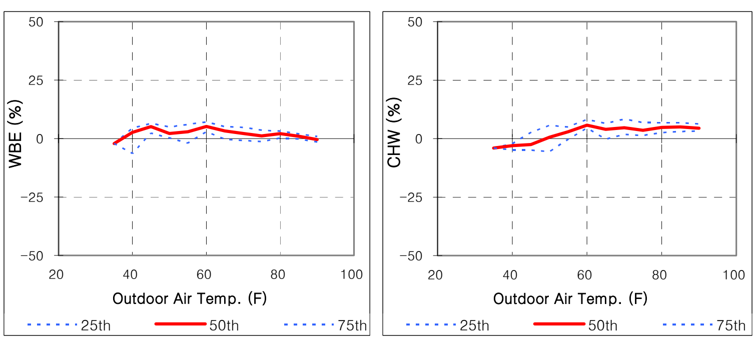
Uncertainty	WBE	CHW	N.G.
MBE (%)	**1.7**	**6.6**	**12.2**
CVRMSE (%)	**7.8**	**10.9**	**32.5**

Figure 5.5.6 Third Calibration Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

5.5.5 Calibration 4: AHU Supply Air Temperature Reset

In the fourth calibration step, the cold deck temperature (i.e., cooling coil leaving temperature or supply air temperature) was changed from a constant temperature setpoint of 55 F to a scheduled temperature based on the outside air temperature. From the measured data, it was observed that when the outdoor air temperature was 65 F or lower, the cold deck temperature was set to 58 F, and when the outdoor temperature was 85 F or higher, it reset to 53 F, which matched the schedules that coded were into the Energy Management Control System (EMCS) of the JBC building.





Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	817
Previous Calibration	2,716	9,050	917
Calibration	**2,721**	**9,090**	**922**
Difference (Cali. - Measured)	52	601	105
Difference (Cali. - Prev. Cali.)	5	40	6

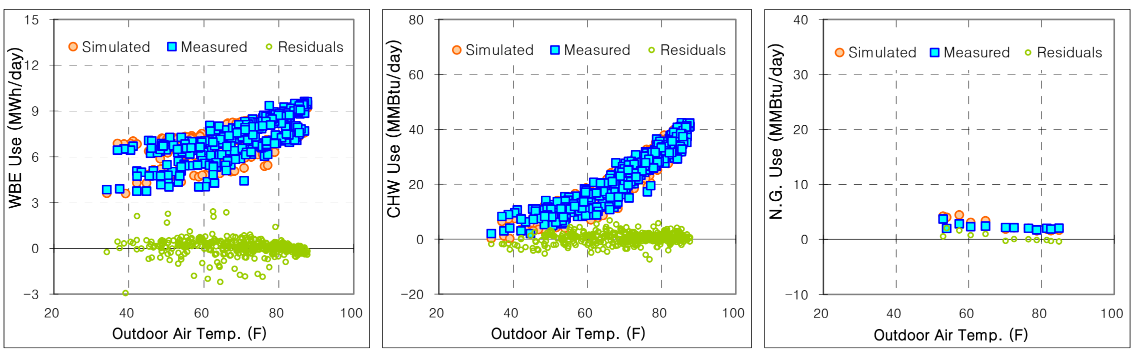
Uncertainty	WBE	CHW	N.G.
MBE (%)	**1.9**	**7.1**	**12.9**
CVRMSE (%)	**7.9**	**11.2**	**33.3**

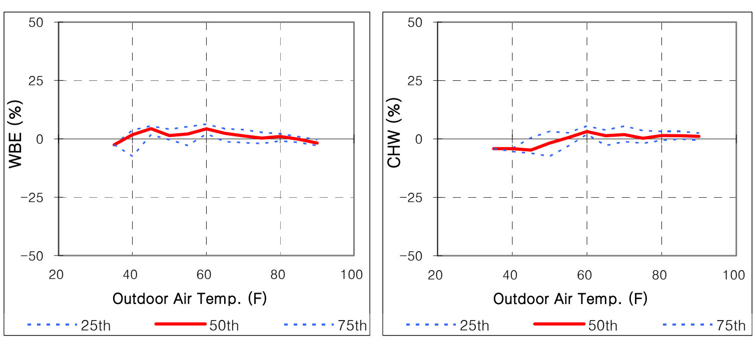
Figure 5.5.7 Fourth Calibration Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

The cold deck temperature also decreases linearly from 58 F to 53 F as the outside air temperature increases from 65 F to 85 F. In this simulation, as shown in Figure 5.5.7, the cooling energy use changed the CV(RMSE) value to 11.2% from 10.9%, increasing the cooling energy use. Also, the CV(RMSE) of WBE decreased to 7.9% from 7.8% and N.G. decreased to 33.3% from 32.5%.

5.5.6 Calibration 5: Room Air Temperature Change

In this calibration step, the room air temperature was changed from a constant value of 72 F to 74 F based on the observation of the data from the portable data loggers as shown in Figure 5.3.15. Figure 5.5.8 shows the results of simulation.





Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	817
Previous Calibration	2,721	9,090	922
Calibration	**2,687**	**8,621**	**960**
Difference (Cali. - Measured)	18	132	143
Difference (Cali. - Prev. Cali.)	-34	-469	38

Uncertainty	WBE	CHW	N.G.
MBE (%)	**0.7**	**1.6**	**17.5**
CVRMSE (%)	**7.7**	**8.5**	**39.0**

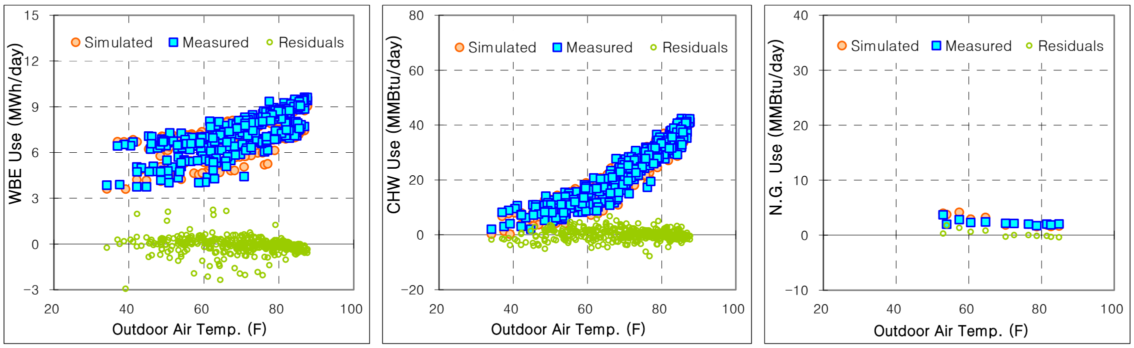
Figure 5.5.8 Fifth Calibration Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

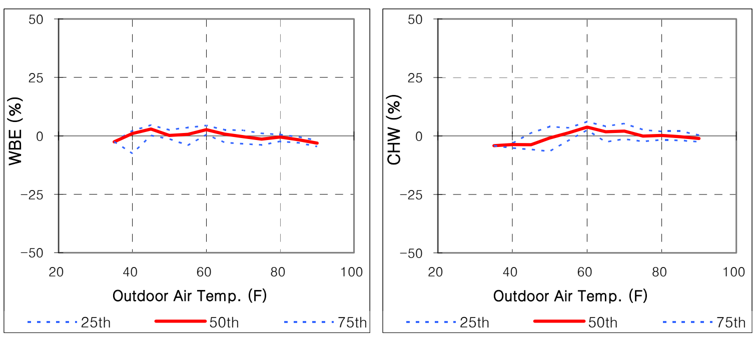
This room temperature change made a substantial impact for cooling and WBE and N.G. energy consumption as well. The cooling energy and WBE consumption decreased resulting in CV(RMSE) improvements of 8.5% from 11.2% for cooling and 7.7% from 7.9 for WBE. However, the N.G. usage increased changing the CV(RMSE) to 39.0% from 33.3%.

5.5.7 Calibration 6: Chiller Efficiency (COP from 4.76 to 5.18)

The final calibration involved a modification to the chiller COP. In this calibration, the chiller COP changed from the DOE-2.1e default, which was a COP of 4.76, to a measured chiller COP of 5.18, which matched the manufacturer's performance data with the electric input of 190 kW and the thermal output of 280-ton cooling as shown in Figure 5.3.27.

Figure 5.5.9 shows the simulation results and comparison with the measured data. The final uncertainties of the simulation were CV(RMSE) of 7.8% (WBE), 8.3% (CHW), and 33.1% (N.G.). These error values are within the tolerance range that ASHRAE published (ASHRAE, 2002), which is 30% (CV(RMSE)), with the exception of the N.G. usage. The discrepancy of the N.G. uses between the measurement and the simulation were because of the boilers operation. In 2006, the hot water boilers were not in active, which was observed by several site visits. The N.G. might only have been used for the service water heating. This caused the discrepancy between measured and simulated N.G. uses.





Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	1,634
Previous Calibration	2,687	8,621	960
Calibration	**2,632**	**8,532**	**925**
Difference (Cali. - Measured)	-38	43	-709
Difference (Cali. - Prev. Cali.)	-56	-89	-35

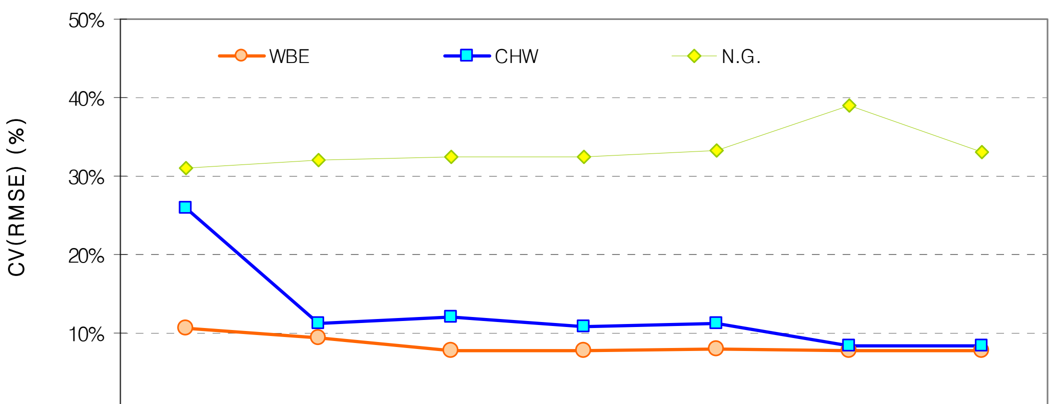
Uncertainty	WBE	CHW	N.G.
MBE (%)	**-1.4**	**0.5**	**13.3**
CVRMSE (%)	**7.8**	**8.3**	**33.1**

Figure 5.5.9 Final Calibration Results vs. Measured WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW.

5.6 Calibration Summary

Figure 5.6.1 shows the CV(RMSE) value changes from the base case through the six calibrations. Figure 5.6.2 shows the MBE changes. The CV(RMSE) of cooling energy improved mostly by changing the weather file from TMY2 to measured TRY data for 2006, although the WBE changed very little. In the WBE calibration, the use of diversity factors for internal heat gain schedule was the largest impact as shown in the graph (Calibration 1 to Calibration 2), changing the CV(RMSE) from 9.5% to 7.8%. The largest impact was occurred when the room temperature changed from 72 F to 74 F, increasing the MBE from 12.9% to 17.5%.

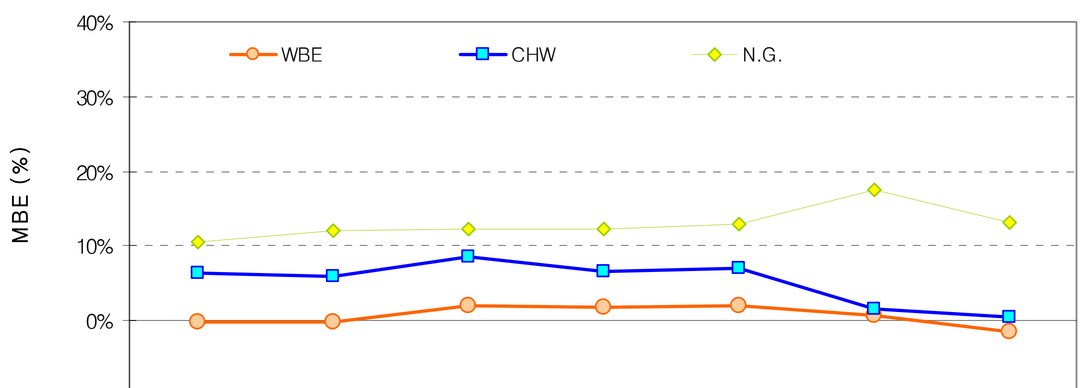
The final errors for both WBE and CHW were all in the tolerance ranges of 30% that ASHRAE published (ASHRAE, 2002). The measured natural gas consumption was unexpectedly low in 2006 compared to the other previous years as shown in Figure 5.2.6, so that there were difficulties matching the N.G. consumption of simulation to the measured data. Based on the field visit and observation, this was due to shutting off the boilers. As a result, the N.G. might be consumed only for the service water heating.



	BaseCase (TMY2)	Calibration1 (TRY)	Calibration2 (Diversity)	Calibration3 (CWF)	Calibration4 (Tsa)	Calibration5 (Trm)	Calibration6 (COP)
WBE	10.6%	9.5%	7.8%	7.8%	7.9%	7.7%	7.8%
CHW	26.0%	11.3%	12.0%	10.9%	11.2%	8.5%	8.3%
N.G.	31.0%	32.1%	32.5%	32.5%	33.3%	39.0%	33.1%

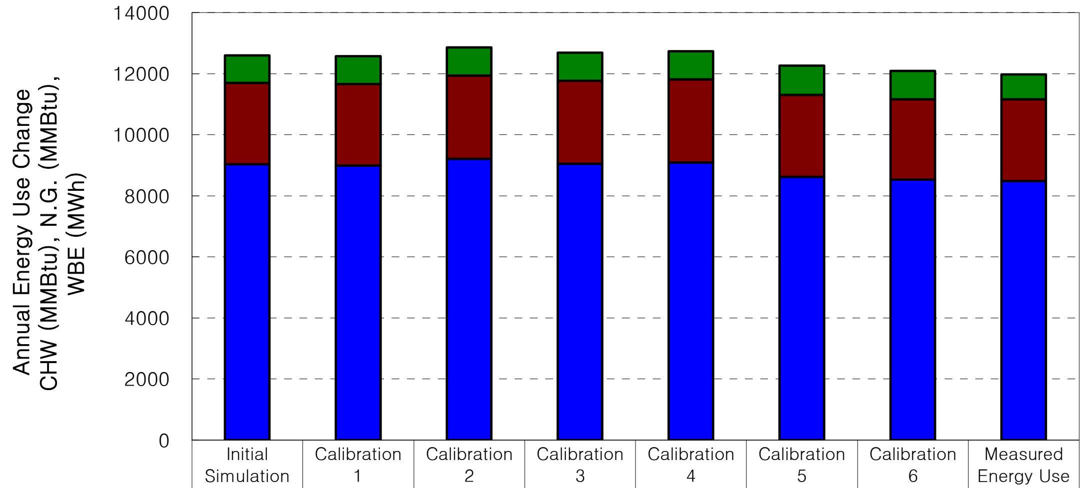
Figure 5.6.1 Summary of CV(RMSE) Changes.

Figure 5.6.3 shows the energy use for chilled water, natural gas, and whole building electricity for each calibration step, including the measured energy use that is shown in the last column of the figure. In addition, Figure 5.6.4 presents more in detail about the changes of differences between the simulation and measured energy use. The initial simulation showed 546 MMBtu higher chilled water usage compared to the measured chilled water use. The highest difference of 727 MMBtu was occurred at the second calibration, and then the chilled water use difference came down to 43 MMBtu at the final calibration. The differences of natural gas usage showed relatively small changes, starting at 87 MMBtu at the initial simulation and finishing with 108 MMBtu at the final calibration. For whole building electricity, the final calibrated simulation showed 38 MWh lower usages than the measured data.



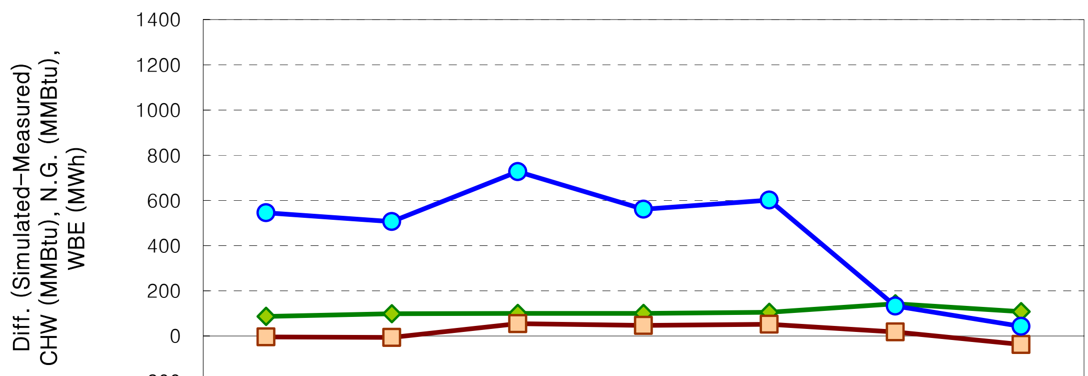
	BaseCase (TMY2)	Calibration1 (TRY)	Calibration2 (Diversity)	Calibration3 (CWF)	Calibration4 (Tsa)	Calibration5 (Trm)	Calibration6 (COP)
WBE	−0.1%	−0.2%	2.1%	1.7%	1.9%	0.7%	−1.4%
CHW	6.4%	6.0%	8.6%	6.6%	7.1%	1.6%	0.5%
N.G.	10.6%	12.0%	12.2%	12.2%	12.9%	17.5%	13.3%

Figure 5.6.2 Summary of MBE Changes.



	Initial Simulation	Calibration 1	Calibration 2	Calibration 3	Calibration 4	Calibration 5	Calibration 6	Measured Energy Use
Natural Gas	904	915	917	917	922	960	925	817
Whole Bldg Electric	2,666	2,663	2,725	2,716	2,721	2,687	2,632	2,669
Chilled Water	9,035	8,995	9,216	9,050	9,090	8,621	8,532	8,489

Figure 5.6.3 Energy Consumption Changes for Chilled Water, Natural Gas, and Whole Building Electricity in the Calibrated Simulation Process.



	Initial Simulation	Calibration 1	Calibration 2	Calibration 3	Calibration 4	Calibration 5	Calibration 6
Natural Gas	87	98	100	99	105	143	108
Whole Bldg Electric	−4	−6	55	47	52	18	−38
Chilled Water	546	506	727	561	601	132	43

Figure 5.6.4 Changes of Energy Use Differences Between Simulation and Measurement in the Calibrated Simulation Process.

CHAPTER VI

PHASE II: MODIFIED-ECALC DOE-2.1E SIMULATION MODEL

6.1 Overview of the eCALC program

The eCALC program, a web-based emissions calculator developed by the Energy Systems Laboratory (ESL), consists of four major components. This program was developed to calculate NOx, SOx, and CO_2 emissions reduction from energy efficiency and renewable energy of buildings in Texas (Haberl et al., 2004d). As shown in Figure 6.1.1, the components are: 1) a web interface, 2) a weather database, 3) a calculation engine, and 4) a general project/operations database. The functions of the four elements are:

1) Web interface: Interacts with users. Receives general project information from users via selected inputs.
2) Weather database: Contains measured 1999 TRY weather data for 17 locations in Texas that have been specially prepared by the Energy Systems Laboratory.
3) Calculation engine: Obtains information from users along with other information from the calculator's libraries. The calculator then transforms the information for use by one of the legacy programs. The legacy programs and their functions are:
   ① DOE-2.1e: Building energy simulation analysis (LBNL, 1981).
   ② F-Chart: Solar thermal systems analysis (Beckman et al., 1977).
   ③ PV F-Chart: Solar Photovoltaic (PV) systems analysis (Klein and

Beckman, 1983).

④ IMT: Monthly utility billing analysis for the analyses of the monthly municipal, traffic light, water, waste-water, and wind energy (Kissock et al., 2002).

⑤ Peak-extractor: Extracts the peak day use from DOE-2.1e simulations or the coefficients that can calculate the peak day use for use by the ozone season day calculation (Haberl et al., 2004d).

4) General project/operations database: Consists of XML (Extensible Markup Language) that supports a wide variety of applications and a SQL (Structured Query Language) database that creates, retrieves, updates, and deletes data from the relational database management system.

Figure 6.1.2 shows the flow of the eCALC analysis process for commercial buildings. In this analysis, the user selects the type of commercial building that is the closest match to their building, and enters the required input parameters the system requests through the web interface. The DOE-2.1e engine in the eCALC program runs based on the pre-defined and code-compliant building characteristics using the weather data for the location where the user's target building is located.

The results show the simulated energy use of the user's building description compared with pre-code values (ASHRAE Standard 90.1-1989) and code-compliant values (ASHRAE Standard 90.1-1999).

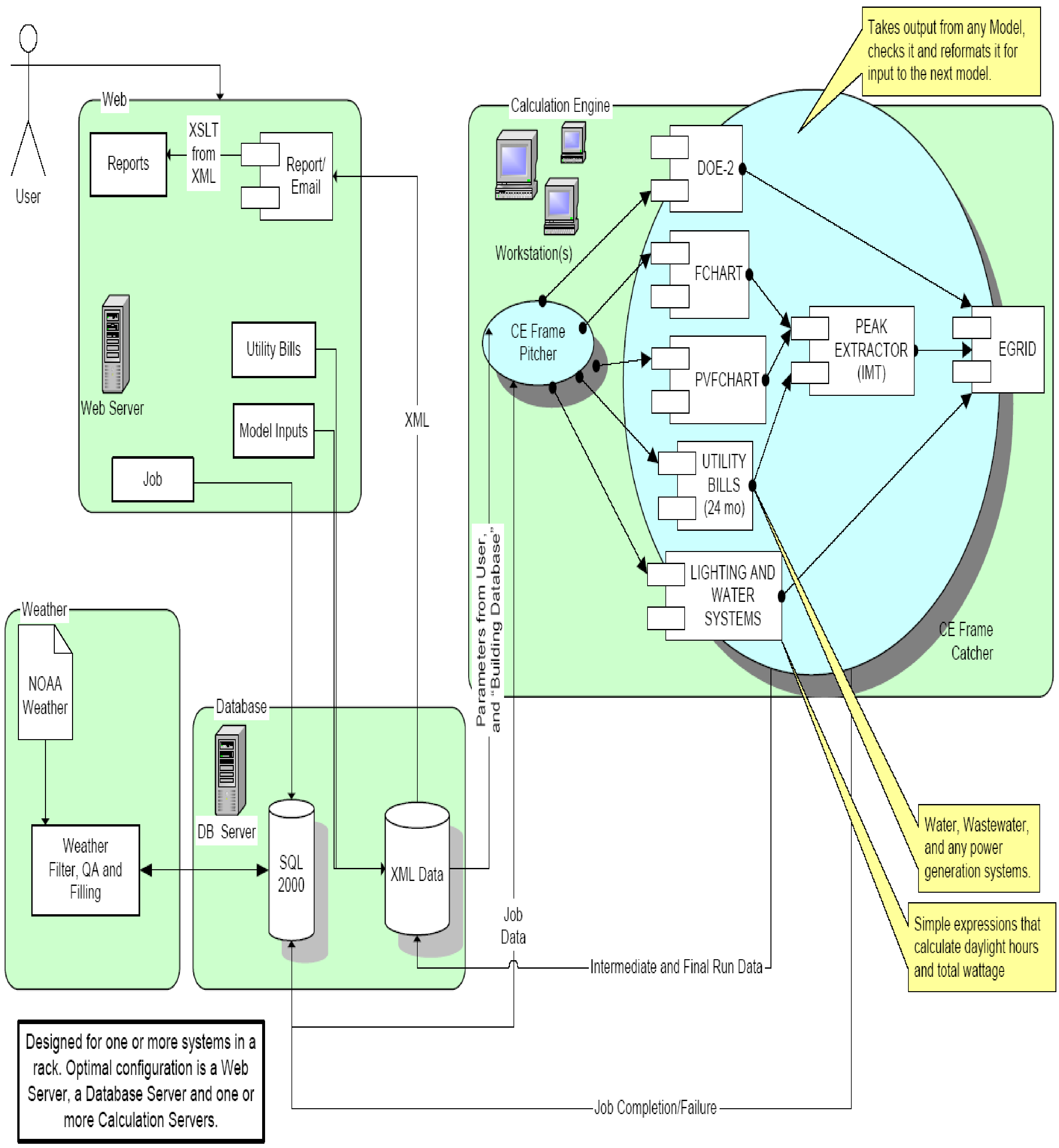


Figure 6.1.1 Block Diagram Showing Interactive-Functionality of the Emissions Reduction Calculator (Haberl et al., 2004d).

After the annual and peak-day savings are calculated, the savings results are then passed to the United States (US) Environmental Protection Agency (EPA)'s eGRID database that includes detailed emissions data for the electric utility suppliers associated with the users' county. The emissions calculator calculates the NOx, SOx and CO_2 emissions using the eGRID database for the ERCOT region in Texas using the 1999 base year and projects estimates for 2007 year. These results (energy and emissions savings) are then conveyed to the users as HTML and XML files through email.

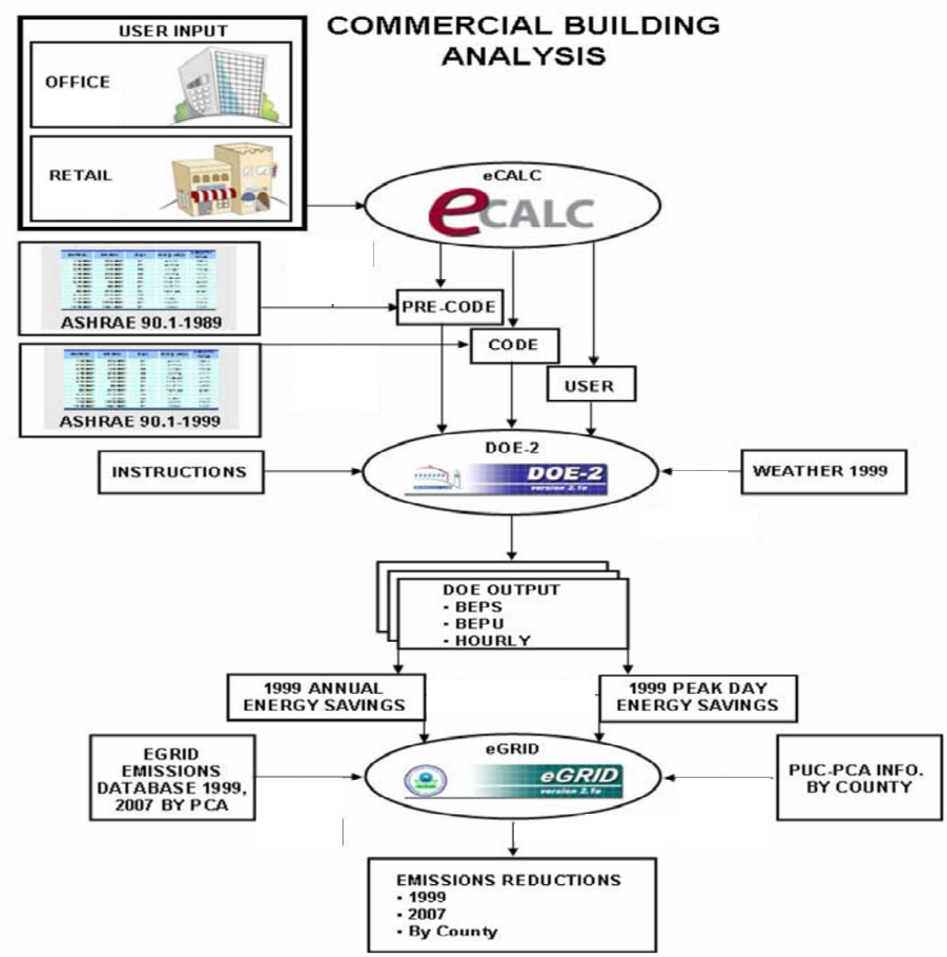


Figure 6.1.2 Example Flow Chart for Office Building Analysis (Haberl et al., 2004d).

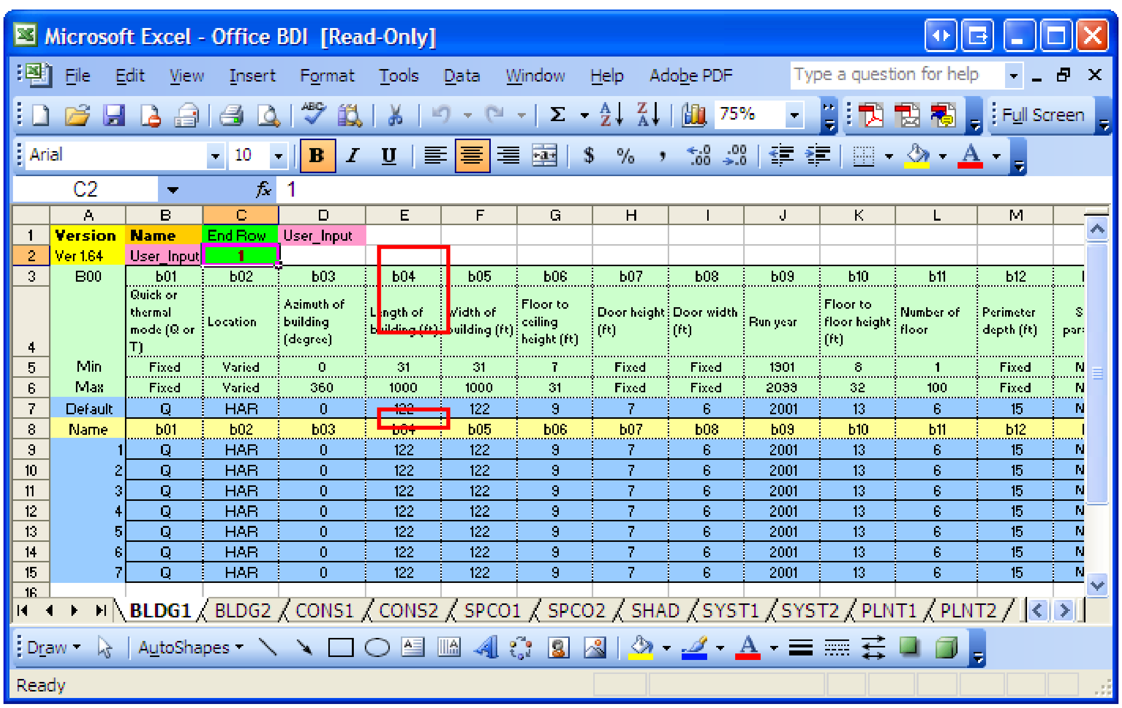
When the user runs a simulation, the DOE-2.1e program creates three output files for each simulation; one for pre-code simulation, one for the code-compliant simulation, and one for the user-defined building simulation. The energy consumption from each simulation is then compared. Then, the eCALC emissions calculator calculates the NOx, SOx and CO_2 emissions reduction using a specially prepared version of the eGRID database that contains measured emissions estimated emission for 1999 and 2007. These results (energy and emissions savings) are then sent to the user as HTML and XML files through email.

6.2 Internal Simulation Procedures for the DOE-2.1e Simulation Program Using the eCALC Program

6.2.1 BDI (Batch DOE-2.1e Input)

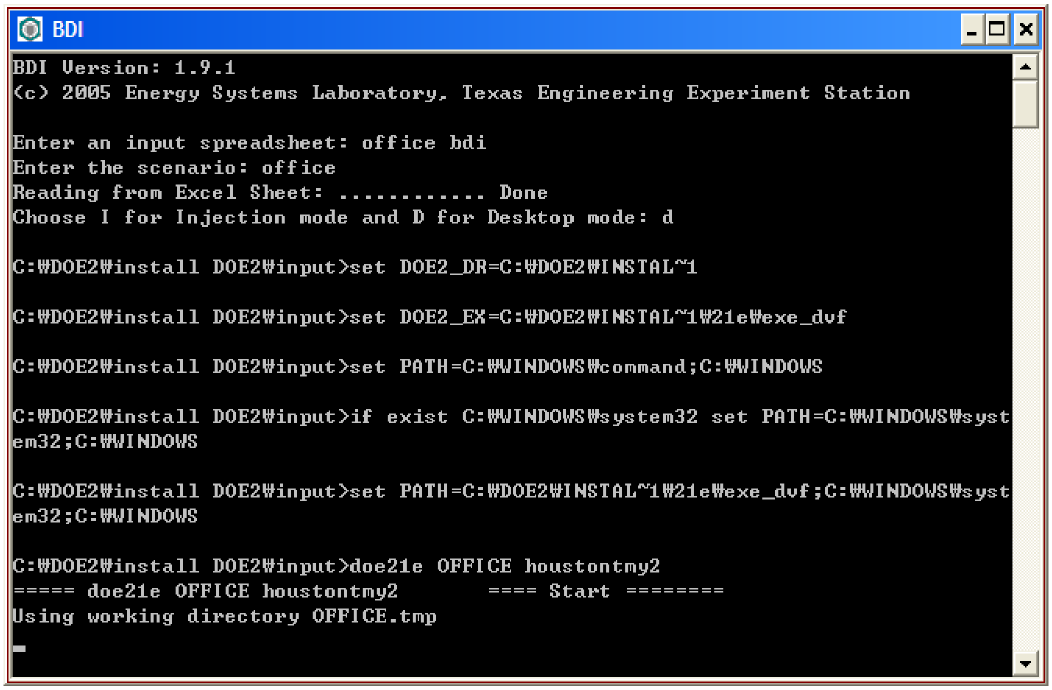
To run the DOE-2.1e simulation with the user input parameters, eCALC uses a BDI (Batch DOE-2.1e Input) program, developed by the ESL, to integrate the user's inputs into a flexible DOE-2.1e simulation input file. Figure 6.2.1 shows a portion of the BDI input Excel spreadsheet. The tabs 'BLDG1' and 'BLDG2' include input information for building geometry while other tabs include information about the building construction, space, shading, systems, and plant equipment. This Excel spreadsheet allocates values to all the parameters needed by the DOE-2.1e input file. As the BDI program runs (Figure 6.2.2), special purpose INCLUDE files (Figure 6.2.3) are created by the Excel spreadsheet that contains the values from each row of the BDI. This is then used by DOE-2.1e to fill-in the variables in the input file when the program is executed.

For example in Figure 6.2.1, the Excel spreadsheet has a parameter indicator ‘b04’ for the length of a building in the column-E and row-3. The first simulation run of seven runs uses the building length of 122 sq-ft, as shown in the column-E and row-9. This value is transferred into the INCLUDE file by the BDI program and then used as an input parameter for the building length in the DOE-2.1e input file. Finally, the BDI runs the DOE-2.1e simulation using the input file created through the BDI process. DOE-2.1e then produces output files, which contain the results of each run.



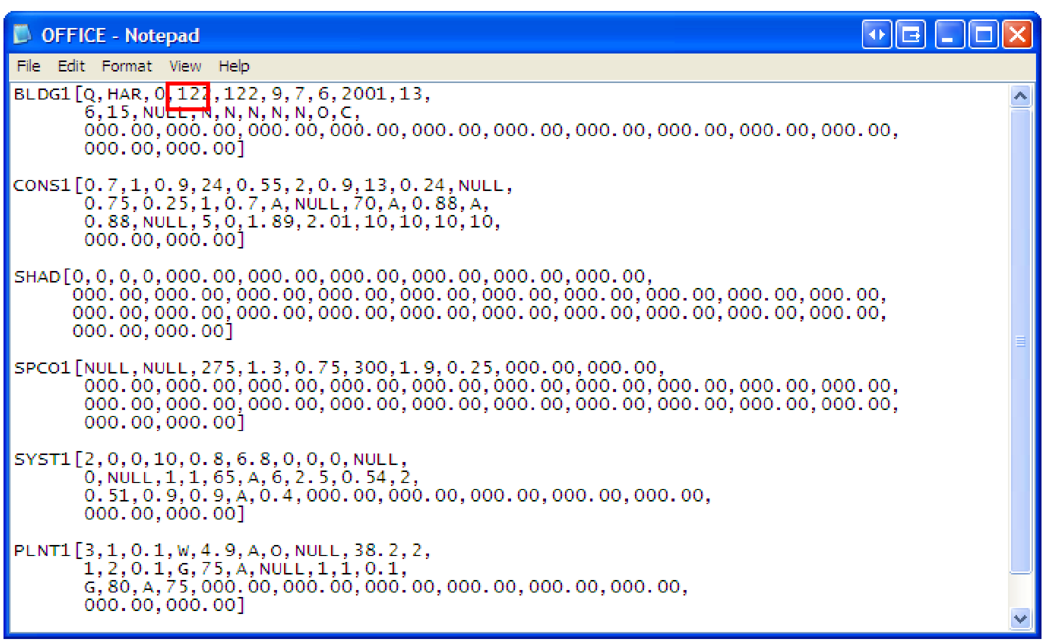
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Version	Name	End Row	User_Input									
2	Ver 1.64	User_Input	1										
3	B00	b01	b02	b03	b04	b05	b06	b07	b08	b09	b10	b11	b12
4		Quick or thermal mode (Q or T)	Location	Azimuth of building (degree)	Length of building (ft)	Width of building (ft)	Floor to ceiling height (ft)	Door height (ft)	Door width (ft)	Run year	Floor to floor height (ft)	Number of floor	Perimeter depth (ft)
5	Min	Fixed	Varied	0	31	31	7	Fixed	Fixed	1901	8	1	Fixed
6	Max	Fixed	Varied	360	1000	1000	31	Fixed	Fixed	2099	32	100	Fixed
7	Default	Q	HAR	0	122	122	9	7	6	2001	13	6	15
8	Name	b01	b02	b03	b04	b05	b06	b07	b08	b09	b10	b11	b12
9	1	Q	HAR	0	122	122	9	7	6	2001	13	6	15
10	2	Q	HAR	0	122	122	9	7	6	2001	13	6	15
11	3	Q	HAR	0	122	122	9	7	6	2001	13	6	15
12	4	Q	HAR	0	122	122	9	7	6	2001	13	6	15
13	5	Q	HAR	0	122	122	9	7	6	2001	13	6	15
14	6	Q	HAR	0	122	122	9	7	6	2001	13	6	15
15	7	Q	HAR	0	122	122	9	7	6	2001	13	6	15

Figure 6.2.1 Example of a BDI Excel Spreadsheet Showing One of the Tabs Including Building Geometry Information.



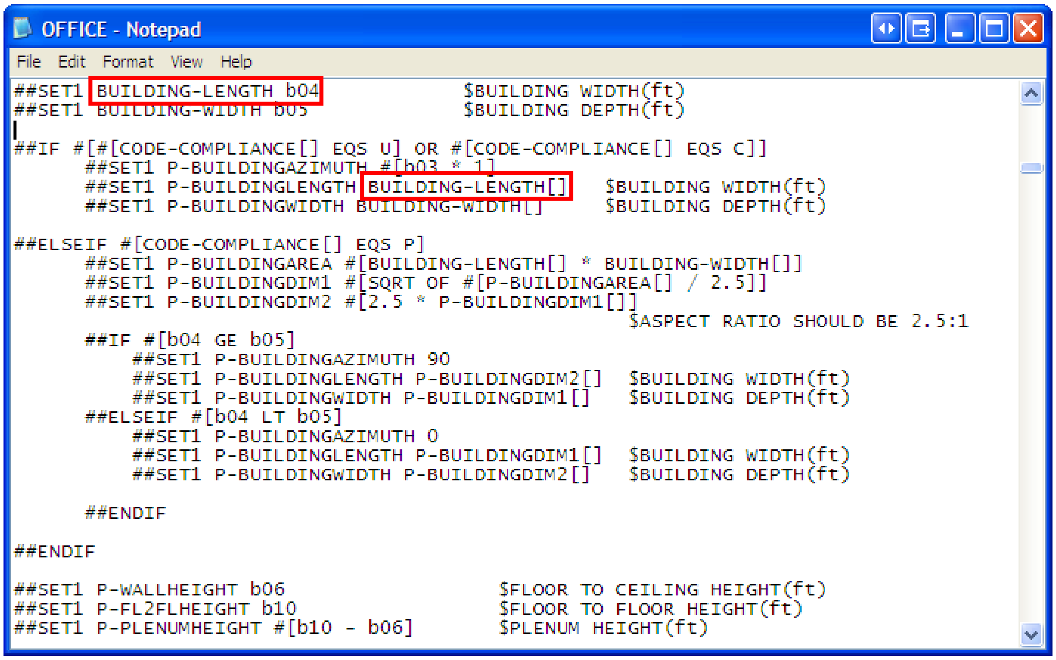
```
BDI
BDI Version: 1.9.1
(c) 2005 Energy Systems Laboratory, Texas Engineering Experiment Station

Enter an input spreadsheet: office bdi
Enter the scenario: office
Reading from Excel Sheet: ............ Done
Choose I for Injection mode and D for Desktop mode: d

C:₩DOE2₩install DOE2₩input>set DOE2_DR=C:₩DOE2₩INSTAL~1

C:₩DOE2₩install DOE2₩input>set DOE2_EX=C:₩DOE2₩INSTAL~1₩21e₩exe_dvf

C:₩DOE2₩install DOE2₩input>set PATH=C:₩WINDOWS₩command;C:₩WINDOWS

C:₩DOE2₩install DOE2₩input>if exist C:₩WINDOWS₩system32 set PATH=C:₩WINDOWS₩syst
em32;C:₩WINDOWS

C:₩DOE2₩install DOE2₩input>set PATH=C:₩DOE2₩INSTAL~1₩21e₩exe_dvf;C:₩WINDOWS₩syst
em32;C:₩WINDOWS

C:₩DOE2₩install DOE2₩input>doe21e OFFICE houstontmy2
===== doe21e OFFICE houstontmy2        ==== Start ========
Using working directory OFFICE.tmp
```

Figure 6.2.2   Example of a DBI Program for DOE-2.1e Simulation in Batch Mode.



```
OFFICE - Notepad
File  Edit  Format  View  Help
BLDG1[Q,HAR,0,122,122,9,7,6,2001,13,
      6,15,NULL,N,N,N,N,N,O,C,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

CONS1[0.7,1,0.9,24,0.55,2,0.9,13,0.24,NULL,
      0.75,0.25,1,0.7,A,NULL,70,A,0.88,A,
      0.88,NULL,5,0,1.89,2.01,10,10,10,10,
      000.00,000.00]

SHAD[0,0,0,0,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00]

SPCO1[NULL,NULL,275,1.3,0.75,300,1.9,0.25,000.00,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

SYST1[2,0,0,10,0.8,6.8,0,0,0,NULL,
      0,NULL,1,1,65,A,6,2.5,0.54,2,
      0.51,0.9,0.9,A,0.4,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

PLNT1[3,1,0.1,W,4.9,A,O,NULL,38.2,2,
      1,2,0.1,G,75,A,NULL,1,1,0.1,
      G,80,A,75,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]
```

Figure 6.2.3   Example of an INCLUDE File Generated by the BDI Program.



OFFICE - Notepad

File Edit Format View Help

```
##SET1 BUILDING-LENGTH b04             $BUILDING WIDTH(ft)
##SET1 BUILDING-WIDTH b05              $BUILDING DEPTH(ft)

##IF #[#[CODE-COMPLIANCE[] EQS U] OR #[CODE-COMPLIANCE[] EQS C]]
      ##SET1 P-BUILDINGAZIMUTH #[b03 * 1]
      ##SET1 P-BUILDINGLENGTH BUILDING-LENGTH[]   $BUILDING WIDTH(ft)
      ##SET1 P-BUILDINGWIDTH BUILDING-WIDTH[]     $BUILDING DEPTH(ft)

##ELSEIF #[CODE-COMPLIANCE[] EQS P]
      ##SET1 P-BUILDINGAREA #[BUILDING-LENGTH[] * BUILDING-WIDTH[]]
      ##SET1 P-BUILDINGDIM1 #[SQRT OF #[P-BUILDINGAREA[] / 2.5]]
      ##SET1 P-BUILDINGDIM2 #[2.5 * P-BUILDINGDIM1[]]
                                                    $ASPECT RATIO SHOULD BE 2.5:1
      ##IF #[b04 GE b05]
          ##SET1 P-BUILDINGAZIMUTH 90
          ##SET1 P-BUILDINGLENGTH P-BUILDINGDIM2[]  $BUILDING WIDTH(ft)
          ##SET1 P-BUILDINGWIDTH P-BUILDINGDIM1[]   $BUILDING DEPTH(ft)
      ##ELSEIF #[b04 LT b05]
          ##SET1 P-BUILDINGAZIMUTH 0
          ##SET1 P-BUILDINGLENGTH P-BUILDINGDIM1[]  $BUILDING WIDTH(ft)
          ##SET1 P-BUILDINGWIDTH P-BUILDINGDIM2[]   $BUILDING DEPTH(ft)

      ##ENDIF

##ENDIF

##SET1 P-WALLHEIGHT b06                   $FLOOR TO CEILING HEIGHT(ft)
##SET1 P-FL2FLHEIGHT b10                  $FLOOR TO FLOOR HEIGHT(ft)
##SET1 P-PLENUMHEIGHT #[b10 - b06]        $PLENUM HEIGHT(ft)
```

Figure 6.2.4 Example of a DOE-2.1e Input File (Part of Input File Showing Building Geometry Choice Dependent on User's Evaluation Objectives).

6.3 Modification of the eCALC Program for the Simulation of the Case-study Building

The case-study building (i.e., JBC building) calibrated simulation model was described in the previous chapter. In the next step, the JBC calibrated simulation model was then used as the baseline model for the development of the modified-eCALC DOE-2.1e simulation model. To accomplish this, the DOE-2.1e input file in the eCALC program that contained the office simulation was modified to match the JBC building's LOADS, SYSTEMS, and PLANT characteristics.

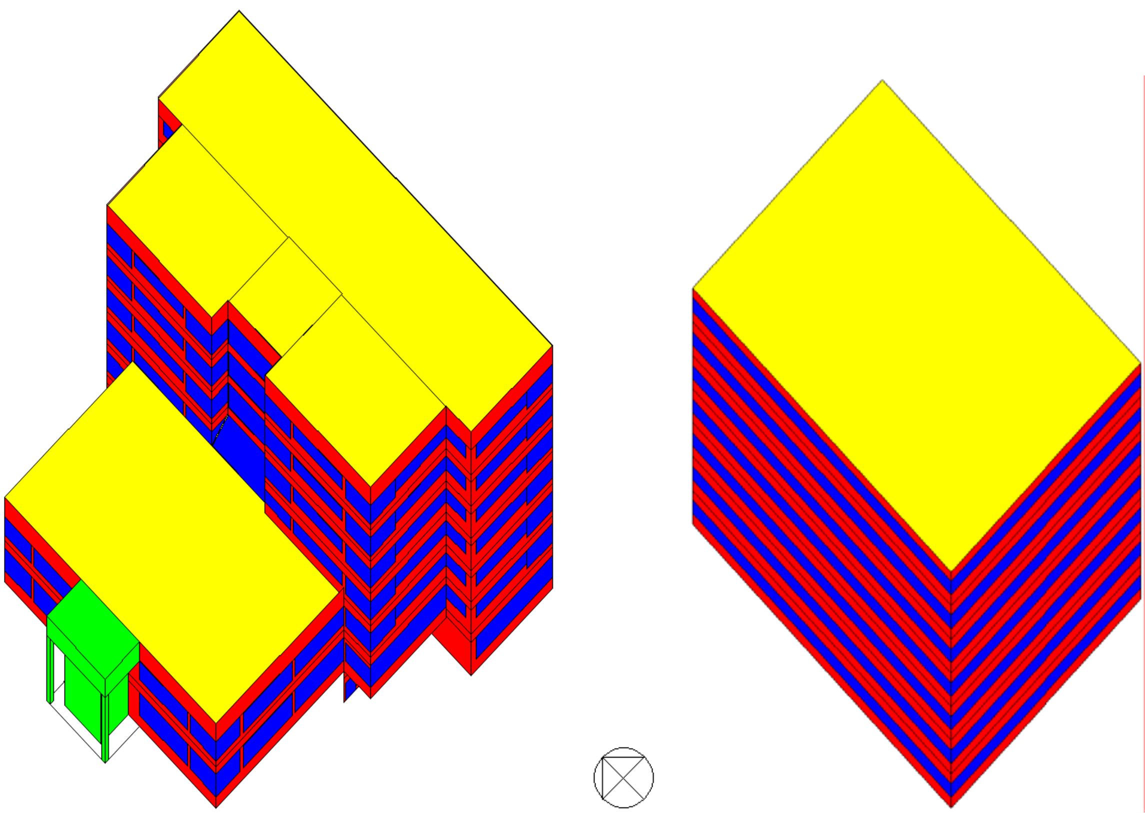
The main changes in the eCALC DOE-2.1e input file were input parameters and schedules from ASHRAE Standard 90.1-1999 minimum requirements to measured characteristics of the JBC building. All the input parameters described in Chapter V were also incorporated into the eCALC DOE-2.1e simulation input file. The following section compares the results from the modified-eCALC DOE-2.1e simulation with those from the JBC building simulation.

6.3.1 As-built Geometry vs. Simplified Geometry

One of the main differences between two simulation models is the building geometry. To evaluate this, an As-built DOE-2.1e model was developed for the building. The As-built DOE-2.1e model used the actual building geometries obtained from the architectural drawings. However, in order to create a simplified simulation program, the modified-eCALC DOE-2.1e model was run with a simple box-shaped geometry. Figure 6.3.1 shows the two different building geometries used for the: a) As-built DOE-2.1e simulation, and the b) simplified box-shaped building geometry. The total conditioned space and window-to-wall areas are the same for both cases.

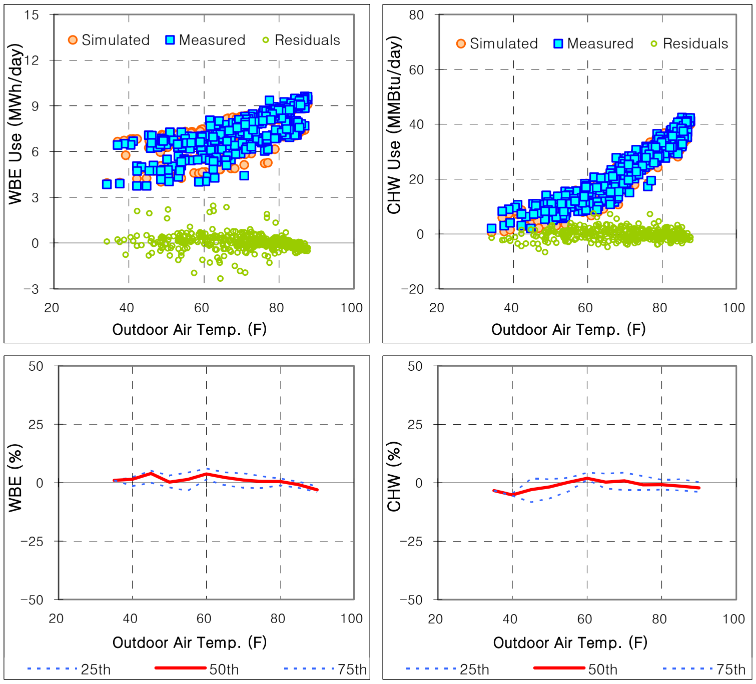
The simulation of the modified-eCALC DOE-2.1e model used the aspect ratio (i.e., North-South: East-West) of 1.4 to 1, which is approximately equivalent to the shape of upper floors of the JBC building. Figure 6.3.2 shows the results from the simulation of the simplified geometry modified-eCALC DOE-2.1e simulation for the JBC building.

The natural gas consumption data is the daily average use for each month versus the average outdoor dry bulb temperature. The gas consumption is relatively small compared to the chilled water consumption for space cooling. This would indicate the building uses only a modest amount of natural gas as compared to the chilled water use.



(a) (b)

Figure 6.3.1 Comparison of Building Geometries Showing: (a) As-built Building Geometry and (b) Simplified Box-shaped Building Geometry.



Use	WBE (MWH)	CHW (MMBtu)	N.G. (MMBtu)
Measured Data	2,669	8,489	1,634
Calibrated Simulation	2,687	8,621	960
Mod.-eCALC DOE-2	**2,681**	**8,416**	**744**
Difference (Mod. - Measured)	12	-73	-890
Difference (Mod. - Cali. Sim.)	-6	-206	-216

Uncertainty	WBE	CHW	N.G.
MBE (%)	**0.4**	**-0.9**	**-9.0**
CVRMSE (%)	**7.7**	**8.4**	**15.8**

Figure 6.3.2 Comparison of Measured and Simulated Energy Consumption Using the Modified-eCALC DOE-2.1e Simulation Model (WBE, Cooling Energy Use, and N.G. Use (Upper) and Calibration Signatures (Lower) for WBE and CHW).

The goodness of fit indicators as evaluated by the CV(RMSE) from the As-built calibrated simulation were 7.8% (WBE), 8.3% (CHW), and 33.1% (N.G.), while those from the simplified geometry modified-eCALC DOE-2.1e model were 7.7% (WBE), 8.4% (CHW), and 15.8% (N.G.). Table 6.3.1 summarizes the results from the two different simulations, including the goodness of fit as measured by the CV(RMSE) and MBE. The largest difference in the simulation results between the two different DOE-2.1e models was in the natural gas consumption. The measured natural gas consumption was 817 MMBtu/yr, which is 108 MMBtu higher than that of the As-built simulation and 73 MMBtu lower than that of simplified simulation. The WBE and CHW consumption of the two different geometry simulations were very similar, showing only a 1.8% lower usage in WBE and a 1.4% higher usage in CHW similar from the As-built model compared to the simplified geometry model.

Table 6.3.1 Energy Consumption Comparisons Between Measured, As-built Geometry Simulation, and Simplified Geometry Simulation.

Comparison	**Energy Type**	**WBE**	**CHW**	**N.G.**
	(Unit)	(MWh/yr)	(MMBtu/yr)	(MMBtu/yr)
Measurement	Energy Use	2,669	8,489	817
As-built Geometry DOE-2 Calibrated Simulation	Energy Use	2,632	8,532	925
	MBE (%)	-1.4%	0.5%	13.3%
	CV(RMSE) (%)	7.8%	8.3%	33.1%
Simplified Geometry Modified-eCALC DOE-2 Simulation	Energy Use	2,681	8,416	744
	MBE (%)	0.4%	-0.9%	-9.0%
	CV(RMSE) (%)	7.7%	8.4%	15.8%
As-built Geometry Model vs. Simplified Geometry Model	Use Difference	-49	117	182
	% Difference	-1.8%	1.4%	24.4%

To see the impact of the aspect ratio change to the energy use, a sensitivity test was performed by changing the aspect ratio from 1 to 2.5 (1:2.5) to 2.5 to 1 (2.5:1). The total conditioned space of 124,000 square feet and the number of floors were maintained the same throughout the sensitivity test. Table 6.3.2 summarizes the results. The aspect ratio of 1 to 1 was the base case for this test showing the percent change of 0% for all three energy use types; WBE, CHW, and N.G. The largest percent change of the energy use was at the aspect ratio of 2.5 to 1 where the chilled water energy use increased by 1.9%

compared to the base case, which has the aspect ratio of 1 to 1. The second largest change was also from the CHW use, which increased by 1.4% compared to the base case, at the aspect ratio of 2 to 1. Other cases showed little change. It can be calculated from these tests that the impact of changing the aspect ratio pn the energy use was minimal.

Table 6.3.2 Sensitivity Test Results by Changing the Building Aspect Ratio for the Simplified Geometry Simulation Model.

Aspect Ratio	Simplified Geometry				WBE		CHW		N.G. Use	
	Width	Depth	Story	Cond. Space	Use (MWh)	Change (%)	Use (MMBtu)	Change (%)	Use (MMBtu)	Change (%)
1:2.5	84	211	7	124,000	2,681	0.2%	8,403	0.4%	746	0.5%
1:2.0	94	188	7	124,000	2,673	-0.1%	8,357	-0.1%	744	0.3%
1:1.5	109	163	7	124,000	2,685	0.4%	8,387	0.2%	743	0.0%
1:1	***133***	***133***	***7***	***124,000***	***2,676***	***0.0%***	***8,367***	***0.0%***	***742***	***0.0%***
1.5:1	155	114	7	124,000	2,675	0.0%	8,395	0.3%	744	0.2%
2.0:1	190	93	7	124,000	2,679	0.1%	8,481	1.4%	748	0.7%
2.5:1	210	84	7	124,000	2,678	0.1%	8,525	1.9%	750	1.1%

6.4 Summary of the Simplified Geometry Modified-eCALC DOE-2.1e Simulation for the JBC Building

The process of using a simplified geometry, simulation model was the second step for the systems selection tool development. In this chapter, the existing eCALC program was reviewed, including how it works. The eCALC DOE-2.1e simulation model is the DOE-2.1e input file for buildings' energy simulation. This eCALC DOE-2.1e simulation input file was modified to match the characteristics of the JBC building. However, the modified eCALC DOE-2.1e model uses simplified geometry inputs, while the As-built DOE-2.1e model used the JBC building's real geometry. The aspect ratio of North-South vs. East-West building length (1.4:1), which represents the JBC building's shape most closely, was used to simulate the JBC building using the modified-eCALC DOE-2.1e model. Finally, the simulation results were compared to those of the As-built DOE-2.1e simulation.

The results showed that the WBE energy use and the CHW energy use of the simplified geometry model matched the annual energy use of the As-built model within 2%. The As-built WBE consumption was 1.8% lower and CHW was 1.4% higher than those of the modified-eCALC. The N.G. consumption results showed that the As-built simulation calculated 24.4% less than the modified-eCALC simulation did. As the modified-eCALC DOE-2.1e model uses the aspect ratio rather than buildings' real geometry, a sensitivity test was performed to see how the energy consumptions of WBE, CHW, and N.G. are impacted by changing the aspect ratios. It was shown from the test that the aspect ratio changes from 1 to 2.5 (1:2.5) to 2.5 to 1 (2.5:1) affected the energy consumption by only 2%, which shows only a small change in energy use. In the next wection, this modified-eCALC DOE-2.1e simulation model is used for the methodology development of the high-performance systems selection tool.

CHAPTER VII

PHASE III: HIGH-PERFORMANCE SYSTEMS SELECTION MODEL

In this section, Simplified Geometry, modified-eCALC DOE-2.1e (SGDOE-2.1e) simulation model was modified and used to analyze high-performance systems and components for improved energy efficiency at the case-study building. This simplified case-study building had the same building characteristics as the John B. Connally building with the exception that it uses a simplified geometry versus the actual geometry of the case-study building. In addition, a version of the simplified model was modified to meet requirements of the ASHRAE Standard 90.1-1999 energy code, which results in different energy use than the JBC building.

7.1 The Code-compliant, SGDOE-2.1e Base-case Building Description

The code-compliant, SGDOE-2.1e base-case building simulation model in this analysis is based on specifications in ASHRAE Standard 90.1-1999. Table 7.1.1 summarizes the code-compliant base-case building characteristics. A comparison of the as-built and code-compliant characteristics is presented in this table. The simulation used the 2006 College Station TRY weather data that was also used for the calibrated simulation of the JBC building. The simulation input values for the development of base-case model were obtained from the ASHRAE 90.1-1999 Standard.

Table 7.1.1 Code-compliant Base Case Building Description.

CHARACTERISTIC	CODE-COMPLIANT BASE CASE	SOURCES
Building		
Building type	Office	
Gross area (sq-ft)	124,000	Prototypical office building size and number of floors (Huang & Franconi, 1999, p.31[1])
Dimension (ft x ft)	155 x 114	
Number of floors	7	
Floor to floor height (ft)	13	ASHRAE Standard 90.1-1989-13.7.1 (p.105)
Construction		
Roof absorptance	0.7	ASHRAE Standard 90.1-1999-11.4.2(b) (p.58)
Roof insulation R-value (hr-sq.ft-F/Btu)	15	ASHRAE Standard 90.1-1999, Table B-5 (11.4.2(a)), (p.95)
Wall absorptance	0.7	ASHRAE Standard 90.1-1989-13.7.3.3 (p.106)
Wall insulation R-value (hr-sq.ft-F/Btu)	13	ASHRAE Standard 90.1-1999, Table B-5 (11.4.2(a)), (p.95)
Ground reflectance	0.2	ASHRAE Standard 90.1-1989-13.7.3.3 (p.106)
U-factor of glazing (Btu/hr-sq.ft-F)	1.22	ASHRAE Standard 90.1-1999, Table B-5 (11.4.2(c)), (p.95)
Solar Heat Gain Coefficient (SHGC)	0.17 (0.44 for North)	ASHRAE Standard 90.1-1999, Table B-5 (11.4.2(c)), (p.95)
Window-to-wall ratio (%)	50	Average WWR of new construction (Huang & Franconi, 1999, p.31[1])
Space		
Area per person (ft^2/person) for office	275 (325 occupants)	ASHRAE Standard 90.1-1989, Table 13-2, (p.103)
Occupancy schedule	8am-10pm (Monday - Saturday)	ASHRAE Standard 90.1-1989, Table 13-3, (p.104)
Space temperature setpoint	70F Heating / 75F Cooling	ASHRAE Standard 90.1-1989-13.7.6.2 (p.110)
Lighting load (W/ft2) for office	1.3	ASHRAE Standard 90.1-1999, Table 9.3.1.1, (p.51)
Lighting schedule	ASHRAE RP-1093 Schedule	Abushakra et al., 2001[2] (ASHRAE RP-1093, p.61)

[1] Huang, J. and E. Franconi. 1999. Commercial Heating and Cooling Loads Component Analysis. Report LBL-37208. Lawrence Berkeley National Laboratory.

[2] Abushakra, B. 2001. Compilation of Diversity Factors and Schedules for Energy and Cooling Load Calculations. Final Report. ESL-TR-01/04-01. Energy Systems Laboratory, Texas A&M University.

Table 7.1.1 continued.

CHARACTERISTIC	CODE-COMPLIANT BASE CASE	SOURCES
Equipment load (W/ft2) for office	0.75	ASHRAE Standard 90.1-1989, Table 13-4, (p.106)
Equipment schedule	24 hours (Monday - Saturday)	Abushakra et al., 2001 (ASHRAE RP-1093, p.62)
HVAC Systems		
HVAC system type	VAV with terminal reheat	ASHRAE Standard 90.1-1999, Table 11.4.3A, (p.59, System2)
Number of HVAC units	5	Serving 5 thermal zones
Supply motor efficiency (%)	90	Kavanaugh, 2003[3] (p.38)
Supply fan efficiency (%)	61	ASHRAE Standard 90.1-1989, Table 13-6, (p.108, System #5)
Supply fan total pressure (in W.G)	2.5	Info. by ESL CC engineers
Plant Equipment		
Chiller type	Centrifugal (280 ton cooling)	ASHRAE Standard 90.1-1999, Table 6.2.1C, (p.29)
Chiller COP	5.55 (For 280 ton chiller)	ASHRAE Standard 90.1-1999, Table 6.2.1C, (p.29)
Boiler type	Hot water boiler	ASHRAE Standard 90.1-1999, Table 11.4.3A, (p.59, System2)
Boiler fuel type	Natural gas	ASHRAE Standard 90.1-1999, Table 11.4.3A, (p.59, System2)
Boiler thermal efficiency (%)	75	ASHRAE Standard 90.1-1999, Table 6.2.1F, (p.31)
DHW fuel type	Natural gas	ASHRAE Standard 90.1-1999, Table 7.2.2, (p.47)
DHW heater thermal efficiency (%)	80	ASHRAE Standard 90.1-1999, Table 7.2.2, (p.47)

However, as shown in Table 7.1.1, there are several cases where the input values came from other sources such as the ASHRAE Standard 90.1-1989 or ASHRAE RP-1093. This was because no information was available from the ASHRAE Standard 90.1-1999.

[3] Kavanaugh, S. 2003. Estimating Demand and Efficiency. ASHRAE Journal. American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

7.1.1 Building Envelope, Lighting, and Fenestration Characteristics

This analysis was performed for the 7-story case-study office building (124,000 sq-ft), with a 40% window-to-wall ratio. Four perimeter zones and a central core zone were modeled for each floor. The weather conditions for College Station were used 1,258 Heating Degree Days (HDD_{65}) and 7,492 Cooling Degree Days (CDD_{50}). Based on climate specific characteristics as recommended in the ASHRAE Standard 90.1-1999, Table B-5 (i.e., the climate zone for College Station), the code-compliant base case was modeled with a wall insulation of R-13 with exterior solar absorptance of 0.7 and a roof insulation of R-15 with a solar absorptance of 0.7. The U-value of the windows in the code-compliant, base-case building was set at 1.22 Btu/hr- ºF- ft2.

In ASHRAE Standard 90.1-1999, the SHGC of the code-compliant, base-case building was set at 0.44 for the north orientation and 0.17 for at other orientations. Window overhangs or shadings were not used. The base-case building was modeled with a lighting power density (LPD) of 1.3 W/ft2, which is the maximum value for office applications allowed by ASHRAE Standard 90.1-1999 (Table 9.3.1.1). The electric lighting profile was set to the recommended profile from ASHRAE's Diversity Factor Toolkit (RP-1093), as shown in Figure 7.1.1 (Abushakra et al. 2001). The total number of people in the base-case building was calculated as 275 square feet per person according to the ASHRAE Standard 90.1-1989 Table 13-2.

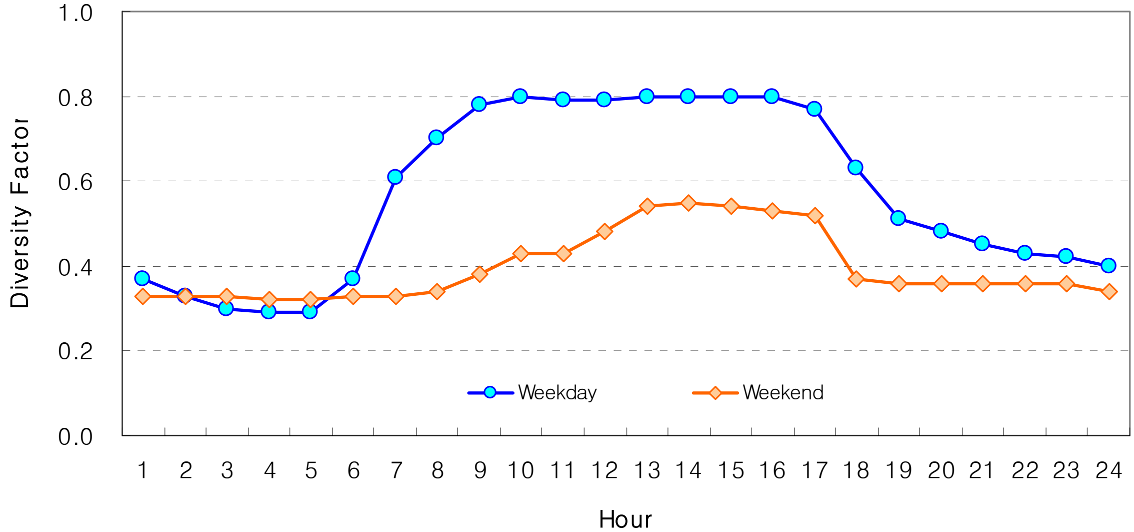


Figure 7.1.1 Code-compliant, Base-case Lighting Profile for a Large Commercial Building (Abushakra et al., 2001).

7.1.2 HVAC System Characteristics

The code-compliant, base-case building model used a variable air volume (VAV) system with terminal reheat that was set to have a total supply air static pressure of 2.5 inches of water (gauge), and has a constant supply air temperature of 55 ºF. The total supply air static pressure value of 2.5 inches of water (gauge) was obtained from the Continuous Commissioning[R] (CC[R]) engineers in the Energy Systems Laboratory (Deng, 2006). The HVAC systems were set to serve five different thermal zones each. Therefore, there are four systems serving four exterior zones and one system serving one interior zone.

7.1.3 Plant Equipment Characteristics

The base-case building has one 280 ton (3.36 MMBtu/hr) centrifugal chiller with a COP of 5.55 and a constant speed chilled water pump. The leaving chilled water temperature was set 44 F, which is DOE-2.1e default value, with a temperature difference of 10 F. The heating fuel type is natural gas. The hot water gas boiler has an efficiency of 75% and the service water heater has an efficiency of 80%. The cooling system has a water-cooled condenser. The entering condenser water temperature was set to 85 F with temperature difference of 10 F.

7.2 SGDOE-2.1e Code-compliant, Base-case (ASHRAE Standard 90.1-1999 Compliant) Model Energy Consumption

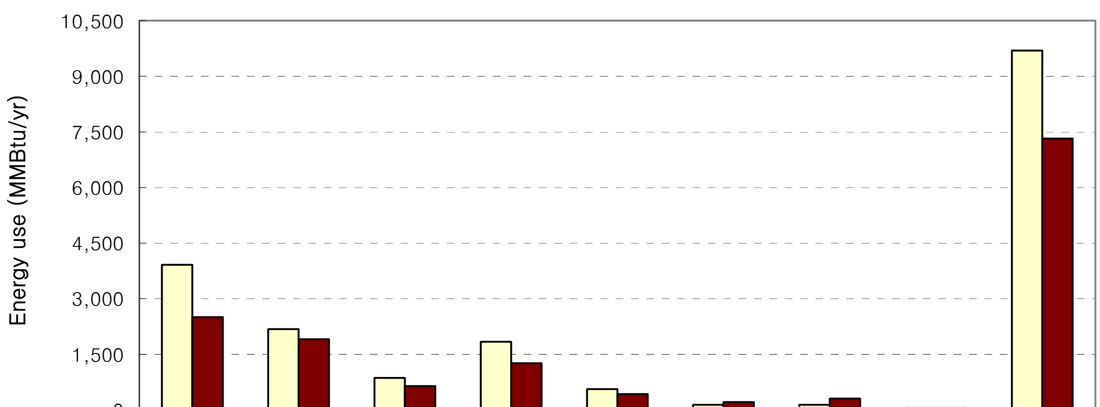
A simulation was performed for the SGDOE-2.1e code-compliant, base-case model using the JBC building characteristics with the ASHRAE Standard 90.1-1999 code requirements. The DOE-2.1e default values were used for miscellaneous simulation input parameters, which were not available from the ASHRAE Standard 90.1-1999 code. As shown in Table 7.2.1, the total energy consumption from the JBC building simulation using the simplified SGDOE-2.1e simulation model was 9,692 MMBtu/yr in 2006. Compared to the energy use of the JBC building, the ASHRAE Standard 90.1-1999 code-compliant building showed 24.5% less energy consumption, which is 7,318

MMBtu/yr. Figure 7.2.1 shows the item-by-item comparison of energy use for the two simulation cases.

Table 7.2.1 Comparison of the Simulation Input Values Between the As-built Simulation and the ASHRAE Standard 90.1-1999 Code-compliant Simulation.

Input Parameters	As-built Simulation	Code-compliant Simulation (ASHRAE Standard 90.1-1999)
Glazing U-factor (Btu/sqft-hr-F)	0.49	1.22
Solar heat Gain Coefficient	0.34	0.17 (All), 0.44 (North)
Glazing Number of Panes	2	1
Window-to-wall Ratio (%)	40	50
Lighting Power Density (W/sqft)	1.90	1.30
Office Equipment Power Density (W/sqft)	1.07	0.75
Chilled Water Pump Control	Variable	Constant
Hot Water Pump Control	Variable	Constant
Supply Fan Total Pressure (in-H_2O)	1.5	2.5
Chiller Efficiency (COP)	6.00	5.55
Boiler Thermal Efficiency (Et)	0.80	0.75
Water Heater Thermal Efficiency (Et)	0.80	0.80
Room Temperature Setpoint (F)	74	68 (Winter) / 78 (Summer)
Total Energy Use (MMBtu/yr)	**9,692**	**7,318**
Energy Use Index (EUI) (kBtu/sqft-yr) – Site	**78.2**	**59.0**
Energy Savings		**24.5%**

The main reasons for making the energy reductions from the ASHRAE Standard 90.1-1999 code-compliant building simulation were lighting and equipment power density changes, where the lighting power density changed from 1.9 Watts per square foot (JBC building) to 1.3 Watts per square foot (ASHRAE Standard 90.1-1999 building). As the lighting and power density reduces, the internal heat gain decreases resulting in the reduction of the cooling load in the building. This ASHRAE Standard 90.1-1999 code-compliant building, which consumes 24.5% less energy than the JBC building, was then used as the base-line for the energy savings evaluation for the energy efficiency measures.



	AREA LIGHTS	MISC EQUIPMT	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	DOMHOT WATER	TOTAL
JBC Building	3,914	2,180	865	1,837	562	138	140	57	9,692
90.1-99 Building	2,506	1,907	641	1,258	427	215	308	57	7,318

Figure 7.2.1 Energy Consumption Comparison Between the JBC Building and the ASHRAE Standard 90.1-1999 Code-compliant Building.

7.3 DOE-2.1e AEDG (Advanced Energy Design Guide) Model

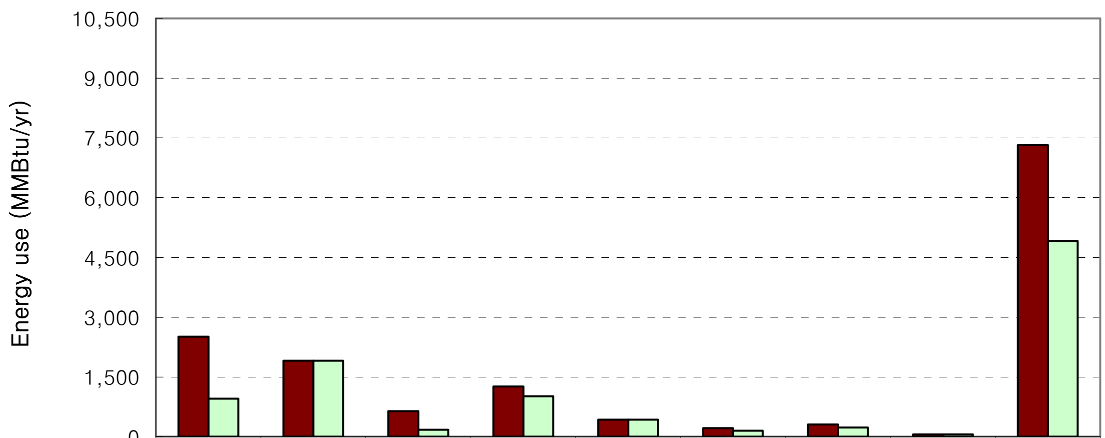
ASHRAE has published a design guide for office buildings, the Advanced Energy Design Guide (ASHRAE, 2000), which is targeted to achieve 30 percent energy savings over the ASHRAE Standard 90.1-1999 energy standard. This guide includes recommendations for different climate zones. In the guide, there are eight climate zones, with the base-line building in this study located in the Climate Zone 2 of the AEDG guide. In this portion of the analysis, the recommendations obtained from the AEDG Climate Zone 2 Recommendation Table were incorporated into the SGDOE-2.1e simulation model. Table 7.3.1 compares input parameters used for the two different simulations. In the AEDG, the U-factor of the glazing improved from 1.22 Btu/hr-sqft-F to 0.45 Btu/hr-sqft-F in the simulation. The AEDG recommends shading for all windows except those facing north, using a projection factor of 0.5. The overhangs of 2.5 feet for east, south, and west walls were applied in the AEDG simulation.

In the AEDG, the maximum window area is limited to 40% and lighting load reduced to 0.9 Watts per square foot. In the ASHRAE Standard 90.1-1999 simulation, the lighting was scheduled based on the ASHRAE RP-1093 report for office buildings. This lighting schedule was changed in the AEDG simulation based on occupancy schedule to implement occupancy sensors application in simulation with a modification for emergency lighting. In the AEDG simulation, the lighting turns on and off based on the occupancy schedule of the building. Hot water boiler and service water heater thermal efficiencies changed from 75% to 80% and 80% to 81%, respectively in the AEDG simulation.

Table 7.3.1 Simulation Input Parameters Comparison Between the ASHRAE Standard 90.1-1999 Code-compliant Building and the AEDG Building.

CHARACTERISTICS	**ASHRAE Standard 90.1-1999 Code Minimum Requirements**		**ASHRAE AEDG Recommendations**	
	Values	**Remarks**	**Values**	**Remarks**
U-factor of glazing (Btu/hr-sqft-F)	1.22	ASHRAE Standard 90.1-1999, Table B-5 (11.4.2(c)), (p.95)	0.45	ASHRAE AEDG Climate Zone 2 Table
Shading (Overhangs) (ft)	None	n/a	2.5	ASHRAE AEDG Climate Zone 2 Table
Window-to-wall ratio (%)	50	Average WWR for new construction (Huang & Franconi, 1999, p.31)	40	ASHRAE AEDG Climate Zone 2 Table
Lighting load (W/sqft) for office	1.3	ASHRAE Standard 90.1-1999, Table 9.3.1.1, (p.51)	0.9	ASHRAE AEDG Climate Zone 2 Table
Lighting schedule	ASHRAE RP-1093 Schedule	Abushakra et al., 2001 (ASHRAE RP-1093, p.61)	Occupancy Sensor	ASHRAE AEDG Climate Zone 2 Table
Boiler thermal efficiency (%)	75	ASHRAE Standard 90.1-1999, Table 6.2.1F, (p.31)	80	ASHRAE AEDG Climate Zone 2 Table
DHW heater thermal efficiency (%)	80	ASHRAE Standard 90.1-1999, Table 7.2.2, (p.47)	81	ASHRAE AEDG Climate Zone 2 Table

In the ASHRAE AEDG simulation, all the measures in Table 7.3.1 impacted the energy consumption substantially except the boiler and heater efficiencies, which is due to relatively low space heating and service water loads compared to the cooling and electric loads. If the energy consumption of 4,913 MMBtu/yr from the ASHRAE AEDG simulation is compared to that of the JBC building simulation, which is 9,692 MMBtu/yr, the energy savings are significant resulting in a 49.3% reduction.



	AREA LIGHTS	MISC EQUIPMT	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	SVCHOT WATER	TOTAL
90.1-99 Building	2,506	1,907	641	1,258	427	215	308	57	7,318
AEDG Building	955	1,907	173	1,018	425	149	232	56	4,913

Figure 7.3.1 Energy Consumption Comparison Between the ASHRAE Standard 90.1-1999 Code-compliant Building and the AEDG Building.

Using the AEDG settings, the total energy consumption from the ASHRAE Standard 90.1-1999 code-compliant simulation was 4,913 MMBtu/yr. Compared to the energy use of the ASHRAE Standard 90.1-1999 code-compliant building, the ASHRAE AEDG building showed 32.9% less energy consumption. Figure 7.3.1 shows item-by-item comparison of energy use for the two simulation cases, the ASHRAE Standard 90.1-1999 code-compliant simulation versus the ASHRAE AEDG building simulation.

7.4 High-performance Measures

In the next set of simulations, a total of 14 measures were considered to develop a high-performance building model. These measures included: improved glazing U-factor, reduced window-to-wall ratio, decreased lighting power density, occupancy sensors, shading devices, cold deck reset, supply fan static pressure reduction, economizer, efficient chiller, condensing boiler, efficient hot water heater, variable-speed chilled water pumps, variable-speed hot water pumps, and chiller staging. Table 7.4.1 provides all 14 high-performance measures and includes the changes to the values from base-case DOE-2.1e simulation.

There are measures already appeared in the ASHRAE's Advanced Energy Design Giode (AEDG) such as variable-speed chilled water pumps and variable-speed hot water pumps. However, these measures were included as high-performance measures in this study because the energy savings evaluation was conducted based on the ASHRAE Standard 90.1-1999 code-compliant case. The ASHRAE AEDG is above the ASHRAE Standard 90.1-1999 code. Following subsections discuss the individual measures along with simulation results.

Table 7.4.1 High-performance Measures Compared to the Base-case Parameters (ASHRAE Standard 90.1-1999 Compliant).

No.	Items	Base Case (ASHRAE Standard 90.1-1999)		High-performance Measures	
		Values	**Remarks**	**Values**	**Remarks**
1	Glazing U Factor	1.22 Btu/hr-sqft-F	ASHRAE Standard 90.1-1999 Table B-5 (11.4.2(c)), (p.95)	0.38 Btu/hr-sqft-F	Hawaii Commercial Building Guidelines for Energy Efficiency
2	WindowToWall Ratio	50%	Average WWR (Huang & Franconi, 1999, p.31)	35%	ASHRAE AEDG (20%-40%)
3	Lighting Load	1.3 W/sqft	ASHRAE Standard 90.1-1999 Table 9.3.1.1, (p.51)	0.9 W/sqft	ASHRAE AEDG (Climate Zone 2 Table)
4	Light Control	ASHRAE RP-1093 Schedule	Abushakra et al., 2001 (ASHRAE RP-1093, p.61)	Occupancy Sensor	ASHRAE AEDG (Climate Zone 2 Table)
5	Shading	None	No shading	2.5 ft	ASHRAE AEDG (Projection factor 0.5)
6	Cold Deck Reset	Constant	100% Constant speed	Reset	Typical reset schedule from TAMU campus buildings
7	Supply Fan Total Pressure	2.5 inH_2O	Conventional value used	1.5 inH2O	Information by CC™ engineers
8	Economizer	None	No economizer	Temperature	Temperature Economizer
9	Chiller COP	5.55	ASHRAE Standard 90.1-1999 Table 6.2.1C, (p.29)	COP7.5	Hongkong Institute of Engineers
10	Boiler Efficiency (Thermal)	75%	ASHRAE Standard 90.1-1999 Table 6.2.1F, (p.31)	95%	RSMEANS
11	DHW Heater Efficiency (Thermal)	80%	ASHRAE Standard 90.1-1999 Table 7.2.2, (p.47)	85%	ASHRAE AEDG (Climate Zone 2 Table)
12	CHW Pump Control	Constant	Constant speed	VSD	Variable-speed
13	HW Pump Control	Constant	Constant speed	VSD	Variable-speed
14	Chiller Staging (One to Three Chillers)	One Chiller	One-3.36 Mbtu/hr chiller	Three Chillers	Three-1.12 MMBtu/hr Chillers

7.4.1 High-performance Measure 1: Improved Glazing U-factor (from 1.22 Btu/hr-sqft-F to 0.38 Btu/hr-sqft-F)

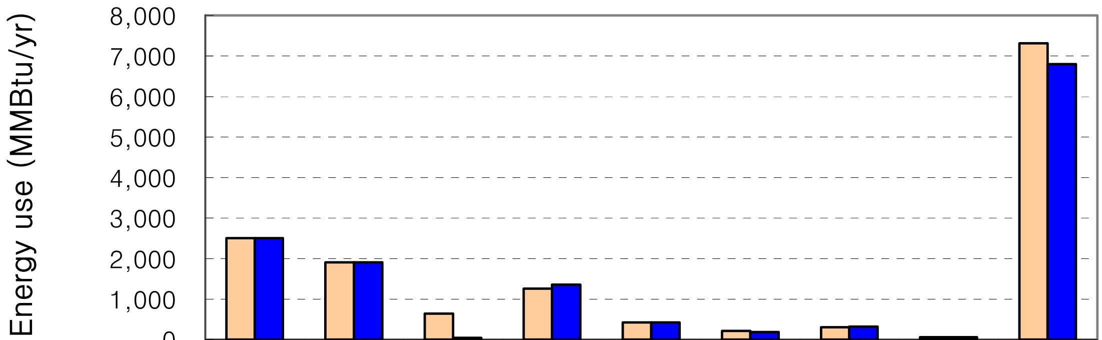
In the ASHRAE Standard 90.1-1999 standard, the U-factor of the windows in buildings were set at 1.22 Btu/hr-sqft-F. The SHGC of the building was set at 0.44 for the north orientation and 0.17 for the other orientations. Window shadings or overhangs were not used. To improve the glazing performance, the U-factor was reduced to 0.38 Btu/hr-sqft-F. This lower U-factor was selected to minimize the winter time heat loss using available commercial glazing products. The SHGC of the base-case building remained at 0.44 for the north orientation and 0.17 for the other orientations.

Figure 7.4.1 shows the simulation results and comparisons between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building and the building with the improved glazing U-factor. This measure:

- Reduced the space heating energy consumption to 44 MMBtu/yr from 641 MMBtu/yr, which is 93.1% lower than the base case. The improved glazing U-factor significantly reduced the heat transfer between inside and outside the building especially in the winter period.
- Increased the space cooling energy consumption to 1,353 MMBtu/yr from 1,258 MMBtu/yr, which is 7.5% higher than the base case. This effect was not expected. However, an analysis of the hourly cooling results reveals that the

lower U-value traps heat in the building in the evenings when it would have radiated to the surroundings.

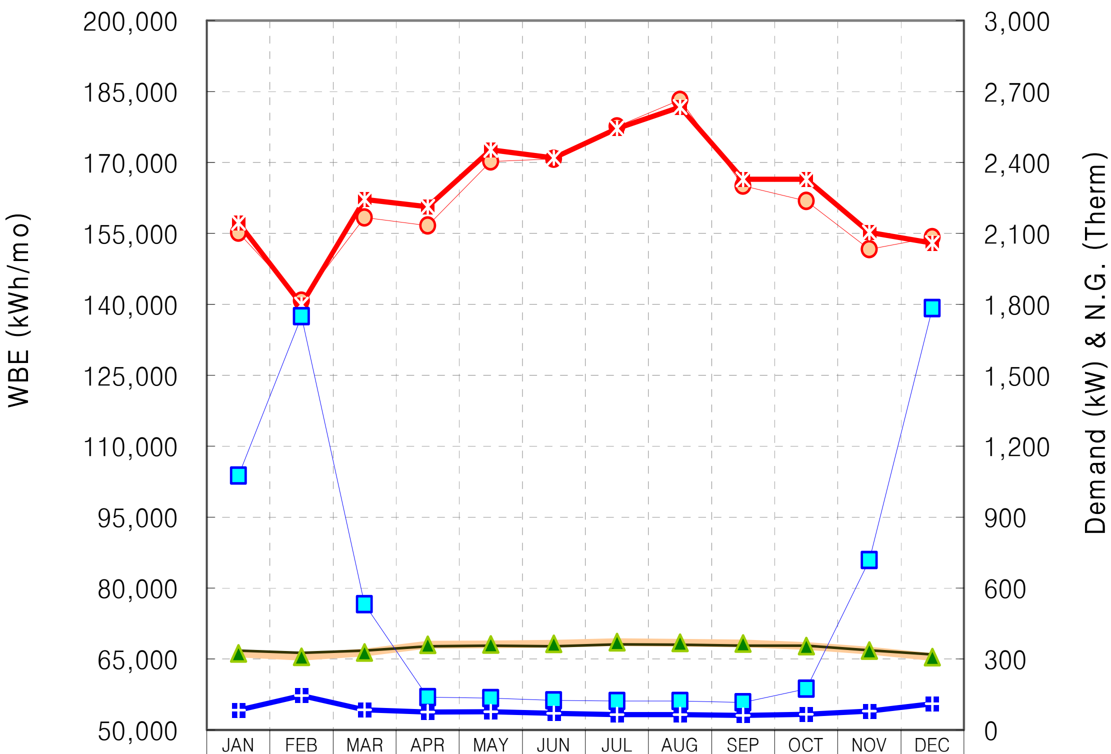
- Reduced the total energy consumption to 6,800 MMBtu/yr from 7,318 MMBtu/yr, which is 7.1% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJEC	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
U-Factor (1.22)	2,506	1,907	641	1,258	427	215	308	57	7,318
U-Factor (0.38)	2,506	1,907	44	1,353	427	186	321	57	6,800

Figure 7.4.1 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation and the Simulation Implementing Improved U-factor from 0.38 Btu/hr-sqft-F to 1.22 Btu/hr-sqft-F.

Figure 7.4.2 compares the energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation and the simulation using the improved glazing U-factor.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (1.22)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (0.38)	157269	139931	162168	160639	172679	170969	177201	181701	166455	166416	155202	152967
DMD (1.22)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (0.38)	335	325	336	354	356	353	362	361	356	356	337	319
N.G. (1.22)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (0.38)	83	146	85	76	77	69	65	65	61	65	79	110

Figure 7.4.2 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results (1.22 Btu/hr-sqft-F) and Improved Glazing U-factor (0.38 Btu/hr-sqft-F) Simulation Results.

This measure:

- Reduced the electric peak demand to 362 kWh from 372 kWh in July, which is 2.7% lower than the base case.
- Reduced the building's natural gas use substantially to 983 therms/yr from 6,789 therms/yr, which is 85.5% lower than the base case.

- Increased the building's total electric use to 1,963,596 kWh/yr from 1,945,395 kWh/yr, which is 0.9% higher than the base case.

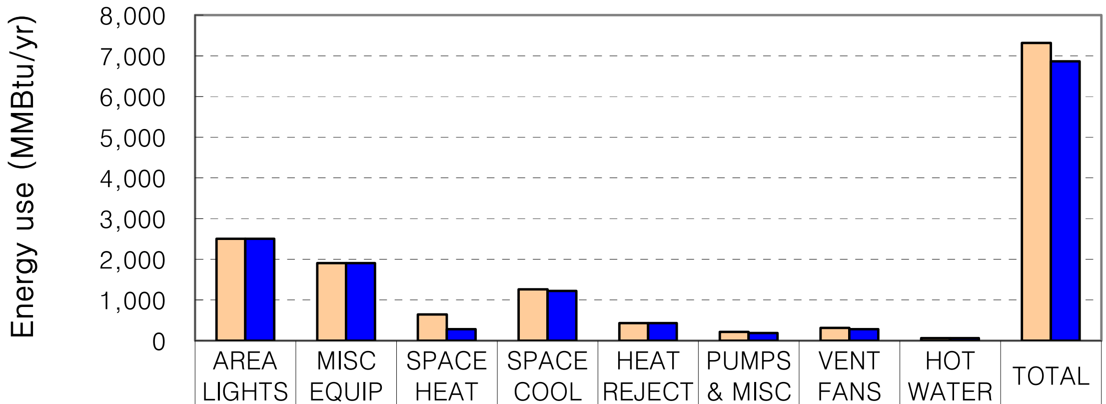
7.4.2 High-performance Measure 2: Reduced Window-to-wall Ratio (from 50% to 35%)

In the ASHRAE Standard 90.1-1999 simulation, the maximum Window-to-Wall (WtW) ratio is 50%. Buildings below this WtW ratio must perform at or below the annual energy costs of a standard building with a 50% WtW ratio. This maximum value was reduced to 35% in the AEDG. ASHRAE's AEDG recommends a reduced window-to-wall ratio for the climate zone in which the case-study building is located, namely a 20%-40% window-to-wall ratio. Therefore, as a high-performance measure in this study, a 35% window-to-wall ratio was chosen and simulated.

Figure 7.4.3 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building and the building with reduced window-to-wall ratio. This measure:

- Reduced the space heating energy consumption to 279 MMBtu/yr from 641 MMBtu/yr, which is 56.5% lower than the base case.
- Reduced the space cooling energy consumption to 1,219 MMBtu/yr from 1,258 MMBtu/yr, which is 3.1% lower than the base case.

- Reduced the total energy consumption to 6,865 MMBtu/yr from 7,318 MMBtu/yr, which is 6.2% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
WWR (50%)	2,506	1,907	641	1,258	427	215	308	57	7,318
WWR (35%)	2,506	1,907	279	1,219	427	188	284	57	6,865

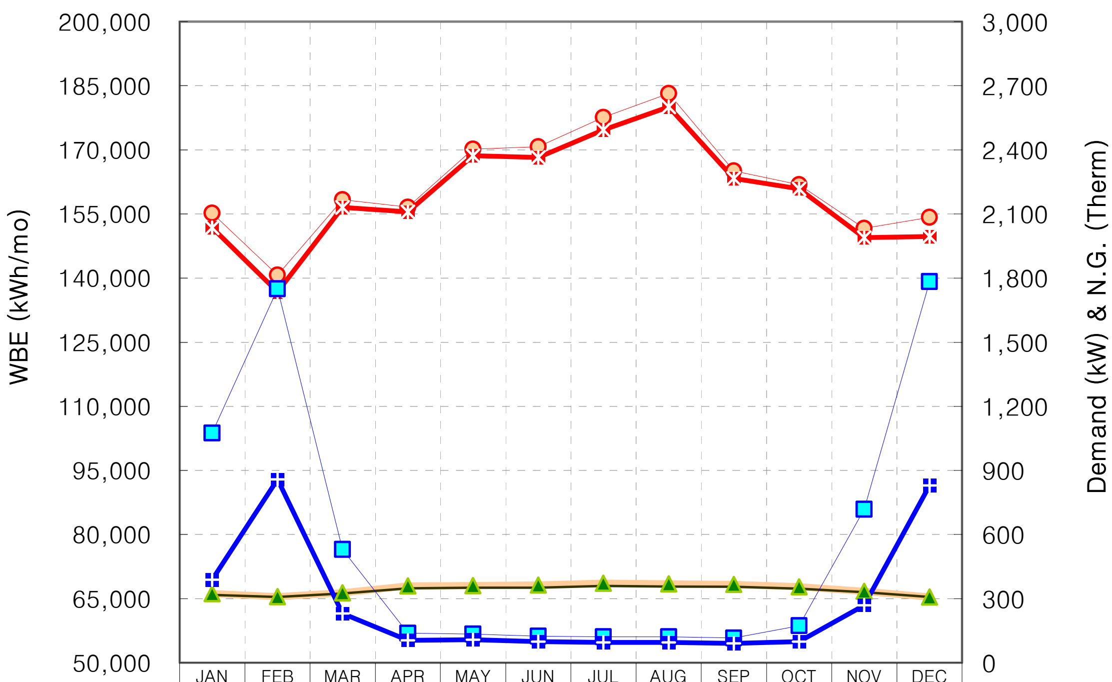
Figure 7.4.3 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation (WWR=0.50) and the Simulation with Reduced Window-to-wall Ratio (WWR=0.35).

Figure 7.4.4 compares the simulated results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation and the simulation with the reduced window-to-wall ratio.

This measure:

- Reduced the electric peak demand to 360 kWh from 372 kWh in July, which is 3.2% lower than the base case.

- Reduced the building's natural gas use substantially to 3,271 therms/yr from 6,789 therms/yr, which is 51.8% lower than the base case. This was due to the less heat loss in the winter period through the window area that has higher U-values that wall areas.
- Reduced the building's total electric use to 1,915,550 kWh/yr from 1,945,395 kWh/yr, which is 1.5% lower than the base case.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (50%)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (35%)	151746	136803	156557	155511	168613	168206	174694	180046	163328	160838	149457	149752
DMD (50%)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (35%)	317	308	324	349	352	352	360	356	355	348	331	308
N.G. (50%)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (35%)	389	859	231	105	108	99	96	96	91	99	269	830

Figure 7.4.4 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results (WWR=0.50) and the Reduced Window-to-wall Ratio Simulation Results (WWR=0.35).

7.4.3 High-performance Measure 3: Reduced Lighting Power Density (from 1.3 W/sq-ft to 0.9 W/sq-ft)

In the ASHRAE Standard 90.1-1999 base-case building, the simulation used a lighting power density (LPD) of 1.3 W/sq-ft, which is the maximum value for office applications, allowed by ASHRAE Standard 90.1-1999 . In the base-case simulation, the electric lighting profile was set to the recommended profile from ASHRAE's Diversity Factor Toolkit (RP-1093), as shown in Figure 7.4.5 (Abushakra et al. 2001).

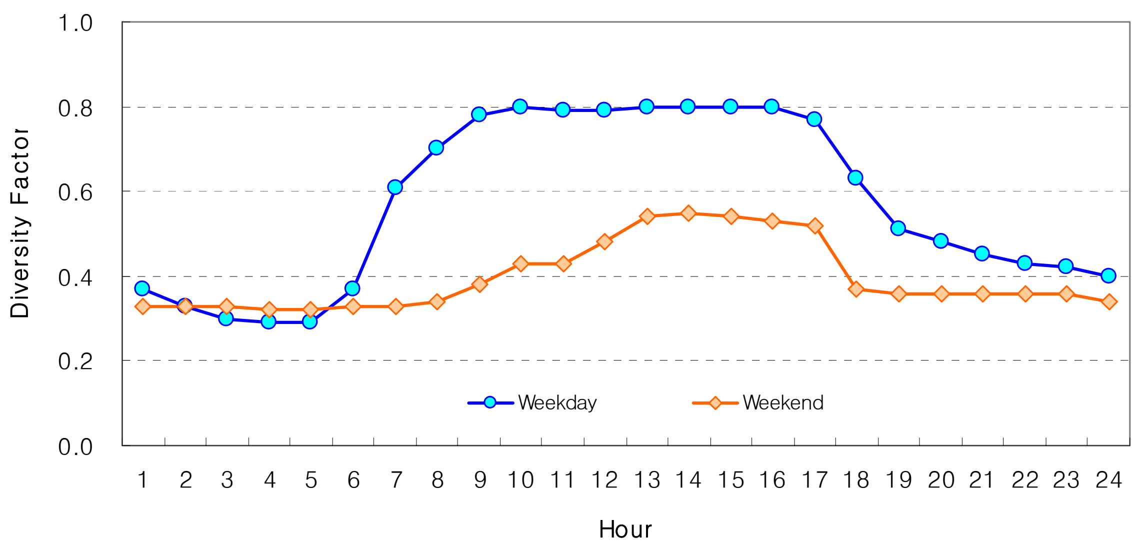


Figure 7.4.5 Base-case Lighting Profile for Large Commercial Buildings (Abushakra et al., 2001).

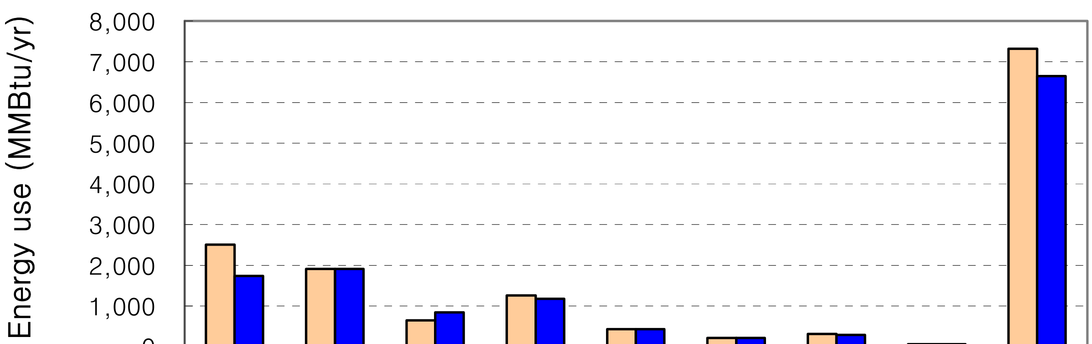
The impact of energy-efficient lighting was determined by reducing the Lighting Power Density (LPD) from 1.3 W/sq-ft to 0.9 W/sq-ft . There are a number of lighting systems available to meet the LPD requirements described above. Some of these include changing the fixture type, fixture size, type of lens or louver, and mounting height. The reduced lighting power density of 0.9 W/sq-ft is a recommended value by the ASHRAE AEDG. Figure 7.4.6 shows the simulation results and comparison with the base-case (ASHRAE Standard 90.1-1999 code-compliant) building and the building with reduced lighting power density of 0.9 W/sq-ft from 1.3 W/sq-ft. This measure:

- Increased the space heating energy consumption to 844 MMBtu/yr from 641 MMBtu/yr, which is 3.2% higher than the base case.
- Reduced the space cooling energy consumption to 1,178 MMBtu/yr from 1,258 MMBtu/yr, which is 6.4% lower than the base case. In contrast to the space heating case, the reduction of internal heat gain by reducing the lighting power density resulted in lower cooling load than the base case.
- Reduced the total energy consumption to 6,647 MMBtu/yr from 7,318 MMBtu/yr, which is 9.2% lower than the base case.

Figure 7.4.7 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation and the simulation with the reduced lighting power density.

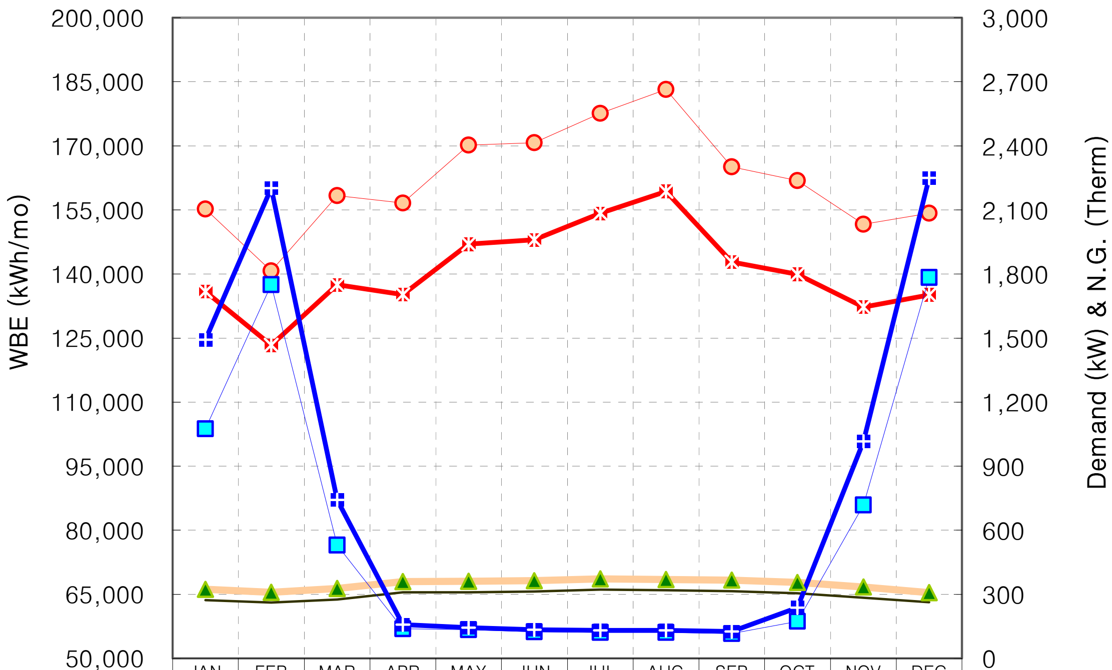
This measure:

- Reduced the electric peak demand to 321 kWh from 372 kWh in July, which is 13.7% lower than the base case.
- Reduced the building's total demand to 3,550 kW from 4,151 kW, which is 14.5% lower than the base case.
- Increased the building's natural gas use to 8,766 therms/yr from 6,789 therms/yr, which is 29.1% higher than the base case. This result was expected due to more space heating required.
- Reduced the building's total electric use to 1,690,640 kWh/yr from 1,945,395 kWh/yr, which is 13.1% lower than the base case. The reduction of the lighting power density directed resulted in the reduction of the total electric consumption of the building.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
LPD (1.3 W/sf)	2,506	1,907	641	1,258	427	215	308	57	7,318
LPD (0.9 W/sf)	1,735	1,907	844	1,178	426	212	288	57	6,647

Figure 7.4.6 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with Lighting Power Density of 1.3 W/sq-ft and the Simulation with Reduced Lighting Power Density of 0.9 W/sq-ft.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (1.3)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (0.9)	135900	123365	137492	135165	147008	148015	154188	159353	142829	139923	132271	135131
DMD (1.3)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (0.9)	273	262	276	309	310	314	321	319	315	305	284	263
N.G. (1.3)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (0.9)	1492	2202	742	159	144	134	132	132	126	237	1016	2250

Figure 7.4.7 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results (LPD=1.3 W/sqft) and the Reduced Lighting Power Density Simulation Results (LPD=0.9 W/sqft).

7.4.4 High-performance Measure 4: Occupancy Sensors for Lighting Control (from No Lighting Control to Occupancy Sensors Installation)

The base-case building was modeled with a lighting power density of 1.3 W/sq-ft, as required by ASHRAE Standard 90.1-1999 (Table 9.3.1.1, p.51). The electric lighting profile was adopted from the ASHRAE RP-1093 report (large office buildings) and is shown in Table 7.4.2, which also includes occupancy profiles from the ASHRAE Standard 90.1-1989 Standard and modified lighting schedule for the implementation of occupancy sensors for lighting control. Figure 7.4.8, Figure 7.4.9, and Figure 7.4.10 show these schedules in graphical formats, respectively. The modified lighting schedule includes minimum lighting requirement in the night time for emergency, which is 5% of the maximum lighting power level.

Table 7.4.2 Comparison of Lighting Profile (ASHRAE RP-1093) and Occupancy Profile (ASHRAE Standard 90.1-1989) for the Development of Lighting Schedule to Implement Occupancy Sensors.

Hour of Day	Lighting Profile (ASHRAE RP-1093)		Occupancy Profile (ASHRAE 90.1-1989)		Modified Lighting Schedule for Occupancy Sensor Implementation	
	Weekdays	Weekends	Weekdays	Weekends	Weekdays	Weekends
1	0.37	0.33	0.00	0.00	0.05	0.05
2	0.33	0.33	0.00	0.00	0.05	0.05
3	0.30	0.33	0.00	0.00	0.05	0.05
4	0.29	0.32	0.00	0.00	0.05	0.05
5	0.29	0.32	0.00	0.00	0.05	0.05
6	0.37	0.33	0.00	0.00	0.05	0.05
7	0.61	0.33	0.10	0.10	0.10	0.10
8	0.70	0.34	0.20	0.10	0.20	0.10
9	0.78	0.38	0.90	0.30	0.78	0.30
10	0.80	0.43	0.90	0.30	0.80	0.30
11	0.79	0.43	0.45	0.30	0.45	0.30
12	0.79	0.48	0.45	0.30	0.45	0.30
13	0.80	0.54	0.90	0.10	0.80	0.10
14	0.80	0.55	0.90	0.10	0.80	0.10
15	0.80	0.54	0.90	0.10	0.80	0.10
16	0.80	0.53	0.90	0.10	0.80	0.10
17	0.77	0.52	0.90	0.10	0.77	0.10
18	0.63	0.37	0.30	0.00	0.30	0.05
19	0.51	0.36	0.10	0.00	0.10	0.05
20	0.48	0.36	0.10	0.00	0.10	0.05
21	0.45	0.36	0.10	0.00	0.10	0.05
22	0.43	0.36	0.00	0.00	0.05	0.05
23	0.42	0.36	0.00	0.00	0.05	0.05
24	0.40	0.34	0.00	0.00	0.05	0.05

Also, as shown in Figure 7.4.10, the weekdays' profile maintain lower than the occupancy profile did for the hours of 9 am, 10 am, and 1-5 pm. This is because the lighting profile of ASHRAE RP-1093 is lower than the occupancy profile of the ASHRAE Standard 90.1-1989 Standard for these hours. The modified lighting schedule was developed not to exceed the lighting level for each hour of day.

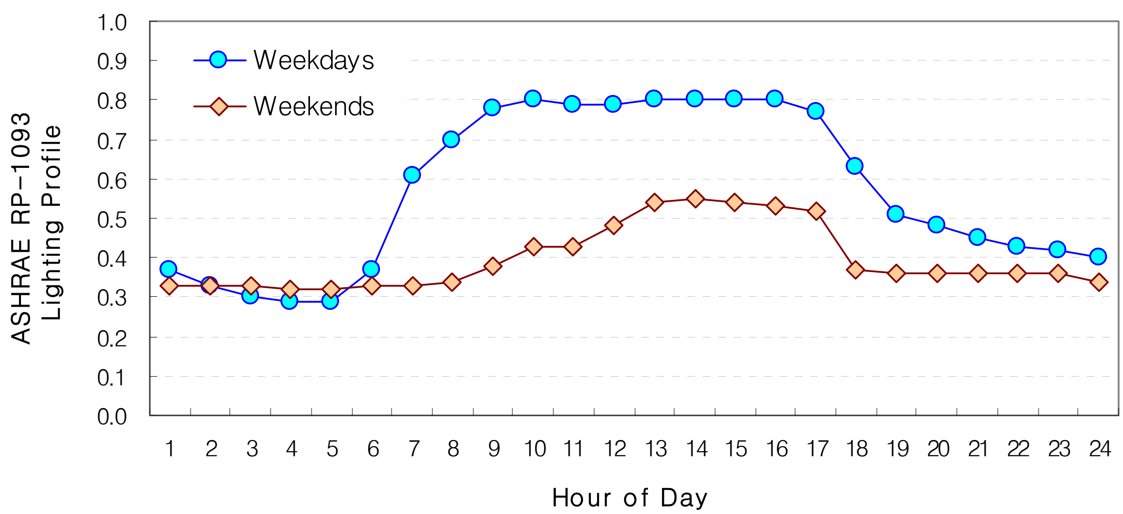


Figure 7.4.8 Base-case Lighting Profile based on the Typical Lighting Profile for Office Buildings Adopted from the ASHRAE RP-1093.

The energy impact from the installation of occupancy sensors for lighting is determined by specifying the electric lighting profile same as the occupancy profile modified, as shown as in Figure 7.4.10. Based on the new profiles, energy savings occur mainly in the night time for both weekdays and weekends. During the weekends, there are additional lighting power reductions expected for the afternoon hours. This assumes the lights are supposed to be shut-off when no people are inside the building during the night except emergency lights and are substantially reduced during the lunch hours.

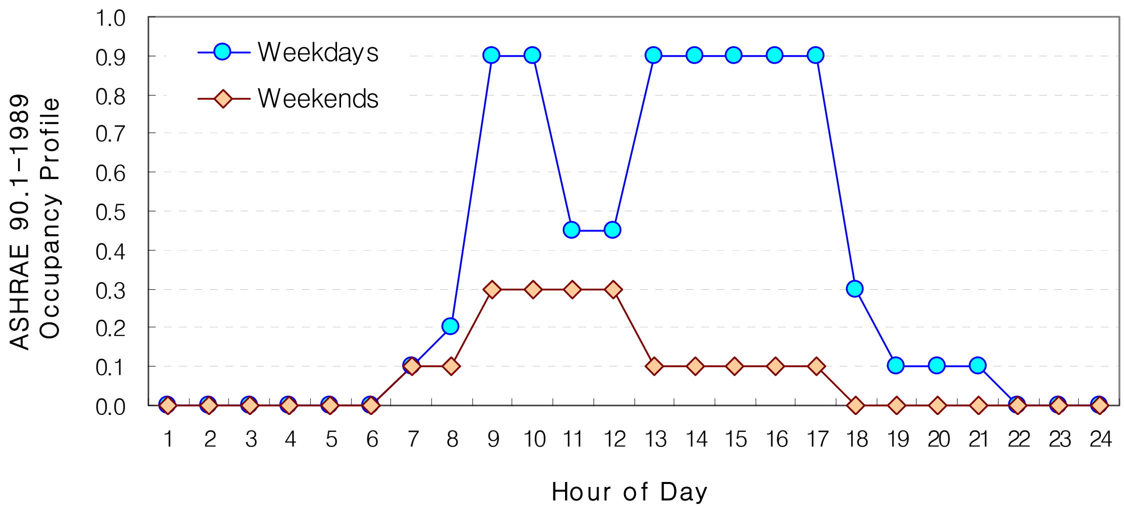


Figure 7.4.9 Occupancy Profile for Typical Office Buildings Obtained from the ASHRAE Standard 90.1-1989 Standard.

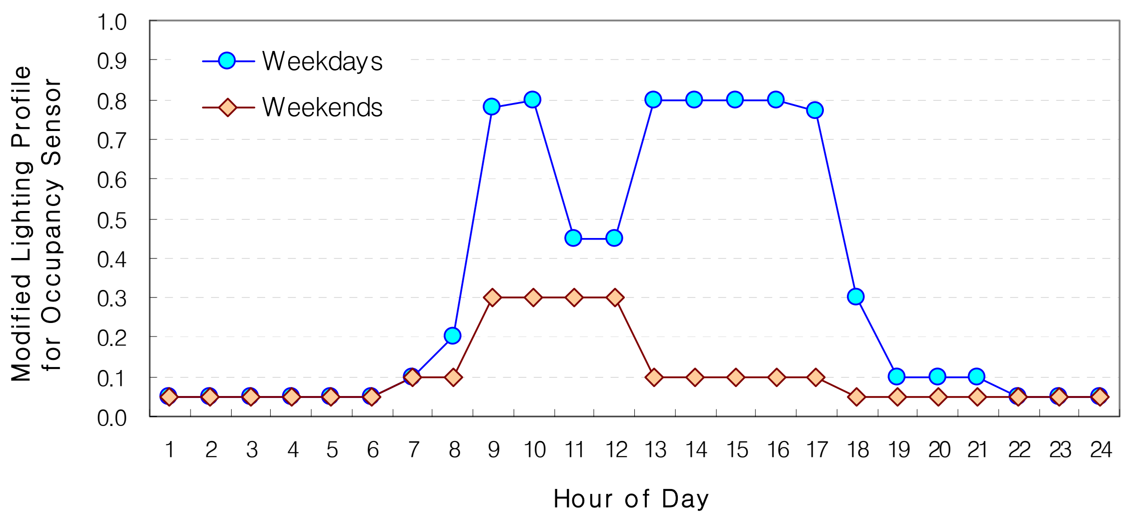
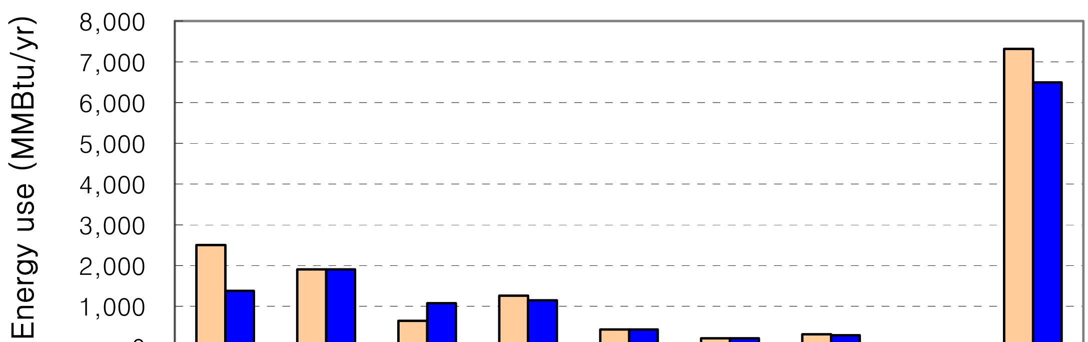


Figure 7.4.10 Modified Lighting Profile for Occupancy Sensor Application Using the Occupancy Profile Adopted from the ASHRAE Standard 90.1-1989 Standard.

Figure 7.4.11 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building without occupancy sensors and the building with occupancy sensors. This measure:

- Increased the space heating energy consumption to 1,077 MMBtu/yr from 641 MMBtu/yr, which is 68.0% higher than the base case. The reduced lighting heat gain from the occupancy sensors resulted in lower internal heat gain, so the space heating load was increased.
- Reduced the space cooling energy consumption to 1,147 MMBtu/yr from 1,258 MMBtu/yr, which is 8.8% lower than the base case. The space cooling energy was supposed to be reduced as the internal heat gain was reduced by this measure.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
No Sensor	2,506	1,907	641	1,258	427	215	308	57	7,318
Occ. Sensor	1,379	1,907	1,077	1,147	426	216	290	57	6,497

Figure 7.4.11 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation without Lighting Control and the Simulation with Lighting Control with Occupancy Sensors.

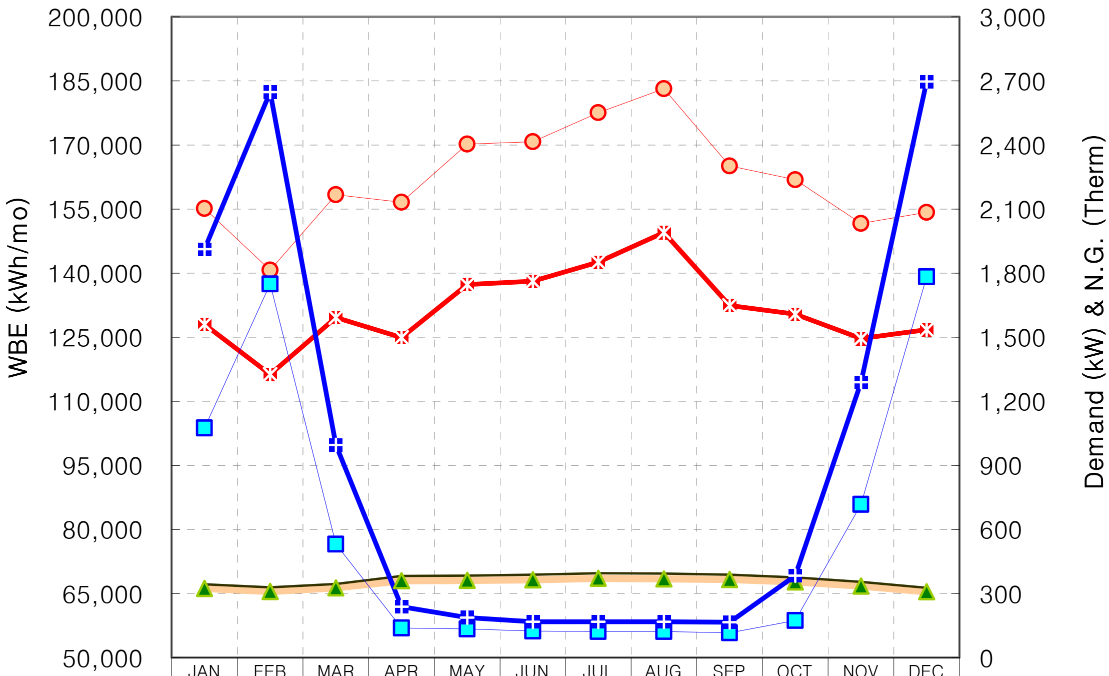
- Reduced the total energy consumption to 6,497 MMBtu/yr from 7,318 MMBtu/yr, which is 11.2% lower than the base case.

Figure 7.4.12 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation without occupancy sensors and the simulation with the occupancy sensors installed in the building. This measure:

- Increased the electric peak demand to 395 kWh from 372 kWh in July, which is 5.8% higher than the base case.
- Increased the building's natural gas use substantially to 11,023 therms/yr from 6,789 therms/yr, which is 62.4% higher than the base case. This results was as expected since the occupancy sensors application reduces the internal heat gain, and as a result, the building requires more heating energy than the base-case building.
- Reduced the building's total electric use to 1,580,711 kWh/yr from 1,945,395 kWh/yr, which is 18.7% lower than the base case.

7.4.5 High-performance Measure 5: Adding Shading Device (from No Shading Device to 2.5 ft Overhangs)

In the base-case building, there were no shades on the windows in the base-case building. Therefore, the impact of window shades was considered. The ASHRAE AEDG recommends window overhangs on the windows, using a projection factor of 0.5. Since the windows used in the base-case simulation were set a height of 5 feet, this implementation resulted in shades that projected 2.5 feet from the top of the windows. Also, these 2.5 foot overhangs were applied to all windows except windows in the facade that faces north, since there is no need to apply the overhangs on the north walls because no sun reaches the north walls during a day.

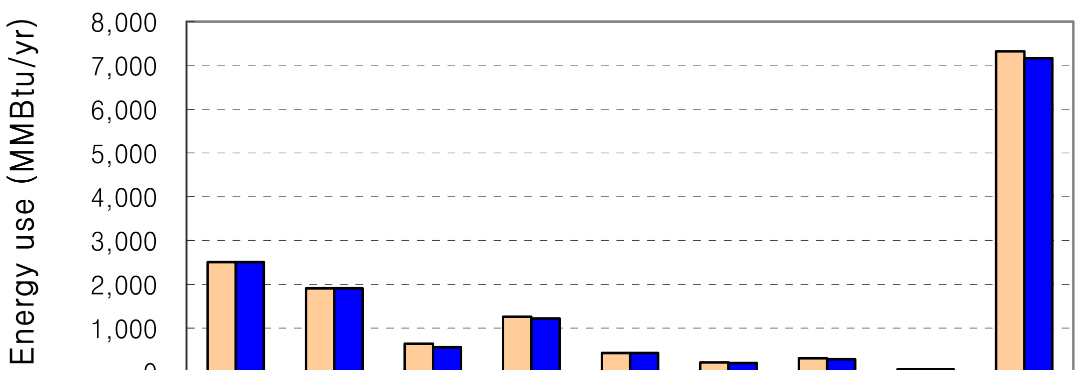


	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (No)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (Occ)	128021	116295	129619	124897	137335	138102	142561	149513	132444	130425	124749	126749
DMD (No)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (Occ)	344	329	344	382	384	388	395	394	388	376	354	326
N.G. (No)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (Occ)	1912	2648	996	239	188	169	168	168	165	384	1290	2697

Figure 7.4.12 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results and the Simulation Results Using Occupancy Sensors.

Figure 7.4.13 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building without building shades on the windows and the building with overhangs of 2.5 ft on the windows except windows facing north. This measure:

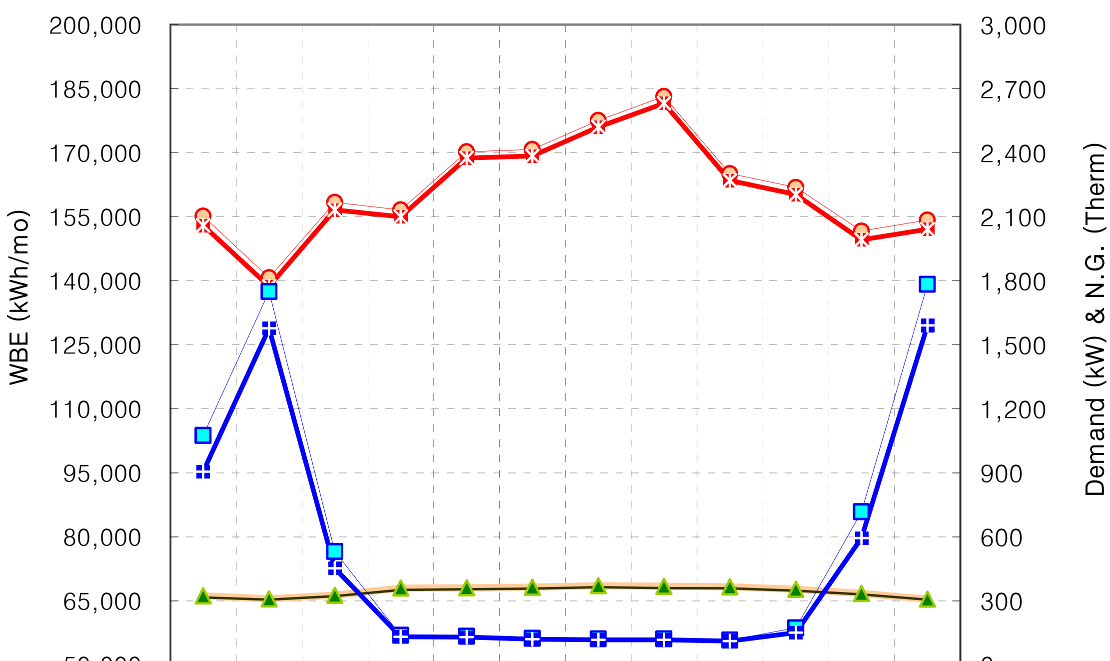
- Reduced the space heating energy consumption to 560 MMBtu/yr from 641 MMBtu/yr, which is 12.6% lower than the base case.
- Reduced the space cooling energy consumption to 1,219 MMBtu/yr from 1,258 MMBtu/yr, which is 3.1% lower than the base case.
- Reduced the total energy consumption to 7,167 MMBtu/yr from 7,318 MMBtu/yr, which is 2.1% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJEC	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
No Shading	2,506	1,907	641	1,258	427	215	308	57	7,318
Overhang (2.5ft)	2,506	1,907	560	1,219	427	203	289	57	7,167

Figure 7.4.13 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation without Overhangs and the Simulation with Overhangs of 2.5 Feet on East, South, and West Walls.

Figure 7.4.14 compares the energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation without building shades and the simulation with the overhangs of 2.5 feet for windows facing east, south, and west.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (No)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (2.5)	152936	138647	156604	154979	168742	169242	175997	181565	163495	160189	149582	152028
DMD (No)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (2.5)	317	306	322	352	354	357	364	361	358	348	331	306
N.G. (No)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (2.5)	905	1577	454	131	130	121	118	118	113	151	595	1591

Figure 7.4.14 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results without Window Shadings and the Simulation Results with Window Shadings (2.5 ft Overhangs for Walls Except North-Facing Wall).

This measure:

- Reduced the electric peak demand to 364 kWh from 372 kWh in July, which is 2.2% lower than the base case.
- Reduced the building's natural gas use to 6,004 therms/yr from 6,789 therms/yr, which is 11.6% lower than the base case.
- Reduced the building's total electric use to 1,924,005 kWh/yr from 1,945,395 kWh/yr, which is 1.1% lower than the base case.

7.4.6 High-performance Measure 6: Supply Air Temperature Reset (from 55 F Constant Temperature to 60 F-55 F Variable Temperature)

In this next measure, the base-case building's supply air temperature was changed. In the base-case simulation, it was set to a constant temperature of 55 F year round. This constant temperature was changed to a variable temperature to further improve the performance of the cooling system. To vary the temperature, the supply air temperature was changed from a constant 55 F to a schedule as shown in the graph in Figure 7.4.15. This saves cooling energy by maintaining the cold deck air temperature at 60 F when outdoor temperature is 55 F or lower and maintains the cold deck temperature at 55 F when outdoor temperature is 85 F or higher . The cold deck temperature decreases linearly from 60 F to 55 F as the outdoor temperature increases from 55 F to 85 F.

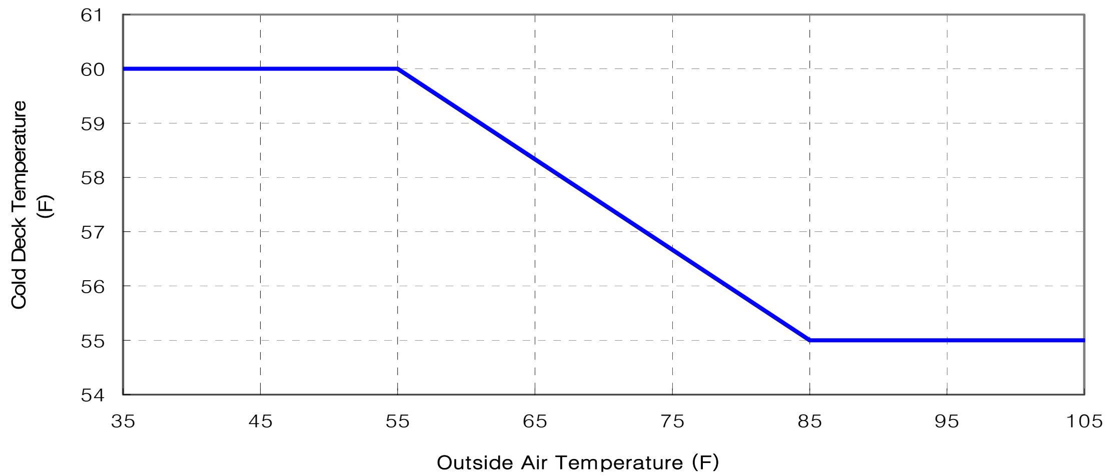


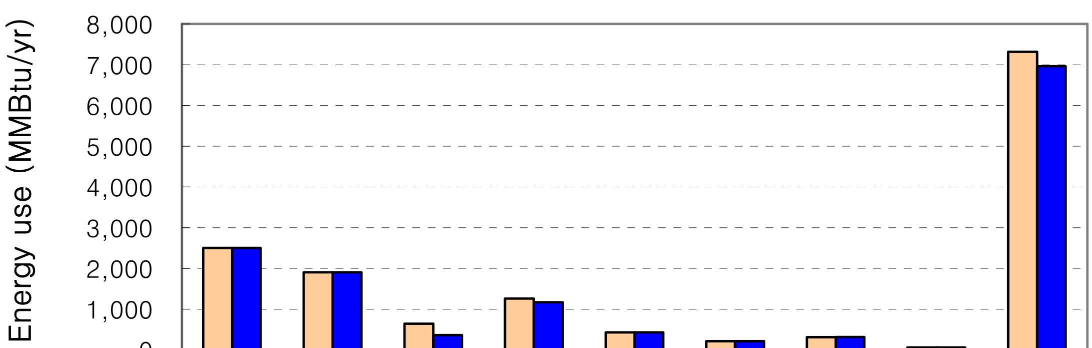
Figure 7.4.15 Cold Deck Temperature Reset Schedule Based on the Outdoor Air Dry-Bulb Temperature.

Figure 7.4.16 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with a constant cold deck temperature of 55 F and the building with a cold deck temperature reset schedule. This measure:

- Reduced the space heating energy consumption to 364 MMBtu/yr from 641 MMBtu/yr, which is 43.2% lower than the base case. When the outdoor temperature is 55 F or lower, the cold deck is set to 60 F. This change reduced the heating energy at the terminal box for reheat.
- Reduced the space cooling energy consumption to 1,173 MMBtu/yr from 1,258 MMBtu/yr, which is 6.8% lower than the base case.
- Reduced the total energy consumption to 6,964 MMBtu/yr from 7,318 MMBtu/yr, which is 4.8% lower than the base case.

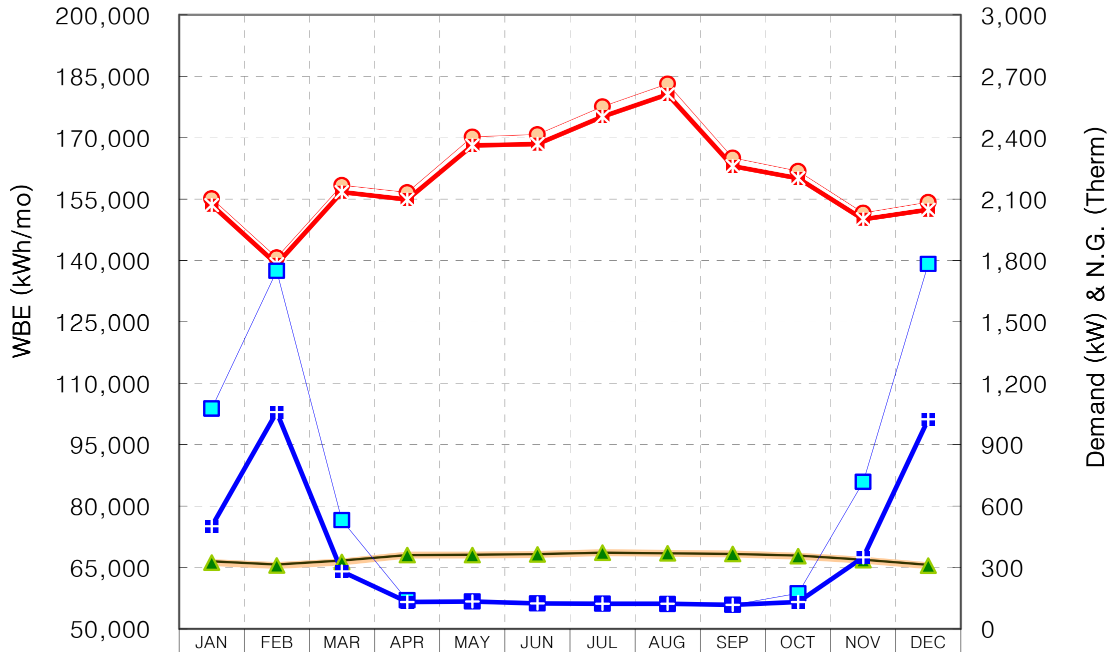
Figure 7.4.17 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with a constant cold deck temperature of 55 F and the simulation with a cold deck temperature reset schedule. This measure:

- Did not make any changes to the electric peak demand in July; however, there were several months that showed changes on the electric demand.
- Reduced the building's natural gas use to 4,095 therms/yr from 6,789 therms/yr, which is 39.7% lower than the base case.
- Reduced the building's total electric use to 1,920,647 kWh/yr from 1,945,395 kWh/yr, which is 1.3% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Const (55F)	2,506	1,907	641	1,258	427	215	308	57	7,318
Vari (60-55)	2,506	1,907	364	1,173	427	215	316	57	6,964

Figure 7.4.16 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with Constant Supply Air Temperature of 55 F and the Simulation with Supply Air Temperature Reset Schedule (Variable Between 55 F and 60 F).



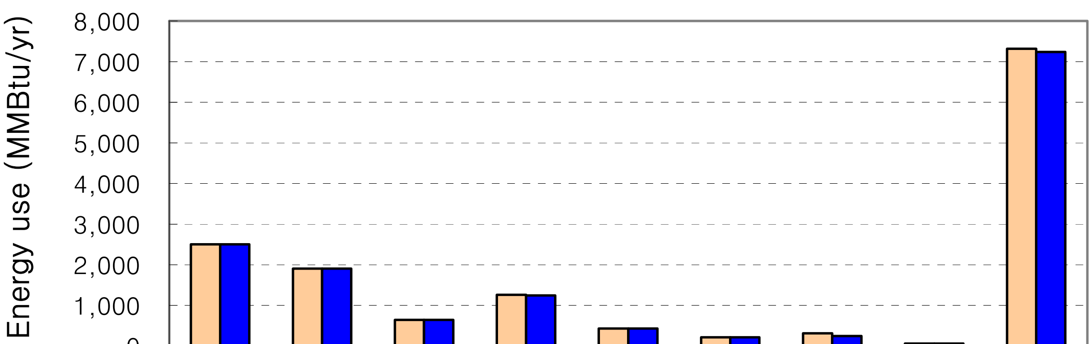
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (55)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (55-60)	153499	139075	156688	154860	168124	168444	175160	180553	162996	160066	150058	152413
DMD (55)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (55-60)	329	315	334	361	362	364	372	369	367	357	338	313
N.G. (55)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (55-60)	502	1059	281	131	134	125	122	122	116	131	349	1024

Figure 7.4.17 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with the Supply Air Temperature of 55 F and the Simulation Results with Supply Air Temperature Reset Schedule (Variable Between 55 F and 60 F).

7.4.7 High-performance Measure 7: Reduced Supply Fan Static Pressure (from 2.5 inH_2O to 1.5 inH_2O)

In this measure, based on the information from the CC$^{(R)}$ group at the ESL, the supply fan static pressure was reduced. The base-case building model had the supply air total static pressure of 2.5 inH_2O. This value was obtained from a survey through CC(R) engineers in the Energy Systems Laboratory. It represents an average value from the Texas A&M University campus buildings. To improve the HVAC systems' performance, the total supply fan static pressure was reduced to 1.5 inH_2O from 2.5 inH_2O. The decreased value of 1.5 inH_2O was a minimum recommendation by the CC(R) engineers. This can be accomplished by: larger-sized ductwork, using low static pressure filters, and other such measures that reduce the pressure drop in the system.

Figure 7.4.18 shows the simulation results and compares the results of the base-case (ASHRAE Standard 90.1-1999 code-compliant) building (total fan static pressure of 2.5 inH_2O) and the building with a reduced total static pressure of 1.5 inH_2O.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
2.5 inH2O	2,506	1,907	641	1,258	427	215	308	57	7,318
1.5 inH2O	2,506	1,907	641	1,248	427	212	242	57	7,239

Figure 7.4.18 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with the Supply Air Total Static Pressure of 2.5 inH_2O and the Simulation with a Reduced Static Pressure of 1.5 inH_2O.

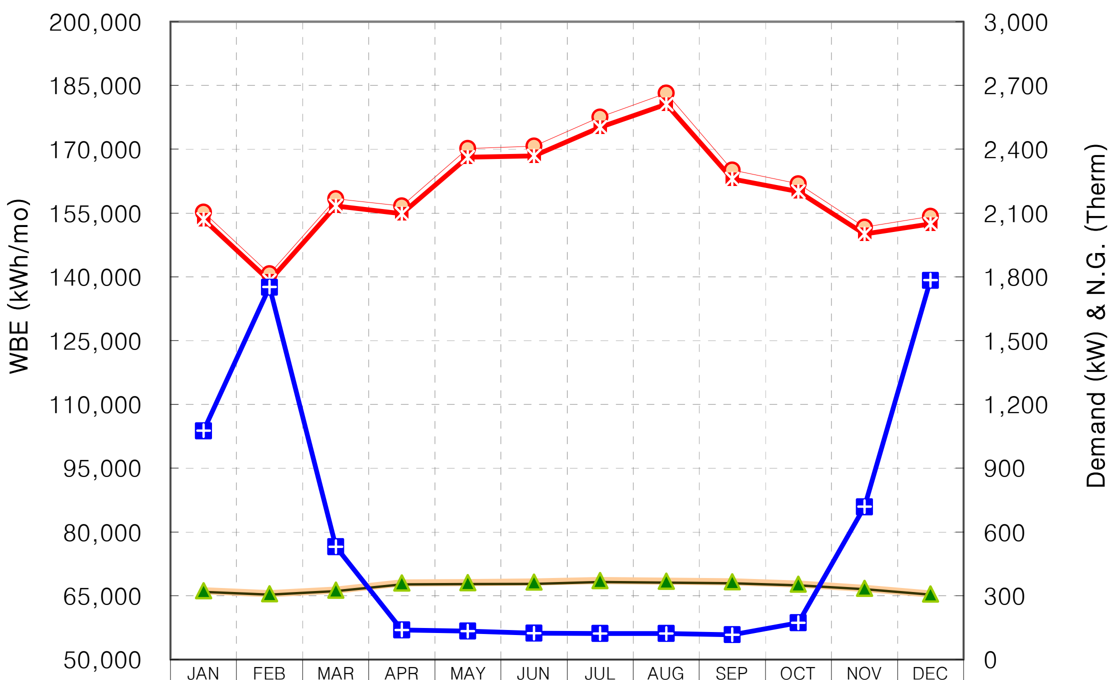
This measure:

- Increased the space heating energy consumption slightly, which is 0.4 MMBtu/yr, compared to the base case, which is 641 MMBtu/yr. The percent increase of the heating energy was 0.06%.
- Reduced the space cooling energy consumption to 1,248 MMBtu/yr from 1,258 MMBtu/yr, which is 0.8% lower than the base case.
- Reduced the pump and miscellaneous energy consumption to 212 MMBtu/yr from 215 MMBtu/yr, which is 1.4% lower than the base case.
- Reduced the fan energy use to 242 MMBtu/yr from 308 MMBtu/yr, which is 21% lower than the base case. The fan energy reduction was the main energy consumption decrease in this measure as this is directly related to the fan control.
- Reduced the total energy consumption to 7,239 MMBtu/yr from 7,318 MMBtu/yr, which is 1.1% lower than the base case.

Figure 7.4.19 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with the total supply air static pressure of 2.5 inH_2O and the simulation with the reduced supply air total static pressure of 1.5 inH_2O.

This measure:

- Reduced the electric peak demand to 365 kWh from 372 kWh in July, which is 1.9% lower than the base case.
- Increased the building's natural gas use slightly to 6,794 therms/yr from 6,789 therms/yr, which is 0.1% higher than the base case.
- Reduced the building's total electric use to 1,921,935 kWh/yr from 1,945,395 kWh/yr, which is 1.2% lower than the base case.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (2.5)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (1.5)	153499	139075	156688	154860	168124	168444	175160	180553	162996	160066	150058	152413
DMD (2.5)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (1.5)	319	306	323	353	355	357	365	362	359	350	330	305
N.G. (2.5)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (1.5)	1076	1751	531	139	134	125	122	122	116	174	719	1785

Figure 7.4.19 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with the Supply Fan Static Pressure of 2.5 in-H2O and the Simulation Results with the Reduced Static Pressure of 1.5 in-H2O.

7.4.8 High-performance Measure 8: Economizer Control (from No Economizer Control to Temperature-based Economizer Control)

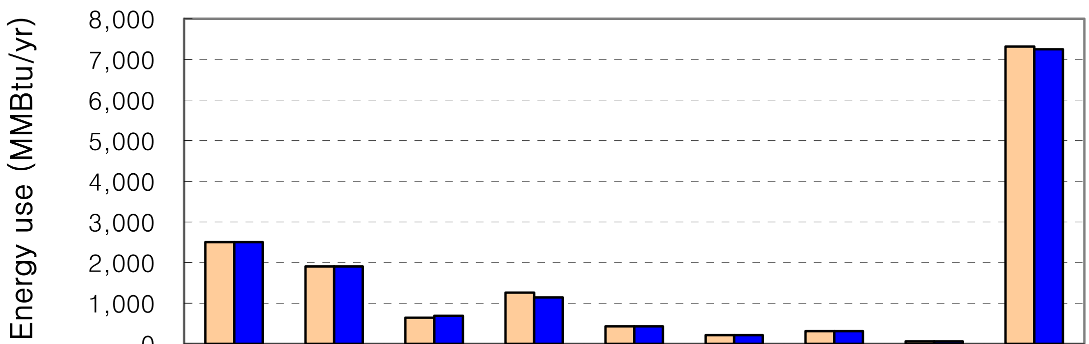
A temperature-based economizer is a way to utilize free cooling when the outside air temperature is cool enough to be used for space cooling. The outside air damper is controlled to be fully opened when the outside air temperature comes down to 65 F. The mixed air will then be lower than the return temperature, which reduces the sensible cooling load, although it increases the humidity level resulting in higher latent cooling load. An enthalpy-based economizer is an improved option for humid climates. However, there are also drawbacks in enthalpy-based system such as the difficulties with maintaining the indoor and outdoor humidity sensors. In this study, therefore, a temperature-based economizer was applied.

Figure 7.4.20 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building without economizer and the building using the temperature economizer.

This measure:

- Increased the space heating energy consumption to 691 MMBtu/yr from 641 MMBtu/yr, which is 7.8% higher than the base case. This is due to the lower mixed air temperature coming into the heating coil when the outside air dry-bulb temperature is 65 F or lower.

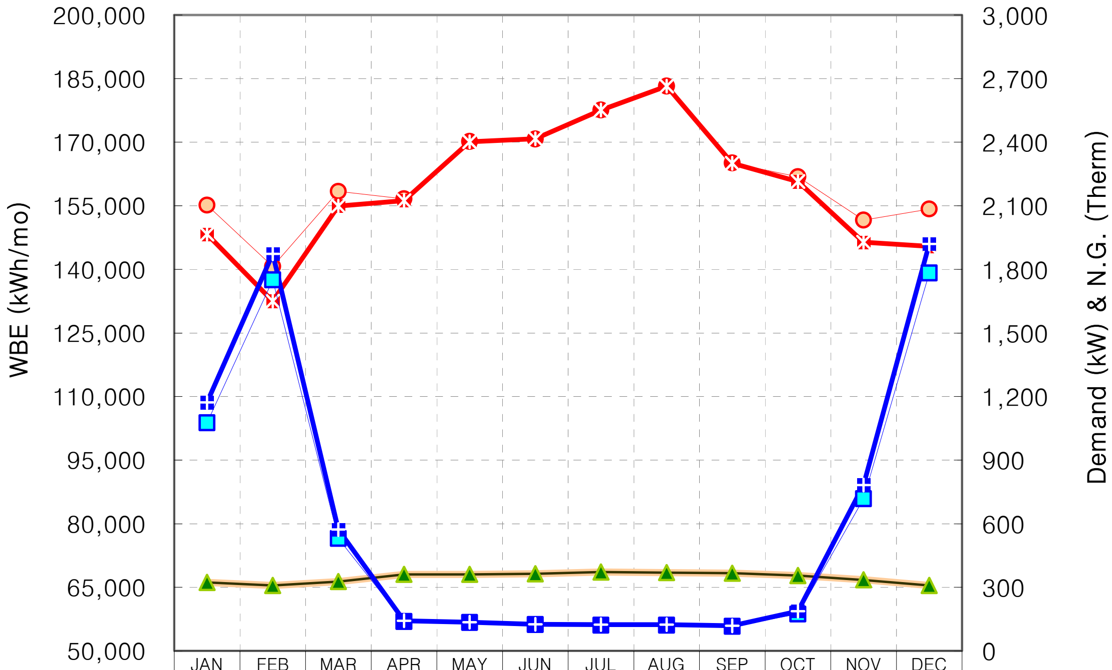
- Reduced the space cooling energy consumption to 1,139 MMBtu/yr from 1,258 MMBtu/yr, which is 9.5% lower than the base case.
- Reduced the total energy consumption to 7,250 MMBtu/yr from 7,318 MMBtu/yr, which is 0.9% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
No Econo.	2,506	1,907	641	1,258	427	215	308	57	7,318
Temp. Econo.	2,506	1,907	691	1,139	427	216	308	57	7,250

Figure 7.4.20 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation without Economizer Control and the Simulation with the Temperature-based Economizer Control.

Figure 7.4.21 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation without the economizer control and the simulation with the temperature economizer control. According to the ASHRAE Standard 90.1-1999 Standard (page 41, Table 6.3.1), economizer control is not required for the weather condition of College Station, TX. As shown in Figure 7.4.21, however, the total electric energy savings are much higher that the N.G. energy increase from this measure, resulting in about 1% energy use reduction of total energy.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (No)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (Eco)	148279	132506	154904	156207	170067	170773	177604	183216	164990	160716	146389	145390
DMD (No)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (Eco)	323	309	327	360	361	364	372	369	366	355	335	308
N.G. (No)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (Eco)	1171	1873	573	143	136	126	124	124	118	187	783	1920

Figure 7.4.21 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results without Economizer and the Simulation Results with Using the Temperature-based Economizer.

This measure:

- Did not make any changes to the electric peak demand in July; however, there were several months that showed changes on the electric demand.

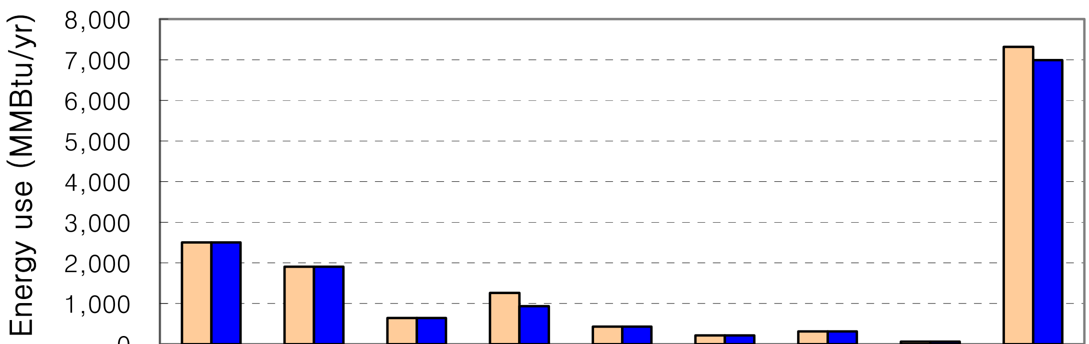
- Reduced the building's total demand slightly compared to the base case, which is 4,151 kW. The small demand reduction occurred in January and December, by only 1 kW each. This was due to the reduced cooling requirement from using the cold outside air in the winter period.
- Increased the building's natural gas use to 7,278 therms/yr from 6,789 therms/yr, which is 7.2% higher than the base case. The space heating energy was required more compared to the base case due to the lower temperature of the air coming into the system.
- Reduced the building's total electric use to 1,911,038 kWh/yr from 1,945,395 kWh/yr, which is 1.8% lower than the base case.

7.4.9 High-performance Measure 9: Efficient Chiller (from COP 5.5 to COP 7.50)

The base-case building has a 280 ton (3.36 MMBtu/hr) centrifugal chiller installed with a COP of 5.55, which is the minimum requirement by the ASHRAE Standard 90.1-1999 building code for this size of the centrifugal chiller. This minimum efficiency of the centrifugal chiller was changed to a higher COP of 7.50, which is 0.47 kW per ton, for the energy efficiency of the base-case building.

Figure 7.4.22 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with the chiller COP of 5.55 and the building with a higher COP of 7.50. This measure:

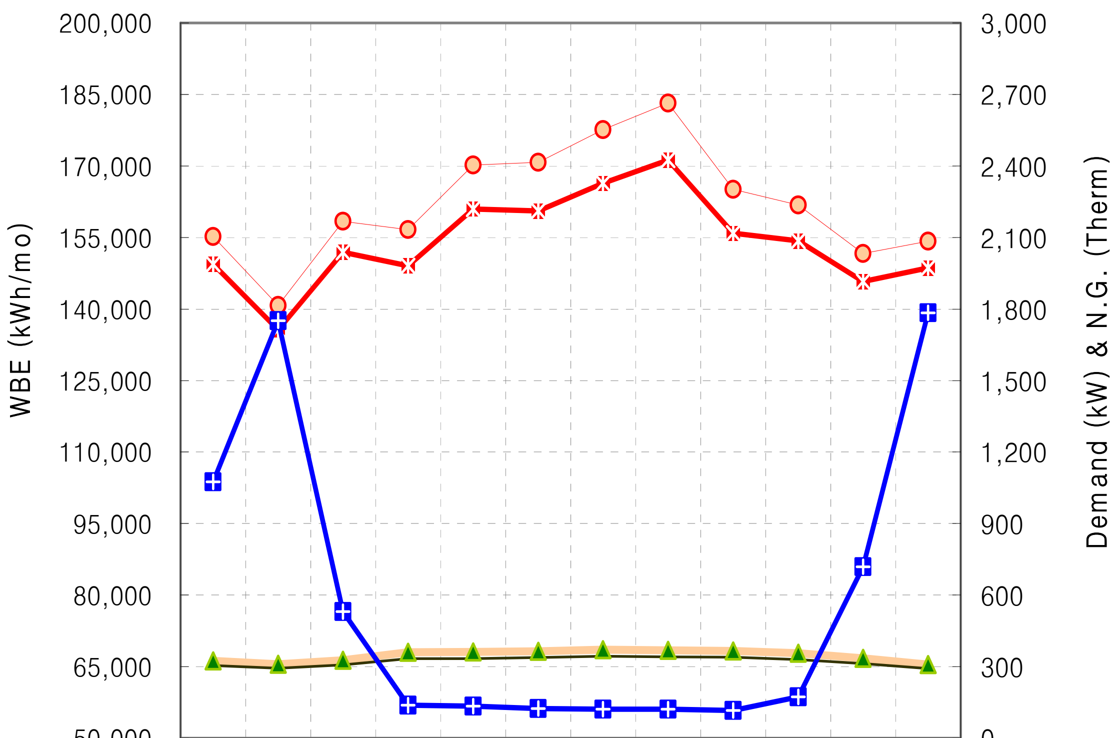
- Maintained the space heating energy consumption the same as the base-case building, which was 641 MMBtu/yr, since the chiller efficiency change did not impact any space heating energy consumption.
- Reduced the space cooling energy consumption to 931 MMBtu/yr from 1,258 MMBtu/yr, which is 26.0% lower than the base case.
- Reduced the total energy consumption to 6,992 MMBtu/yr from 7,318 MMBtu/yr, which is 4.5% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
COP5.55	2,506	1,907	641	1,258	427	215	308	57	7,318
COP7.50	2,506	1,907	641	931	427	215	308	57	6,992

Figure 7.4.22 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with a Chiller COP of 5.55 and the Simulation with a Higher Chiller COP of 7.50.

Figure 7.4.23 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with the chiller COP of 5.55 and the simulation with the increased chiller COP of 7.50.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (5.55)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (7.50)	149392	135632	151923	149014	160969	160534	166376	171263	155872	154286	145774	148631
DMD (5.55)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (7.50)	304	293	307	334	334	337	343	341	339	329	313	292
N.G. (5.55)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (7.50)	1076	1750	531	139	134	125	122	122	116	174	718	1783

Figure 7.4.23 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with a Chiller COP of 5.55 and the Simulation Results Using the Improved Chiller COP of 7.50.

This measure:

- Reduced the electric peak demand to 343 kWh from 372 kWh in July, which is 7.8% lower than the base case.
- Maintained the same natural gas use as the base-case building, which was 6,789 therms/yr.
- Reduced the building's total electricity use to 1,849,667 kWh/yr from 1,945,395 kWh/yr, which is 4.9% lower than the base case.

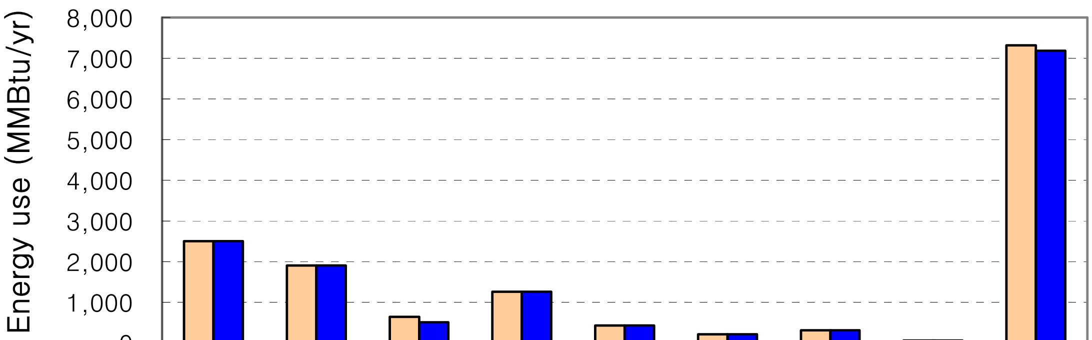
7.4.10 High-performance Measure 10: Efficient Hot Water Boiler (from 75% Thermal Efficiency to 95% Thermal Efficiency)

The base-case building model has two hot water gas boilers, which both have a capacity of 473 kBtu/hr. ASHRAE Standard 90.1-1999 (Table 6.2.1F, p.31) requires minimum boiler thermal efficiency of 75%. The building's heating system efficiency was improved by increasing the natural gas boiler efficiency to 95% (condensing boiler) from 75% (conventional boiler), which was set for the base-case simulation.

Figure 7.4.24 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with a boiler efficiency of 75% and the building with improved boiler thermal efficiency of 95%. This measure:

- Reduced the space heating energy consumption to 510 MMBtu/yr from 641 MMBtu/yr, which is 20.4% lower than the base case.

- Maintained the same space cooling energy consumption as the base-case building's consumption, which was 1,258 MMBtu/yr.
- Reduced the total energy consumption to 7,187 MMBtu/yr from 7,318 MMBtu/yr, which is 1.8% lower than the base case. This energy consumption reduction was only from the space heating energy decrease as this measure is only related to the hot water boilers for space heating.



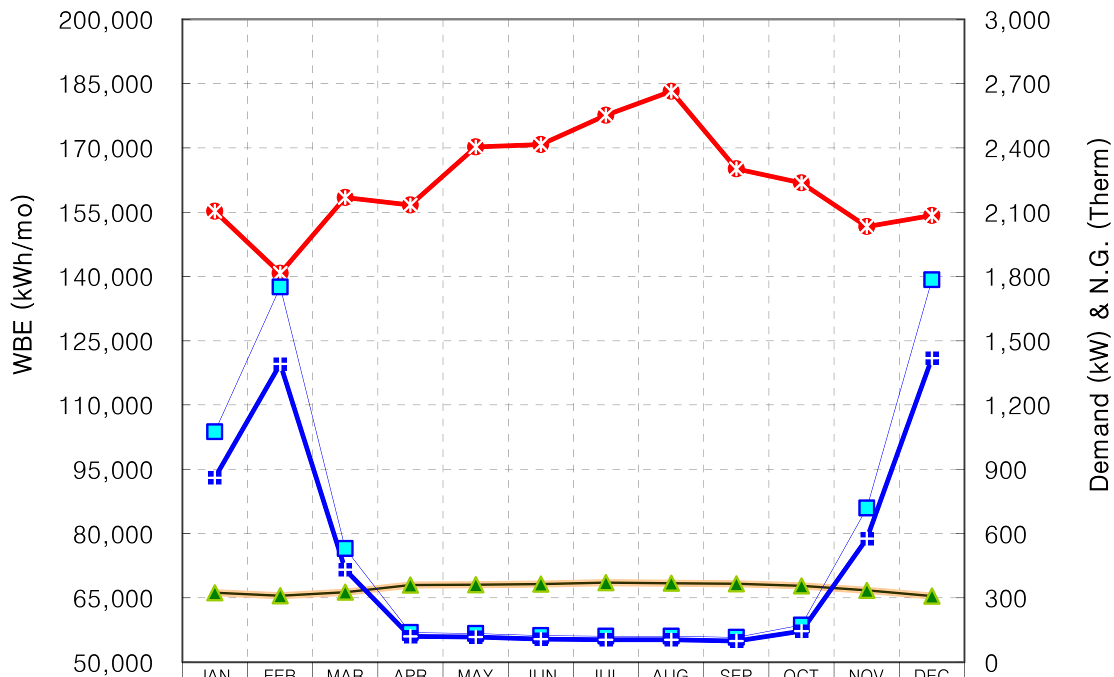
	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Et (75%)	2,506	1,907	641	1,258	427	215	308	57	7,318
Et (95%)	2,506	1,907	510	1,258	427	215	308	57	7,187

Figure 7.4.24 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with a Boiler Thermal Efficiency of 75% and the Simulation with a Higher Boiler Efficiency of 95%.

Figure 7.4.25 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with a boiler thermal efficiency of 75% and the simulation with a higher boiler thermal efficiency of 95%.

This measure:

- Did not change the building's electric peak demand.
- Reduced the building's natural gas use to 5,479 therms/yr from 6,789 therms/yr, which is 19.3% lower than the base case.
- Did not change the building's total electricity use of 1,945,395 kWh/yr.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (75%)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (95%)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
DMD (75%)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (95%)	324	309	327	360	361	364	372	369	366	355	335	309
N.G. (75%)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (95%)	860	1393	432	121	117	108	105	105	100	146	577	1418

Figure 7.4.25 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with a Boiler Thermal Efficiency of 75% and the Simulation Results with the Higher Boiler Efficiency of 95%.

7.4.11 High-performance Measure 11: Efficient Service Water Heater (from 80% Thermal Efficiency to 85% Thermal Efficiency)

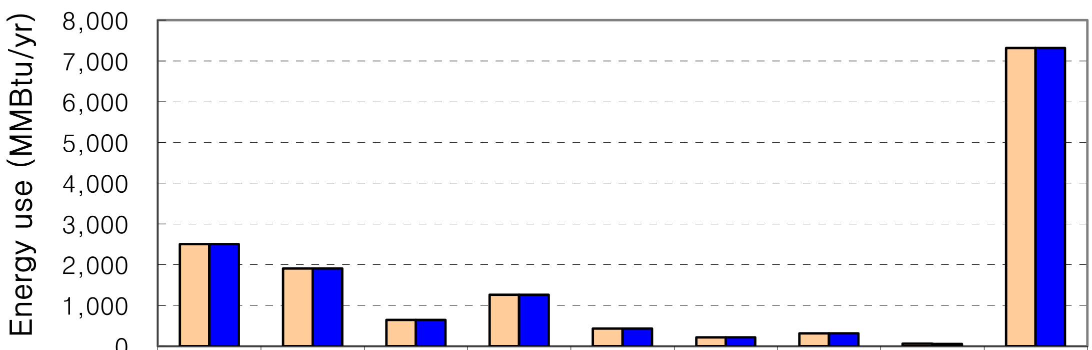
As per the ASHRAE Standard 90.1-1999 Standard, the minimum thermal efficiency requirement for the service water heater is 80%. This minimum efficiency was improved to a thermal efficiency of 85%. The impact of this measure to the total energy consumption was relatively small since the service water heating energy is small compared to the base-case building's electric use, space heating energy, or space cooling energy.

Figure 7.4.26 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with the thermal efficiency of the service water heater of 80% and the building with the efficiency of 85%.

This measure:

- Reduced only the service water heating energy to 53 MMBtu/yr from 57 MMBtu/yr, which is 7.0% lower than the base case.
- Reduced the total energy consumption to 7,315 MMBtu/yr from 7,318 MMBtu/yr, which is less than 0.1% lower than the base case.

Figure 7.4.27 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with a heater thermal efficiency of 80% and the simulation with the higher thermal efficiency of 85%.

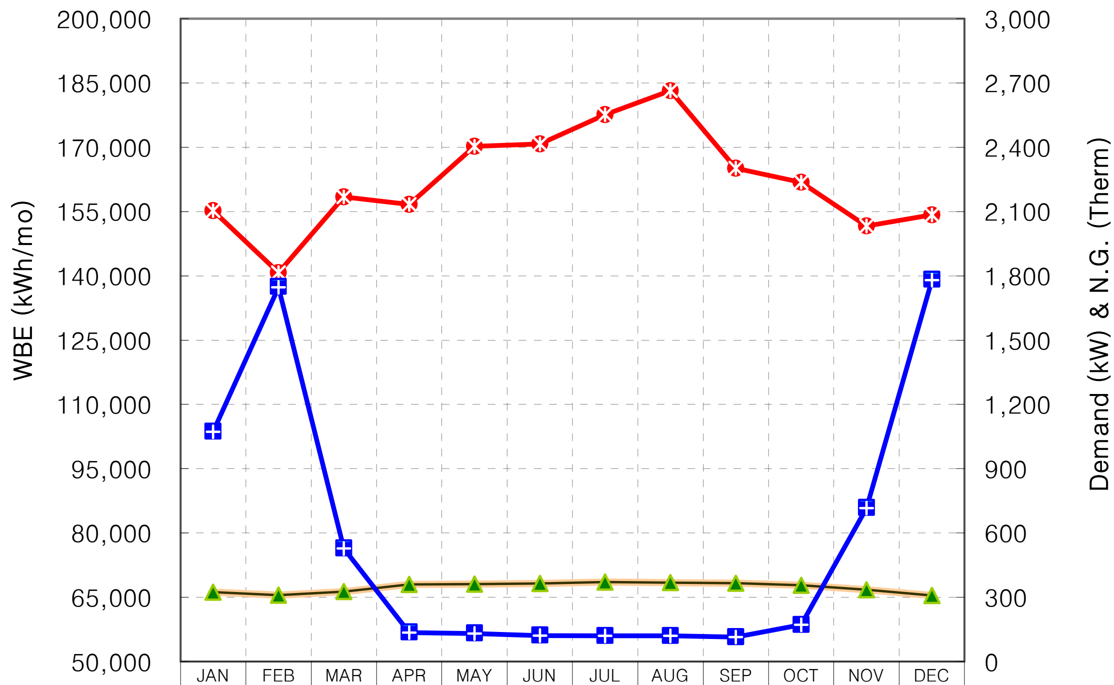


	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Et (80%)	2,506	1,907	641	1,258	427	215	308	57	7,318
Et (85%)	2,506	1,907	641	1,258	427	215	308	53	7,315

Figure 7.4.26 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with a Natural Gas Heater Thermal Efficiency of 80% and the Simulation with the Improved Heater Thermal Efficiency of 85%.

This measure:

- Did not change the building's electric peak demand.
- Reduced the building's natural gas use to 6,756 therms/yr from 6,789 therms/yr, which is 0.5% lower than the base case. This measure affected only the natural gas consumption as it is only related on the service water heating for the building.
- Did not change the building's total electricity use of 1,945,395 kWh/yr from the base case.



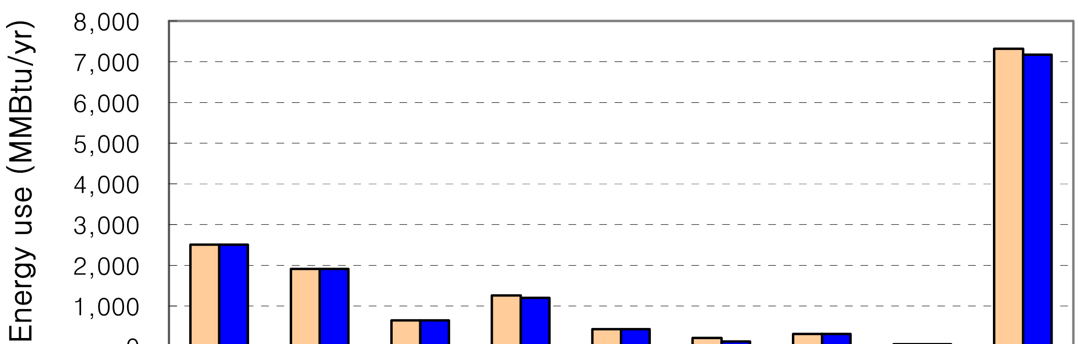
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (80%)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (85%)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
DMD (80%)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (85%)	324	309	327	360	361	364	372	369	366	355	335	309
N.G. (80%)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (85%)	1072	1747	528	136	131	122	120	119	114	171	716	1781

Figure 7.4.27 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with a Heater Thermal Efficiency of 80% and the Simulation Results with the Heater Thermal Efficiency of 85%.

7.4.12 High-performance Measure 12: Chilled Water Pump Control (from Constant Speed to Variable-speed)

The base-case building model has a chilled water pump with a constant speed control. To improve the performance of the cooling system, the constant speed chilled water pump was replaced with a variable-speed chilled water pump. Figure 7.4.28 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with a constant speed chilled water pump and the building with a variable-speed chilled water pump. This measure:

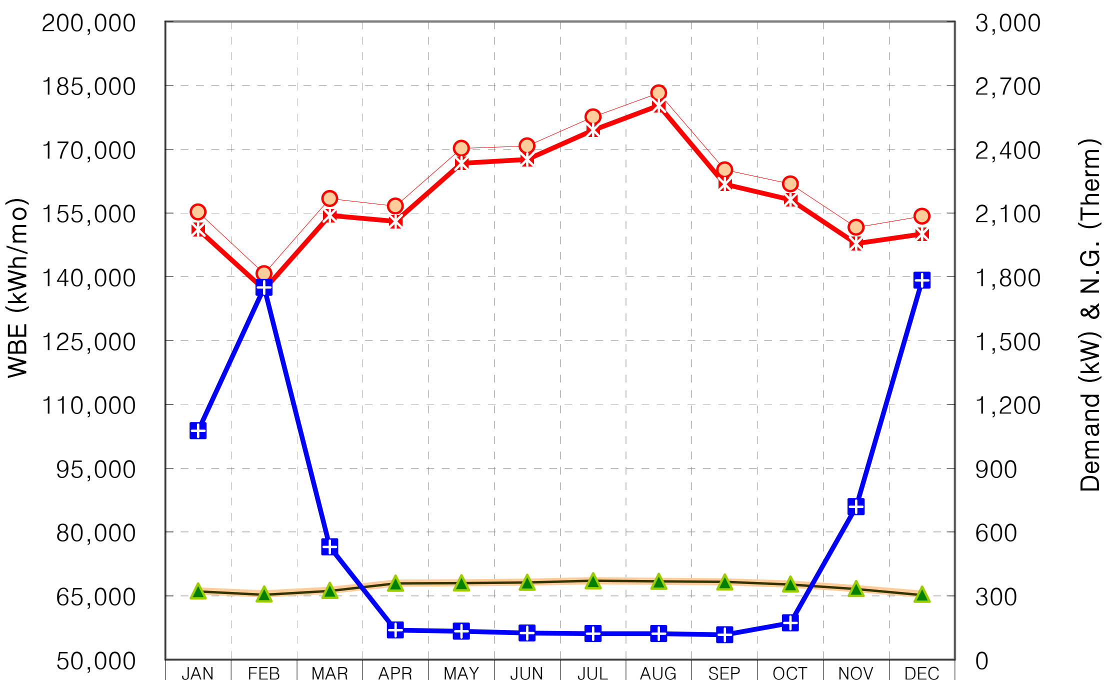
- Did not change the space heating energy consumption of 641 MMBtu/yr.
- Reduced the space cooling energy consumption to 1,197 MMBtu/yr from 1,258 MMBtu/yr, which is 4.8% lower than the base case.
- Reduced the pump energy use to 129 MMBtu/yr from 215 MMBtu/yr, which is 40% lower than the base case.
- Reduced the total energy consumption to 7,172 MMBtu/yr from 7,318 MMBtu/yr, which is 2.0% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Const. Speed	2,506	1,907	641	1,258	427	215	308	57	7,318
Variable Speed	2,506	1,907	641	1,197	427	129	308	57	7,172

Figure 7.4.28 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with a Constant Speed Chilled Water Pump and the Simulation with a Variable Speed Chilled Water Pump.

Figure 7.4.29 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with a constant speed chilled water pump and the simulation with a variable-speed chilled water pump.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (Cons)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (Vari)	151155	137007	154453	153012	166660	167612	174471	180255	161759	158088	147798	150055
DMD (Cons)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (Vari)	320	305	324	359	360	363	371	368	365	354	332	305
N.G. (Cons)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (Vari)	1076	1750	531	139	134	125	122	122	116	174	718	1783

Figure 7.4.29 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with a Constant Speed Chilled Water Pump and the Simulation Results with a Variable Speed Chilled Water Pump.

This measure:

- Slightly reduced the electric peak demand to 371 kWh from 372 kWh in July, which is 0.3% lower than the base case.
- Did not change the building's natural gas use 6,789 therms/yr.
- Reduced the building's total electricity use to 1,902,324 kWh/yr from 1,945,395 kWh/yr, which is 2.2% lower than the base case.

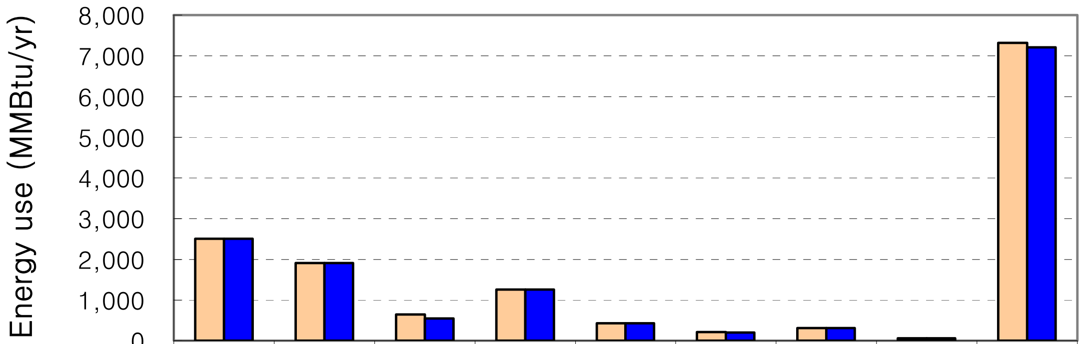
7.4.13 High-performance Measure 13: Hot Water Pump Control (from Constant Speed to Variable-speed)

The base-case building model also has a hot water pump with a constant speed control. To improve the performance of the heating system, the constant speed hot water pump was replaced with a variable-speed hot water pump.

Figure 7.4.30 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with a constant speed hot water pump and the building with a variable-speed hot water pump. This measure:

- Reduced the space heating energy consumption to 546 MMBtu/yr from 641 MMBtu/yr, which is 14.8% lower than the base case.
- Did not change the space cooling energy consumption of 1,258 MMBtu/yr.
- Reduced the pump energy use to 200 MMBtu/yr from 215 MMBtu/yr, which is 7% less than the base case.

- Reduced the total energy consumption to 7,208 MMBtu/yr from 7,318 MMBtu/yr, which is 1.5% lower than the base case.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
Const. Speed	2,506	1,907	641	1,258	427	215	308	57	7,318
Variable Speed	2,506	1,907	546	1,258	427	200	308	57	7,208

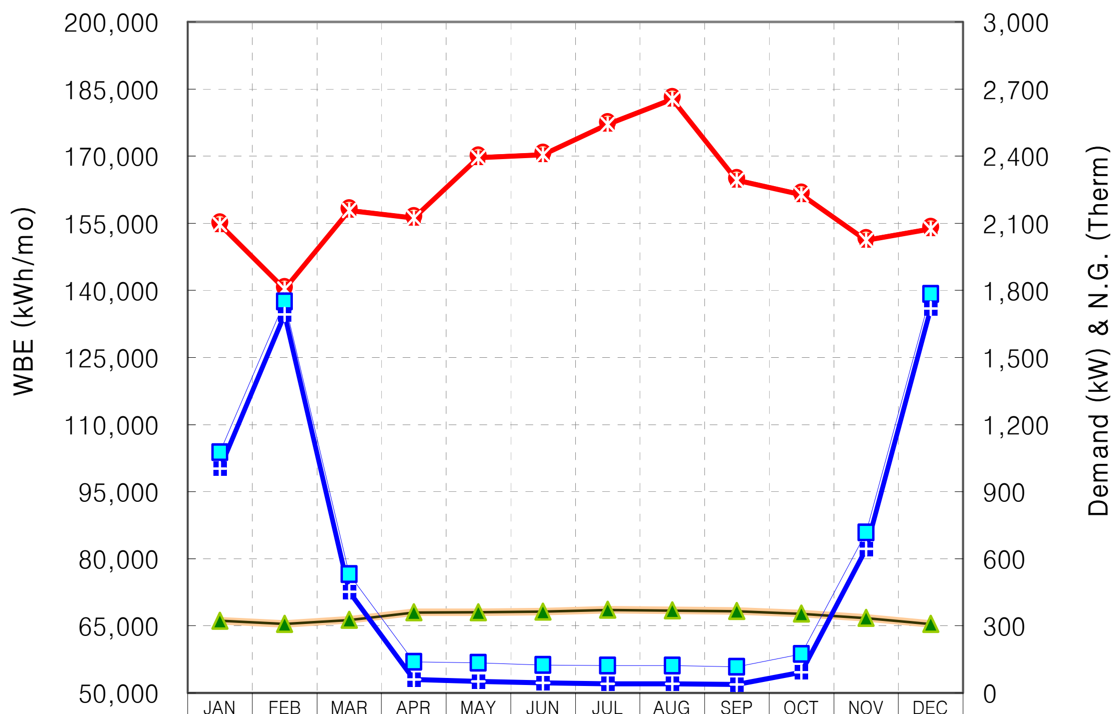
Figure 7.4.30 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with a Constant Speed Hot Water Pump and the Simulation with a Variable Speed Pump.

Figure 7.4.31 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with a constant speed hot water pump and the simulation with a variable-speed hot water pump.

This measure:

- Slightly reduced the electric peak demand to 371 kWh from 372 kWh in July, which is 0.3% lower than the base case.

- Reduced the building's natural gas use to 5,880 therms/yr from 6,789 therms/yr, which is 13.4% lower than the base case.
- Reduced the building's total electricity use to 1,939,661 kWh/yr from 1,945,395 kWh/yr, which is 0.3% lower than the base case.

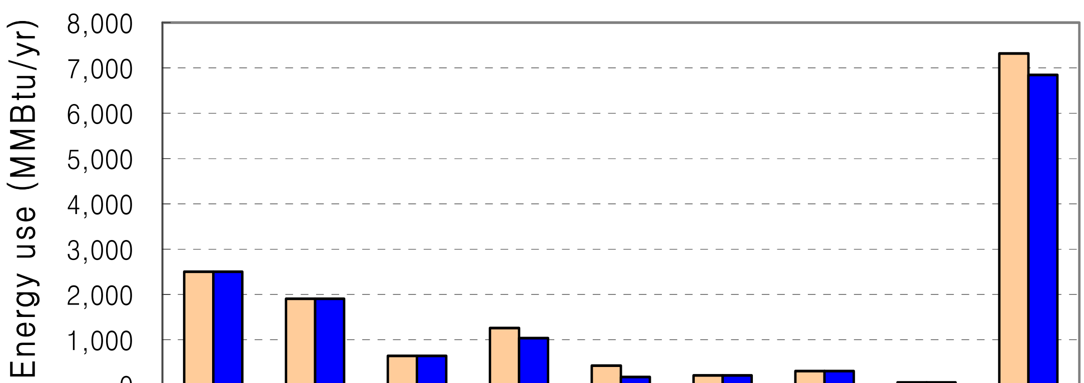


	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (Cons)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (Vari)	154697	140324	157876	156147	169675	170269	177083	182695	164603	161348	151187	153756
DMD (Cons)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (Vari)	323	309	326	360	360	363	371	368	366	355	334	308
N.G. (Cons)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (Vari)	1003	1692	453	60	53	46	40	40	37	92	645	1719

Figure 7.4.31 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with a Constant Speed Hot Water Pump and the Simulation Results with a Variable Speed Hot Water Pump.

7.4.14 High-performance Measure 14: Chiller Staging (from One Chiller to Three Small Identical Chillers)

For most chillers, the chiller efficiency increases as the load ratio increases from 40% to 80%. However, when the load ratio is lower than 40% of the maximum load, the chiller efficiency reduces. Running chillers in the efficient load ranges can reduce the electric energy use for chillers. To optimize the chiller performance, chiller staging is an option, using more than one chiller rather than using only one large chiller. The 280 ton chiller used in the base-case model simulation was replaced with three small chillers having 93.3 tons each.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	HOT WATER	TOTAL
One Chiller	2,506	1,907	641	1,258	427	215	308	57	7,318
Three Chillers	2,506	1,907	641	1,037	177	215	308	57	6,847

Figure 7.4.32 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation with One 280 Ton Chiller and the Simulation with Three Small Chillers.

Figure 7.4.32 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building with one 280 chiller and a building with three small chillers identically sized having the same total capacity with one 280 ton chiller. This measure:

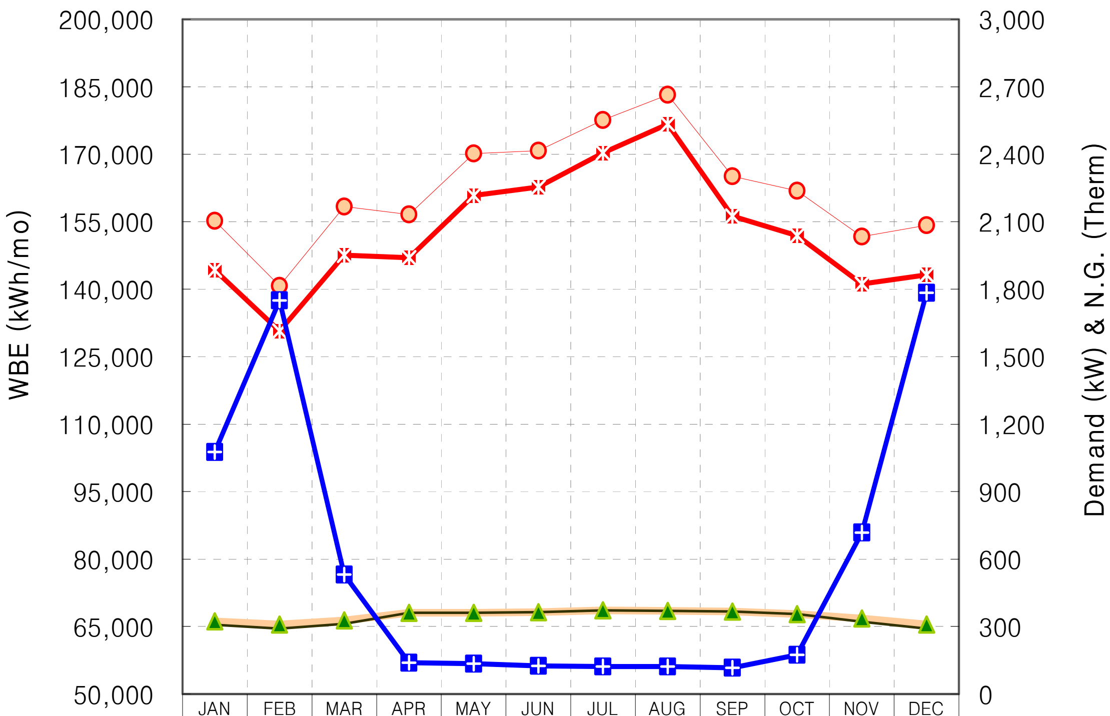
- Did not change the space heating energy consumption of 641 MMBtu/yr as this measure is only related to the chiller operation.
- Reduced the space cooling energy consumption to 1,037 MMBtu/yr from 1,258 MMBtu/yr, which is 17.6% lower than the base case.
- Reduced the heat rejection energy use to 177 MMBtu/yr from 427 MMBtu/yr, which is 58.5% less than the base case.
- Reduced the total energy consumption to 6,847 MMBtu/yr from 7,318 MMBtu/yr, which is 6.4% lower than the base case.

Figure 7.4.33 compares energy consumption results of the monthly whole building electricity, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation with one 280 ton chiller and the simulation with three small chillers.

This measure:

- Did not make any changes to the electric peak demand in July; however, there were several months that showed changes on the electric demand such as in

December where the electric demand was reduced to 290 kW from 309 kW, which is 6.1% lower than the base case.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE (1 Chlr)	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE (2 Chlr)	144223	130683	147534	146959	160815	162697	170284	176675	156259	151893	141121	143215
DMD (1 Chlr)	324	309	327	360	361	364	372	369	366	355	335	309
DMD (2 Chlr)	308	291	312	360	361	364	372	369	366	355	322	290
N.G. (1 Chlr)	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G. (2 Chlr)	1076	1750	531	139	134	125	122	122	116	174	718	1783

Figure 7.4.33 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case Simulation Results with One 280 Ton Chiller and the Simulation Results with Three Small Chillers.

- Did not change the building's natural gas use of 6,789 therms/yr.
- Reduced the building's total electricity use to 1,807,206 kWh/yr from 1,945,395 kWh/yr, which is 7.1% lower than the base case. This electric

energy savings was uniformly achieved month by month as shown in the figure.

7.5 Summary of 14 High-performance Measures

7.5.1 Individual Savings Summary of the 14 High-performance Measures

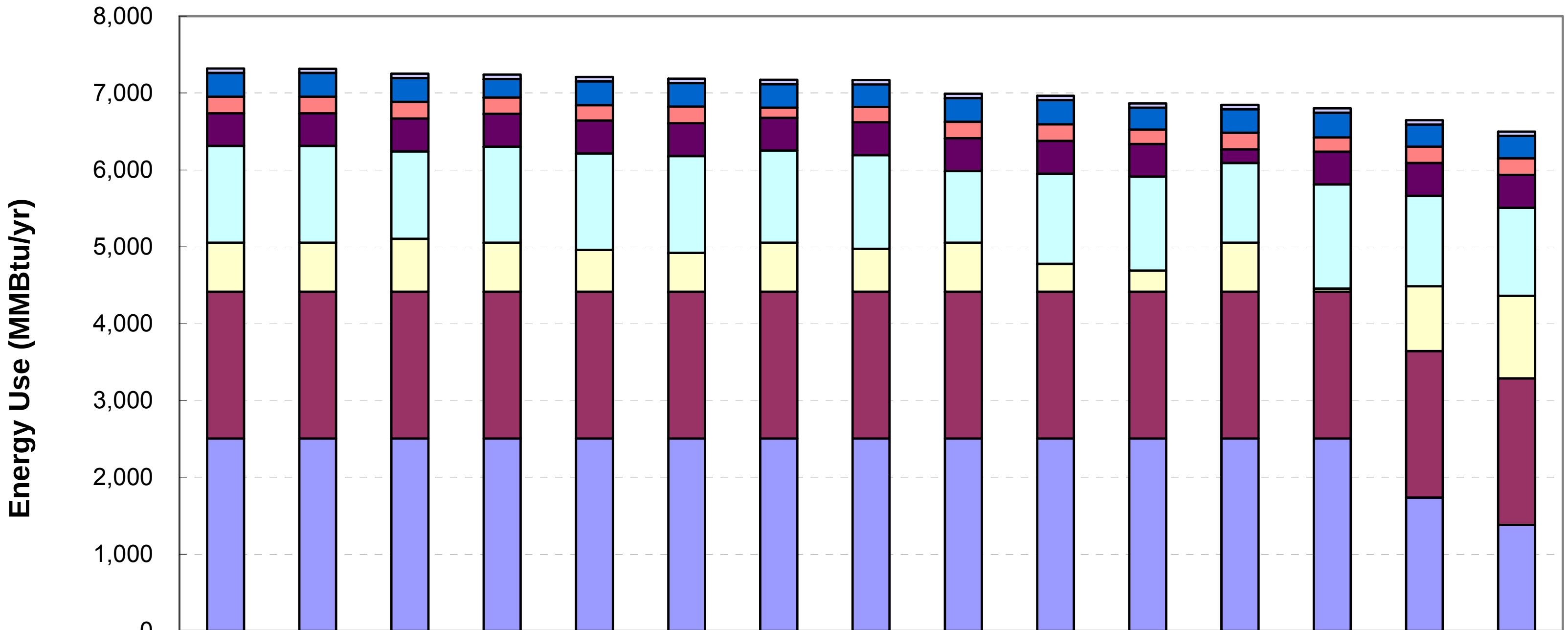
Table 7.5.1 and Figure 7.5.1 show the individual savings results of the 14 high-performance measures. The base-case building model simulation was performed using the ASHRAE Standard 90.1-1999 minimum code requirements. This base case consumed a total of 7,318 MMBtu/yr using the 2006 College Station TRY weather file.

Of the 14 high-performance measures, the implementation of occupancy sensors (high-performance measure 4) impacted the energy consumption the most, saving the total energy by 11.2 percent. In this measure, the indoor lights were shut-off when spaces are not occupied, leaving only the emergency lights on, which requires the minimum lighting power density of 5%.

This reduced the lighting energy substantially by 50%, while the space heating energy increased by 68%. As a result, the total energy reduction from the lighting was much substantial. The space cooling energy savings were also achieved by 8.8% due to lower internal heat gains.

Table 7.5.1 Individual Savings Summary of the 14 High-performance Measures.

High-performance Building DOE-2 Simulation Results (BEPS) Units: MMMBtu/yr											
No.	Energy Efficiency Measures	AREA LIGHTS	MISC EQUIP.	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	SHW	TOTAL	Total Savings (%)
	Base Case	2,506	1,907	641	1,258	427	215	308	57	7,318	-
1	Glazing U Factor (1.22 to 0.38 Btu/hr-sf-F)	2,506	1,907	44	1,353	427	186	321	57	6,800	7.1%
2	WindowToWall Ratio (50% to 35%)	2,506	1,907	279	1,219	427	188	284	57	6,865	6.2%
3	Lighting Load (1.3 to 0.9 w/sq-ft)	1,735	1,907	844	1,178	426	212	288	57	6,647	9.2%
4	Light Control (None to Occupancy Sensors)	1,379	1,907	1,077	1,147	426	216	290	57	6,497	11.2%
5	Shading (none to 2.5 ft overhangs)	2,506	1,907	560	1,219	427	203	289	57	7,167	2.1%
6	Cold Deck Reset (Constant to Variable by OA)	2,506	1,907	364	1,173	427	215	316	57	6,964	4.8%
7	Supply Fan Total Pressure (2.5 to 1.5 in-H2O)	2,506	1,907	641	1,248	427	212	242	57	7,239	1.1%
8	Economizer (None to Temp. Economizer)	2,506	1,907	691	1,139	427	216	308	57	7,250	0.9%
9	Chiller COP (5.55 to 7.5)	2,506	1,907	641	931	427	215	308	57	6,992	4.5%
10	Boiler Efficiency (75% to 95%)	2,506	1,907	510	1,258	427	215	308	57	7,187	1.8%
11	SHW Heater Thermal Efficiency (80% to 85%)	2,506	1,907	641	1,258	427	215	308	53	7,315	0.05%
12	CHW Pump Control (Constant to VSD)	2,506	1,907	641	1,197	427	129	308	57	7,172	2.0%
13	HW Pump Control (Constant to VSD)	2,506	1,907	546	1,258	427	200	308	57	7,208	1.5%
14	Chiller Staging (One to Three Chillers)	2,506	1,907	641	1,037	177	215	308	57	6,847	6.4%



	Base-Case	SHW Et (0.80 to 0.85)	Temp.-Based Economizer	Sta. Pres. (2.5 to 1.5 inH2O)	HW Pump Control (VSD)	Boiler Et (0.75 to 0.95)	CHW Pump Control (VSD)	Overhangs (2.5 ft)	Chiller COP (5.55 to 7.5)	Cold Deck Reset	WWR (0.5 to 0.35)	Chiller Staging (3 Chillers)	Glazing U-Factor (1.22 to 0.38)	LPD (1.3 to 0.9 w/sq-ft)	Light Control (Occupancy Sensors)
SERVICE HOT WATER	57	53	57	57	57	57	57	57	57	57	57	57	57	57	57
VENT FANS	308	308	308	242	308	308	308	289	308	316	284	308	321	288	290
PUMPS & MISC	215	215	216	212	200	215	129	203	215	215	188	215	186	212	216
HEAT REJECT	427	427	427	427	427	427	427	427	427	427	427	177	427	426	426
SPACE COOL	1258	1258	1139	1248	1258	1258	1197	1219	931	1173	1219	1037	1353	1178	1147
SPACE HEAT	641	641	691	641	546	510	641	560	641	364	279	641	44	844	1077
MISC EQUIP.	1907	1907	1907	1907	1907	1907	1907	1907	1907	1907	1907	1907	1907	1907	1907
AREA LIGHTS	2506	2506	2506	2506	2506	2506	2506	2506	2506	2506	2506	2506	2506	1735	1379

Figure 7.5.1 Individual Energy Consumption Changes from the Simulation of 14 High-performance Measures.

The second largest energy savings were also achieved in another lighting reduction measure (high-performance measure 3). In this measure, the lighting power density changed to 0.9 W/sq-ft from 1.3 W/sq-ft, which achieved a total energy savings of 9.2%. This measure also increased the space heating energy by 31.7%.

The third largest energy savings were achieved by changing the glazing U-factor to 0.38 Btu/hr-sqft-F from 1.22 Btu/hr-sqft-F, where the total energy savings were 7.1%. In this measure, the space heating energy saving was the most substantial of 14 measures. After the U-factor measure was implemented, the space heating energy reduced to 44 MMBtu/yr from the base-case model's space heating energy use 641 MMBtu/yr, which is 93% consumption reduction. In terms of space cooling energy savings, the change of chiller COP to 7.5 from 5.55 was the most impact of 14 measures, saving the space cooling energy by 26%.

Figure 7.5.2 shows the total individual energy savings of the 14 measures, in which the most energy saving measure was placed the first (left side) and the least energy savings measure the last (right side) of the figure. The least energy savings were occurred with the service water heater thermal efficiency change from 80% to 85%. Although the hot water saving achieved from the measure was about 6%, the energy reduction was only 3.3 Mbtu/yr, which was relatively too small compared to the total energy use of 7,318 MMBtu/yr for the building.

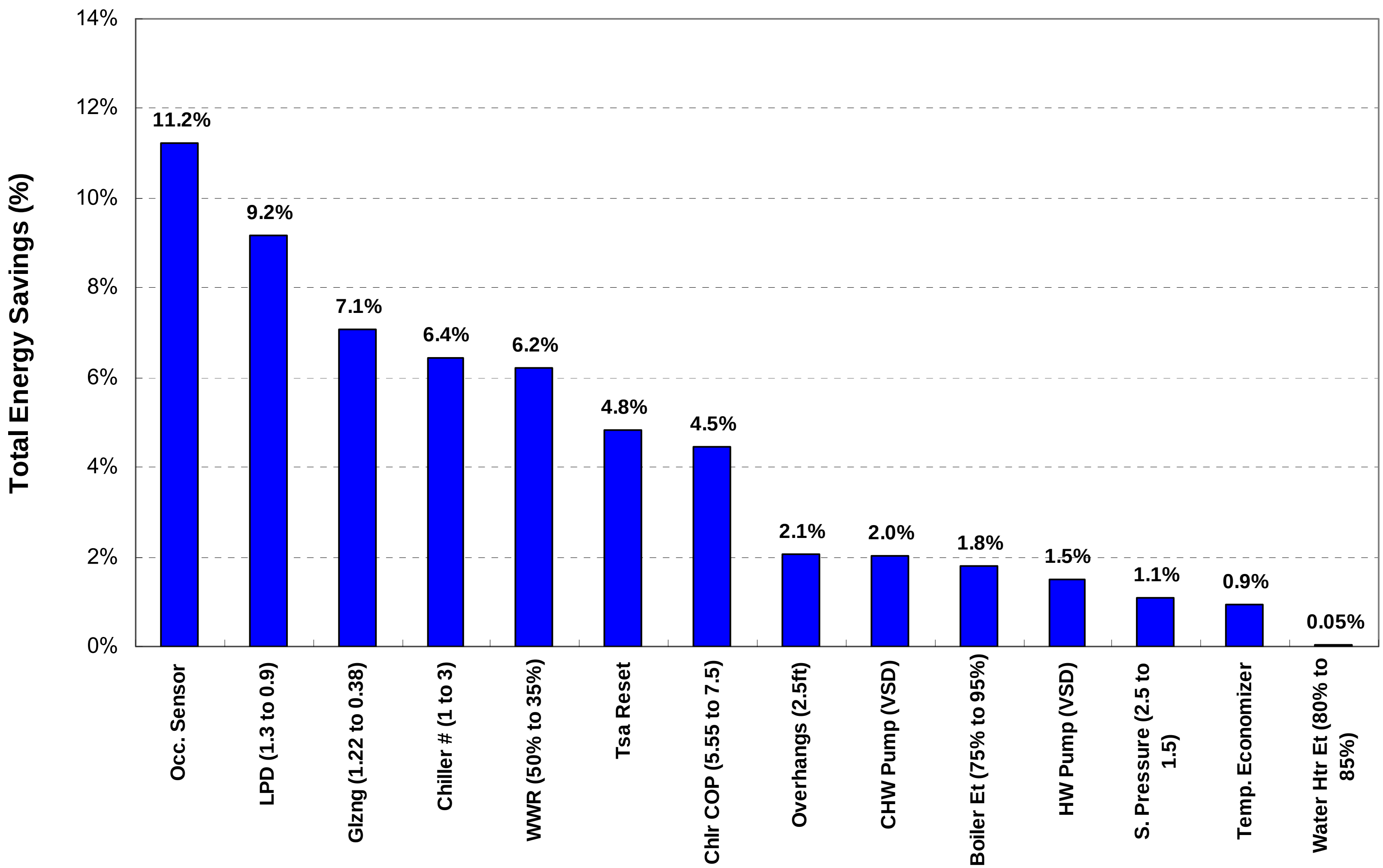


Figure 7.5.2 Energy Savings from the 14 Individual Measures.

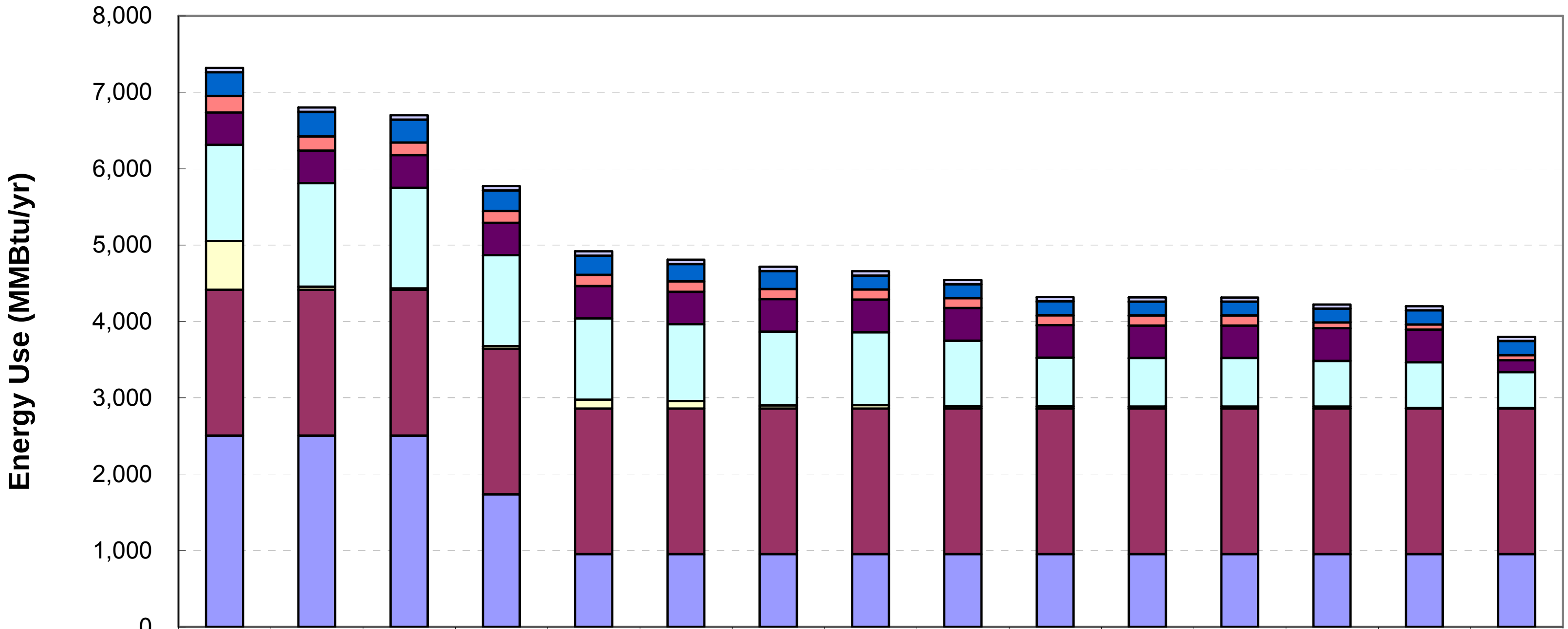
7.5.2 Cumulative Savings of 14 High-performance Measures

When the individual 14 high-performance measures are added together, the total savings amount to 64.8%. However, the cumulative savings of 64.8% may or may not be the case when the 14 measures are applied all together at the same time since each individual measures affect one another when combined. The combined 14 measures could achieve more or less total energy savings. To analyze the combined effect, 14 cumulative simulations were performed by adding measures 1+2, 1+2+3, 1+2+3+4, …, etc.

Table 7.5.2 and Figure 7.5.3 show the summary of the cumulative savings of the 14 high-performance measures. The first high-performance measure, or glazing U-factor, achieved energy savings of 7.1%, and the second measure, or window to wall ratio, achieved 6.2% when it was applied as a single measure. However, the energy savings from these two combined measures was only 8.5% as shown in Table 7.5.2, which is 4.8% less than 13.3% that is from the simple addition of 7.1% and 6.2%. This change was due to the reduction of the window area by the second measure, or window-to-wall ratio change from 50% to 35%. Hence, the glazing U-factor impact reduced as the window-to-wall ratio was reduced. This is an example of the change in the impact when the individual measures are combined together. After combining the 14 high-performance measures, the cumulative energy savings was 48.1%.

Table 7.5.2 Cumulative Energy Savings of the 14 High-performance Measures.

High-performance Building DOE-2 Simulation Results (BEPS) Units: MMMBtu/yr											
No.	Energy Efficiency Measures	AREA LIGHTS	MISC EQUIP.	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	SHW	TOTAL	Total Savings (%)
	Base Case	2,506	1,907	641	1,258	427	215	308	57	7,318	-
1	Glazing U Factor (1.22 to 0.38 Btu/hr-sf-F)	2,506	1,907	44	1,353	427	186	321	57	6,800	7.1%
2	Window-to-wall Ratio (50% to 35%)	2,506	1,907	19	1,318	427	165	301	57	6,700	8.5%
3	Lighting Load (1.3 to 0.9 w/sq-ft)	1,735	1,907	37	1,189	426	155	268	57	5,772	21.1%
4	Light Control (None to Occupancy Sensors)	955	1,907	115	1,063	425	148	247	57	4,917	32.8%
5	Shading (none to 2.5 ft overhangs)	955	1,907	97	1,006	425	136	226	57	4,807	34.3%
6	Cold Deck Reset (Constant to Variable by OA)	955	1,907	42	964	425	134	234	57	4,716	35.6%
7	Supply Fan Total Pressure (2.5 to 1.5 in-H2O)	955	1,907	43	956	425	133	184	57	4,657	36.4%
8	Economizer (None to Temp. Economizer)	955	1,907	30	859	425	130	182	57	4,544	37.9%
9	Chiller COP (5.55 to 7.5)	955	1,907	30	636	425	130	182	57	4,321	41.0%
10	Boiler Efficiency (75% to 95%)	955	1,907	24	636	425	130	182	57	4,315	41.0%
11	SHW Heater Thermal Efficiency (80% to 85%)	955	1,907	24	636	425	130	182	53	4,312	41.1%
12	CHW Pump Control (Constant to VSD)	955	1,907	24	600	425	75	182	53	4,221	42.3%
13	HW Pump Control (Constant to VSD)	955	1,907	5	600	425	71	182	53	4,198	42.6%
14	Chiller Staging (One to Three Chillers)	955	1,907	5	470	154	71	182	53	3,797	48.1%



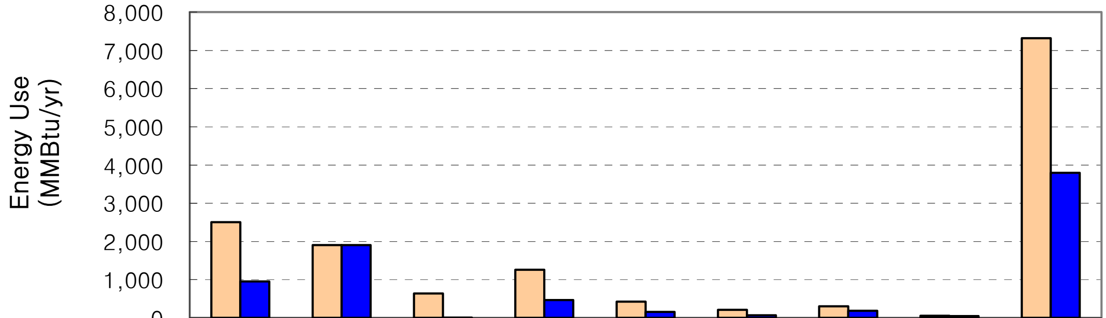
	Base-Case	Glazing U-Factor (1.22 to 0.38)	WWR (0.5 to 0.35)	LPD (1.3 to 0.9 w/sq-ft)	Light Control (Occupancy Sensors)	Overhangs (2.5 ft)	Cold Deck Reset	Sta. Pres. (2.5 to 1.5 inH2O)	Temp.-Based Economizer	Chiller COP (5.55 to 7.5)	Boiler Et (0.75 to 0.95)	SHW Et (0.80 to 0.85)	CHW Pump Control (VSD)	HW Pump Control (VSD)	Chiller Staging (3 Chillers)
SERVICE HOT WATER	57	57	57	57	57	57	57	57	57	57	57	53	53	53	53
VENT FANS	308	321	301	268	247	226	234	184	182	182	182	182	182	182	182
PUMPS & MISC	215	186	165	155	148	136	134	133	130	130	130	130	75	71	71
HEAT REJECT	427	427	427	426	425	425	425	425	425	425	425	425	425	425	154
SPACE COOL	1,258	1,353	1,318	1,189	1,063	1,006	964	956	859	636	636	636	600	600	470
SPACE HEAT	641	44	19	37	115	97	42	43	30	30	24	24	24	5	5
MISC EQUIPMT	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907
AREA LIGHTS	2,506	2,506	2,506	1,735	955	955	955	955	955	955	955	955	955	955	955

Figure 7.5.3 Cumulative Energy Use Reductions from the 14 High-performance Measures.

Figure 7.5.4 shows the simulation results and compares between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building and the high-performance building including the 14 high-performance measures. This 14 combined measure:

- Reduced the lighting energy use to 955 MMBtu/yr from 2506 MMBtu/yr, which is 61.9% lower than the base case.
- Did not change the equipment electric energy at all. There was no measure that affected the equipment energy use.
- Reduced the space heating energy consumption to 5 MMBtu/yr from 641 MMBtu/yr, which is 99.2% lower than the base case. As shown in Table 7.5.1, the main space heating energy reduction was occurred when the window U-factor changed to 0.38 Btu/sqft-hr-F from 1.22 Btu/sqft-hr-F and the window-to-wall ratio changed to 35% from 50%.
- Reduced the space cooling energy consumption to 470 MMBtu/yr from 1,258 MMBtu/yr, which is 62.6% lower than the base case. The main impact of reducing the cooling energy was by improving the chiller COP to 7.5 from 5.55 as shown in Table 7.5.1.
- Reduced the heat rejection energy to 154 MMBtu/yr from 427 MMBtu/yr, which is 63.9% lower than the base case. For this energy reduction, the chiller staging measure was the main reason where the one large chiller was divided into three smaller chillers.
- Reduced the pumps and miscellaneous equipment energy to 71 MMBtu/yr from 215 MMBtu/yr, which is 67.0%. This energy use was directly reduced

by implementing the chilled water pumps control from constant speed to variable speed.



	AREA LIGHTS	MISC EQUIP	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	SERVICE HOT WATER	TOTAL
Base Case	2,506	1,907	641	1,258	427	215	308	57	7,318
High-Performance	955	1,907	5	470	154	71	182	53	3,797

Figure 7.5.4 Energy Consumption Comparison Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building Simulation and the Simulation with the 14 High-performance Measures.

- Reduced the fan energy to 182 MMBtu/yr from 308 MMBtu/yr, which is 40.9% lower than the base case. The most fan energy reduction was occurred when the supply fan static pressure was changed to 1.5 in-H2O from 2.5 in-H2O.
- Reduced the service hot water energy to 53 MMBtu/yr from 57 MMBtu/yr, which is 7.0% lower energy than the base case. This energy consumption reduction was occurred only when the service hot water heater's thermal efficiency changed to 85% from 80%.

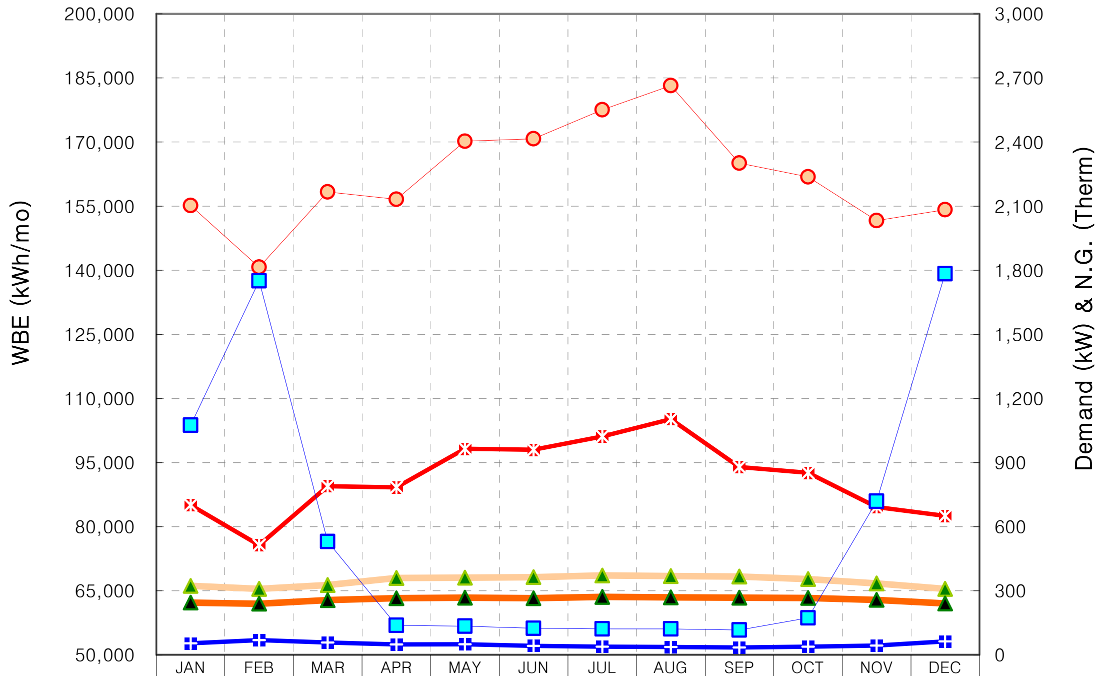
- Reduced the total energy consumption to 3,797 MMBtu/yr from 7,318 MMBtu/yr, which is 48.1% lower than the base case.

Figure 7.5.5 compares energy consumption results of the monthly WBE, demand, and N.G. between the base-case (ASHRAE Standard 90.1-1999 code-compliant) building simulation and the simulation with the 14 high-performance measures combined. This 14 combined measure:

- Reduced the electric peak demand to 271 kWh from 372 kWh in July, which is 27.1% lower than the base case.
- Reduced the building's natural gas use to 578 therms/yr from 6,789 therms/yr, which is 91.5% lower than the base case.
- Increased the building's total electricity consumption to 1,095,539 kWh/yr from 1,945,395 kWh/yr, which is 43.7% higher than the base case.

After all the 14 high-performance measures were combined together, the simulation results showed the total combined savings of 48.1%, as shown in Figure 7.5.6. The combined total savings of 48.1% is above the ASHRAE Standard 90.1-1999 building energy code, which is substantial.

Figure 7.5.7 shows how much energy the case-study building could save energy by complying the ASHRAE Standard 90.1-1999 code and implementing the 14 high-performance measures. The case-study building consumed energy of a total of 9,692



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
WBE_Code	155170	140721	158366	156633	170178	170755	177586	183198	165090	161849	151652	154198
WBE_High Perf	85018	75674	89461	89202	98271	98019	101124	105144	93931	92579	84589	82526
DMD_Code	324	309	327	360	361	364	372	369	366	355	335	309
DMD_High Perf	245	239	256	265	268	266	271	269	268	267	258	240
N.G._Code	1076	1750	531	139	134	125	122	122	116	174	718	1783
N.G._High Perf	53	70	57	49	50	43	38	38	35	38	44	63

Figure 7.5.5 Comparison of the Monthly WBE, Demand, and N.G. Use Between the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Simulation Results and the Simulation Results with the 14 High-performance Measures.

MMBtu/yr. This energy consumption reduced to 7,318 MMBtu/yr after applying the ASHRAE Standard 90.1-1999 code requirements, which was about 25% less energy consumption compared to the base case. This energy consumption was further reduced down to 3,797 MMBtu/yr by implementing the 14 high-performance measures, which was about 48% less energy consumption than the code-compliant model. When the energy consumption of the high-performance model was compared to that of the as-built model, the energy savings were about 61%.

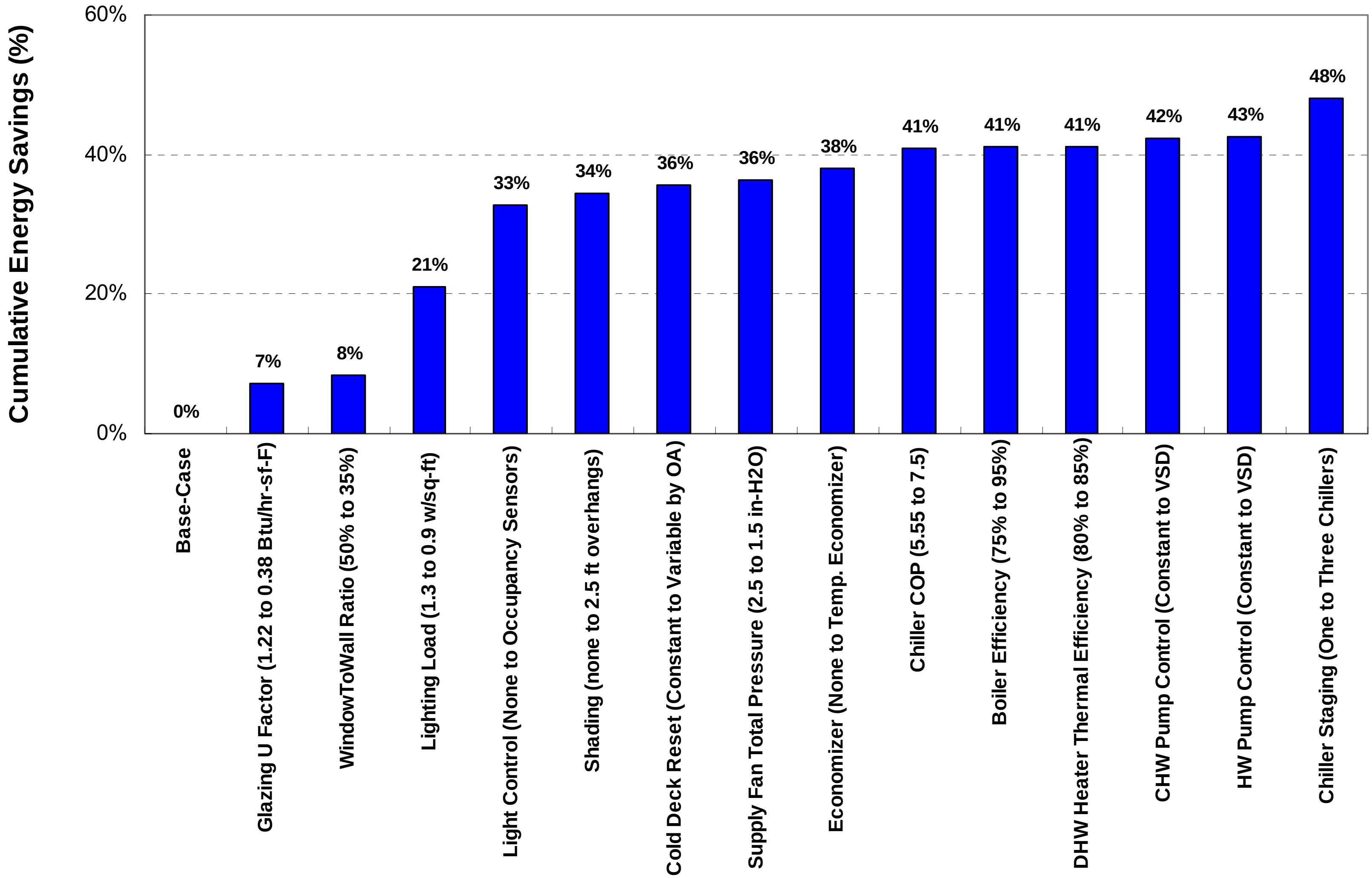
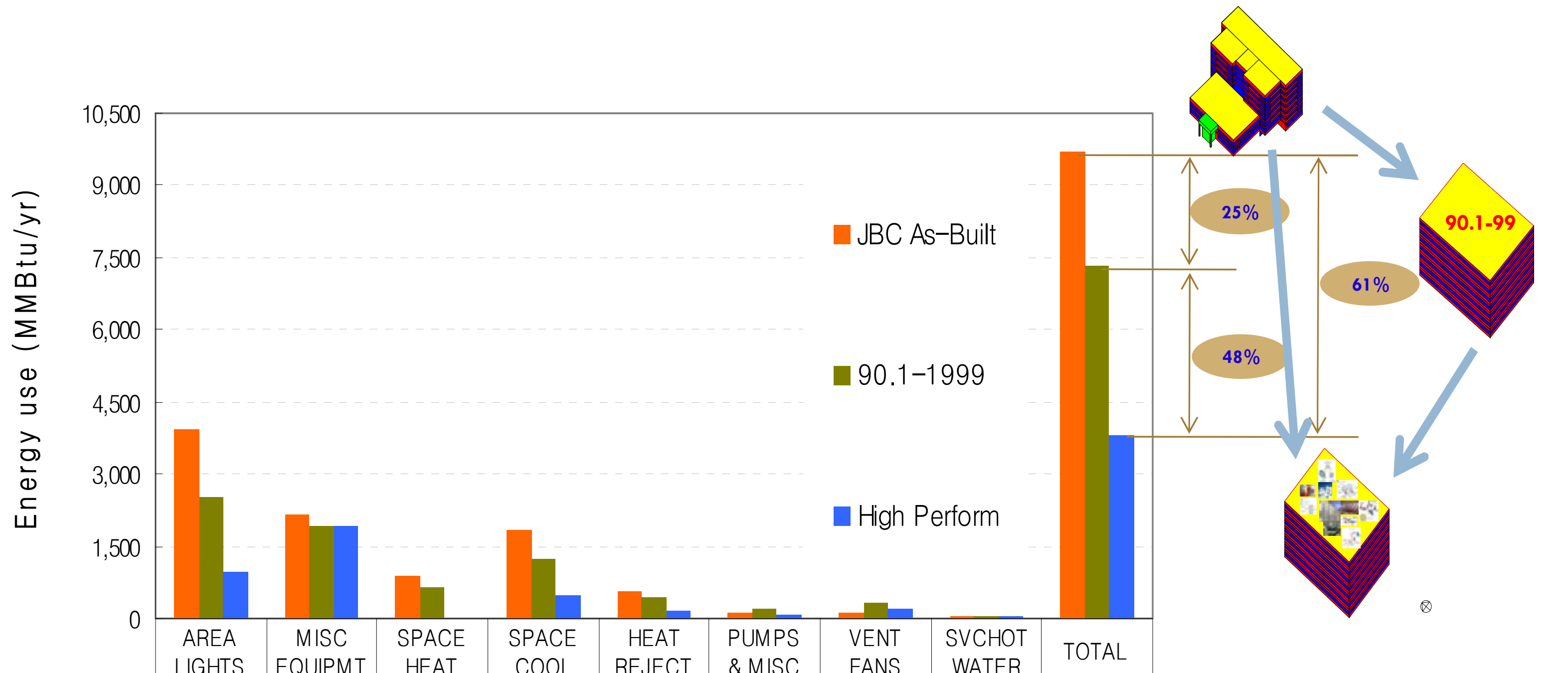


Figure 7.5.6 Cumulative Energy Savings as from the 14 High-performance Measures.



	AREA LIGHTS	MISC EQUIPMT	SPACE HEAT	SPACE COOL	HEAT REJECT	PUMPS & MISC	VENT FANS	SVCHOT WATER	TOTAL
JBC As-Built	3,914	2,180	865	1,837	562	138	140	57	9,692
90.1-1999	2,506	1,907	641	1,258	427	215	308	57	7,318
High Perform	955	1,907	5	470	154	71	182	53	3,797

Figure 7.5.7 Comparison of Energy Uses Between the Base-case (As-built JBC) Building, the ASHRAE Standard 90.1-1999 Code-compliant Model, and the High-performance Model that Includes the 14 High-performance Measures.

CHAPTER VIII

SOLAR THERMAL AND PHOTOVOLTAIC SYSTEMS APPLICATION

In the previous chapter, a total of 14 high-performance measures were described and simulated. The maximum cumulative savings from the 14 measures were 48.1% compared to the ASHRAE Standard 90.1-1999 code-compliant building, which was achieved by selecting more efficient equipment or improving operations. In this chapter, renewable energy sources were analyzed to achieve further energy consumption reductions. To accomplish this, the F-Chart program was used for the solar thermal system analysis and the PV F-Chart program for the solar photovoltaic (PV) system analysis.

8.1 Application of Solar Thermal System

A large portion of a building's service hot water and/or space heating hot water can be provided by solar thermal systems. To determine the thermal loads, two simulation results are available from the DOE-2.1e simulation, one for the service hot water energy use and the other for space heating energy use.

In the DOE-2.1e simulation, SYSTEMS outputs (DOE-2.1e Report SS-A & SS-P) yield the space heating energy and service water heating energy provided by the boilers and water heaters in plant, while PLANT output (DOE-2.1e Report PS-E) includes the fuel energy for the boilers and water heaters that include their fuel efficiencies. Therefore, the PLANT outputs typically show more energy use than the SYSTEMS reports due to the equipment fuel conversion efficiencies.

Table 8.1.1 Comparison of Loads and Energy Uses for Space Heating and Service Hot Water for the Base-case (ASHRAE Standard 90.1-1999 Code-compliant) Building.

Month	Tdb	SYSTEMS Report (kBtu/mo)		PLANT Report (kBtu/mo)	
		Heating (SS-A)	SHW (SS-P)	Heating (PS-E)	SHW (PS-E)
JAN	57.4	64,127	3,988	102,147	5,398
FEB	53.0	113,311	3,816	169,833	5,166
MAR	64.6	26,253	4,361	47,188	5,903
APR	72.5	473	3,820	8,717	5,171
MAY	76.4	0	3,884	8,160	5,258
JUN	81.5	0	3,363	7,897	4,552
JUL	82.6	0	2,978	8,160	4,031
AUG	84.8	0	2,966	8,160	4,016
SEP	78.7	0	2,756	7,897	3,731
OCT	70.2	3,196	3,004	13,290	4,067
NOV	60.5	40,248	3,300	67,362	4,468
DEC	53.9	114,972	3,566	173,514	4,828
Total		362,580	41,800	622,325	56,589

Table 8.1.1 compares the monthly thermal loads reports from the DOE-2.1e simulation for both SYSTEMS and PLANT. In this table, the Tdb is the monthly average dry bulb temperature from the College Station 2006 TRY weather data. Monthly space heating loads and service water heating loads are shown in both cases from the SYSTEMS simulation and from the PLANT simulation. The SYSTEMS monthly loads were

retrieved from the SYSTEMS reports, SS-A for space heating loads and SS-P for service water heating loads. The PLANT simulation's monthly loads were retrieved from the PLANT reports, PS-E. As shown, the PLANT reports show higher energy uses than the SYSTEMS reports do.

Due to the fact that the solar thermal systems analysis program, F-Chart, takes into account the system efficiencies in its loads calculation of the building, it is therefore necessary to use the SYSTEMS output of DOE-2.1e simulation when integrating an F-Chart solar thermal system with results from the DOE-2.1e program.

8.1.1 Integrating the DOE-2.1e Space Heating and Service Water Heating Loads with the F-Chart Program

The F-Chart program uses Heating Degree Days (HDDs) to calculate the building's heating loads. Also needed for the loads calculation are the building's UA value and a balance temperature (Tbal or Tb) for the calculation of the HDDs.

The HDD calculation equation is:

$$HDD = Tb - Ta$$

Where,

Ta is an average between maximum and minimum temperatures of a day, $(T_{max}+T_{min})/2$.

Tb is a balance temperature for the HDDs,

Tb=Tdesign – Qi/(UA)total

Where

Tdesign is the room design temperature

Qi is internal heat gain, and

(UA)total is total UA value of the building

Figure 8.1.1 is a scatter plot of the monthly space heating energy use (DOE-2.1e Report SS-A) from the base-case building model versus the monthly average ambient temperature. The 12 symbols in the figure indicate each month's energy use. The solid line is a linear regression model representing the monthly energy consumption pattern developed using the ASHRAE's Inverse Model Toolkit (IMT). The linear line's slope is -11,789.5 and the changing point or Tb is 66.3 F. For the solar thermal analysis, the absolute value of the slope or 11,789.5 from the regression model was used as the building's UA value in the F-Chart calculation (Malhotra and Haberl, 2008). The monthly space heating load calculation equation in the F-Chart program is:

$$Q_{Month} = (UA)total * (HDD_{Tb})_{Month} * 24 \text{ (hours)}$$

Where UA (Btu/hr-F) is the measure of whole-building heat loss relative to the ambient temperature difference below 66.3 F.

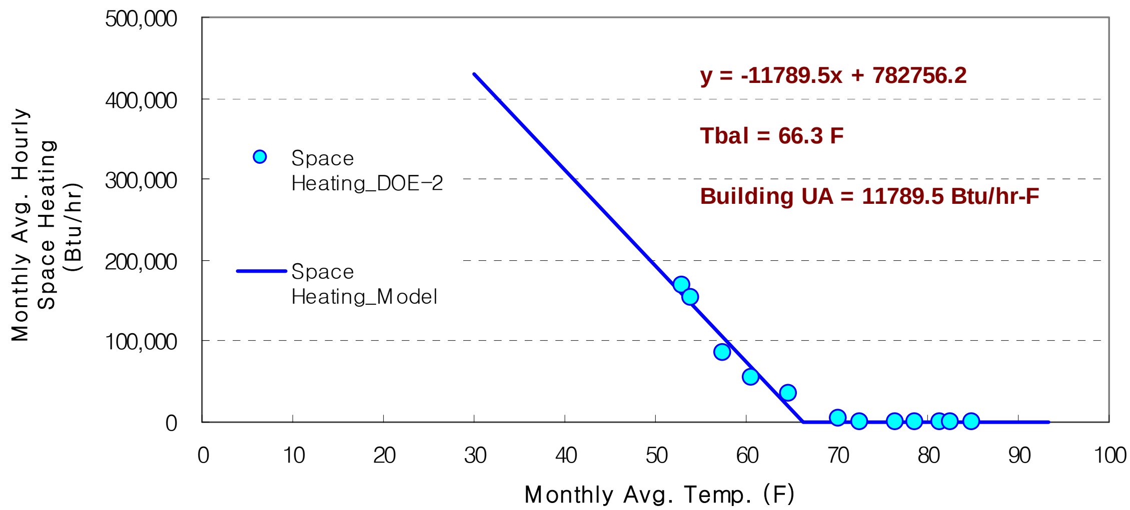


Figure 8.1.1 Scatter Plot and Regression Model of the Monthly Space Heating Energy Consumption of the Base-case (ASHRAE Standard 90.1-1999 Compliant) Building Model.

To run the F-Chart program, a new weather file was created using the same measured weather data used for the DOE-2.1e simulation. Table 8.1.2 shows the F-Chart monthly weather data inputs for College Station, TX in 2006. The monthly average solar radiation, temperature, and humidity ratio data were retrieved from the TRY measured weather file developed for the DOE-2.1e simulation of this study.

For the mains water temperature, the monthly average ground temperatures from the DOE-2.1e simulation output that used the measured weather data. The ground reflectance of 0.2 is the same value used for the DOE-2.1e simulation.

Table 8.1.2 Weather Data Input of the F-Chart Program Run for College Station, TX.

City: College Station		Latitude: 30.4		Degree-day base: 66.3 F		
Month	**Solar Rad. (Btu/sqft)**	**Temp. (F)**	**Humidity (lbw/lba)**	**Mains (F)**	**Reflect.**	**HDDs**
Jan	964	57.4	0.0058	64.1	0.2	286
Feb	966	53.0	0.0060	61.7	0.2	375
Mar	1,186	64.6	0.0089	61.5	0.2	102
Apr	1,669	72.5	0.0118	62.6	0.2	10
May	1,833	76.4	0.0130	67.3	0.2	0
Jun	2,088	81.5	0.0138	71.9	0.2	0
Jul	1,897	82.6	0.0169	75.9	0.2	0
Aug	1,941	84.8	0.0164	78.4	0.2	0
Sep	1,468	78.7	0.0129	78.6	0.2	0
Oct	1,223	70.2	0.0112	76.6	0.2	24
Nov	976	60.5	0.0081	72.7	0.2	192
Dec	713	53.9	0.0066	68.2	0.2	389

The HDDs of each month are automatically calculated by the F-Chart program based on the balance-point temperature of 66.3 F (Degree Day base in the program screen), which is the balance point temperature where the heating is required.

F-Chart consists of two input screens, one for the collector parameters and the other for the systems parameters as shown in Table 8.1.3 and Table 8.1.4, respectively. The type of the collector used was an evacuated tubular collector as shown in Table 8.1.3. In this analysis a total of 22 collectors were used with a collector area of 32 sq-ft each, totaling 704 square feet of collector area.

Table 8.1.3 Collector Input for F-Chart Program.

Evacuated Tubular Collector		
Number of collector panels	22	
Collector panel area	32	sqft
FR*UL (Test Slope)	0.05	Btu/hr-sqft-F
Collector slope	35	degree
Collector azimuth (South=0)	0	degree
Receive orientation	NS	
Incidence angle modifier (Perpendicular)	AngDep	
Incidence angle modifier (Parallel)	AngDep	
Collector flow rate/area	11	lb/hr-sqft
Collector fluid specific heat	1	Btu/lb-F
Modify test values	NO	

The FR*UL (Test Slope) of 0.05 and the FR*TAU*ALPHA (Test Intercept) of 0.42 were obtained from test results for the evacuated tube type (Newton and Gilman, 1981). The collector was designed to face south and was tilted at 35 degrees from the roof surface. The water flow rate in the collector loop was eleven pounds per hour per unit square foot of collector area. The specific heat of water is one Btu/lb- F.

In Table 8.1.4, the building UA value in the third row was input in case where the user wants to evaluate the space heating availability from the solar thermal system. The UA value of 11,789.5 Btu/hr-F was input, which was the slope of the regression model in Figure 8.1.1. In this analysis, natural gas was used as the heating source and the efficiency of the auxiliary heater was 85 percent. In this analysis, both space heating and service water heating were provided by the solar thermal system.

For the service hot water usage evaluation, the daily hot water usage was calculated based on the information available in the ASHRAE Applications Handbook (ASHRAE, 1999), which recommends a maximum daily value of 0.4 gallon per person for office buildings. The service hot water schedule used the schedule published in the ASHRAE Standard 90.1-1989, which is shown in Figure 8.1.2. Using these values, the average daily hot water usage was calculated as 343 gallons per day (Table 8.1.4). The hot water temperature was set to 110 F. An environmental temperature of 69.7 was used as the annual average temperature of College Station, TX in 2006.

Table 8.1.4 System Inputs for F-Chart Program.

Water Storage Heating System		
Location	College Station, TX	
Water volume / collector area	2.00	gallon/sqft
Building UA (0 if only DHW)	11789.5	Btu/hr-F
Fuel	Gas	
Efficiency of fuel usage	85.00	%
Domestic (Service) hot water?	Yes	
Daily hot water usage	343	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	

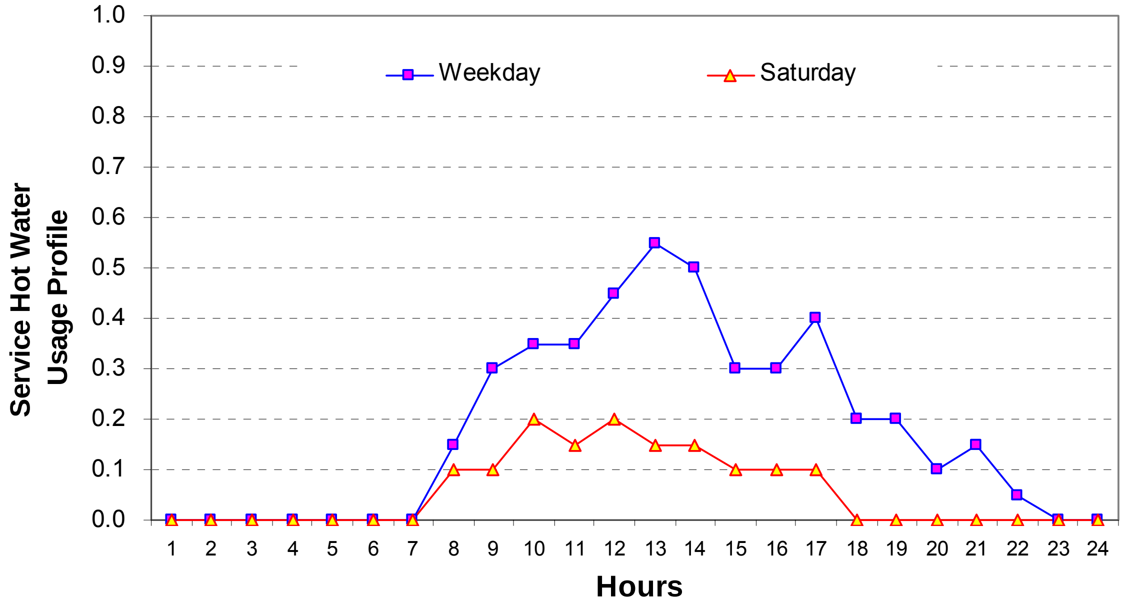


Figure 8.1.2 Service Hot Water Usage Profiles for Office Buildings.

The results of the F-chart run are shown in Table 8.1.5. In this figure, the first column of results shows the monthly available solar energy incident on the solar collector. As the user increases or decreases the type, number, and size of the collector, the available solar energy changes. The second column shows the monthly heating loads.

This was calculated based on the HDDs at the balance-point temperature of 66.3 F and UA value of the building. The third column shows the service hot water loads of the building. The forth column is the thermal energy requirement from another source to meet the building space heating and service hot water loads.

Table 8.1.5 F-Chart Results Using the UA Value as the Slope of the Linear Regression Model Representing the Space Heating Energy Consumption of the Base-case Building.

Thermal Output					
Month	**Solar (10^6 Btu)**	**Heat (10^6 Btu)**	**SHW (10^6 Btu)**	**Aux. (10^6 Btu)**	**f**
Jan	30.27	78.5	4.080	70.8	0.143
Feb	22.43	103.9	3.867	99.1	0.081
Mar	26.25	27.3	4.298	22.1	0.299
Apr	31.41	2.6	4.070	0.0	1.000
May	31.28	0.0	3.811	0.0	1.000
Jun	32.31	0.0	3.315	0.0	1.000
Jul	31.50	0.0	3.090	0.0	1.000
Aug	35.58	0.0	2.880	0.0	1.000
Sep	30.41	0.0	2.771	0.0	1.000
Oct	31.35	6.3	3.031	0.4	0.958
Nov	28.12	52.3	3.250	44.8	0.193
Dec	21.33	107.6	3.736	103.0	0.075
Year	352.24	378.5	42.199	340.2	0.191

The last column shows the fraction of the building thermal loads that was provided by the solar thermal system. The results show there are six months when the solar thermal system supplies all the needed thermal energy and another six months when the system supplies less energy than required. The total annual fraction of the loads that meets thermal loads was 19.1%, which reflects the large space heating loads in the winter.

Table 8.1.6 compares the load calculations results for the space heating and service hot water. The annual space heating loads were 365,580 kBtu/yr from the DOE-2.1e base-case model simulation (DOE-2.1e SYSTEMS Report SS-A) and 378,500 kBtu/yr from the F-Chart program, which is 4.2% higher than the DOE-2.1e results. The service hot water use was 41,800 kBtu/yr from the DOE-2.1e base-case simulation (DOE-2.1e SYSTEMS Report SS-P) and 42,199 kBtu/yr from the F-Chart program, which is 0.9% higher.

Table 8.1.6 Comparison of Results Between DOE-2.1e and F-Chart for the Space Heating and Service Hot Water Load Calculations.

Month	Tdb	DOE-2 (kBtu/mo)		F-Chart (kBtu/mo)	
		Heating	SHW	Heating	SHW
JAN	57.4	64,127	3,988	78,500	4,080
FEB	53.0	113,311	3,816	103,900	3,867
MAR	64.6	26,253	4,361	27,300	4,298
APR	72.5	473	3,820	2,600	4,070
MAY	76.4	0	3,884	0	3,811
JUN	81.5	0	3,363	0	3,315
JUL	82.6	0	2,978	0	3,090
AUG	84.8	0	2,966	0	2,880
SEP	78.7	0	2,756	0	2,771
OCT	70.2	3,196	3,004	6,300	3,031
NOV	60.5	40,248	3,300	52,300	3,250
DEC	53.9	114,972	3,566	107,600	3,736
Annual Total		362,580	41,800	378,500	42,199

These comparisons show acceptable differences, which indicate that the DOE-2.1e SYSTEMS simulation results can be used to develop the UA value of buildings, which can then used to calculate the buildings' space heating loads in the F-Chart program. Figure 8.1.3 shows the monthly average hourly heating loads from both DOE-2.1e and

F-Chart along with the regression model for the development of the building UA value. The results indicate that the values from the DOE-2.1e simulation could be used for the load calculations in the F-Chart program.

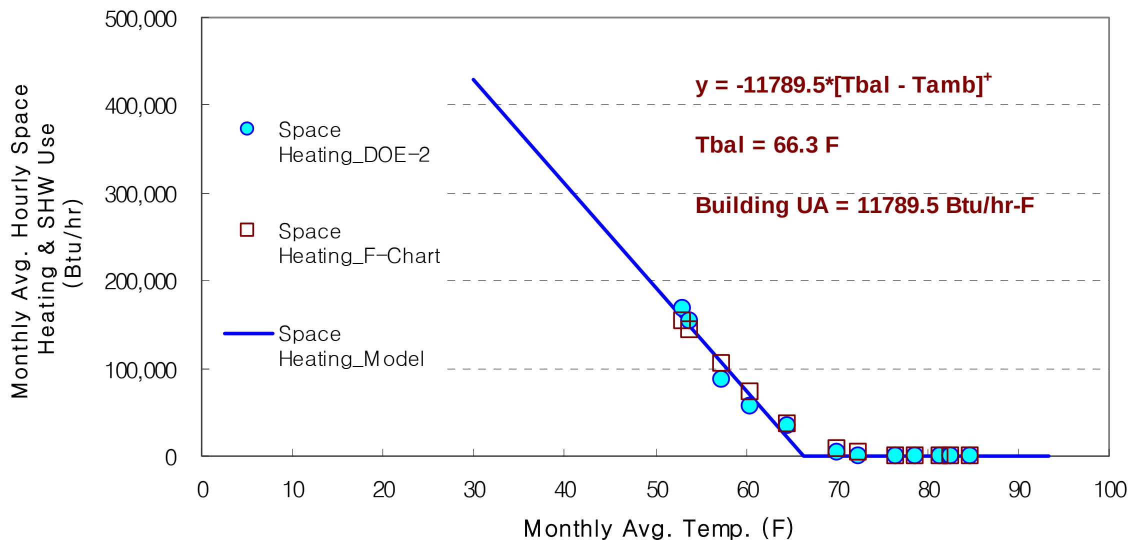


Figure 8.1.3 Comparison of DOE-2.1e Space Heating Load and the F-Chart Space Heating Load that Used the UA Value from the Regression Model.

8.1.2 Energy Savings from the Solar Thermal Systems

Although the space heating and the service water heating energy can be provided by the solar thermal systems, only the service water heating was considered to be supplied by the solar thermal systems in this case-study analysis. As shown in Table 8.1.5, the service water heating loads could be met by the solar thermal systems year round.

However, the space heating loads could not be met by the solar thermal systems for the winter period. To meet all the winter space heating loads, the required solar collector would have been 220 collectors, which are ten times the collectors used in this analysis. Unfortunately, such a large system would not be well utilized during the summer period with the current electric cooling system. To absorb all this thermal energy, an absorption system or liquid desiccant system would have to be used, which are beyond the scope of this thesis.

In contrast, the service water heating loads were 56,589 kBtu/yr, which are easily met by a properly-sized solar thermal system.

8.2 Application of Solar Photovoltaic (PV) Systems

Solar PV systems were considered as the renewable electric power generating systems for the case-study building. In this study, the PV F-Chart program was used for the evaluation of the PV systems. Like the F-Chart program, a new weather file was created for the measured College Station weather conditions. As shown in Table 8.2.1, the monthly solar, temperature, and ground reflectance data were input into the PV F-Chart program.

To evaluate the performance of the PV systems, a directly connected system was considered, which sends electricity directly into the building's electrical systems without the use of batteries. Table 8.2.2 shows the inputs for the PV system. A city number was selected for College Station. The PV cell temperature was set to 113 F, which was obtained from a manufacturer for a specific product, Suntech STP170 (Suntech, 2008). Other parameters such as array reference efficiency, array reference temperature, and other related efficiencies were also referenced by the manufacturer's data. The array slope was set to 35 degree and faces south. An array area of 2,000 square feet was used.

Table 8.2.1 PV F-Chart Weather File Created for the College Station Weather Conditions.

City: College Station, TX		Latitude: 30.4	
Month	**Solar (Btu/sqft)**	**Temp (F)**	**Ground Albedo**
Jan	964	57.4	0.20
Feb	966	53.0	0.20
Mar	1,186	64.6	0.20
Apr	1,669	72.5	0.20
May	1,833	76.4	0.20
Jun	2,088	81.5	0.20
Jul	1,897	82.6	0.20
Aug	1,941	84.8	0.20
Sep	1,468	78.7	0.20
Oct	1,223	70.2	0.20
Nov	976	60.5	0.20
Dec	713	53.9	0.20

Table 8.2.2 PV F-Chart Inputs for the Utility Feedback System with Flat-Plate PV Panels Using 2000 sqft PV Array Area.

Utility Feedback PV System			
1	City number for College Station, TX	247	
2	Output: 1 for summary, 2 for detailed (Neg: graph)	1	
3	Cell temperature at NOCT conditions	113	F
4	Array reference efficiency	0.133	
5	Array reference temperature	77	F
6	Max. power eff. temperature coeff. (times 1000)	2.5	1/F
7	Eff. Of maximum power point tracking electronics	0.9	
8	Efficiency of power conditioning electronics	0.88	
9	Percent standard deviation of the load	0	%
10	Array area	2,000	sqft
11	Array slope	35	deg
12	Array azimuth (south=0)	0	deg

Table 8.2.3 shows the PV F-Chart analysis results. The building electric load was set to all "0" (third column) for 12 months to see how many kWh of electricity can be generated. As a result, the last column shows the available electricity from the PV systems. As a consequence, the fourth column (F) shows all "100%" for twelve months and there is no month to buy (fifth column) electricity from grid. The annual total electricity generation by the PV systems was 28,769.2 kWh/yr, which was 2.6% of the total electricity consumption of 1,095,509 kWh/yr from the high-performance building model.

Again, if a situation, in which the redundant electricity is available from the PV systems and exported to the grid, is considered, more PV panels can be installed. Multiple PV F-

Chart runs showed that the electricity generation was linearly increased by adding more PV array areas.

Table 8.2.3 PV F-Chart Summary Output Showing the Amount of Electricity Generation Each Month Using 2000 sqft PV Array Area.

PV F-Chart Output Summary					
Month	**Solar (kWh)**	**Load (kWh)**	**F (%)**	**Buy (kWh)**	**Sell (kWh)**
Jan	24,145.5	0.0	100.0	0.0	2,342.0
Feb	18,570.8	0.0	100.0	0.0	1,825.6
Mar	22,894.1	0.0	100.0	0.0	2,161.7
Apr	28,650.6	0.0	100.0	0.0	2,620.9
May	29,737.5	0.0	100.0	0.0	2,685.2
Jun	31,435.9	0.0	100.0	0.0	2,786.9
Jul	30,215.0	0.0	100.0	0.0	2,678.9
Aug	33,209.2	0.0	100.0	0.0	2,924.3
Sep	26,878.8	0.0	100.0	0.0	2,425.5
Oct	26,333.5	0.0	100.0	0.0	2,441.5
Nov	22,639.3	0.0	100.0	0.0	2,178.4
Dec	17,183.3	0.0	100.0	0.0	1,698.3
Year	311,893.5	0.0	100.0	0.0	28,769.2

As shown in Table 8.2.4, the PV array area of 8,000 square feet was considered, which was less than half of the case building's roof area of 17,670 square feet. In the case-study building, there are some equipment on the roof such as outside air handing units and exhaust fans, so that using half of the roof area was reasonably considered. Table 8.2.5 shows the results of using the array area of 8,000 square feet. The annual total electricity generation was 115,077.1 kWh/yr, which was 10.5% of the total building's electric consumption of 1,095,509 kWh/yr.

Table 8.2.4 PV F-Chart Inputs for the Utility Feedback System with Flat-Plate PV Panels Using 8,000 sqft PV Array Area.

Utility Feedback PV System			
1	City number for College Station, TX	247	
2	Output: 1 for summary, 2 for detailed (Neg: graph)	1	
3	Cell temperature at NOCT conditions	113	F
4	Array reference efficiency	0.133	
5	Array reference temperature	77	F
6	Max. power eff. temperature coeff. (times 1000)	2.5	1/F
7	Eff. Of maximum power point tracking electronics	0.9	
8	Efficiency of power conditioning electronics	0.88	
9	Percent standard deviation of the load	0	%
10	Array area	8,000	sqft
11	Array slope	35	deg
12	Array azimuth (south=0)	0	deg

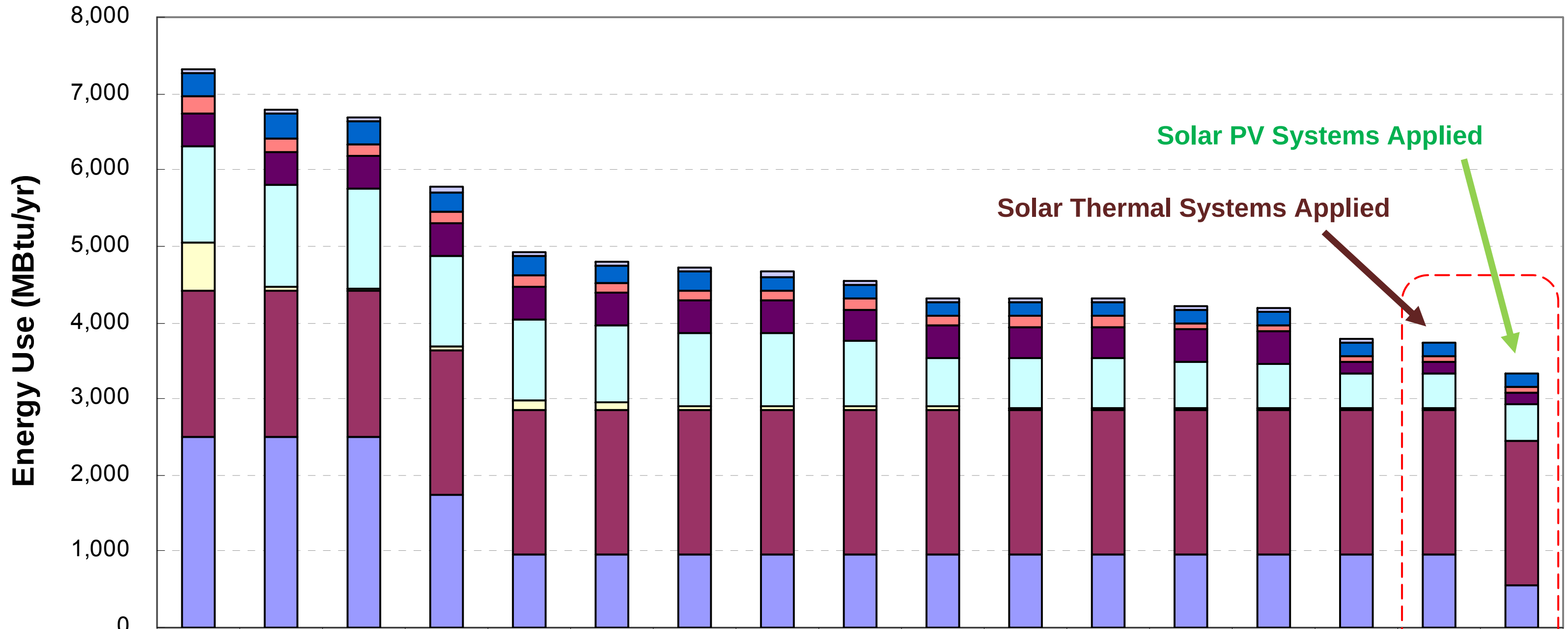
The high-performance building model's energy consumption was then finally reduced to 3,346 MMBtu/yr after the electricity generation of 115,077.1 kWh/yr was subtracted from the total electricity consumption. The final energy consumption of 3,346 MMBtu/yr was 54.3% lower than that of the base-case (ASHRAE Standard 90.1-1999 compliant) building, which was 7,318 MMBtu/yr.

Table 8.2.5 PV F-Chart Summary Output Showing the Amount of Electricity Generation Each Month Using 8000 PV Array Area.

PV F-Chart Output Summary					
Month	**Solar (kWh)**	**Load (kWh)**	**F (%)**	**Buy (kWh)**	**Sell (kWh)**
Jan	96,582.0	0.0	100.0	0.0	9,368.0
Feb	74,283.2	0.0	100.0	0.0	7,302.4
Mar	91,576.4	0.0	100.0	0.0	8,646.8
Apr	114,602.4	0.0	100.0	0.0	10,483.6
May	118,950.0	0.0	100.0	0.0	10,740.8
Jun	125,743.6	0.0	100.0	0.0	11,147.6
Jul	120,860.0	0.0	100.0	0.0	10,715.6
Aug	132,836.8	0.0	100.0	0.0	11,697.2
Sep	107,515.2	0.0	100.0	0.0	9,702.0
Oct	105,334.0	0.0	100.0	0.0	9,766.0
Nov	90,557.2	0.0	100.0	0.0	8,713.6
Dec	68,733.2	0.0	100.0	0.0	6,793.2
Year	1,247,574.0	0.0	100.0	0.0	115,076.8

8.3 Summary of the Solar Systems Application

In this chapter, a methodology was presented for the integration of the solar thermal and PV systems with the DOE-2.1e simulation program. In addition, energy savings were calculated by using properly sized solar thermal and solar PV systems for the case-study building. Figure 8.3.1 shows additional energy reductions by supplying renewable energy from the solar systems. This is actually not reducing energy use of the building but subtracting the energy amount generated by the solar energy source from the building's total energy use. The solar thermal energy obtained from the solar thermal system fully covered the service water heating energy that leaves the "SERHOT WATER", service water heating energy use, to be "0" MMBtu/yr from 53 MMBtu/yr in Figure 8.3.1. This saved additional 1% of total energy, making the total energy savings of 49% as shown in Figure 8.3.2. In addition, the total electricity use was subtracted by the electricity generation of 115,077.1 kWh/yr obtained from the PV systems that used 8,000 square feet of array area. The energy savings were further increased by 5%, resulting in the total energy savings of 54% as shown in Figure 8.3.2.



	Base-Case	Glazing U Factor (1.22 to	WindowToWall Ratio	Lighting Load (1.3 to 0.9	Light Control (None to	Shading (none to 2.5 ft	Cold Deck Reset	Supply Fan Total Pressure	Economizer (None to	Chiller COP (5.55 to	Boiler Efficiency (75%	DHW Heater Thermal	CHW Pump Control	HW Pump Control	Chiller Staging (One to	Solar Thermal Service	Solar PV Electric Generati
SERHOT WATER	57	57	57	57	57	57	57	57	57	57	57	53	53	53	53	-	-
VENT FANS	308	321	301	268	247	226	234	184	182	182	182	182	182	182	182	182	182
PUMPS & MISC	215	186	165	155	148	136	134	133	130	130	130	130	75	71	71	71	71
HEAT REJECT	427	427	427	426	425	425	425	425	425	425	425	425	425	425	154	154	154
SPACE COOL	1,258	1,353	1,318	1,189	1,063	1,006	964	956	859	636	636	636	600	600	470	470	470
SPACE HEAT	641	44	19	37	115	97	42	43	30	30	24	24	24	5	5	5	5
MISC EQUIPMT	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907
AREA LIGHTS	2,506	2,506	2,506	1,735	955	955	955	955	955	955	955	955	955	955	955	955	545

Figure 8.3.1 Energy Use Reductions by Solar Thermal and PV Systems with the 14 High-performance Measures.

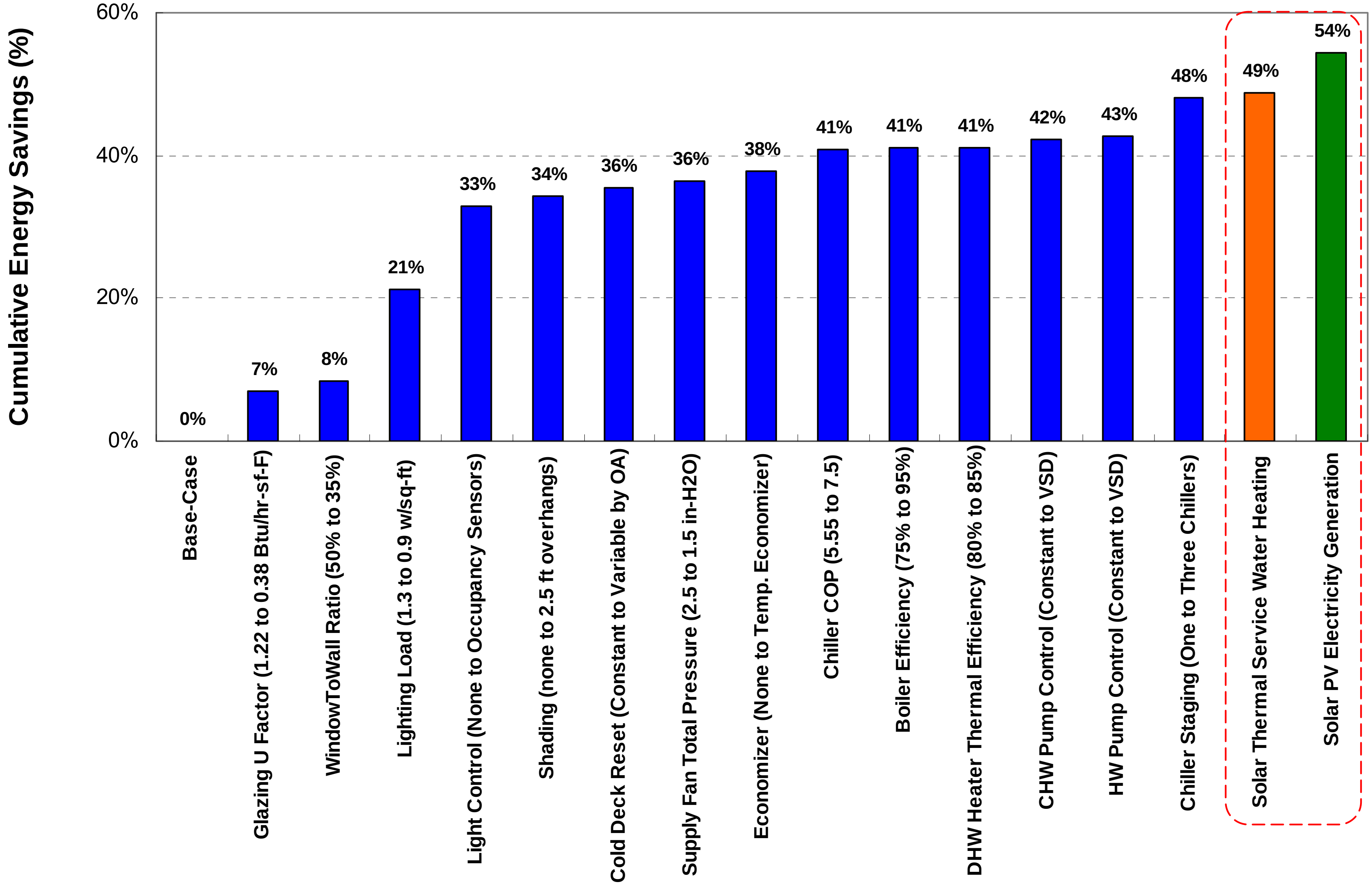


Figure 8.3.2 Energy Savings by Solar Thermal and PV Systems with the 14 High-performance Measures.

CHAPTER IX

PROPOSED EASY-TO-USE SYSTEMS SELECTION TOOL

This chapter describes the proposed easy-to-use tool, including: its intended appearance, how it is intended to work, and comparison with other similar tools.

9.1 Mock-up Screens of the Proposed Easy-to-use Tool

The proposed easy-to-use tool will include a graphic user interface for the selection of building systems and components. In the proposed tool, there would be seven sections in the user interface and a final report section, including: 1) Building, 2) Shade, 3) Construction, 4) System, 5) Plant, 6) Solar Thermal, 7) Solar Photovoltaic, and 8) Report. The figures from Figure 9.1.1 to Figure 9.1.18 show the input screens for seven sections and Figure 9.1.21 for the final report. Each input screen consists of five orange tabs on the top of the screen, one of which is blue indicating the user is in the section with blue color, two green tabs for solar thermal and PV, and one maroon tab for final calculation. The maroon tab can be used in any sections for final calculations.

Users need to input values in the box next to the descriptions. The default values (maroon) shown in the screens are values for the ASHRAE 90.1-1999 code-compliant model. There are endnotes in some parameter descriptions, which are the parameters that high-performance measures are available for. Another column with blue is to show the high-performance measures available for the input. These high-performance measures can be selected by changing the code-compliant values with them. Figure 9.1.1 shows the input screen for “Building” parameters. In this screen, there are two high-performance parameters available, which are LPD of 0.9 W/sqft and occupancy sensors.

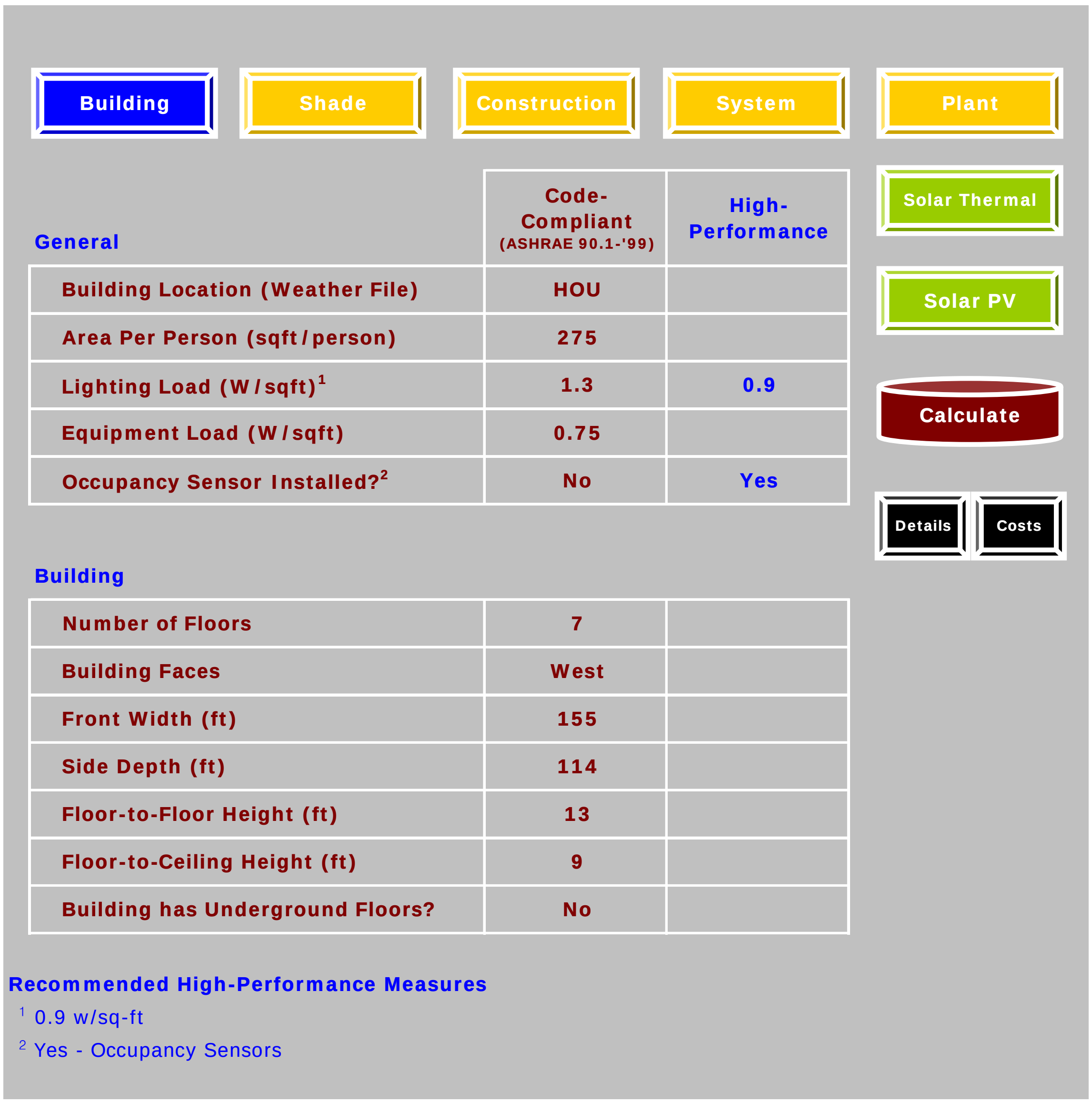


Figure 9.1.1 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of “Building”.

In Figure 9.1.1, there are also two more buttons, “Details” and “Costs”. The “Details” button is to show users more detailed input parameters for the simulation, which are not shown in the front screen of the proposed easy-to-use tool. Figure 9.1.2 shows detailed parameters, which pops up when the “Details” button is selected by users in the “Building” screen of the proposed tool. It includes input parameters for space conditions, lighting schedule, equipment schedule, and occupancy schedule.

Details

Space Conditions

Room Temperature (F)	72.5
Area Per Person (sqft/person)	275
People Heat Gain (Sens) (Btu/hr-person)	245
People Heat Gain (Lat.) (Btu/hr-person)	155
Light-to-Space	0.8
Floor Weight (lb)	70

Lighting Schedule

Weekdays
1am-8am: 0.37,0.33,0.30,0.29,0.29,0.37,0.61,0.70
9am-4pm: 0.78,0.80,0.79,0.79,0.80,0.80,0.80,0.80
5pm-0am: 0.77,0.63,0.51,0.48,0.45,0.43,0.42,0.40
Weekends
1am-8am: 0.33,0.33,0.33,0.32,0.32,0.33,0.33,0.34
9am-4pm: 0.38,0.43,0.43,0.48,0.54,0.55,0.54,0.53
5pm-0am: 0.52,0.37,0.36,0.36,0.36,0.36,0.36,0.34

Figure 9.1.2 Screen of the Detailed Simulation Input Parameters for the “Building” Screen of the Proposed Easy-to-use Tool.

Equipment Schedule

Weekdays
1am-8am: 0.63,0.61,0.60,0.58,0.58,0.59,0.65,0.76
9am-4pm: 0.86,0.88,0.89,0.88,0.89,0.88,0.88,0.85
5pm-0am: 0.78,0.71,0.68,0.67,0.66,0.65,0.65,0.64
Weekends
1am-8am: 0.59,0.59,0.58,0.57,0.57,0.57,0.58,0.58
9am-4pm: 0.58,0.59,0.59,0.60,0.59,0.59,0.59,0.59
5pm-0am: 0.59,0.59,0.60,0.60,0.61,0.61,0.60,0.59

Occupancy Schedule

Weekdays
1am-8am: 0.02,0.00,0.00,0.00,0.02,0.06,0.24,0.62
9am-4pm: 0.88,0.98,1.00,1.00,0.98,0.98,1.00,0.96
5pm-0am: 0.74,0.48,0.38,0.34,0.22,0.12,0.08,0.06
Weekends
1am-8am: 0.04,0.02,0.02,0.00,0.02,0.02,0.02,0.04
9am-4pm: 0.06,0.08,0.10,0.10,0.10,0.10,0.10,0.08
5pm-0am: 0.06,0.04,0.02,0.02,0.02,0.02,0.02,0.00

Figure 9.1.2 continued.

The “Costs” button in Figure 9.1.1 is designed to show the implementation costs of the high-performance measures. Figure 9.1.3 shows the cost information of implementing the high-performance lighting measure and the occupancy sensor measure. Also, the figure includes the layout of spaces for occupancy sensors. The space is divided in to eight sections, which are open office, private office, lobby, corridor, conference room, copy room, restrooms, and mechanical and electrical room.

Costs

Lighting Costs

Space type	Area Distribution	Basecase Lighting (W/sqft)	Basecase Lamp/Fixture Type	Watt Per Fixture	Improved Model Lighting (W/sqft)	Energy-Efficient Lamp/Fixture Type	Watt Per Fixture
Open Office	45%	1.3	3-F34T12 Lamp Fixture	115	1.06	3-F32T8 Lamp Fixture	85
			Incandescent 25W	25		CF20W Screw in Lamp	20
Private Office	25%	1.5	3-F34T12 Lamp Fixture	115	1.13	3-F32T8 Lamp Fixture	85
			Incandescent 25W	25		CF20W Screw in Lamp	20
Lobby	5%	1.8	3-F34T12 Lamp Fixture	115	1.32	3-F32T8 Lamp Fixture	85
			Mercury Vapor 75W	93		Metal Halide 50W, Electronic Ballast	57
Corridor	10%	0.7	3-F34T12 Lamp Fixture	115	0.46	3-F32T8 Lamp Fixture	85
			Exit Incand. 15W	15		Exit LED 2W	9
Conference Room	4%	1.5	3-F34T12 Lamp Fixture	115	1.13	3-F32T8 Lamp Fixture	85
			Incandescent 25W	25		CF20W Screw in Lamp	20
Copy Room	2%	1.1	3-F34T12 Lamp Fixture	115	0.76	3-F32T8 Lamp Fixture	85
Restrooms	5%	1	3-F34T12 Lamp Fixture	115	0.86	3-F32T8 Lamp Fixture	85
			Incandescent 25W	25		CF20W Screw in Lamp	20
Mech./Elec. Room	4%	1.3	3-F34T12 Lamp Fixture	115	1.45	3-F32T8 Lamp Fixture	85

Case	Fixture	Lamp	Ballast	Watt Per Lamp	Watt Per Fixture
Basecase	F43EE (3-48”, 34W, T-12 Lamps Fixture)	F34T12	Magnetic-ES	34	115
Energy-Efficient Lighting	F43ILL (3-48”, 32W, T-8 Lamps Fixture)	F32T8	Instant Star Electronic	32	85

Figure 9.1.3 Screen of the Cost Information of Implementing High-performance Measures in “Building” Screen of the Proposed Easy-to-use Tool .

Case	Lamp	Brand	Cost Per Unit [1]	Ballast	Brand	Cost Per Unit [2]
Basecase	F34T12 Fluorescent Bulb	Philips	\$1.19-\$1.99	277 Volt One or Two Lamp F34T12 Magnetic Ballast	Advance Transformer	\$11.99-\$21.49
Energy-efficient Lighting	F32T8 Fluorescent Bulb	General Electric	\$1.29-\$2.19	120-277 Volt Three Lamp F32T8 Electronic Ballast	Advance Transformer	\$16.99-\$24.99

[1] http://www.bulbs.com/Fluorescent_Bulbs/results.aspx

[2] http://www.bulbs.com/Fluorescent_Ballasts_--_Linear/results.aspx

Occupancy Sensor Costs

Space	Area Distribution	No. of Sensors	Brand	Model	Cost Per Unit (\$)	Remarks
Open office	45%	4	Leviton	ODC20-MRW	\$179.97 [1]	Commercial Grade Multi-Tech, Ceiling-Mount
Private office	25%	32	Leviton	ODS15ID	\$69.95 [2]	PIR, wall switch
Lobby	5%	None	-	-	-	None
Corridor	10%	4	Leviton	OSWLR-I0W + OSP20-0D0	\$150.51 [3]	PIR Long Range Aisle Wall Mount + Power Pack
Conference room	4%	4	Leviton	OSC05-M0W + OSP20-0D0	\$139.66 [4]	Multi-Tech 500 Sq. Ft. Ceiling Mount + Power Pack
Copy room	2%	1	Leviton	ODS15ID	\$69.95	PIR, wall switch
Restrooms	5%	2	Leviton	OSC05-M0W + OSP20-0D0	\$139.66	Multi-Tech 500 Sq. Ft. Ceiling Mount + Power Pack
Mechanical & Electrical Room	4%	1	Leviton	ODS15ID	\$69.95	PIR, wall switch

[1] http://www.twacomm.com/catalog/model_ODC20-MRW.htm?sid=BF03E11CEDBD9FB4C3B490D4606B483A

[2] http://www.homecontrols.com/cgi-bin/main/co_disp/displ/carfnbr/398/prrfnbr/1185/Wall-Switch-Occ-Sensor

[3] http://www.onestopbuy.com/OSWLR-I0W-5735.asp

[4] http://www.onestopbuy.com/OSC05-M0W-5712.asp

Figure 9.1.3 continued.

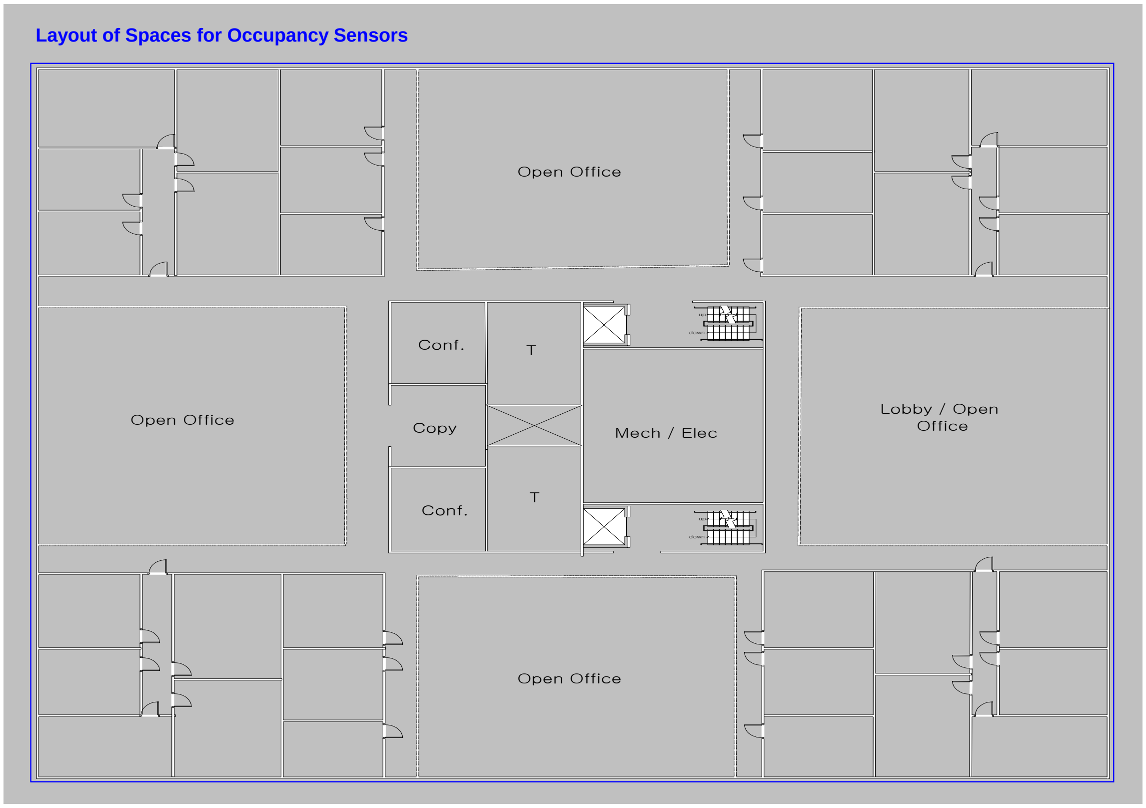


Figure 9.1.3 continued.

Figure 9.1.4 shows the input screen for “Shade” parameters. Overhangs can be selected as high-performance measure. The size of the overhangs is calculated with a projection factor of 0.5. This projection factor of 0.5 is a recommendation from the ASHRAE’s Advanced Energy Design Guide (AEDG) for small office buildings (ASHRAE, 2004). As the base-case code-compliant building simulation includes the window height of 5 feet, the size of overhang is calculated to be 2.5 feet for the case of high-performance measure in this screen.

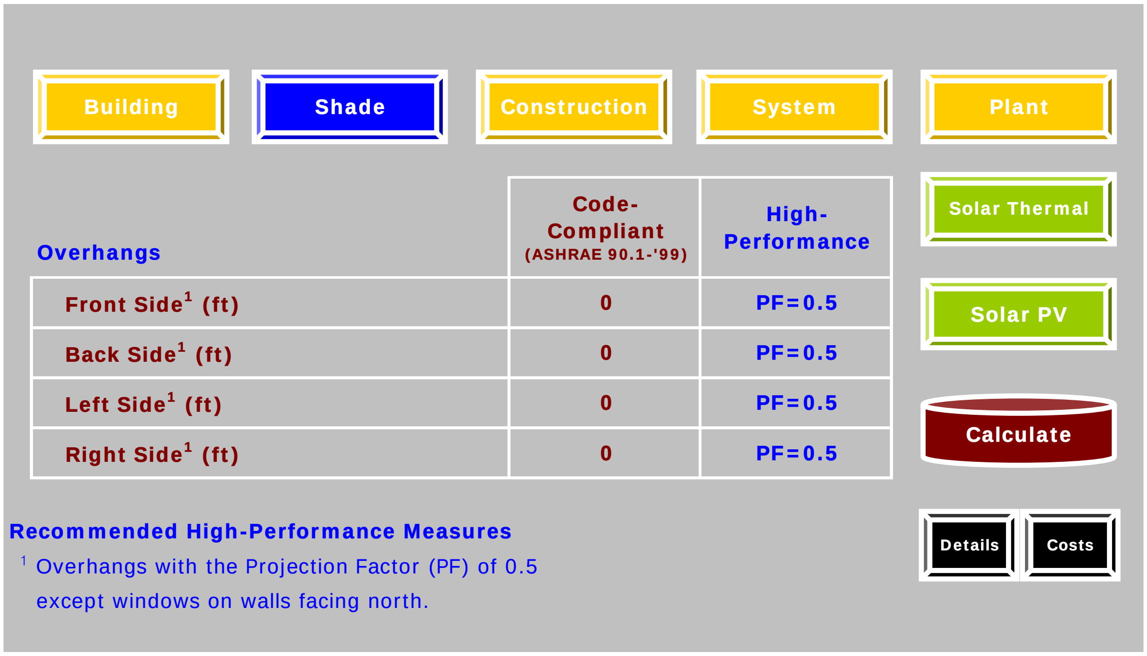


Figure 9.1.4 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of "Shade".

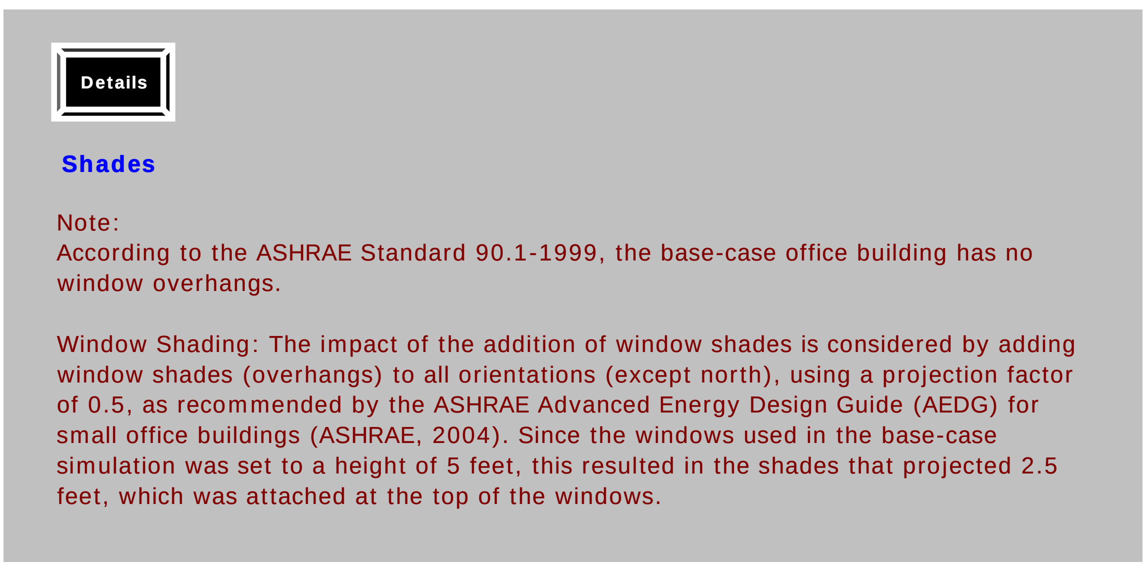


Figure 9.1.5 Screen of the Detailed Simulation Input Information for the "Shade" Screen of the Proposed Easy-to-use Tool.

Figure 9.1.5 is popped up when the “Details” button is clicked in the “Shade” screen and explains how the size of shades (overhangs) are calculated. Figure 9.1.6 shows the cost information for the implementation of overhangs.

Costs

Shading Device (Overhang) Costs

NO	Type of Overhangs	Width of Overhangs (ft)	Increase Unit Cost ($/sqft)
1	3' Closed Overhangs	2.5	12.37 [1]
2	Louvered Metal Overhangs	2.5	58 [2]
3	3” Reinforced Concrete Slab	2.5	20 [3]

[1] http://www1.eere.energy.gov/femp/pdfs/buscase_appendixb.pdf &
http://www1.eere.energy.gov/femp/pdfs/buscase_frontmat.pdf

[2] “Construction bid for louvered overhang sun shades on a fire station project
in College Station, Texas”
Thomas Parker, AIA, Director, BRW Architects, Inc.
College Station, TX 77845

[3] Estimated Cost

Figure 9.1.6 Screen of the Cost Information of Implementing Overhangs in “Shades” Screen of the Proposed Easy-to-use Tool.

Figure 9.1.7 is the input screen for “Construction”. The insulation values are selected for roof, wall, window, and floor along with other important values that affect building energy consumption such as glazing U-factor and window-to-wall ratio. The improved U-factor of glazing (0.38 Btu/hr-sqft-F) is a high-performance measure. Also there is another high-performance measure (35% window-to-wall ratio) that has a significant impact on energy consumption.

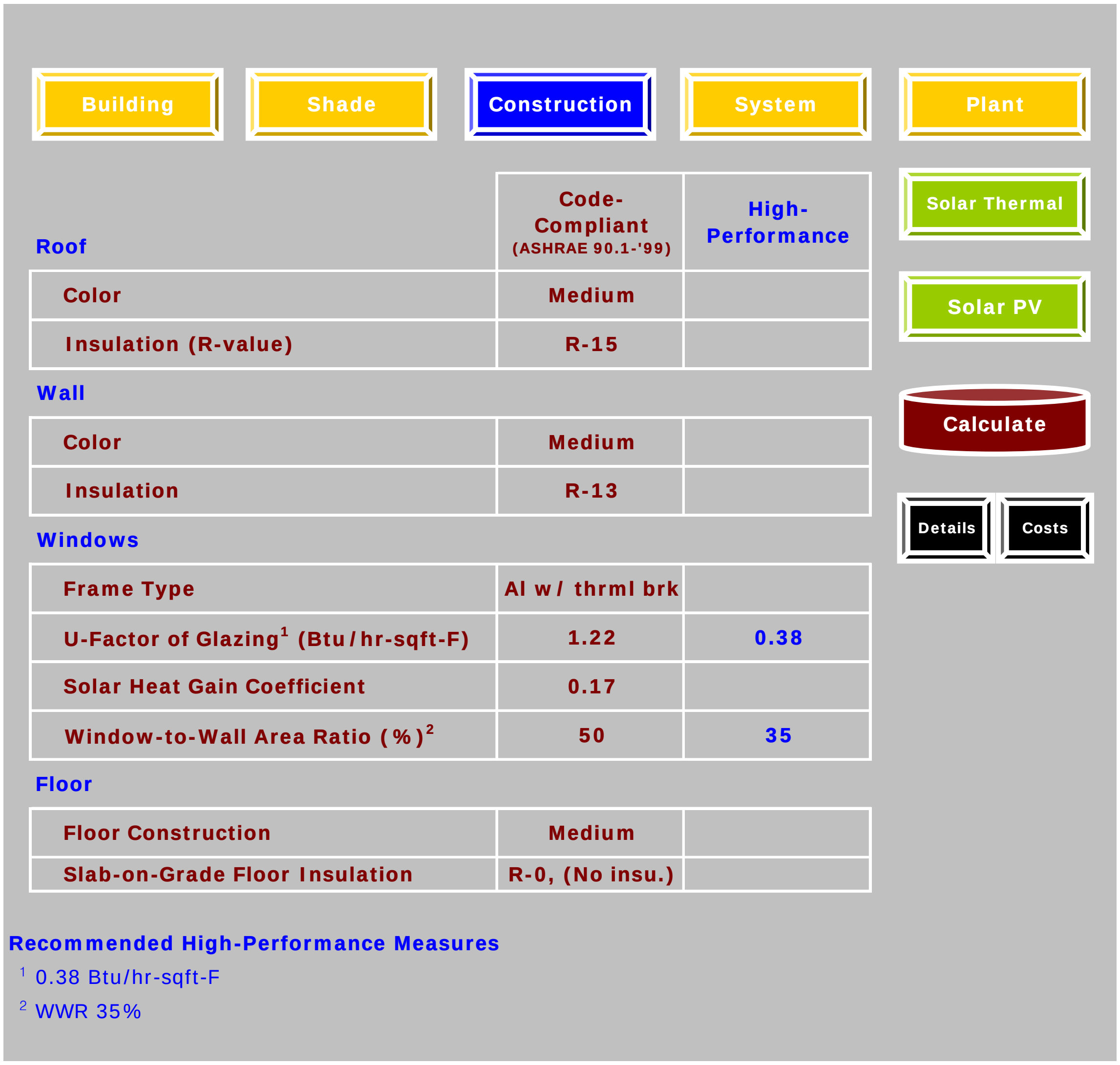


Figure 9.1.7 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of "Construction".

Figure 9.1.8 shows the details of the input parameters for "Construction" screen of the proposed easy-to-use tool. It includes specific information for each area of the building envelop such as roof, exterior wall, ceiling, interior wall, underground floor and wall, windows.

Details

Roof

Roof Color	Medium
Roof U-Value (Btu/sqft-hr-F)	0.034
Inside Visible Reflectance	0.5
Inside Solar Absorptance	0.5
Outside Emissivity	0.9

Exterior Wall

Ext. Wall Color	Medium
Ext. Wall U-Value (Btu/sqft-hr-F)	0.105
Ground Reflectance	0.2
Solar Fraction	0.2
Inside Visible Reflectance	0.5
Inside Solar Absorptance	0.5
Outside Emissivity	0.9

Ceiling

Ceiling U-Value (Btu/sqft-hr-F)	0.562
Floor U-Value (Btu/sqft-hr-F)	0.230

Interior Wall

Int. Wall U-Value (Btu/sqft-hr-F)	0.339
Inside Visible Reflectance	0.3-0.7
Sloar Fraction	0.1
Inside Solar Absorptance	0.5

Figure 9.1.8 Screen of the Detailed Simulation Input Parameters for the "Construction" Screen of the Proposed Easy-to-use Tool.

Underground

U.G. Floor U-Value (Btu/sqft-hr-F)	0.065
U.G. Wall U-Value (Btu/sqft-hr-F)	0.065

Windows

Window Glass Panes	2
U-Factor of Glazing (Btu/hr-sqft-F)	1.22
Solar Heat Gain Coefficient	0.17
Visible Transmittance	0.19
Window Frame Type	Al w/ thrml brk
Frame Conductance (Btu/sqft-hr-F)	0.434
Frame Absorptance (Btu/sqft-hr-F)	0.7
Spacer Type	Aluminum
Window-to-Wall Area Ratio (%)	50

Figure 9.1.8 continued.

Figure 9.1.9 shows the cost information of various glazing types. It includes detailed glazing properties and also the incremental costs per unit area. The total costs can be compared by multiplying the incremental first cost by total glazing area of the target building. As clicking the "Costs" button, the user of the proposed easy-to-use tool can easily see all the glazing properties in one screen. The price varies not just with one value but several different values in one glazing type, so the user needs to select the optimal and cost-effective glazing types for his or her climate conditions and the usage of the building as well.

Costs

Glazing

No.	Name	U_{Crit}	U_{Act}	SC	SHGC	VLT	Kd	kWh	U_{Fixed}	ΔFC/sqft [1]
1	Mtl/Clr (Base Case)	1.27	1.26	0.94	0.82	0.80	0.63	1.21	1.22	$ -
2	Brk/Clr	1.08	1.15	0.91	0.79	0.80	0.63	1.21	1.11	$ 1.95
3	Vnl/Clr	0.90	1.02	0.84	0.73	0.77	0.62	1.23	0.98	$ 4.88
4	Mtl/Clr-Std-Clr	0.81	0.73	0.83	0.72	0.71	0.60	1.29	0.72	$ 3.90
5	Mtl/ClrSbe-Std-Clr	0.69	0.59	0.51	0.44	0.45	0.48	1.67	0.57	$ 5.27
6	Brk/Clr-Std-Clr	0.60	0.62	0.78	0.68	0.71	0.60	1.29	0.60	$ 5.85
7	Brk/ClrSbe-Std-Clr	0.49	0.48	0.46	0.40	0.45	0.48	1.67	0.46	$ 7.22
8	Brk/Clr-Ins-Clr	0.57	0.59	0.78	0.68	0.71	0.60	1.29	0.57	$ 6.34
9	Brk/ClrSbe-Ins-Clr	0.46	0.44	0.46	0.40	0.45	0.48	1.67	0.43	$ 7.71
10	Brk/Clr-Ins-ClrPye	0.48	0.45	0.74	0.64	0.66	0.58	1.34	0.46	$ 7.12
11	Brk/Clr-Ins-ClrSpe	0.46	0.44	0.64	0.56	0.66	0.58	1.34	0.43	$ 7.12
12	Brk/Clr-Ins-ClrSue	0.44	0.42	0.53	0.46	0.62	0.57	1.39	0.42	$ 7.12
13	Vnl/Clr-Std-Clr	0.53	0.51	0.72	0.63	0.68	0.59	1.32	0.50	$ 8.78
14	Vnl/ClrSbe-Std-Clr	0.42	0.37	0.41	0.36	0.43	0.47	1.71	0.37	$ 10.14
15	Vnl/Clr-Std-ClrPye	0.44	0.39	0.68	0.59	0.63	0.57	1.38	0.40	$ 9.56
16	Vnl/Clr-Std-ClrSpe	0.42	0.37	0.59	0.51	0.63	0.57	1.38	0.37	$ 9.56
17	Vnl/Clr-Std-ClrSue	0.41	0.36	0.47	0.41	0.60	0.56	1.42	0.36	$ 9.56
18	Vnl/Clr-Ins-Clr	0.50	0.48	0.72	0.63	0.68	0.59	1.32	0.47	$ 9.27
19	Vnl/ClrSbe-Ins-Clr	0.39	0.34	0.41	0.36	0.43	0.47	1.71	0.34	$ 10.63
20	Vnl/Clr-Ins-ClrPye	0.41	0.35	0.68	0.59	0.63	0.57	1.38	0.37	$ 10.05
21	Vnl/Clr-Ins-ClrSpe	0.39	0.33	0.59	0.51	0.63	0.57	1.38	0.34	$ 10.05

Figure 9.1.9 Screen of the Cost Information of Implementing High-performance Glazing in "Construction" Screen of the Proposed Easy-to-use Tool .

22	Vnl/Clr-Ins-ClrSue	0.38	0.32	0.47	0.41	0.60	0.56	1.42	0.33	$ 10.05
23	Brk/Clr-Ins-Clr-Ins-Clr	0.43	0.42	0.68	0.59	0.64	0.58	1.37	0.42	$ 10.24
24	Brk/Clr-Ins-V88-Ins-Clr	0.33	0.35	0.61	0.53	0.63	0.57	1.38	0.30	$ 14.14
25	Vnl/Clr-Ins-Clr-Ins-Clr	0.37	0.33	0.63	0.55	0.61	0.57	1.41	0.33	$ 13.17
26	Vnl/Clr-Ins-V88-Ins-Clr	0.28	0.26	0.55	0.48	0.61	0.57	1.41	0.22	$ 17.07

[1] ΔFC/sqft is incremental first cost for energy conservation measures (dollars/sqft).
Source: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-16250.pdf, p.E-1

Figure 9.1.9 continued.

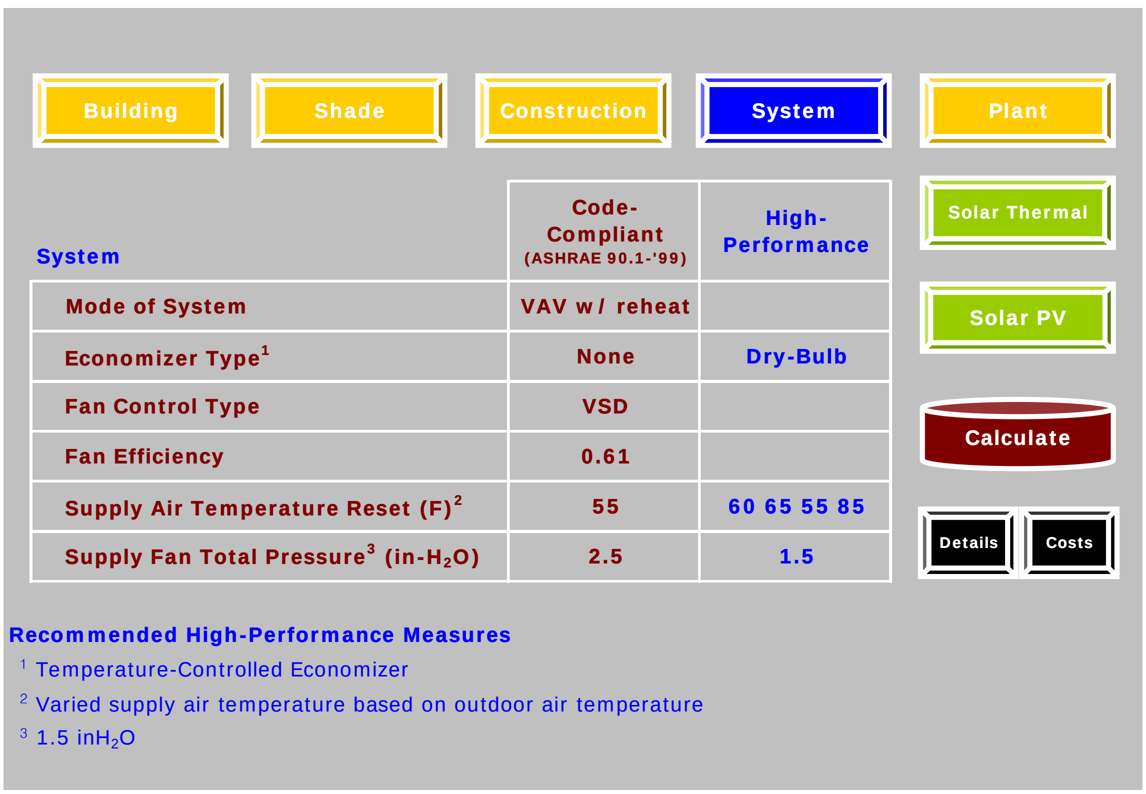


Figure 9.1.10 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of "System".

Figure 9.1.10 is the input screen for "System". A building's HVAC system is selected in this screen. Temperature-based economizer can be selected as a high-performance measure. Fan control has two selections, constant speed and variable speed. Supply air temperature can be reset to variable temperatures from the constant speed of 55 F. Another high-performance measure available in this screen is the supply fan total pressure. Figure 9.1.11 shows detailed input parameters for the "System" input. It includes the simulation information about zone control, zone air, system control, system air, system terminal, system, sizing, plant assignment, fan schedule, space cooling schedule, space heating schedule, and service hot water schedule.

Details

Zone Control

Design Heat Temperature (F)	70
Design Cool Temperature (F)	75
Thermostat Type	Reverse
Throttling Range	4

Zone Air

Total Flow Rate (cfm/sqft)	1
Outside Air Flow Rate (cfm/sqft)	0.2

System Control

Maximum Supply Temperature (F)	105
Minimum Supply Temperature (F)	55

Figure 9.1.11 Screen of the Detailed Simulation Input Parameters for the "System" Screen of the Proposed Easy-to-use Tool.

System Air

Outside Air Control	Temperature
Maximum Outside Air Fraction	1
Minimum Outside Air Fraction	0.1
Return Air Path	Plenum
Duct Air Loss	1
Duct Delta T. (F)	0

System Terminal

Reheat Delta T. (F)	50
Minimum CFM Ratio	0.3

System

Heat Source	Hot Water

Sizing

Sizing Ratio	1
Cooling Sizing Ratio	1
Heating Sizing Ratio	1

Plant Assignment

Service Hot Water Size	Plant
Service Hot Water (GPM)	Calculated
Service Hot Water Supply Temperature (F)	140
Service Hot Water Loss	0.03

Fan Schedule

Weekdays
1am-8am: 1,1,1,1,1,1,1,1
9am-4pm: 1,1,1,1,1,1,1,1
5pm-0am: 1,1,1,1,1,1,1,1

Figure 9.1.11 continued.

Weekends
1am-8am: 1,1,1,1,1,1,1,1
9am-4pm: 1,1,1,1,1,1,1,1
5pm-0am: 1,1,1,1,1,1,1,1

Space Cooling Schedule

Weekdays
1am-8am: 83,83,83,83,83,83,75,75
9am-4pm: 75,75,75,75,75,75,75,75
5pm-0am: 75,83,83,83,83,83,83,83
Weekends
1am-8am: 83,83,83,83,83,83,75,75
9am-4pm: 75,75,75,75,75,75,75,75
5pm-0am: 75,83,83,83,83,83,83,83

Space Heating Schedule

Weekdays
1am-8am: 60,60,60,60,60,60,68,68
9am-4pm: 68,68,68,68,68,68,68,68
5pm-0am: 68,60,60,60,60,60,60,60
Weekends
1am-8am: 60,60,60,60,60,60,68,68
9am-4pm: 68,68,68,68,68,68,68,68
5pm-0am: 68,60,60,60,60,60,60,60

Service Hot Water Schedule

Weekdays
1am-8am: 0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.15
9am-4pm: 0.30,0.35,0.35,0.45,0.55,0.50,0.30,0.30
5pm-0am: 0.40,0.20,0.20,0.10,0.15,0.05,0.00,0.00

Figure 9.1.11 continued.

Weekends
1am-8am: 0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.10
9am-4pm: 0.10,0.20,0.15,0.20,0.15,0.15,0.10,0.10
5pm-0am: 0.10,0.00,0.00,0.00,0.00,0.00,0.00,0.00

Figure 9.1.11 continued.

Building | Shade | Construction | System | Plant

Solar Thermal

Solar PV

Calculate

Details | Costs

General	Code-Compliant (ASHRAE 90.1-'99)	High-Performance
Cooling Type	Electric	
Cooling Efficiency (COP)[1]	5.55	7.5
Chilled Water Pump Control[2]	Constant	VSD
Chiller Staging[3]	1 chiller	3 chillers
Heating		
Space Heating Fuel Type	Natural Gas	
Boiler Efficiency, E_t (%)[4]	75	95
Hot Water Pump Control[5]	Constant	VSD
Service Water Heater		
Water Heater Fuel Type	Natural Gas	
Water Heater Efficiency, E_t (%)[6]	80	85

Recommended High-Performance Measures

[1] COP 7.5 [2] VSD
[3] 3 chillers [4] 95%
[5] VSD [6] 85%

Figure 9.1.12 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of "Plant".

Figure 9.1.13 shows the detailed simulation input parameters for the “Plant” screen of the proposed tool. It includes specific chiller performance data including curve-fit coefficients and the parameters for cooling towers. Information about boiler, service water heater, and pumps for chilled water and hot water is also specified in the “Details” screen.

Details

Chiller

Chiller Type	Centrifugal
Chiller Fuel Source	Electricity
Curvefit Coefficients for OPEN-CENT-CAP-FT	
Bi-Quadratic: -0.29862, 0.029961, -0.000801, 0.017363, -0.000326, 0.000631	
Curvefit Coefficients for OPEN-CENT-EIR-FT	
Bi-Quadratic: 0.517772, -0.004004, 2e-005, 0.006988, 8.3e-005, -0.000155	
Curvefit Coefficients for OPEN-CENT-EIR-FPLR	
Quadratic: 0.171493, 0.588202, 0.237373	
Chiller Minimum Ratio	0.1
Chiller Operating Ratio	1.0
Electric Input Ratio	0.192
Chilled Water Temperature (F)	44
Chilled Water Throttle (F)	2.5

Figure 9.1.13 Screen of the Detailed Simulation Input Parameters for the “Plant” Screen of the Proposed Easy-to-use Tool .

Cooling Tower

Cooling Tower Type	Open
Electric Input Ratio	0.0105
Tower Design Wet-Bulb Temperature (F)	75
Tower Set-Point Temperature (F)	85
Minimum Tower Water Temperature (F)	65
Tower Fan Control	Two Speed

Boiler

Boiler Type	Hot Water
Boiler Fuel Source	Natural Gas
HW Boiler Heat Input Ratio	1.25
HW Boiler Heat Loss	0.02

Service Water Heater

Service Water Heater Type	Hot Water
Service Water Heater Fuel Source	Natural Gas
Water Heater Heat Input Ratio	1.39
Water Heater Heat Loss	0.03

Pumps

CHW Pump Control Type	Constant
HW Pump Control Type	Constant

Figure 9.1.13 continued.

Figure 9.1.14 shows the cost information of implementing the high-performance measures in the "Plant". As the "Costs" button is clicked, the screen is popped up for the user to find cost information for chillers, boilers, pumps for chilled water and hot water.

Costs

Chiller Costs [1]

Rotary-Screw Water Chillers						
Code	Reciprocating Water Chillers	Daily Output	Labor Hours	Unit	Bare Material	Bare Labor
4130	110 ton cooling	0.15	213.000	Ea.	55,000	6,150
4140	120 ton cooling	0.14	223.000	Ea.	59,000	6,450
4150	140 ton cooling	0.14	233.000	Ea.	69,500	6,750
Code	Screw, Liquid Chiller, Air Cooled, Insulated Evaporator	Daily Output	Labor Hours	Unit	Bare Material	Bare Labor
0120	130 ton	0.14	228.000	Ea.	63,500	6,600
0124	160 ton	0.13	246.000	Ea.	78,000	7,100
0128	180 ton	0.13	250.000	Ea.	87,500	7,250
0132	210 ton	0.12	258.000	Ea.	96,500	7,450
0136	270 ton	0.12	266.000	Ea.	110,500	7,675
0140	320 ton	0.12	275.000	Ea.	138,500	7,950
0200	Packaged Unit, Water Cooled					
0210	80 ton	0.14	223.000	Ea.	35,100	6,450
0220	100 ton	0.14	230.000	Ea.	41,000	6,650
0230	150 ton	0.13	240.000	Ea.	58,500	6,950
0240	200 ton	0.13	251.000	Ea.	67,000	7,250
0250	250 ton	0.12	260.000	Ea.	72,000	7,525
0260	300 ton	0.12	266.000	Ea.	82,000	7,675
0270	350 ton	0.12	275.000	Ea.	116,000	7,950
Direct Expansion Water Chillers						
Code	Direct Expansion, Shell and Tube Type, for Built up Systems	Daily Output	Labor Hours	Unit	Bare Material	Bare Labor
	1 ton	2.00	8.000	Ea.	5,050	218
	5 ton	1.90	8.421	Ea.	8,400	229
	10 ton	1.70	9.412	Ea.	10,400	257
Centrifugal Water Chillers						
Code	Absorption Water Chillers	Daily Output	Labor Hours	Unit	Bare Material	Bare Labor
	1125 ton	0.08	421.000	Ea.	458,500	12,200
	1250 ton	0.07	444.000	Ea.	493,000	12,800
	1465 ton	0.07	463.000	Ea.	584,500	13,400
	1660 ton	0.07	477.000	Ea.	687,500	13,800
Code	Centrifugal/Screw/Reciprocating Water Chillers	Daily Output	Labor Hours	Unit	Bare Material	Bare Labor
	400 ton	0.11	283.000	Ea.	135,500	8,175
	450 ton	0.11	290.000	Ea.	142,000	8,375
	500 ton	0.11	296.000	Ea.	165,000	8,600
	550 ton	0.11	304.000	Ea.	181,500	8,800
	600 ton	0.10	310.000	Ea.	195,000	8,950
	650 ton	0.10	320.000	Ea.	211,500	9,225
	700 ton	0.10	326.000	Ea.	228,000	9,425
	750 ton	0.10	333.000	Ea.	243,000	9,650
	800 ton	0.09	340.000	Ea.	254,000	9,850
	850 ton	0.09	351.000	Ea.	273,500	10,100
	900 ton	0.09	359.000	Ea.	301,500	10,400
	950 ton	0.09	363.000	Ea.	318,000	10,500
	1000 ton	0.09	372.000	Ea.	352,500	10,800
	1100 ton	0.08	385.000	Ea.	368,000	11,100
	1200 ton	0.08	395.000	Ea.	401,500	11,400

[1] https://www.meanscostworks.com//subscription/trialoffer.aspx?mailDrop=IGC2&pCode=1007

Figure 9.1.14 Screen of the Cost Information of Implementing High-performance Measures in "Plant" Screen of the Proposed Easy-to-use Tool.

Boiler Costs [2]

Maker	Type	Thermal Efficiency	Capacity	Cost
Lochinvar (Tom Watson, Twatson@Huntongroup.com)	CBN0495	81%	495 kBtu/hr	Equipment: $3424, Labor: $3000 Total: $6424 ==> Two Boilers Total: $12,848
Lochinvar (Tom Watson, Twatson@Huntongroup.com)	PBN0500	88%	500 kBtu/hr	Equipment: $8479, Labor: $3000 Total: $11,479 ==> Two Boilers Total: $22,958
Laars (Steve Aytes, Saytes@oslinnation.com)	Conventional	85%	758 kBtu/Hr	Equipment: $5,000
Laars (Steve Aytes, Saytes@oslinnation.com)	Condensing	95%	758 kBtu/Hr	Equipment: $20,000 (4 times the conventional boiler)
Market-Available Energy-Efficient Boilers	Fulton PHW-0500	95%	500 kBtu/hr	n/a
	Fulton PHW-1000	95%	1000 kBtu/hr	n/a

Boilers, Gas-Fired Natural or Propane, Standard Control						
Code	Cast-Iron Boilers	Daily Output	Labor Hours	Unit	Bare Material	Bare Labor
2480	6100 MBH	0.13	246.000	Ea.	60,500	7,100
2500	6390 MBH	0.12	266.000	Ea.	64,000	7,675
2520	6680 MBH	0.11	290.000	Ea.	65,000	8,375
2540	6970 MBH	0.10	320.000	Ea.	68,000	9,200
3000	Hot Water, Gross Output, 80 MBH	1.46	21.918	Ea.	1,500	635
3020	100 MBH	1.35	23.704	Ea.	1,700	685
3040	122 MBH	1.10	29.091	Ea.	1,850	845
3060	163 MBH	1.00	32.000	Ea.	2,225	930
3080	203 MBH	1.00	32.000	Ea.	2,475	930
3100	240 MBH	0.95	33.684	Ea.	2,575	965
3120	280 MBH	0.90	35.556	Ea.	2,625	1,025
3140	320 MBH	0.80	40.000	Ea.	3,025	1,150
3160	360 MBH	0.71	45.070	Ea.	3,450	1,300
3180	400 MBH	0.64	50.000	Ea.	3,675	1,450
3200	440 MBH	0.58	54.983	Ea.	3,950	1,575
3220	544 MBH	0.51	62.992	Ea.	6,800	1,800
3240	765 MBH	0.46	70.022	Ea.	8,225	2,025
3260	1088 MBH	0.40	80.000	Ea.	10,200	2,300
3280	1275 MBH	0.36	89.888	Ea.	11,700	2,600
3300	1530 MBH	0.31	104.000	Ea.	12,300	3,025
3320	2000 MBH	0.26	125.000	Ea.	13,300	3,600
3340	2312 MBH	0.22	148.000	Ea.	15,400	4,275
3360	2856 MBH	0.20	160.000	Ea.	18,200	4,625
3380	3264 MBH	0.18	179.000	Ea.	19,300	5,175
3400	3808 MBH	0.16	195.000	Ea.	21,300	5,625

[2] http://huntonggroup.com
http://www.oslination.com
https://www.meanscostworks.com//subscription/trialoffer.aspx?mailDrop=IGC2&pCode=1007

Figure 9.1.14 continued.

Pump Costs [3]

Maker	Type	Capacity	CHW / HW	Cost
CHW Pump (B&G)	1510-3E-15HP	340 GPM @ 85'	CHW Pump (1 VFD needed)	Equipment: Pump - $2,300 each VFD - $1,700 each (Need labor cost) RSMeans: $3175 (15HP VFD) = Labor and VFD
HW Pump (B&G)	1510-1.5BC-5HP	64 GPM @85'	HW Pump (2 VFDs needed)	Equipment: Pump - $1,400 each VFD - $750 each RSMeans: $2200 (5HP VFD) = Labor and VFD

[3] https://www.meanscostworks.com//subscription/trialoffer.aspx?mailDrop=IGC2&pCode=1007
Inverter (VFD) cost information: http://www.electrodepot.net/vfd.htm, http://www.electrodepot.net/monitor.htm
Inverter motor cost: http://web4.automationdirect.com/adc/Overview/Catalog/AC_Drives_-z-_Motors

Figure 9.1.14 continued.

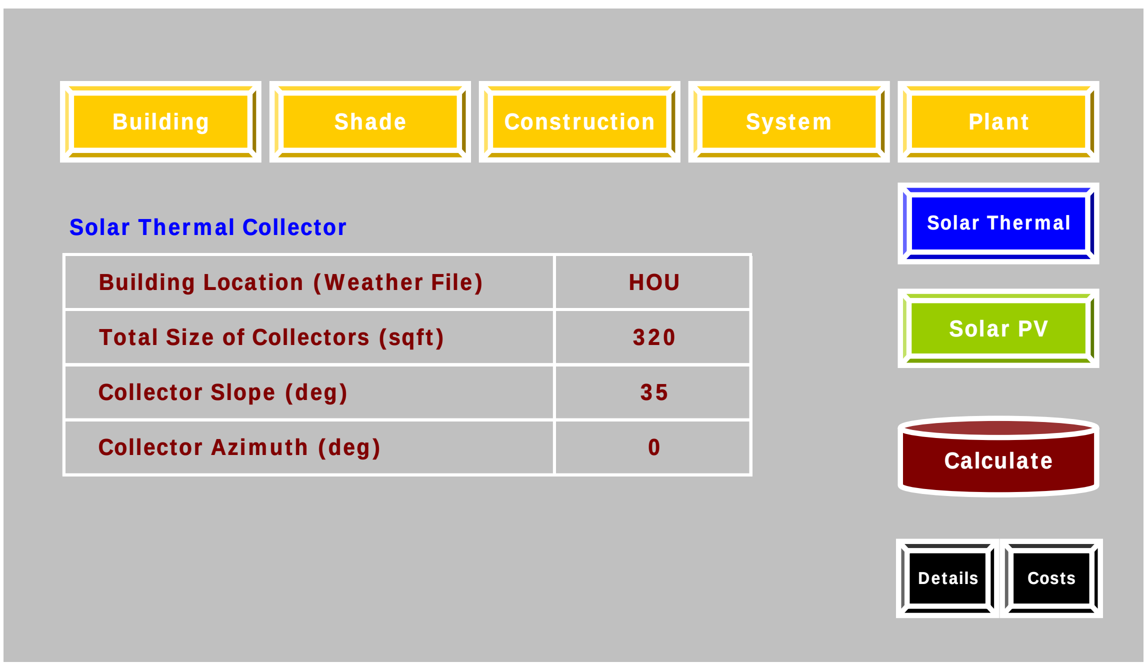


Figure 9.1.15 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of "F-Chart".

Figure 9.1.15 and Figure 9.1.16 show the input screen of "Solar Thermal" and the details of input parameters of the F-Chart program for the solar thermal systems analysis, respectively. Input parameters are simplified for analysis in the front screen; however, as shown in Figure 9.1.16, the F-Chart program is internally run for the solar thermal systems analysis. The "Details" screen for the solar thermal systems analysis includes the specific parameters for the evacuated tubular collectors and the water storage system.

Details

Evacuated Tubular Collector

Number of Collector Panels	10
Collector Panel Area (sqft)	32
FR*UL (Test Slope) (Btu/sqft-hr-F)	0.05
FR*TAU*ALPHA (Test Intercept) (Degree)	0.42
Collector Slope (Degree)	35
Collector Azimuth (South=0) (Degree)	0
Receiver Orient (1=EW, 2=NS)	2
Incidence Angle Mode (Perpendicular)	
1 .999 .998 .995 .981 .953 .882 .700 .350 .000	
Incidence Angle Mode (Parallel)	
1 .999 .998 .995 .981 .953 .882 .700 .350 .000	
Collector Flow Rate/Area (lb/sqft-hr)	11

Figure 9.1.16 Screen of the Detailed Simulation Input Parameters for the "Solar Thermal" Screen of the Proposed Easy-to-use Tool .

Modify Test Values (1=Yes, 2=No)	2
Test Collector Flowrate/Area (lb/sqft-hr)	11
Test Fluid Specific Heat (Btu/lb-F)	1

Water Storage System

City Call Number for Houston, TX	96
Water Storage Volume (Gallons)	500
Building UA (0 for SHW only) (Btu/hr-F)	0
Fuel (1=EL, 2=NG, 3=OIL, 4=OTHER)	2
Efficiency of Fuel Usage (%)	100
Service Hot Water (1=Yes, 2=No)	1
Daily Hot Water Usage (Gallons)	325
Water Set Temperature (F)	120
Environment Temperature (F)	68
Service HW Storage Tank Size (Gallons)	200
UA of AUX Storage Tank (Btu/hr-F)	7.6
Pipe Heat Loss (1=Yes, 2=No)	2
Inlet Pipe UA (Btu/hr-F)	5
Outlet Pipe UA (Btu/hr-F)	5
Relative Load HX Size	1
Collector Storage HX (1=Yes, 2=No)	2
Tank Side Flowrate/Area (lb/sqft-hr)	11
Heat Exchanger Effectiveness	0.5

Figure 9.1.16 continued.

Figure 9.1.17 shows the cost information of solar thermal systems. This screen is activated by clicking the “Costs” button in the “Solar Thermal” screen of the proposed tool. It includes the unit cost for two different hot water supply temperature cases, 140 F and 110 F. As shown in the figure, the costs are specified based on the system configurations.

Costs

Solar Thermal Collector Costs

Source		Product Details	Hot water Supply Temperature (F)	Unit Cost ($)
RS Means Costworks [1]	Assembly Cost	D2020 295 Solar, Closed Loop, Hot Water Systems, immersed heat exchanger with 1/2" tubing, 4 ea. 4'x4'4" vacuum tube collector, 120 gallon tank	140	$8,525.00
			110	$8,525.00
SolarMaxx [2]	Pre-packaged System	Sunmaxx-25 Evacuate Tube Collector with80 gal. tank, Nalves, Pumps, Expansion Tank and Controls	140	$2,999.95
			110	$2,999.95
Apricus [3]	Packaged Cost	TS200-4-30-PC (4 collectors + 200 gallon tank)	110	$12,469.01
		TS300-5-30-PC (5 collectors + 300 gallon tank)	140	$14,960.86
		TS300-6-30-PC (6 collectors + 300 gallon tank)	140	$16,911.15
	Component Cost	4 AP-30 Collectors, TS200-200 gallon Tank, Pump, Control, Valves and other Accessories	110	$13,230.29
		5 AP-30 Collectors, TS300-300 gallon Tank, Pump, Control, Valves and other Accessories	140	$15,981.97
		6 AP-30 Collectors, TS300-300 gallon Tank, Pump, Control, Valves and other Accessories	140	$17,973.65

[1] https://www.meanscostworks.com//subscription/trialoffer.aspx?mailDrop=IGC2&pCode=1007

[2] http://fortressgreenbuildingsupply.com/index.php?option=com_content&task=blogsection&id=5&Itemid=29

[3] http://www.apricus.com/

Figure 9.1.17 Screen of the Cost Information of Implementing Solar Thermal Systems in “Solar Thermal” Screen of the Proposed Easy-to-use Tool.

Figure 9.1.18 is the screen of “Solar PV” of the proposed tool. It includes only basic input parameters. The user can see details of input parameters of the PV F-Chart program, which analyzes solar photovoltaic systems, by selecting the “Details” button in the screen of Figure 9.1.18.

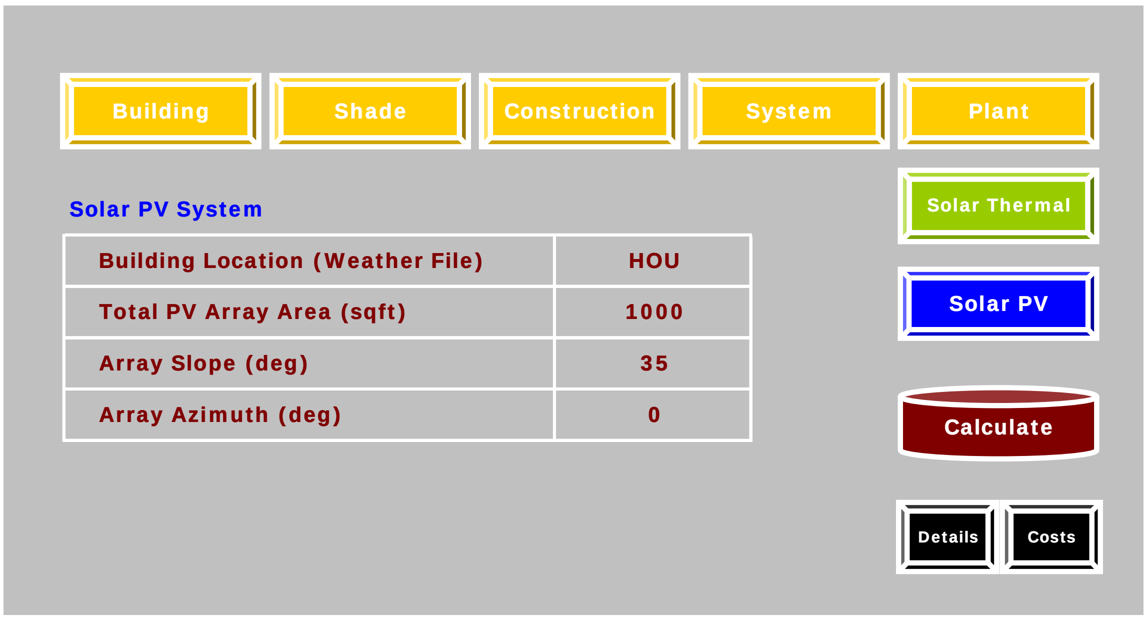


Figure 9.1.18 Prototype Input Screen of the Proposed Easy-to-use tool for the Section of “PV F-Chart”.

Figure 9.1.19 shows the detailed input parameters for the PV F-Chart program. In this screen, the PV system is utility feedback photovoltaic system, which does not include electricity storage systems such as battery storage systems. The “Details” screen shows the PV array efficiency and the slope of the system. Figure 9.1.20 shows a cost screen for the PV systems. There are total of thirty-six different solar PV systems introduced in the screen.

These solar PV panels are the panels available in the current market in 2009. Each PV model includes information about power (Watts), Amps, Volts, weight, and size of the panels.

Details

Utility Feedback PV System

City Call Number for Houston, TX	96
Output (1=Summary, 2=Detailed)	1
Cell Temperature at NOCT Conditions (F)	113
Array Reference Efficiency	0.15
Array Reference Temperature (F)	77
Maximum Power Efficiency Temperature Coefficient (Times 1000) (1/F)	2.5
Efficiency of Maximum Power Point Tracking Electronics	0.90
Efficiency of Power Conditioning Electronics	0.88
Percent Standard Deviation of the Load (%)	0
Array Area (sqft)	1000
Array Slope (Degree)	35
Array Azimuth (South=0) (Degree)	0

Figure 9.1.19 Screen of the Detailed Simulation Input Parameters for the "Solar PV" Screen of the Proposed Easy-to-use Tool.

Costs

Solar Thermal Collector Costs [1]

Maker & Model	Watts	Amps	Volts	Weight (lbs.)	Size (Inches)	Price
Kyocera KC 130TM	130	7.39	17.6	26.8	56.1x25.7x2.2	$555
Kyocera KD135GX-LP	135	7.63	17.7	28.7	59.1 X 26.3 X 1.42	$540
Kyocera KD180GX-LP	180	7.63	23.6	36.4	52.8 X 39 X 1.4	$648
Kyocera KD205GX-LP	205	7.71	26.6	40.8	59.1 X 39 X 1.4	$775
Kyocera KD210GX-LP	210	7.9	26.6	40.8	59.1 X 39 X 1.4	$762
Kyocera KC 40T	40	2.24	17.9	10	20.7x25.7x2.125	$265
Kyocera KC 50T	50	3	16.7	10	25x26	$280
Kyocera KC 65T	65	3.75	17.4	13.2	29.8x25.7x2.125	$340
Kyocera KC 85T	85	4.75	17.4	18.3	39.65x25.67x2.2	$425
Mitsubishi MF125UE5N	125	7.23	17.3	29.8	58.9 x 26.5 x 1.81	$665
Mitsubishi MF125UE4N	125	7.23	17.3	29.8	58.9 x 26.5 x 1.81	$635
Mitsubishi MF185UD5	185	8.13	24.4	37	65.3 x 32.6 x 1.81	$899
SunWize SW1750 Solar panel	175	4.8	36.5	37.5	62.20x31.81	$656
Sanyo HIT-200BA19 HIT	200	3.59	55.8	31	51.9x34.6x1.8	$1,032
Sanyo HIT Power N 205N/HIP-205NKHA5	205	5.05	40.7	35.3	62.2x31.4x1.8	$944
Sanyo HIT Power N 210N/HIP-210NKHA5	210	5.09	41.3	35.3	62.2x31.4x1.8	$959
Sanyo HIT Power N 215N/HIP-215NKHA5	215	5.13	42	35.3	63.2x32x72.8	$989
Kaneka G-SA060 Solar Panels	60	0.9	67	30.2	39x39x1.6	$227
REC SCM 210WP	210	7.5	28.2	48.4	66.55x39.01x1.69	$958
REC SCM 215WP	215	7.6	28.3	48.4	66.55x39.01x1.69	$998
REC SCM 220WP	220	7.7	28.3	48.4	66.55x39.01x1.69	$1,015.00
REC SCM 225WP	225	7.9	28.4	48.4	66.55x39.01x1.69	$1,015.00
Canadian Solar CSI CS6P-190	190	7.33	36	40.7	66.55x39.01x1.69	$625
PowerUp BSP10	10	0.58	17.3	4.2	16.5x10.7x1.31	$108
PowerUp BSP20	20	1.2	17.3	4.8	19x16.7x1.31	$152
PowerUp BSP30	30	1.67	18	5	19x16.7x1.31	$245
PowerUp BSP40	40	2.4	17.8	5	25x21.1x1.31	$260

Figure 9.1.20 Screen of the Cost Information of Implementing Solar PV Systems in "Solar PV" Screen of the Proposed Easy-to-use Tool .

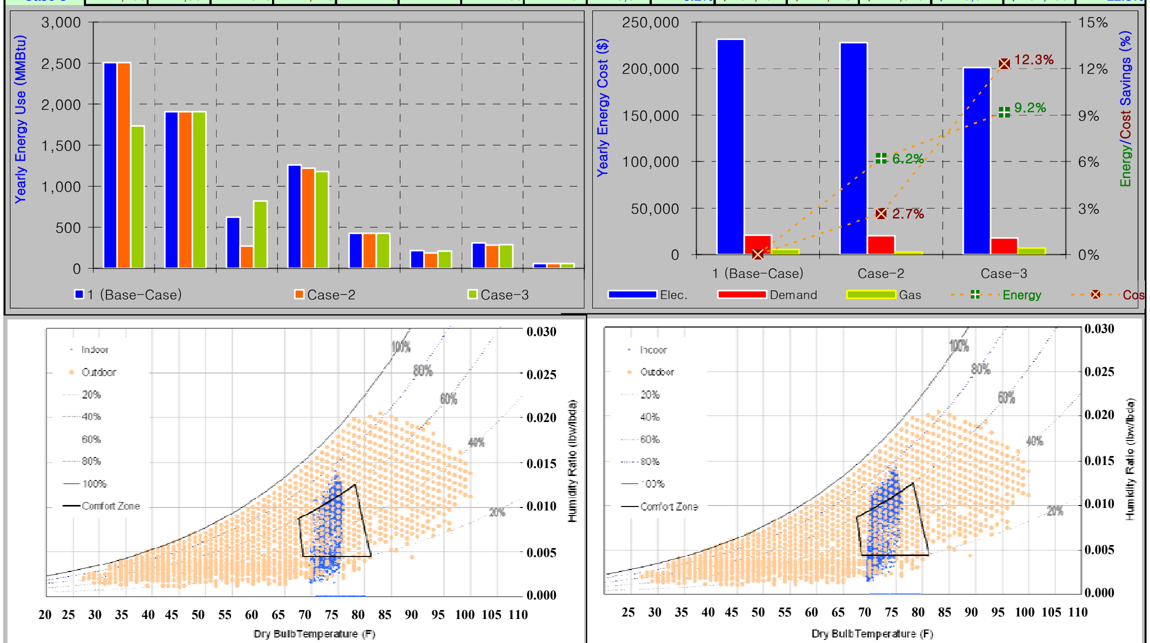
Sharp 170	170	4.9	34.8	38	62x35.5x1.8	$580
Sharp 175	175	4.95	35.4	38	62x33	$699
Sharp 180	180	5.02	35.86	38	66.93x38.19x5.12	$675
Sharp 80	80	4.67	17.1	19	48x21	$450
Sharp ND-216U2	216	7.53	28.71	46.3	64.6x39.1x1.8	$1,004
Sharp ND-224U2	224	8.33A	36.6	45	65.16 x 39.76 x 4.25	$1,100
Sharp ND-224U1F	224	8.33A	36.6	44.1	64.6 x 39.1 x 1.8	$899
SolarWorld SW 175	175	4.9	35.7	40	63.9x32x1.6	$855
SunTech 175	175	4.95	35.2	34.1	62.2x31.8x1.38	$749

[1] http://www.wholesalesolar.com/solar-panels.html

Figure 9.1.20 continued.

Figure 9.1.21 is an example of the final report of the proposed Easy-to-use tool. In the final report, the users will see the energy consumption results for each energy use category with the total energy consumption. Energy costs are also displayed for different fuel types such as electricity and natural gas and electric demand as well. In the example of Figure 9.1.21, three different simulations were run to allow for comparisons. The first case is the base case and the others for implementing two different high-performance measures. The indoor air conditions are plotted in the psychrometric charts for each case to show the indoor air condition. The users can see which category of energy use changed the most and/or the least. The cost savings can be compared with the energy savings, so that the user can have better idea for their design decision between energy savings and cost savings.

Run #	Energy Use by Category								Energy Total		Cost by Category			Cost Total		
	Lighting (MMBtu)	Equip. (MMBtu)	Heating (MMBtu)	Cooling (MMBtu)	HtRj. (MMBtu)	Misc. (MMBtu)	Fans (MMBtu)	DHW (MMBtu)	Use (MMBtu)	Savings (%)	Elec. ($)	Demand ($)	Gas ($)	Cost ($)	Savings ($)	Savings (%)
1 (Base-Case)	2,506	1,907	622	1,258	427	215	308	57	7,318	-	$ 231,500	$ 20,755	$ 5,432	$ 257,686	-	-
Case-2	2,506	1,907	271	1,219	427	188	284	57	6,865	6.2%	$ 227,949	$ 20,290	$ 2,617	$ 250,856	$ 6,831	2.7%
Case-3	1,735	1,907	820	1,178	426	212	288	57	6,647	9.2%	$ 201,187	$ 17,748	$ 7,013	$ 225,947	$ 31,739	12.3%



Case-2 IEQ | Case-3 IEQ

Figure 9.1.21 Prototype Report Screen of the Proposed Easy-to-use tool.

9.2 Comparison with Other Similar Tools

Several simplified, easy-to-use, and/or user-friendly building simulation programs have already been developed, so that designers and engineers can easily access to the programs and get quick results for their building designs. The proposed easy-to-use tool would be an improvement over all existing tools surveyed, including COMCheck-web (PNNL, 2006), eQuest (eQUEST, 2008), eCALC (Haberl et al., 2004d), Energy IQ (LBNL, 2008b), BCHP Screener (ORNL, 2008b), Green Building Studio (Autodesk, 2008b), ECOTECT (Autodesk, 2008a), and EnergyGauge Summit (EnergyGauge, 2009).

However, there are similarities and differences between the proposed easy-to-use tool and the other programs. In the following sections each of these previous works are reviewed.

9.2.1 The Proposed Easy-to-use Tool vs. eCALC Program

The framework of the proposed easy-to-use tool originally came out of the eCALC program (Haberl et al., 2004d). The SGDOE-2.1e input file has a similar structure with the DOE-2.1e simulation input file in the eCALC program for energy performance evaluation of office buildings. However, the SGDOE-2.1e simulation model has gone through an empirical validation process, including a calibrated simulation using measured data from a prototypical large office building, the John Connally Building (JCB), in College Station, TX.

Through the calibration process to the measured data of the JBC building, the SGDOE-2.1e simulation model was shown to be a reliable model, which represents reasonably a real building's energy consumption. The simplified analysis was then used to evaluate the 14 high-performance measures in the previous chapter. The 14 high-performance measures are included in the proposed easy-to-use tool for users to select for their design of high-performance buildings, while the eCALC program does not offer the function. In addition, the proposed tool provides solar thermal and PV analyses.

9.2.2 The Proposed Easy-to-use Tool (Above Commercial Building Code Simulation) vs. COMCheck-web

COMCheck-web requires only simple inputs and basic knowledge of a building (PNNL, 2006). It runs on an internet website and provides a simple check of the code compliance of a commercial building. However, COMCheck-web only analyzes typical features of commercial buildings including high-rise residential buildings (greater than three stories) to test code compliances such as building construction and loads. Therefore, many high-performance systems and renewable energy systems cannot be simulated. Also, this is not a performance evaluation tool but a code-compliance assessment tool and as a consequence it does not provide thermal comfort information.

In contrast to the COMCheck-web program, the proposed easy-to-use tool would have multiple functions and applications including not only commercial code-compliant simulation but also above-code simulations using high-performance measures. The proposed easy-to-use tool could handle many of the high-performance measures, and as a result, a maximum energy efficient office building could be designed. As shown in the previous chapters, a high-performance building could be 48.1% less consumption than a building built to be compliant with the ASHRAE Standard 90.1-1999 using the 14 high-performance measures analyzed in this study for College Station, TX. In addition, the energy savings could exceed 50% when a modest amount of renewable (solar) energy is incorporated with it.

9.2.3 The Proposed Easy-to-use Tool (Solar Energy Integration) vs. eQUEST

eQUEST is also one of the available easy-to-use programs for building energy performance analysis (eQUEST, 2008). It is based on DOE-2-2 program, with a graphical user interface on to it. Like the proposed easy-to-use tool, the eQUEST program also has allows multiple simulation runs and allows for the comparison of simulation results. In contrast to eQUEST, however, the proposed easy-to-use tool has the ASHRAE Standard 90.1-1999 code-compliant model as a base case for a prototypical large office building. Also in the proposed tool, the users would not have to go through the ASHRAE Standard 90.1-1999 building code to develop a code-compliant simulation model for their use. Also, the automatic integration of the solar thermal energy systems would be available for the proposed easy-to-use tool. The eQUEST program does not currently have a solar thermal systems analysis function in its analysis capabilities. Finally, the current eQUEST program is not a web-based program, but instead requires the users to download and install the package to run on their computer.

9.2.4 The Proposed Easy-to-use Tool (Indoor Environmental Quality) vs. EnergyIQ

EnergyIQ is a web-based tool that users can use to benchmark existing or design-stage buildings compared to a wide range of energy-related metrics for other buildings (LBNL, 2008b) at the present time. The focus of EnergyIQ is on energy, money, and carbon emissions. This program is still under development and is only available for demonstration purposes. The demonstration version includes three interactive internet web pages, which are the Benchmarking, Actions, and MyIQ web pages. These are the web pages and working interfaces for users of this program. The Benchmarking web page deals with the matters in which users find their interests and benchmark them. In the Action web page, a user can select his/her energy-efficiency opportunities from a list of qualitative measures. The MyIQ web page manages a user's building compared with other buildings.

However, this program does not analyze the Indoor Environmental Quality (IEQ), while the proposed easy-to-use tool would. The proposed easy-to-use tool has gone through the process of checking the IEQ for the base case and all the cases of implementing high-performance measures as well.

9.2.5 The Proposed Easy-to-use Tool vs. BCHP Screener

BCHP (Building Cooling, Heating, and Power) Screener is a tool that uses the DOE-2.1e simulation program as the main engine for evaluations of combined cooling, heating, and power in commercial buildings. This tool has a graphical user interface, so that users can easily access the program and choose options from a computer screen. It calculates building cooling, heating, hot water, and electrical loads. In addition, the cost of site energy is calculated such as electric power and natural gas. Energy cost savings can also be calculated for time-of-day rates (ORNL, 2008b). The main purpose of this tool is to assess the energy performance of existing commercial facilities. Users of this tool need to collect data from their existing facilities and set a target for energy efficiency or energy savings of their buildings. The BCHP Screener helps users develop simulation models of their commercial buildings and evaluates the energy performance and calculates energy costs. Then, users can implement Energy Conservation Measures (ECMs) into the simulation models of their buildings. This tool runs the DOE-2.1e simulation program, retrieves results from output files, and compares results between as-is simulation model and simulation model with ECMs.

In contrast to the BCHP Screener, the proposed easy-to-use tool would have an ASHRAE Standard 90.1-1999 code-compliant model as the baseline and other options. Application of solar energy systems into the proposed easy-to-use tool would be another difference in terms of utilizing a renewable energy source. In addition, the proposed easy-to-use tool would include the sources, which are savings results from 14 high-performance measures, to help users have ideas of consequences in advance of implementing high-performance measures either into their new building designs or into their existing buildings' ECMs.

9.2.6 The Proposed Easy-to-use Tool vs. Green Building Studio

Green Building Studio is a web-based energy analysis tool for architects and designers to evaluate how building components impact energy consumption and to improve a project's economic and environmental performance in the design process. This program integrates with the Revit Architecture (Autodesk, 2008b) and Revit MEP (Autodesk, 2008a) software. Users can incorporate the Green Building Studio program with the Revit programs through a plug-in (Autodesk, 2008b). This tool focuses on the evaluation of the energy profiles and carbon footprints of the building designs in the early design cycle. Architects, designers, and engineers can share the files created by Green Building Studio using their architecture and engineering programs to design sustainable buildings.

Green Building Studio is similar to the proposed easy-to-use tool in terms of user interface (web-based) and energy performance evaluation for new design. However, it does not include the evaluation function for Indoor Environmental Quality (IEQ). Also, its functions are only focused on the new building design, and does not easily deal with existing buildings. In contrast to Green Building Studio, The proposed easy-to-use tool includes functions for dealing with IEQ and the energy performance evaluation of existing buildings.

9.2.7 The Proposed Easy-to-use Tool vs. ECOTECT

ECOTECT is an environmental design tool that combines a 3-D modeling interface (Autodesk, 2008a). This tool includes solar, thermal, lighting, acoustic, and cost analysis functions. Users can play with design ideas at the conceptual design stages. Since the program was designed and developed by architects for architects, the main focus of this tool is to help design easily and graphically as one of the most visual and interactive tools. This tool includes functions interfacing with Radiance, EnrgyPlus, and many other analysis tools such as AutoCAD DXF, ESP-r, and XML.

In contrast to the advantage that ECOTECT can manage various other simulation and/or analysis programs, it does not include in-depth thermal simulation functions that other simulation engines can provide such as DOE-2.1e, EnergyPlus, and ESP-r. The proposed easy-to-use tool would include capabilities of simulating detailed thermal simulations as it has the DOE-2.1e program as its simulation engine. The 14 high-performance measures of the proposed easy-to-use tool can be useful information for users to have a quick picture for their high-performance building design, while ECOTECT could not provide that level of details for users. Also, indoor comfort analysis function is another important role that the proposed easy-to-use tool can offer.

9.2.8 The Proposed Easy-to-use Tool vs. EnergyGauge Summit

EnergyGauge Summit (EnergyGauge, 2009) is one of user-friendly, easy-to-use tools. It automatically generates reference buildings, allowing time-savings for the analysis of code-compliance and green building certification (EnergyGauge, 2009). Economic analysis is also available for proposed energy improvements. The platform of this software is the DOE-2.1e simulation program. This tool compares a user's case building to ASHRAE Standard 90.1-2001, 2004, and 2007 code-compliant models and the ASHRAE's Advanced Energy Design Guide (AEDG). Accompanying capacities contain the capability to run a simulation for LEED New Construction 2.2 and for calculating Federal Tax Deductions for EPACT 2005 guidelines from the Internal Revenue Service (IRS) and Department of Energy (DOE). This tool also includes the function of directly presenting the LEED 2.2 PDF file for energy optimization points to the United States Green Building Council (USGBC) (EERE, 2009).

The EnergyGauge Summit program includes some similarities such as same simulation engine (DOE-2.1e), code-compliant simulation, and use of the ASHRAE's Advanced Design Guide. In contrast to the proposed easy-to-use tool, however, the EnrgyGauge Summit program does not provide high-performance measures available for achieving more energy savings on top of the ASHRAE's AEDG. It would be desirable for users to have specific ideas of possible energy savings from individual high-performance measures. The indoor comfort analysis function of the proposed easy-to-use tool is another difference that EnergyGauge Summit does not include.

It is important to know the indoor comfort condition when the energy savings effort is made. Moreover, the EnergyGauge does not offer the analysis function for solar energy. The proposed easy-to-use tool integrates the building thermal simulation with the solar energy system analysis as renewable energy sources become more important for achieving ultimate goal of net zero (or zero) energy buildings.

9.2.9 Summary of Comparison

In this section the proposed easy-to-use tool was compared to several existing similar tools, including eCALC, COMCheck-web, eQUEST, EnergyIQ, BCHP Screener, Green Building Studio, ECOTECT, and EnergyGauge Summit. These programs were all designed for users to work easily for their energy efficiency targets. Also, there were similarities between the proposed easy-to-use tool and the other programs as presented in the previous subsections. Table 9.2.1 compares functions between tools. The main common function is graphic user interface that is provided by all programs shown. The application of the programs is mainly to new building design practices except for two tools, Energy IQ and BCHP Screener. More than half of the programs use the internet web browser as their interfaces, which are the proposed easy-to-use tool, eCALC, COMCheck-web, Energy IQ, and Green Building Studio. There are three programs that deal with issues for existing buildings, including the proposed easy-to-use tool, Energy IQ, and BCHP Screener.

However, there are also functions that only the proposed easy-to-use tool includes. First, the proposed easy-to-use tool includes the fourteen high-performance measures that could provide building practitioners with specific ideas and numbers of the energy impact from choosing the individual high-performance measures for both the new and existing building cases. Second, the proposed easy-to-use tool integrates the solar energy analysis functions with the DOE-2.1e simulation program, which could provide combined analyses of energy generation through the renewable energy source in buildings. Finally, the proposed easy-to-use tool includes the indoor comfort analysis, which would help users understand how their energy efficiency practices could impact the indoor environmental quality of their target buildings.

Table 9.2.1 Comparison of the Proposed Easy-to-use Tool with Other Similar Tools.

Tools	Reference	Graphic User Interface	Web-Based Tool	New Building Simulation	Existing Building Simulation	Indoor Comfort Analysis	High-Performance Measures	Solar Energy Integration
Proposed Easy-to-use Tool	Cho (2009)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
eCALC	Haberl et al. (2004)	Yes	Yes	Yes	No	No	No	No
COMCheck-web	PNNL (2006)	Yes	Yes	Yes	No	No	No	No
eQUEST	Hirsch (2003)	Yes	No	Yes	No	No	No	No
EnergyIQ	LBNL (2008)	Yes	Yes	No	Yes	No	No	No
BCHP Screener	ORNL (2008)	Yes	No	No	Yes	No	No	No
Green Building Studio	Autodesk (2008)	Yes	Yes	Yes	No	No	No	No
ECOTECT	Autodesk (2008)	Yes	No	Yes	No	No	No	No
EnergyGauge Summit	EnergyGauge (2009)	Yes	No	Yes	No	No	No	No

9.3 Applications of the Proposed Easy-to-use Tool

In the previous section the characteristics of the proposed easy-to-use tool were compared with other similar tools. The following subsections show the application examples of the proposed easy-to-use tool to three different scenarios: 1) application to a new building design, 2) application to a new building design with solar energy systems, and 3) application to facilities management for an existing building.

9.3.1 Application to New Building Design

This section provides an example of the application of the proposed easy-to-use tool to a new building design where a user could easily select building systems to develop a high-performance building. As this building is a new building design, the target building design is compared in terms of energy efficiency to the design that follows the ASHRAE Standard 90.1-1999 minimum code requirements.

9.3.1.1 ASHRAE Standard 90.1-1999 code-compliant design inputs (Case-1)

The code-compliant building simulation model in this example is based on specifications in ASHRAE Standard 90.1-1999. This example building is a typical large office building in Houston, Texas. Figure 9.3.1 shows the inputs of the proposed easy-to-use tool for the selection of general “Building” simulation input parameters. In this example a high-performance building is evaluated in Houston, Texas. This office building has six floors and faces south. Two high-performance measures, lighting power density and occupancy sensor installation, are available in the “Building” screen as shown in the blue column.

The Houston TMY2 weather file is selected for this location. Other general parameters are default values that the proposed easy-to-use tool includes as the ASHRAE Standard 90.1-1999 code-compliant parameters.

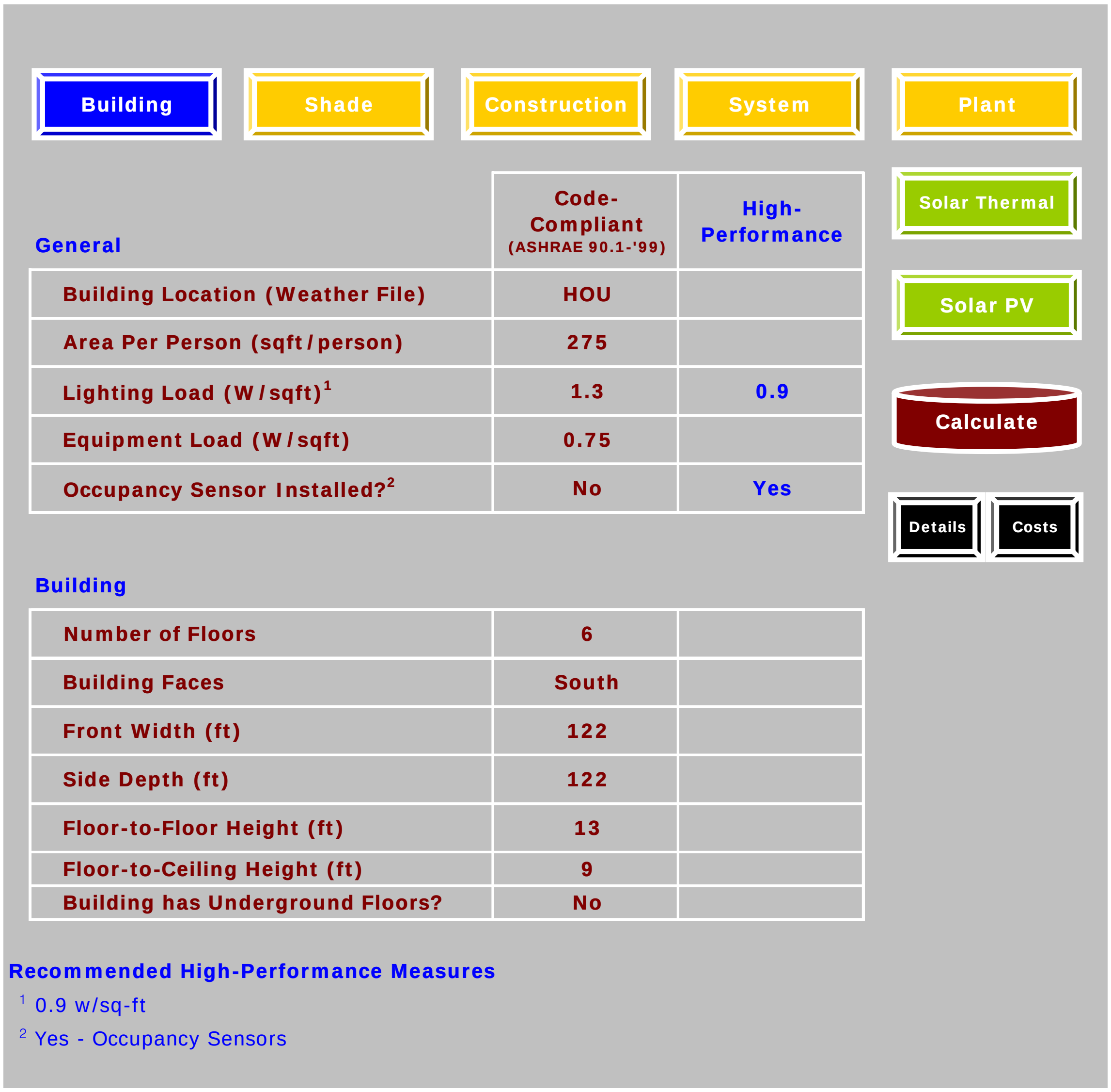


Figure 9.3.1 Input Screen of the Proposed Easy-to-use Tool for the Selection of General Building Parameters.

These are: area per person of 275 (sqft/person), lighting power density of 1.3 (W/sqft), equipment power density of 0.75 (W/sqft), and no occupancy sensors. In this figure the building construction parameters are also included. This building consists of six stories and faces south. The total conditioned space is 89,304 square feet having the front width of 122 feet and the side depth of 122 feet. Each floor has the ceiling height of 9 feet consisting of total floor-to-floor height of 13 feet. This example building has no underground floors. There are two high-performance measures recommended by the proposed tool: 1) low lighting power density of 0.9 W/sqft, which is 0.4 W/sqft lower than the ASHRAE Standard 90.1-1999 code minimum requirement of 1.3 W/sqft and 2) the implementation of occupancy sensors.

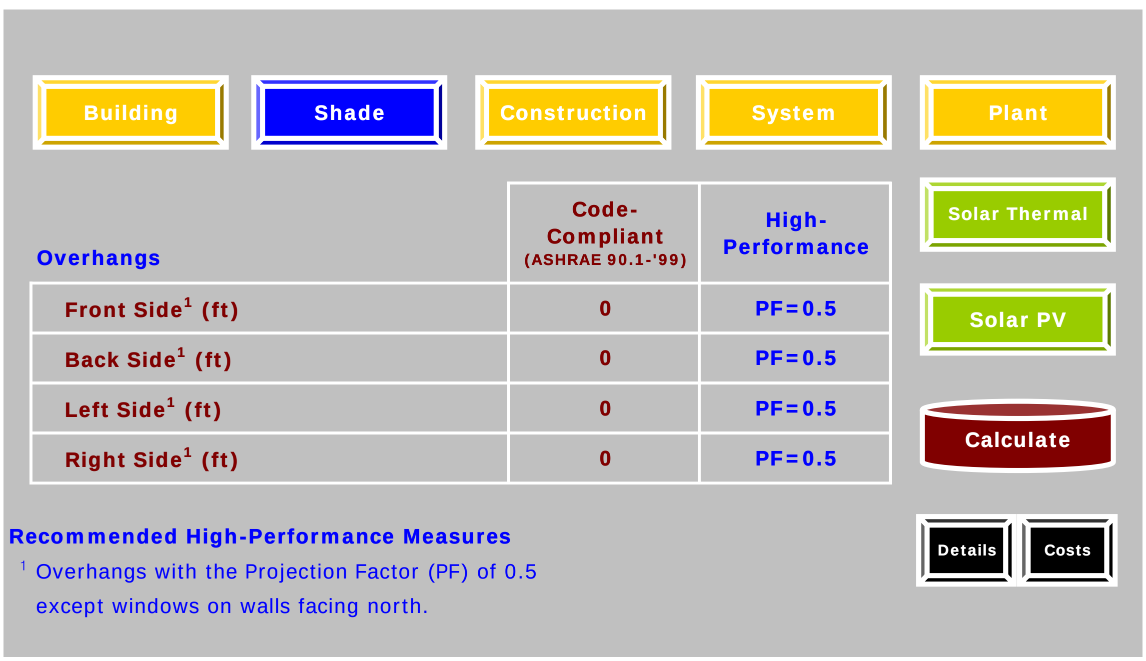


Figure 9.3.2 Input Screen of the Proposed Easy-to-use Tool for the Selection of Shades.

Figure 9.3.2 shows the screen of the proposed easy-to-use tool for the selection of shades. Since the code-compliant simulation does not include any shades, there are no shades selected in the screen for the code-compliant building. However, the proposed high-performance tool would recommend using overhangs with the projection factor of 0.5.

Building | Shade | Construction | System | Plant

Solar Thermal

Solar PV

Calculate

Details | Costs

Roof	Code-Compliant (ASHRAE 90.1-'99)	High-Performance
Color	Medium	
Insulation (R-value)	R-15	
Wall		
Color	Medium	
Insulation	R-13	
Windows		
Frame Type	Al w/ thrml brk	
U-Factor of Glazing[1] (Btu/hr-sqft-F)	1.22	0.38
Solar Heat Gain Coefficient	0.17	
Window-to-Wall Area Ratio (%)[2]	50	35
Floor		
Floor Construction	Medium	
Slab-on-Grade Floor Insulation	R-0, (No insu.)	

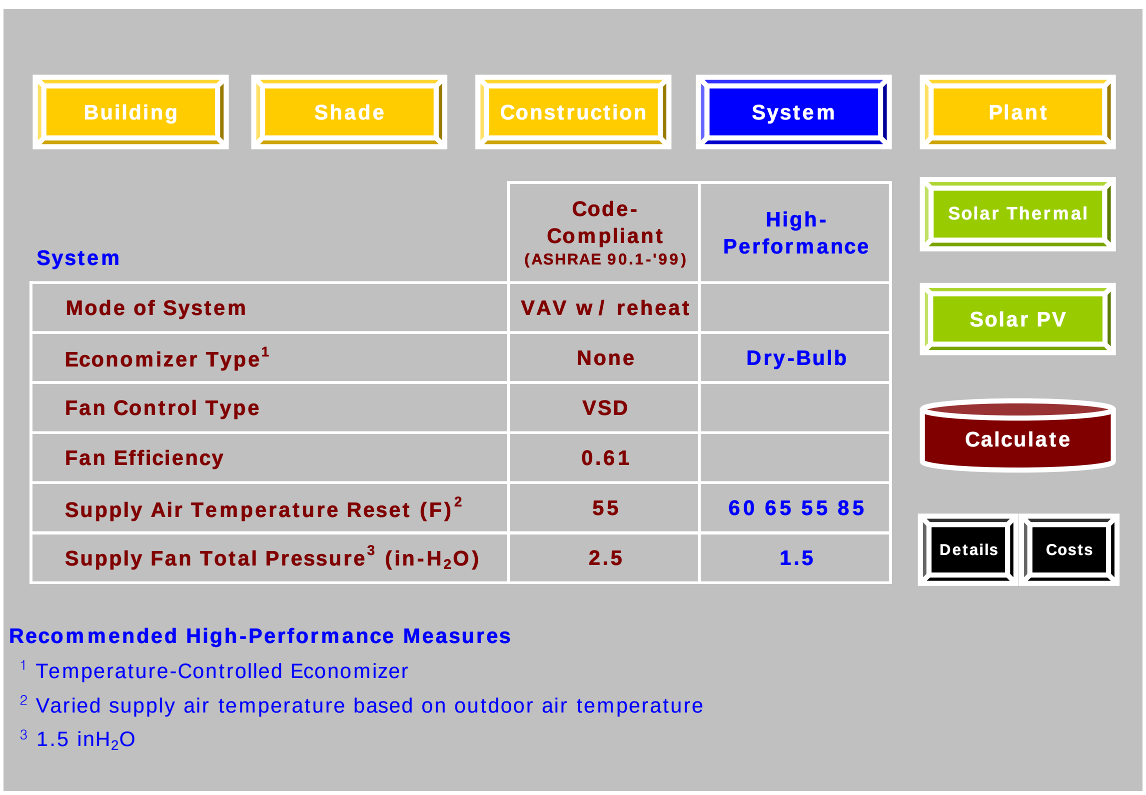
Recommended High-Performance Measures

[1] 0.38 Btu/hr-sqft-F

[2] WWR 35%

Figure 9.3.3 Input Screen of the Proposed Easy-to-use Tool for the Selection of the Building Construction Parameters.

The construction of this example building is illustrated in Figure 9.3.3. The roof has medium color and R-15 insulation. The color of the walls is also medium and the insulation R-value is 13 sqft-F-hr/Btu. The frame type of the windows is aluminum with thermal break. This building consists of 50% window area and 50% wall area for exterior except roof area. The glazing U-value is 1.22 Btu/hr-sqft-F and the solar heat gain coefficient is 17 percent. There is no insulation in the slab-on-grade floor. The floor construction is medium. The recommended high-performance measures would be to lower the window U-value of 0.38 Btu/sqft-hr-F and change the window-to-wall ratio to 35%.



System	Code-Compliant (ASHRAE 90.1-'99)	High-Performance
Mode of System	VAV w/ reheat	
Economizer Type[1]	None	Dry-Bulb
Fan Control Type	VSD	
Fan Efficiency	0.61	
Supply Air Temperature Reset (F)[2]	55	60 65 55 85
Supply Fan Total Pressure[3] (in-H_2O)	2.5	1.5

Recommended High-Performance Measures

[1] Temperature-Controlled Economizer

[2] Varied supply air temperature based on outdoor air temperature

[3] 1.5 inH_2O

Figure 9.3.4 Input Screen of the Proposed Easy-to-use Tool for the Selection of the Building HVAC System Parameters.

ASHRAE Standard 90.1-1999 requires a VAV system with terminal reheat for this type of building as shown in Figure 9.3.4. No economizer is required for this building and the location. The fans run with variable speed with a fan efficiency of 61 percent. The supply air temperature after the cooling coil is set to a constant temperature of 55 F and the total supply fan pressure is 2.5 in-H_2O. In this screen shown are three high-performance measures recommended that are temperature-controlled economizer, supply air temperature reset, and the lower fan static pressure of 1.5 in-H_2O.

In the “Plant” input screen are input parameters for cooling, heating, and service hot water equipment as shown in Figure 9.3.5. The cooling energy source for chiller is electricity and the cooling equipment efficiency is 4.9 (COP). The chilled water pump runs at constant speed. This code-compliant case model has only one chiller to meet the cooling load. The heating energy source is natural gas for the hot water boiler with a thermal efficiency of 75 percent. The hot water pump also runs at constant speed. The service water heater uses natural gas as a heat source having the thermal efficiency of 80 percent.

This screen includes the most recommended high-performance measures. Three of six measures are related to the cooling equipment: the chiller Coefficient of Performance (COP) can be improved to 7.5 from 4.9, the constant-speed chilled water pump can be replaced with the variable speed pump. Chiller staging would also be an option to improve the energy performance of the building. Two measures are related to the space heating equipment: the efficiency of heating equipment can be 95 percent when the condensing boiler is used and the constant-speed hot water pump can be replaced with the variable speed pump. Also, the efficiency of the service hot water equipment can be increased to 85 percent from 80 percent.

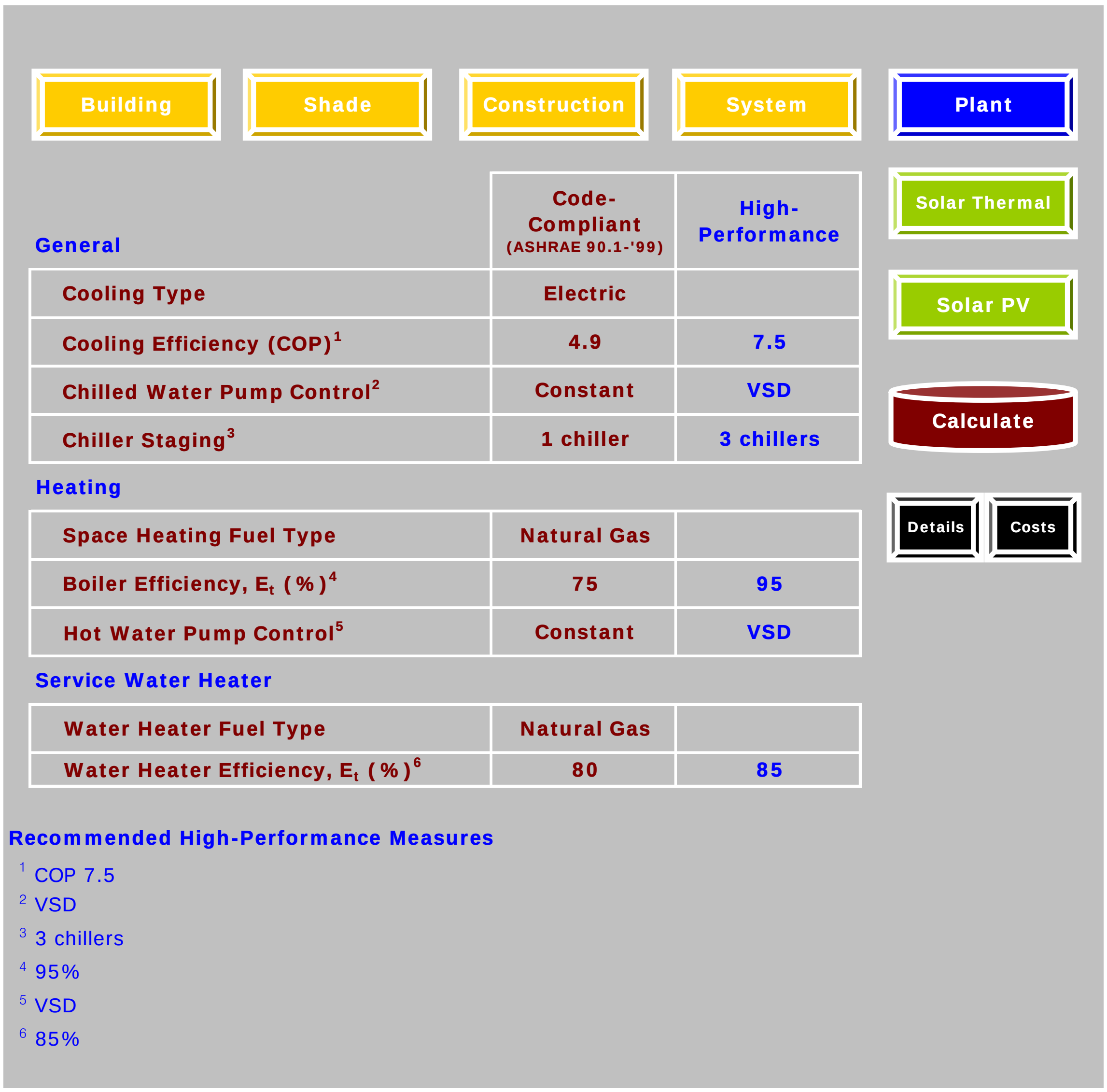


Figure 9.3.5 Input Screen of the Proposed Easy-to-use Tool for the Selection of the Building Plant Parameters.

9.3.1.2 High-performance building systems selection inputs (Case-2 and Case-3)

After the code-compliant simulation is modeled based on the ASHRAE Standard 90.1-1999 (Case-1), the energy consumption of high–performance simulation would be modeled by selecting high-performance measures recommended by the proposed easy-to-use tool. Two cases (Case-2 and Case-3) were selected.

In Case-2, two high-performance systems are selected to see the impact on the building energy performance, which are the glazing U-factor change to 0.38 Btu/sqft-hr-F from 1.22 Btu/sqft-hr-F (Figure 9.3.6) and the lighting power density decrease to 0.9 W/sqft from 1.3 W/sqft (Figure 9.3.7). Energy savings potentials from these measures were demonstrated from the previous chapter. These two measures were ones of most effective energy savings measures. Also, the lighting power reduction is relatively easy to implement for both new construction and existing buildings. In this case study, the lighting power density reduction can be achieved by choosing high-performance light bulbs and fixtures as well. The various lighting cost information was shown in the previous sections.

Figure 9.3.6 shows the glazing U-factor change from 1.22 Btu/sqft-hr-F to 0.38 Btu/sqft-hr-F, which is a high-performance measure. From the previous chapter, it was shown that the energy savings potential from this measure was 7.1% of the case-study building's total energy, which include electricity and natural gas.

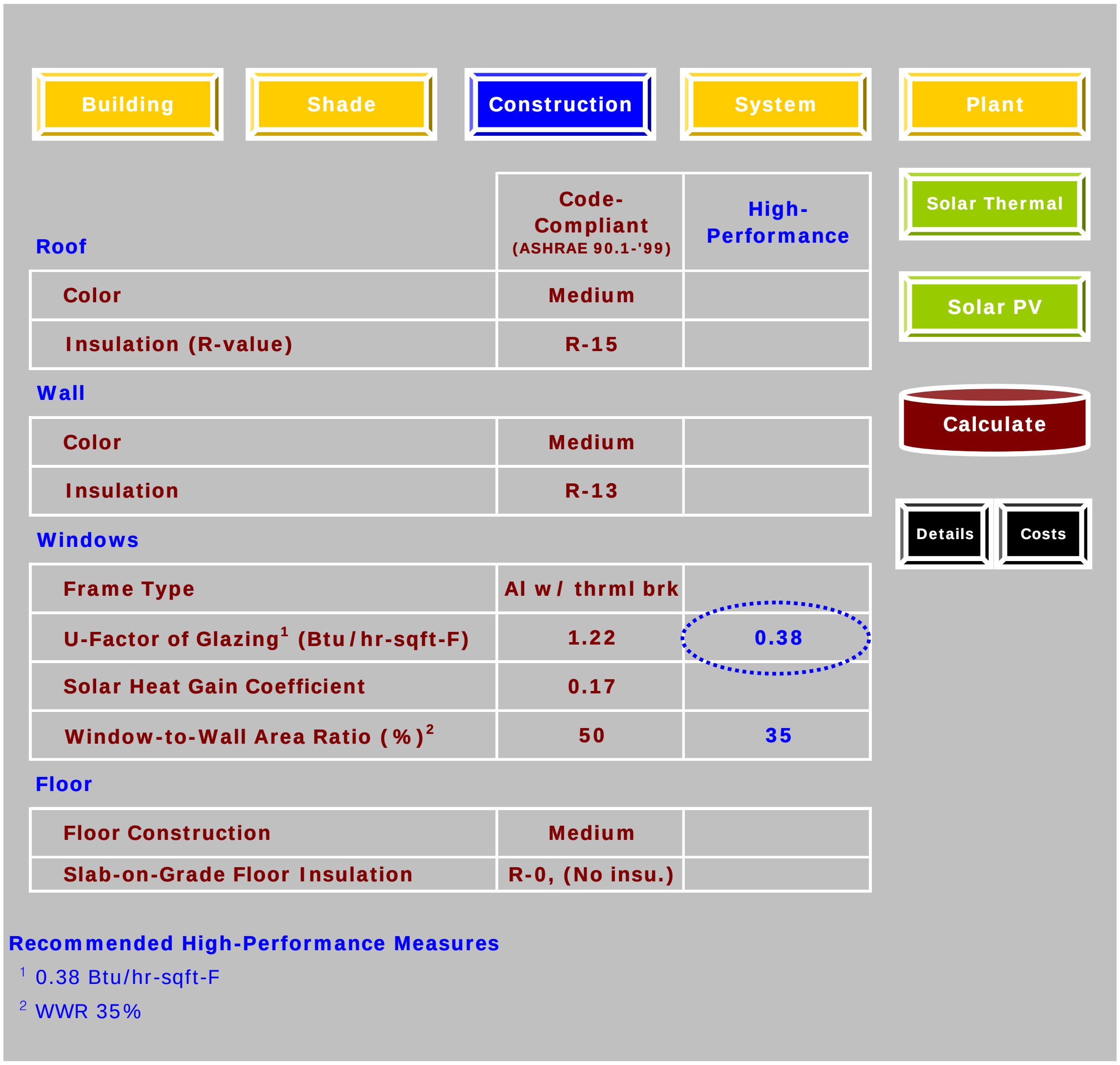


Figure 9.3.6 High-performance Systems Selection Screen for "Construction" Showing the Glazing U-factor Change to 0.38 Btu/sqft-hr-F from 1.22 Btu/sqft-hr-F.

Figure 9.3.7 shows the input screen for "Building" where the lighting power density was set to 1.3 W/sqft as the code baseline. This minimum requirement is changed to 0.9 W/sqft, which is a high-performance measure. The other input parameters stay the same for the simulation.

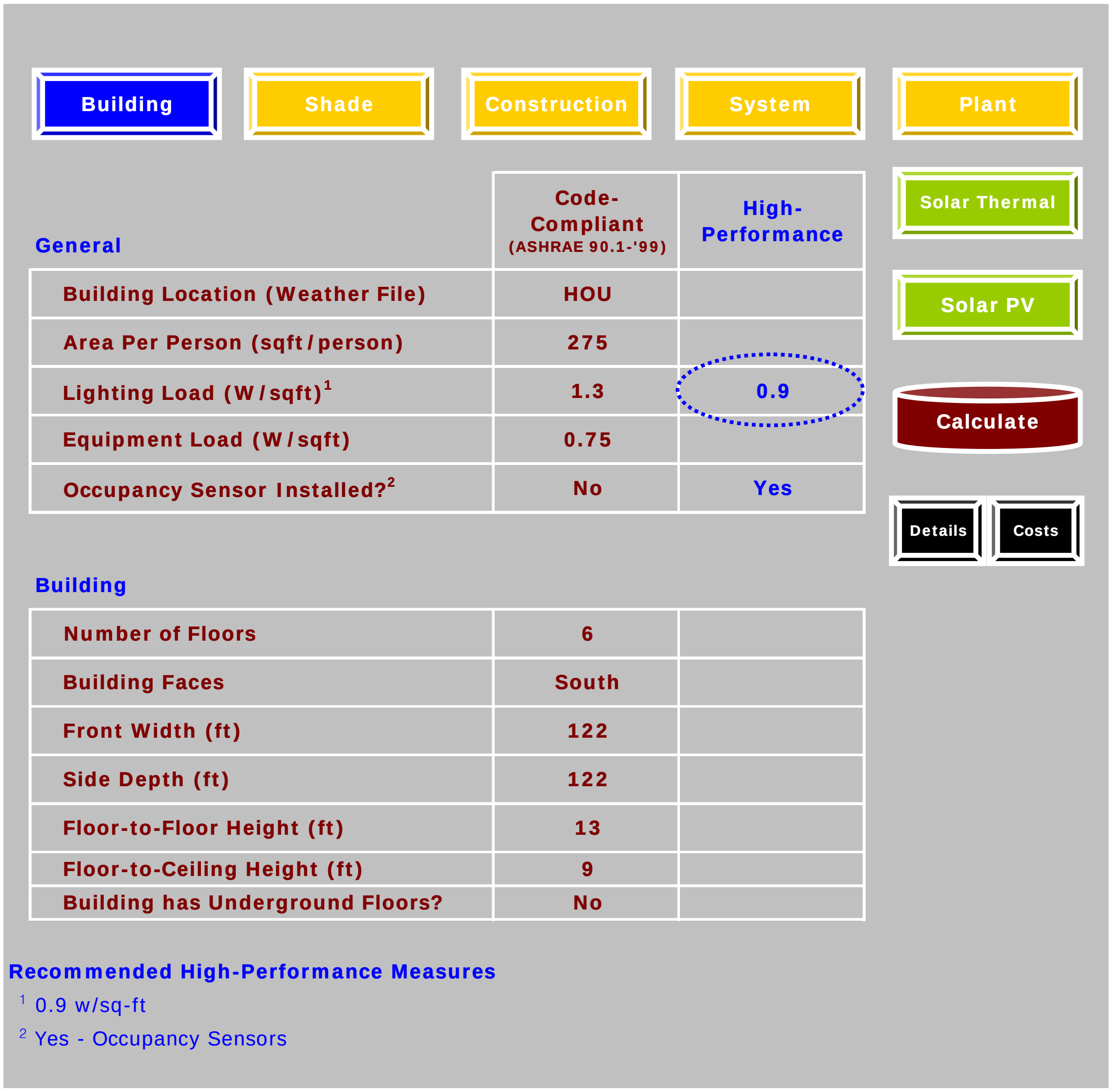


Figure 9.3.7 High-performance Systems Selection Screen for "Building" Showing the Lighting Power Density Change to 0.9 W/sqft from 1.3 W/sqft.

In Case-3, other two high-performance systems are selected for the comparison with Case-1 and Case-2. Figure 9.3.8 shows the selection of occupancy sensors implementation. As the occupancy sensor is implemented in the simulation, the lighting schedule is changed from a lighting schedule of ASHRAE Standard 09.1-1989 for office buildings to an occupancy schedule while a minimum lighting level is maintained for emergency.

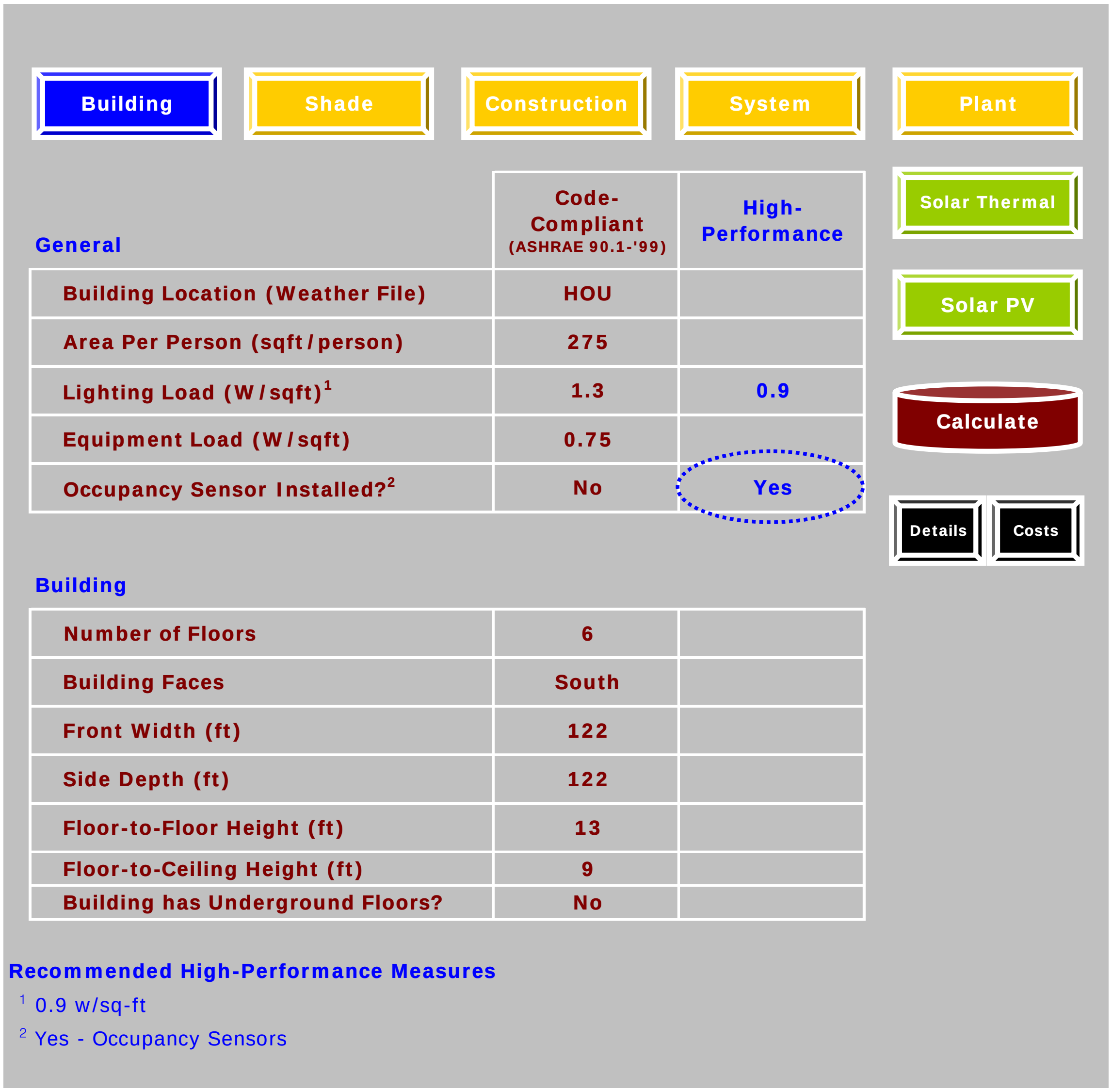


Figure 9.3.8 High-performance Systems Selection Screen for "Building" Showing the Selection of Occupancy Sensors Implementation.

Figure 9.3.9 shows the selection of the high-efficiency chiller with the COP of 7.5.

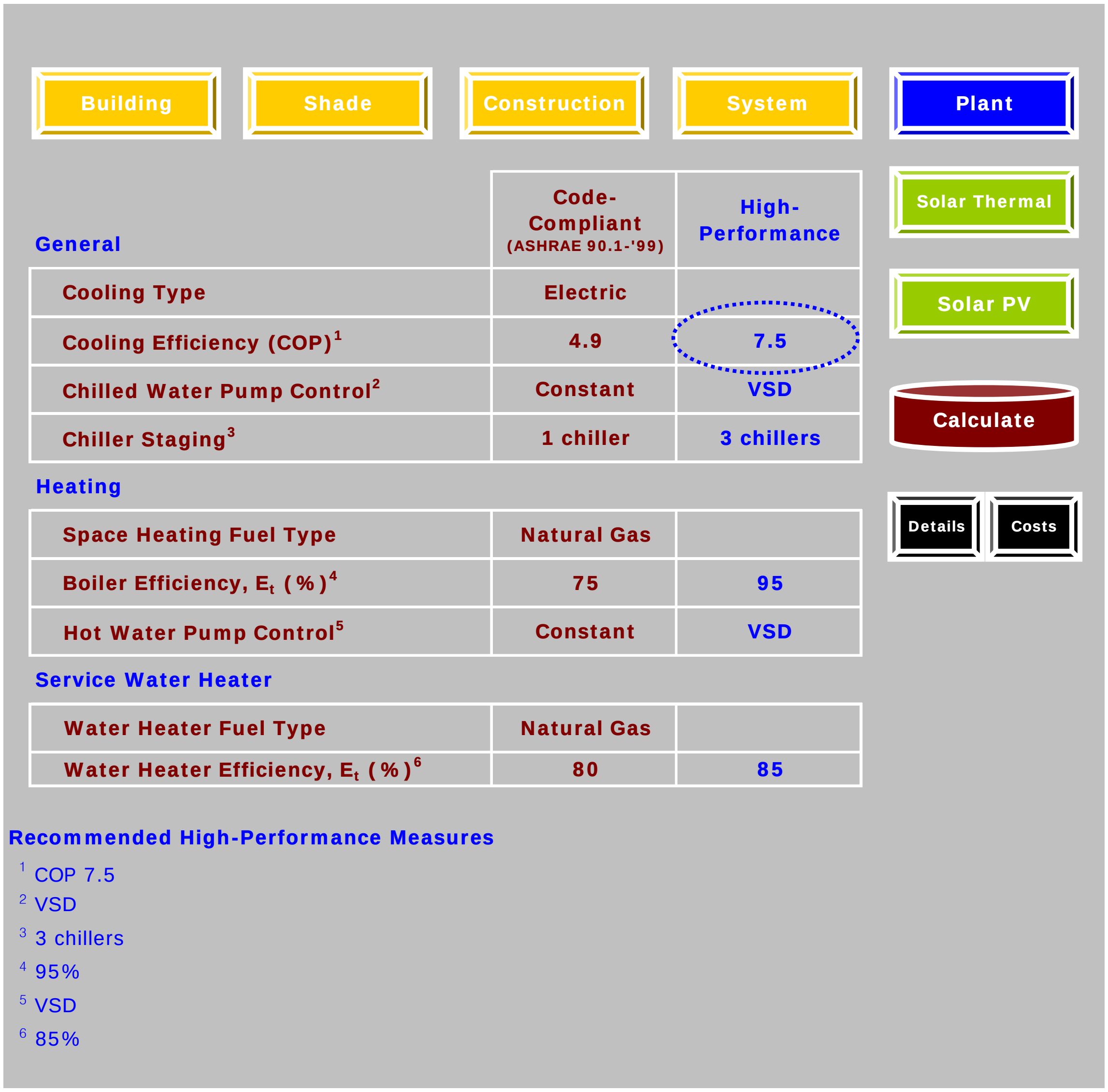


Figure 9.3.9 High-performance Systems Selection Screen for "Plant" Showing the Chiller Efficiency Change to 7.5 COP from 4.9 COP.

9.3.1.3 Results screen of the proposed easy-to-use tool for the new building design

Figure 9.3.10 shows and compares the simulation results between three cases. The Case-1 is the base case that follows the ASHRAE Standard 90.1-1999 code minimum requirements. The Case-2, which uses two high-performance systems (lower glazing U-factor of 0.38 Btu/sqft-hr-F and lower lighting power density of 0.9 W/sqft), shows the total energy savings of 20.3 percent and the total cost savings of 14.4 percent. In contrast to the Case-2, the Case-3 shows a little bit less energy savings of 19.5 percent and substantially higher cost savings of 19.5 percent.

Run #	Energy Use by Category								Energy Total		Cost by Category			Cost Total		
	Lighting (MMBtu)	Equip. (MMBtu)	Heating (MMBtu)	Cooling (MMBtu)	HtRj. (MMBtu)	Misc. (MMBtu)	Fans (MMBtu)	DHW (MMBtu)	Use (MMBtu)	Savings (%)	Elec. ($)	Demand ($)	Gas ($)	Cost ($)	Savings ($)	Savings (%)
1 (Base-Case)	1,811	1,377	610	1,126	250	201	239	43	5,678	-	$ 175,208	$ 16,298	$ 5,060	$ 196,566	-	-
Case-2	1,393	1,377	95	1,033	216	152	215	43	4,528	20.3%	$ 153,038	$ 14,084	$ 1,070	$ 168,192	$ 28,374	14.4%
Case-3	999	1,377	619	888	220	186	217	43	4,569	19.5%	$ 136,283	$ 16,855	$ 5,129	$ 158,267	$ 38,299	19.5%

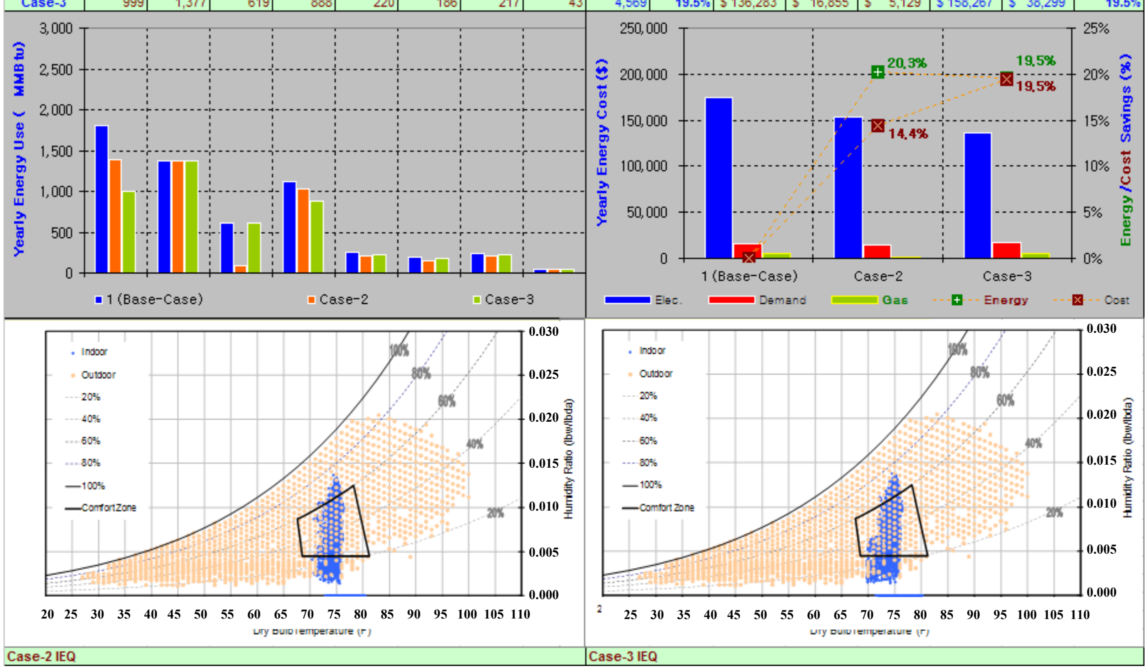


Figure 9.3.10 Results Screen of the Proposed Easy-to-use Tool for the Example of a New Building Design (Energy Cost Calculation: $0.119/kWh, $5.00/kW, and $8.00/MCF).

Based on this example for the new building design, the users of the proposed easy-to-use tool would be able to recommend different measures. By deciding to choose the Case-2, more energy savings could be expected than the Case-3; however, much less cost savings will possibly be anticipated.

Likewise, users of the proposed easy-to-use tool could try as many scenarios as they would like and find the most energy-effective and/or cost-effective systems selection scenarios for their new building design.

9.3.2 Application to Facility Management (Existing Buildings)

In this section the application of the proposed easy-to-use tool to an existing large office building as a facility management tool is discussed. One definition of facility management is "…a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, processes and technology…" (IFMA, 2009). The role of facility management is to make certain a suitable operation of all fundamental building services, including but not limited to normal and emergency power systems, environmental conditions (HVAC), monitoring systems, building life and safety systems and office spaces.

In facility management, the building Operation and Management (O&M) accounts for about 50 percent of the total building cost over 40 years of building life (ASHRAE, 2003). Seventy-five percent of commercial building energy consumption is from HVAC, lighting, and water heating (Swenson, 1998). However, it was revealed from several studies that many commercial buildings are not operating as designed (Hinge et al., 2009; Rios, 2005; Piette and Norman, 1996). The International Facility Management Association's (IFMA's) trend report identified that linking facility management to strategy, sustainability, and emerging technologies as "top issues" faced by facility managers (IFMA, 2007).

In terms of sustainable operation and maintenance in facility management, performance Measurement and Verification (M&V) is one of key elements. The proposed easy-to-use tool could be used for facility managers to access energy conservation measures, to verify energy savings, and to calculate the cost-effectiveness of the implementation of high-performance measures.

9.3.2.1 Simulation input parameters for an existing commercial office building (Case-I)

In this example the same case-study building, the John B. Connally building, is used to demonstrate the proposed easy-to-use tool. Figure 9.3.11 shows the input parameters of the proposed easy-to-use tool for the selection of the general "Building" simulation input parameters.

Although the JBC building is located in College Station, Texas, The Houston TMY2 weather file was used for this location since the closest TMY2 weather station is the

Houston. The total conditioned space of this building is 124,000 square feet and the total number of people is 252, or 492 sqft/person. The lighting power density is 1.90 W/sqft and the equipment power density is 1.07 W/sqft. There are no occupancy sensors installed in the building.

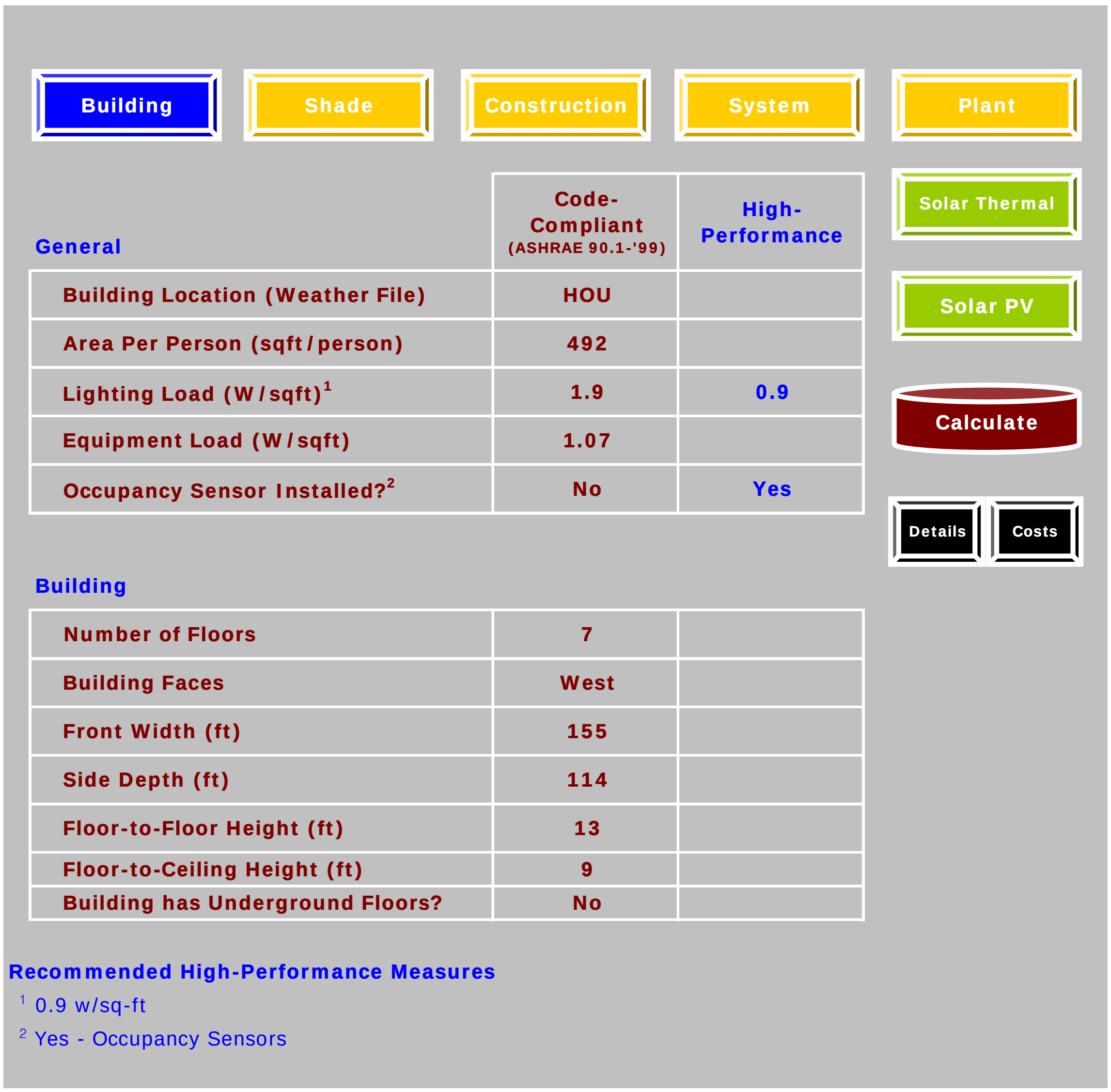


Figure 9.3.11 Input Screen of the Proposed Easy-to-use Tool for the Selection of General Building Parameters for the JBC Building.

The building construction parameters are also included in this figure. This building consists of seven stories and the main entrance to the building faces west. The total conditioned space is 124,000 square feet with a front width of 155 feet and the side depth of 114 feet. Each floor has the ceiling height of 9 feet and a total floor-to-floor height of 13 feet.

Figure 9.3.12 shows the screen of the proposed easy-to-use tool for the selection of building overhangs. The JBC building does not have any external shades, so there are no shades selected in this screen. Overhangs are possible high-performance measure for this screen.

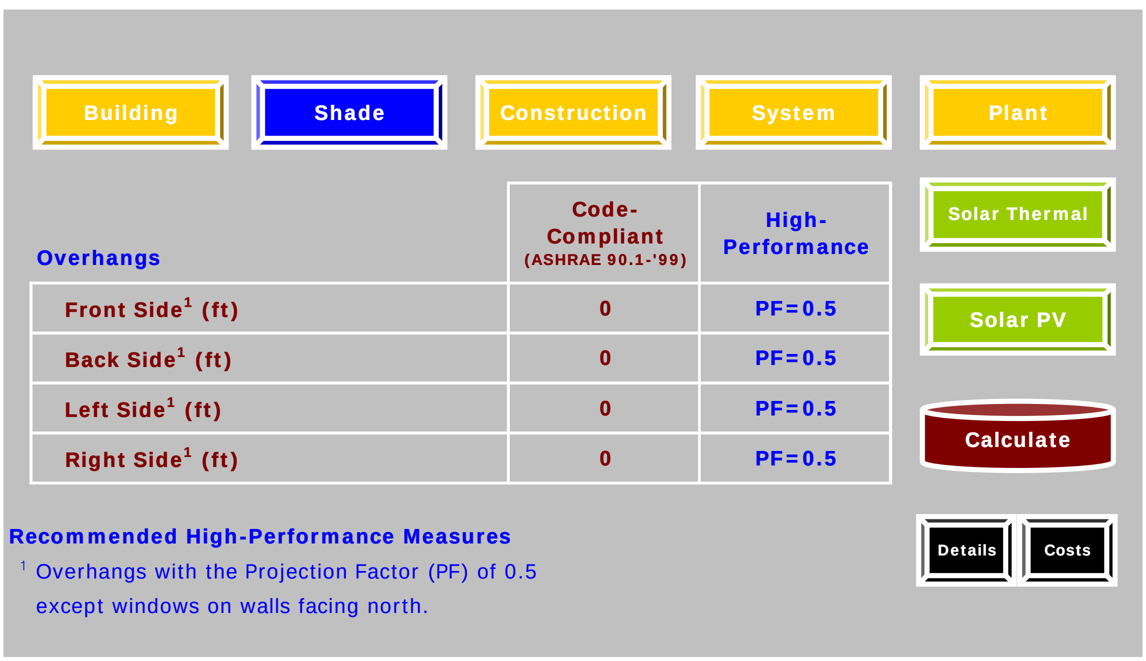


Figure 9.3.12 Input Screen of the Proposed Easy-to-use Tool for the Selection of Shades for the JBC Building.

The construction details of the JBC building are illustrated in Figure 9.3.13. The roof has a medium color with R-29 insulation. The color of the walls is also medium with the insulation R-value is 13 sqft-F-hr/Btu. The frame type of the windows is aluminum with a thermal break. This building consists of 40 percent window-to-wall ratio.

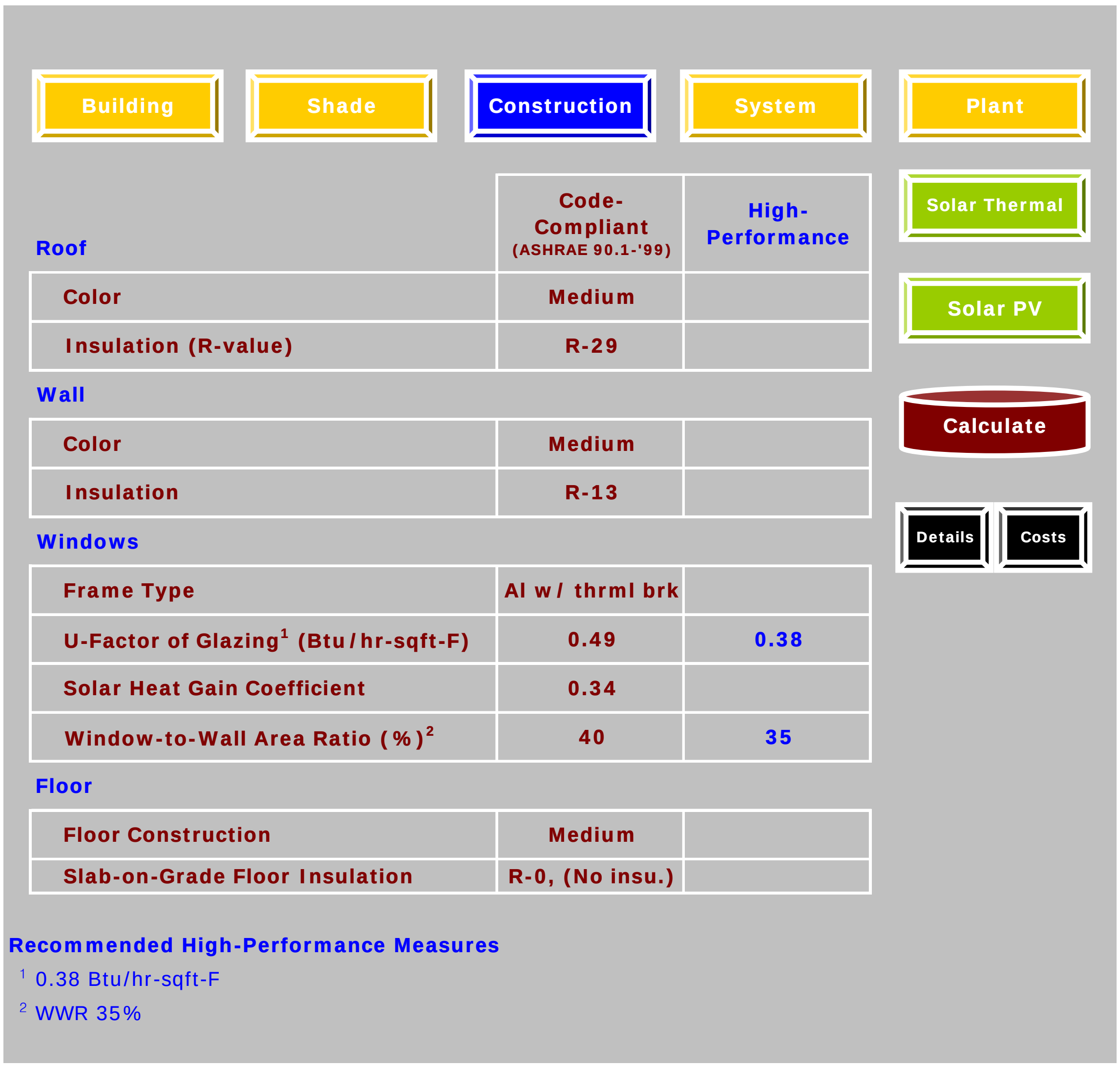


Figure 9.3.13 Input Screen of the Proposed Easy-to-use Tool for the Selection of Construction Parameters for the JBC Building.

The glazing U-value is 0.49 Btu/hr-sqft-F and the solar heat gain coefficient is 34 percent. There is no insulation in the slab-on-grade floor. The floor construction is medium. The HVAC system of this building is single duct VAV with terminal reheat system as shown in Figure 9.3.14.

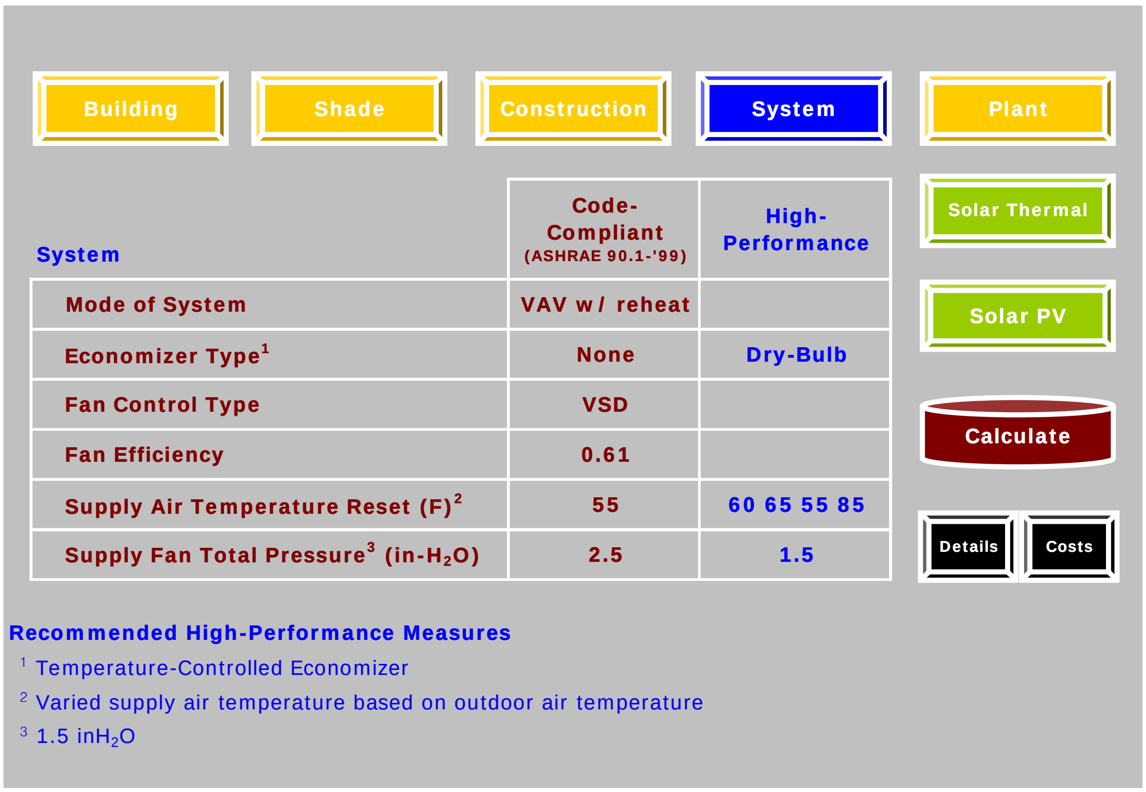


Figure 9.3.14 Input Screen of the Proposed Easy-to-use Tool for the Selection of System Parameters for the JBC Building.

There is no economizer control. The fans run with variable speed with a fan efficiency of 61 percent. The supply air temperature after the cooling coil was set to a variable schedule based on the outside air dry-bulb temperature where the supply air temperature is set to 60 F when the outside air temperature is 65 F or lower. When the outside air temperature is 85 F or higher, the supply air temperature is set to 55 F. The supply air temperature is decreases linearly from 60 F to 55 F as the outside air temperature increases from 65 F to 85 F. The total supply fan pressure is 2.5 in-H_2O.

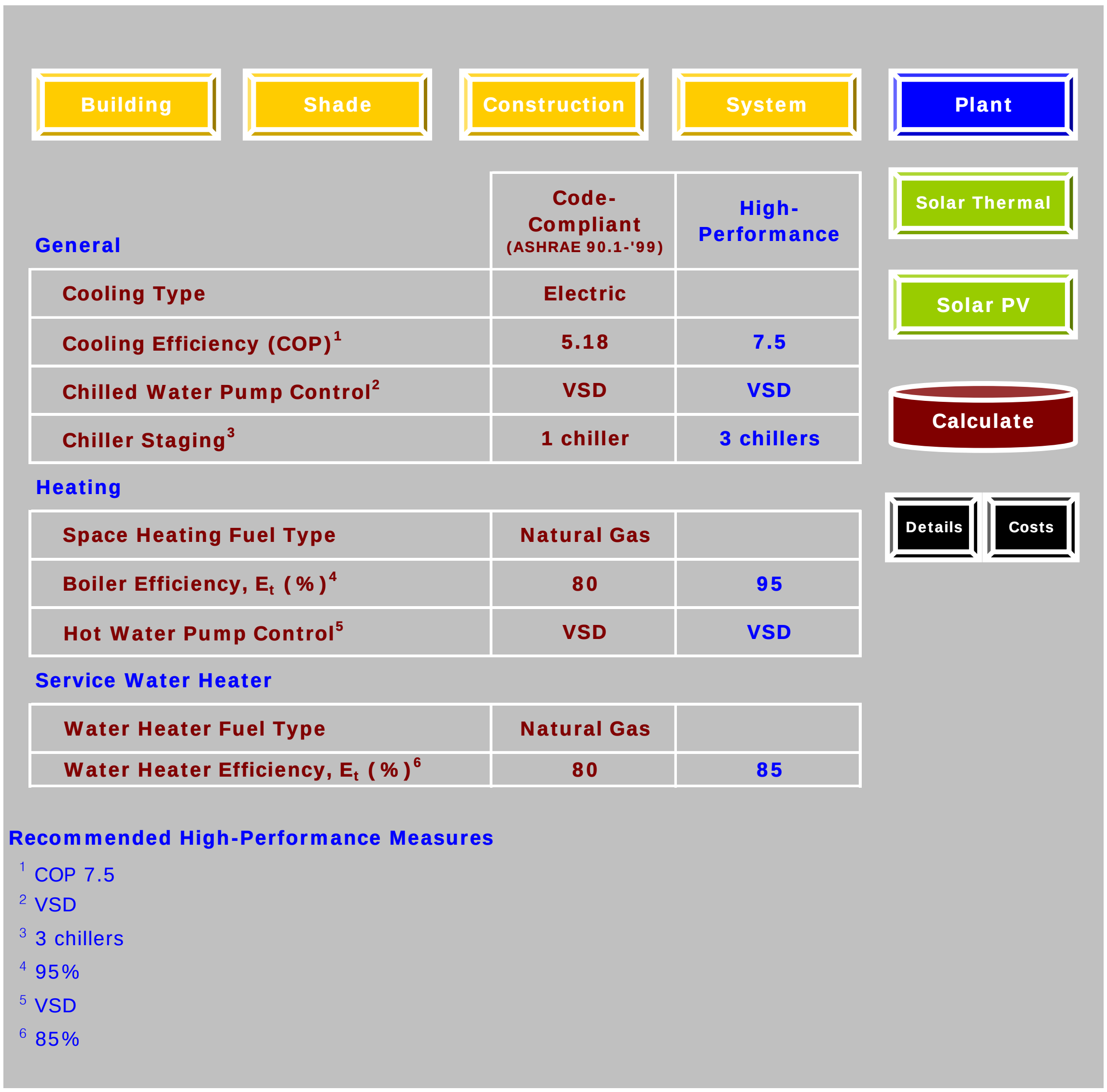


Figure 9.3.15 Input Screen of the Proposed Easy-to-use Tool for the Selection of Plant Parameters for the JBC Building.

The input parameters for cooling, heating, and service hot water equipment in the "Plant" input screen are shown in Figure 9.3.15. The cooling energy source for the chiller is electricity. The electric input for the chiller is 190 kW and the thermal output is 280 tons, so the rated chiller performance is 5.18 (COP). The chilled water pump control is variable speed control. There are two identical chillers with one chiller running to meet the loads while the other chiller stands by. Both chillers operate at higher loads. The heating energy source is natural gas for the hot water boiler with a thermal efficiency of 80 percent. The hot water pump is a variable speed pump. The service water heater uses natural gas as the heat source having the thermal efficiency of 80 percent.

9.3.2.2 High-performance building systems selection inputs (Case-2 and Case-3)

After the as-built simulation was modeled for the JBC building based on the information available from the facility (Case-1), two building improvements were considered for better performance in terms of energy efficiency. The two improvements or cases are: first, reducing the lighting power density to 0.9 W/sqft from 1.9 W/sqft (Case-2) and second, implementing the occupancy sensors (Case-3) for lighting.

Based on the simulation results from the 14 high-performance measures, these two measures are ones that achieved the most energy savings. Also, reducing the lighting power density is one of the most simple and effective energy efficiency measures.

Figure 9.3.16 shows the systems selection screen for the building's general simulation input section of the proposed easy-to-use tool. All the simulation input parameters remain the same as the previous base case (Case-1) except the lighting power density changed to 0.90 W/sqft from 1.90 W/sqft (Case-2).

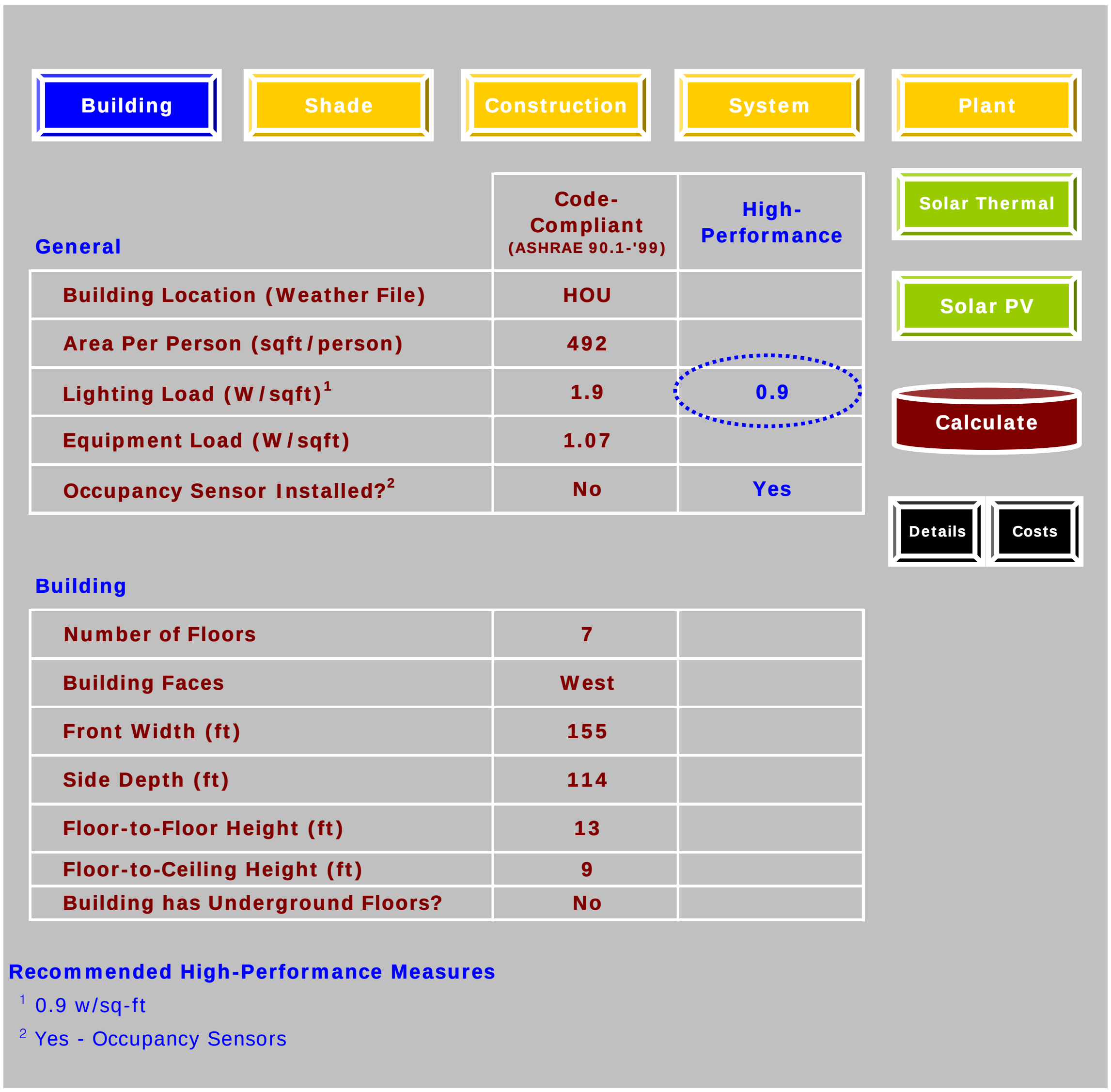


Figure 9.3.16 High-performance Systems Selection Screen for "Building" Showing the Lighting Power Density Change to 0.90 W/sqf from 1.90 W/sqft (Case-2).

Figure 9.3.17 shows the other case (Case-3) in which the occupancy sensor were implemented to the base case. As shown in the figure, only the occupancy sensors option changed to "Yes" from "No".

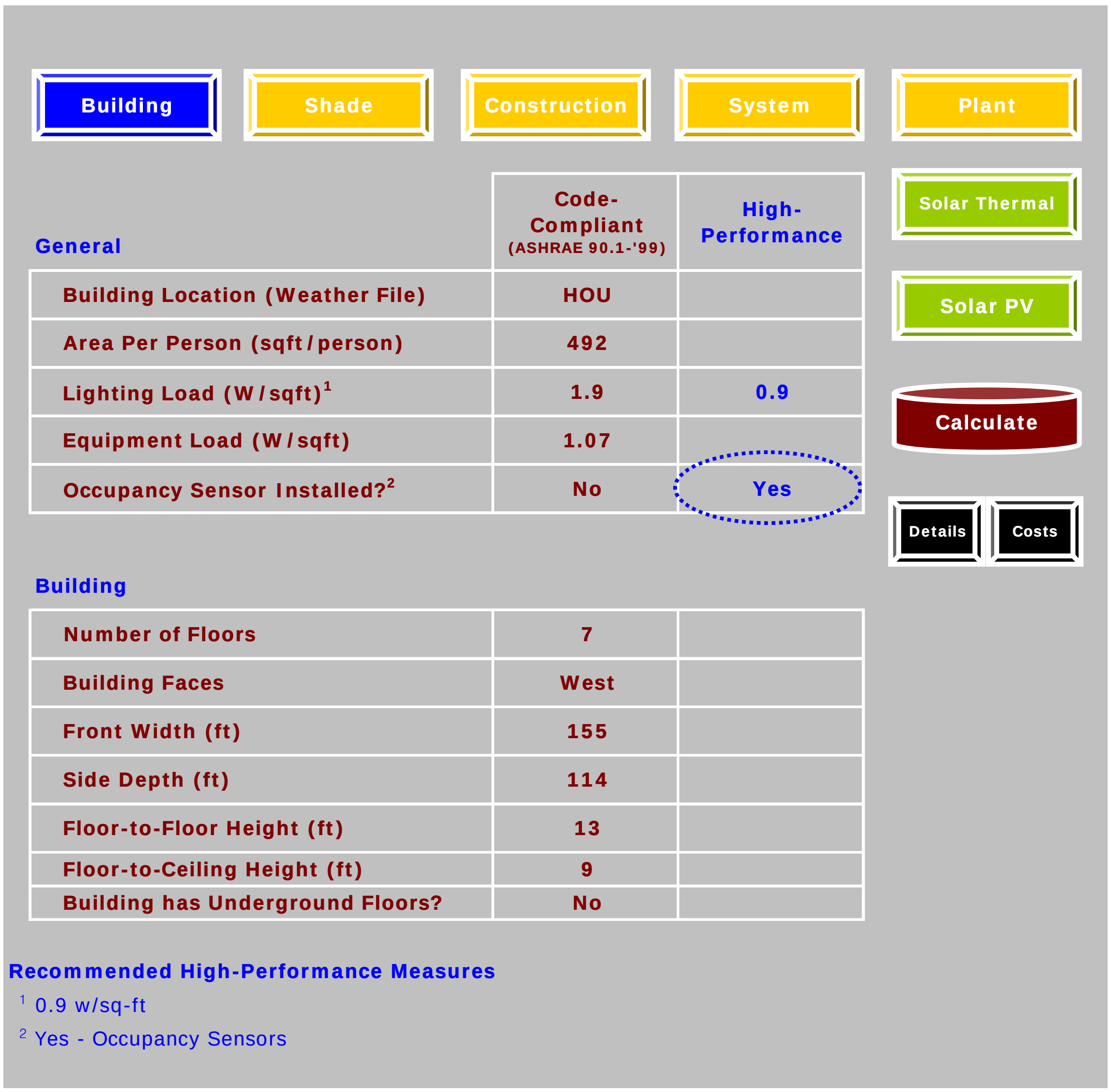


Figure 9.3.17 High-performance Systems Selection Screen for "Building" Showing the Implementation of the Occupancy Sensors to an Existing Building (Case-3).

These measures are common and relatively straightforward ideas for facility managers to apply to existing buildings compared to other measures such as high-performance glazing, high-performance chillers, and high-performance boilers.

9.3.2.3 Results screen of the proposed easy-to-use tool for an existing building analysis

Figure 9.3.18 compares the simulation results between three cases. Case-1 is the base case that uses the existing case-study building parameters. According to the previous chapter, Chapter VII, the measure of lighting power density change (to 0.9 W/sqft from 1.3 W/sqft) achieved energy savings of 9.2 percent. However, as shown in the figure, the total energy savings are 27.2 percent. The much higher energy savings are because of the initial lighting power density (1.9 W/sqft) that the case-study building has. It is not surprising that the lighting power density difference was 0.4 W/sqft (1.3 W/sqft-0.9 W/sqft) for the previous chapter where the lighting power density of 1.3 W/sqft was the ASHRAE Standard 90.1-1999 code requirement. In contrast to it, the base case of this example used a measured lighting power density of 1.9 W/sqft, which is 1.0 W/sqft higher than the high-performance measure of 0.9 W/sqft.

Occupancy sensor implementation (Case-3) saved 22.6 percent of the total building energy. This savings number (22.6%) is also substantially higher than 11.2% that was shown in the high-performance building model (Chapter VII) when compared to the

ASHRAE Standard 90.1-1999 code compliant model. This happened due to the similar reason. The base-case building's lighting power density was so higher (1.9 W/sqft) that more energy savings were achieved by implementing the occupancy sensors.

Run #	Energy Use by Category								Energy Total		Cost by Category			Cost Total		
	Lighting (MMBtu)	Equip. (MMBtu)	Heating (MMBtu)	Cooling (MMBtu)	HtRj. (MMBtu)	Misc. (MMBtu)	Fans (MMBtu)	DHW (MMBtu)	Use (MMBtu)	Savings (%)	Elec. ($)	Demand ($)	Gas ($)	Cost ($)	Savings ($)	Savings (%)
1 (Base-Case)	3,663	2,720	0	1,582	367	124	554	57	9,066	-	$ 314,127	$ 29,428	$ 4,528	$ 348,083	-	-
Case-2	1,735	2,720	0	1,258	321	108	398	57	6,596	27.2%	$ 228,006	$ 21,421	$ 4,592	$ 254,019	$ 94,063	27.0%
Case-3	2,015	2,720	3	1,324	332	115	446	57	7,013	22.6%	$ 242,423	$ 31,505	$ 4,784	$ 278,712	$ 69,371	19.9%

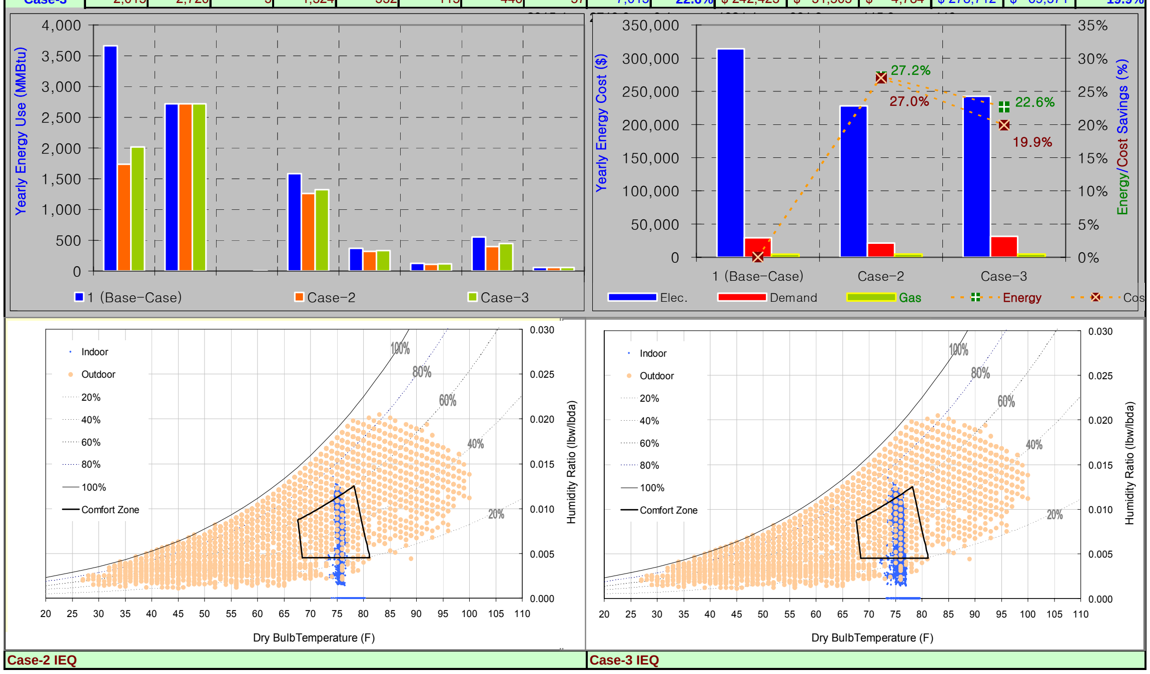


Figure 9.3.18 Results Screen of the Proposed Easy-to-use Tool for the Example of an Existing Building (Energy Cost Calculation: $0.119/kWh, $5.00/kW, and $8.00/MCF).

The most energy savings were from the lighting energy for both cases, although there is no change in the equipment energy portion. The space heating energy for the base-case model was zero. The high internal heat gains from the heat sources, such as lights (1.9 W/sqft), equipment (1.07 W/sqft), and people, met all space heating loads of the building located in Houston, Texas. There was also no heating energy required even for the Case-2 in which the lighting power density was reduced substantially.

However, a small amount of heating energy was used for the Case-3 in which the occupancy sensors were implemented to make up for the displaced heat from the lights. Other energy categories such as cooling, heat rejection, and fans showed energy savings from the two cases.

In both Case-3 and Case-3, the cost savings were significant, which were 27 percent for the Case-2 and 19.9 percent for the Case-3 compared to the Case-1. Existing building owners and/or facility managers could then decide which way they want to go between two applications for their building. There are other factors for them to consider such as implementation cost and time and payback period. However, the proposed easy-to-use tool would be a useful source for facility managers and/or building owners to be able to obtain quick results for the energy and cost side of their evaluation list.

9.4 Summary of the Proposed Easy-to-use Systems Selection Tool

In this chapter, the proposed easy-to-use systems selection tool was described including its intended appearances, how it is intended to work, and a comparison with other similar tools. Also, two examples of applying the proposed easy-to-use tool were demonstrated for both a new building design case and an existing building case as a facility management tool.

Based on the comparison of the proposed easy-to-use tool with other existing easy-to-use tools such as eCALC, COMCheck-web, eQUEST, EnergyIQ, BCHP Screener, Green Building Studio, ECOTECT, and EnergyGauge Summit, there existed similarities and differences between programs.

However, there are also functions that only the proposed easy-to-use tool includes, which are: 1) the fourteen high-performance measures that could provide building practitioners with specific ideas and numbers of the energy impact from choosing the individual high-performance measures for both the new and existing building cases; 2) integration of the solar energy analysis functions with the DOE-2.1e simulation program, which could provide combined analyses of energy generation through the renewable energy source in buildings; and 3) analysis of indoor environmental quality, which would help users understand how their energy efficiency practices could impact the indoor environmental quality of their target buildings.

CHAPTER X

SUMMARY, LESSONS LEARNED, AND FUTURE WORK

10.1 Summary

The purpose of this research was to improve the analysis of the energy performance of office buildings. To accomplish this, a methodology to develop an easy-to-use tool has been developed for the preliminary selection of high-performance systems for office buildings in hot and humid climates. As the first step, high-performance building systems and components were surveyed for office buildings, which were applicable for buildings in hot and humid climates. Next, a calibrated DOE-2.1e simulation model of a case-study building, the John B. Connally building in College Station, TX, as a prototypical large office building was developed. Then, a simplified simulation model, which is a modified eCALC DOE-2.1e or SGDOE-2.1e model, was developed and compared to the measured data of the case-study building. The SGDOE-2.1e model is a simplified geometry rather than the actual detailed geometry of the case-study building. The calibrated SGDOE-2.1e showed a good match to the measured data and to the calibrated simulation.

The calibrated SGDOE-2.1e model was then modified to be compliant with the ASHRAE Standard 90.1-1999 commercial building energy code. The calibrated code-compliant (ASHRAE Standard 90.1-1999) SGDOE-2.1e simulation model was then used as a baseline for the implementation of high-performance measures. A total of 14 high-performance measures were implemented and evaluated to calculate energy and cost savings, while the indoor comfort conditions were maintained based on the ASHRAE comfort zone. The 14 high-performance measures were:

① improved glazing U-factor,

② reduced window-to-wall ratio,

③ reduced lighting power density,

④ occupancy sensors,

⑤ overhangs (building external shading),

⑥ supply air temperature reset,

⑦ reduced fan static pressure,

⑧ use of a temperature-based economizer,

⑨ improved chiller COP,

⑩ improved boiler efficiency,

⑪ improved service water heater efficiency,

⑫ variable-speed chilled water pumps,

⑬ variable-speed hot water pumps, and

⑭ chiller staging.

The most energy savings were resulted from the implementation of occupancy sensors for lighting control, which reduced the annual total energy consumption by 11% compared to the base-case (ASHRAE Standard 90.1-1999 code-compliant) building. In addition to the 14 high-performance measures, solar thermal and solar PV systems were integrated with the SGDOE-2.1e simulation model.

The energy savings were calculated during each step of this process. The energy savings from making the building compliant with the ASHRAE Standard 90.1-1999 code were 25% compared to the case-study building. After the 14 high-performance measures were implemented to the ASHRAE Standard 90.1-1999 code-compliant model, the energy savings were 48% compared to the ASHRAE Standard 90.1-1999 code-compliant model and 61% compared to the case-study building model. In addition, the energy savings could be higher if the solar thermal and/or solar PV systems were applied to the building. This study showed the energy savings of 54% above the code-compliant building by additionally applying the solar thermal and PV systems on about half of the case-study building's roof area.

The proposed easy-to-use systems selection tool was then presented. This tool includes not only the potential application of the 14 high-performance measures, but also the integrated solar thermal and PV systems. The proposed easy-to-use preliminary systems selection tool can be used for new building practitioners and existing building owners as well to evaluate the performance of their new buildings compared to the ASHRAE Standard 90.1-1999 code-compliant building and to assess the feasibility of implementing high-performance measures to their existing buildings in terms of energy and cost savings.

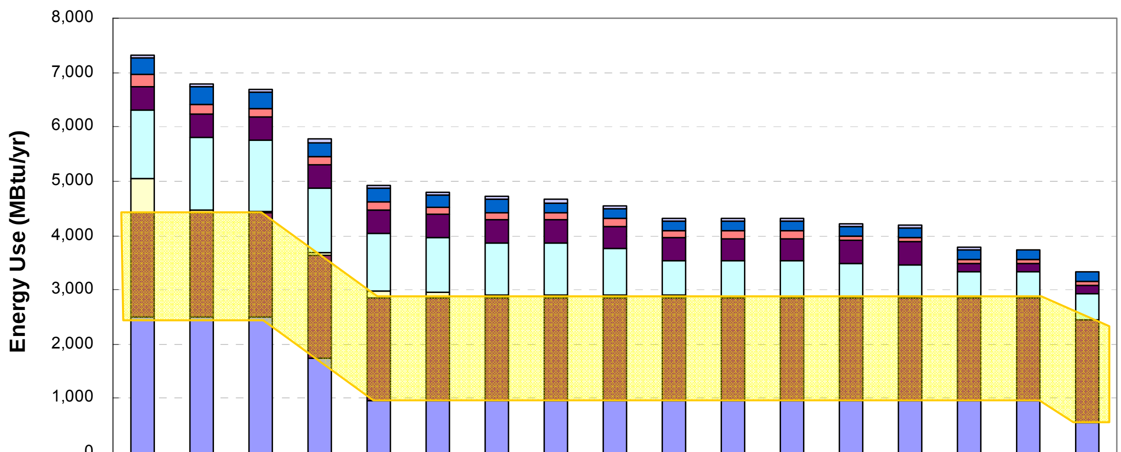
10.2 Lessons Learned

Substantial energy savings available from common technologies

This study showed substantial energy savings, 48.1% above ASHRAE Standard 90.1-1999, by implementing the commonly available, 14 high-performance measures outlined in this study. The measures selected were not high-tech measures such as Under Floor Air Distribution (UFAD) or double skin façade, but are readily available technologies that can be simulated with the DOE-2.1e program. Such measures were specifically chosen to demonstrate that high performance can be achieved without having to resort to systems that require special purpose simulations.

Energy savings efforts needed on the "Equipment" electricity use

Figure 10.2.1 shows cumulative energy savings of the 14 high-performance measures including additional energy reductions by solar energy systems. In this figure, the loads highlighted with the yellow color represent the office equipment electricity use that was not changed by any of the measures. For the base-case model (the first bar from the left) the electricity use by the office equipment was 26% (1,907 MMBtu/yr) of total energy use. However, this same usage of 1,907 MMBtu/yr becomes 50% of the total energy use after the 14 high-performance measures are implemented and 57% after the solar systems were applied. As shown in the last bar of the figure, this is a substantially larger portion of the total. Therefore, to reduce energy use further, the standard office equipment would need to be studied to look for opportunities to reduce energy use while maintaining the same function. Examples might include laptop PCs vs. desktop PCs and laser LCD projectors vs. quartz-halogen LCD projectors.



	Base-Case	Glazing U Factor (1.22 to	WindowToWall Ratio	Lighting Load (1.3 to 0.9	Light Control (None to	Shading (none to 2.5 ft	Cold Deck Reset	Supply Fan Total Pressure	Economizer (None to	Chiller COP (5.55 to	Boiler Efficiency (75%	DHW Heater Thermal	CHW Pump Control	HW Pump Control	Chiller Staging (One to	Solar Thermal Service	Solar PV Electric Generati
SERHOT WATER	57	57	57	57	57	57	57	57	57	57	57	53	53	53	53	-	-
VENT FANS	308	321	301	268	247	226	234	184	182	182	182	182	182	182	182	182	182
PUMPS & MISC	215	186	165	155	148	136	134	133	130	130	130	130	75	71	71	71	71
HEAT REJECT	427	427	427	426	425	425	425	425	425	425	425	425	425	425	154	154	154
SPACE COOL	1,258	1,353	1,318	1,189	1,063	1,006	964	956	859	636	636	636	600	600	470	470	470
SPACE HEAT	641	44	19	37	115	97	42	43	30	30	24	24	24	5	5	5	5
MISC EQUIPMT	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907	1,907
AREA LIGHTS	2,506	2,506	2,506	1,735	955	955	955	955	955	955	955	955	955	955	955	955	545

Figure 10.2.1 Energy Savings by Individual High-performance Measures and Equipment Electricity Use Highlighted with Yellow Color.

Guidelines needed for energy cost savings calculation

Energy savings are calculated with the aid of guidelines such as ASHRAE Guideline 14-2002 (ASHRAE, 2002), IPMVP (IPMVP, 2002), and FEMP (FEMP, 2000). Cost savings calculations always involve not only the energy cost but also the demand cost in case of commercial buildings. The ASHRAE Standard 90.1 includes the Energy Cost Budget (ECB) method for energy cost savings evaluation. However, the ECB method calculates the energy (electricity use) cost only, excluding the electric demand cost that often charges more money than the electricity use. Unfortunately, building owners have concerns about the demand cost reductions. Therefore, it is necessary to develop a standardized energy cost savings procedure that includes electric demand savings.

10.3 Future Work

This research presented a methodology of integrating the DOE-2.1e energy simulation program with the solar thermal (F-Chart) and solar PV (PV F-Chart) analysis programs as part of the development of a procedure for the high-performance systems selection tool. In this study, however, the energy performance simulation was limited to the systems that can be simulated by the DOE-2.1e program. For future study, another energy simulation program, such as the EnergyPlus program, EQUEST, or TRNSYS could be utilized as the simulation engine as it has functions to simulate more and newer systems than DOE-2.1e can.

As more systems and additional features could be evaluated by an advanced program, below are the items that need to be studied further in depth and to be integrated into the proposed easy-to-use tool.

① ***Double skin façade system*** is a pair of glass skins with an air corridor between them. The air space between the layers of glass performs as an insulator from extreme weather conditions such as hot/cold outside temperature, winds, and sound (Harrison and Boake, 2003). A study was conducted for an office building in Turkey (Cakmanus, 2007) and showed the energy savings potential of 45%.

② ***Underground Floor Air Distribution (UFAD) system*** is an HVAC system that uses the open space (under-floor plenum) between the structural slab and the underside of a raised floor to deliver conditioned air to supply outlets located at or near floor level within the occupied zone. There are several benefits of this system such as reduced energy use, improved thermal comfort, and reduced floor-to-floor height in new construction (Im et al., 2005).

③ ***Displacement ventilation*** is an air distribution system where air comes in at floor level and rises up to exhaust outlets at the upper level of the walls or ceiling. Air is delivered to interior rooms through diffusers on the floor-level, displacing upper air, which is exhausted through ceiling-level vents. Displacement ventilation systems basically utilize 100% outside air, and, as a result, air pollutants generated within a room are removed at the source and are not re-circulated. In addition, heat generated by ceiling level lights is removed, and thus heat is not included when estimating building cooling loads (Cho et al., 2005).

④ ***Natural ventilation*** is taking advantage of a natural phenomenon such as wind, humidity, and warm air buoyancy through design of building form to bring fresh outdoor air in and force stale indoor air out. There are several strategies for natural ventilation, including operable windows, exhaust vents located in the building's envelop, intake vents located low in building's envelop, open building plan to facilitate air movement, atria, internal stairwells, ventilation chimneys, and small fans (CGBC, 2005).

⑤ ***Daylighting system*** uses sunlight as a light source for buildings. This system reflects sunlight through openings in the roof and/or sidewalls of a building into the desired room or spaces. This process reduces and/or replaces the electric energy for lighting in buildings.

⑥ ***Heat-driven liquid desiccant system*** is an approach to effectively manage humidity under challenging conditions such as buildings with high outdoor requirements located in humid regions. This system removes moisture and latent heat from process air via a liquid desiccant material such as lithium chloride (LiCl) or halide salts. In humid climates, it can save energy, especially when used as part of a dedicated outdoor air systems (DOAS) because the liquid desiccant DOAS manages main latent load, which removes the need to overcool ventilation air to reduce humidity and decreases reheat energy consumption (Dieckmann et al., 2008).

⑦ ***Renewable energy sources*** such as wind and geothermal are alternative energy sources for buildings. The wind power generation is the most fast growing source among the renewable energy sources that include solar, geothermal, biomass, hydro, and wind. To achieve net zero energy buildings, these renewable energy sources need to be integrated into building design.

⑧ ***Water savings from rainwater systems***

Rainwater systems collect rainwater mostly from roof surfaces of buildings. The water is then transported through gutters and other pipes into cisterns or tanks. This collected water can be used for irrigation, laundry, or even potable water, depending on the materials used in the collection system and the treatment undertaken (NSF, 2009). Water savings from rainwater systems need to be considered for the design of buildings.

⑨ ***Maintenance and replacement costs*** account for about 50 percent of the total building cost over 40 years of building life (ASHRAE, 2003). The analysis for the cost of maintenance and replacement helps make cost-effective decisions for choosing high-performance building systems.

⑩ ***Heat/chilled slabs with Dedicated Outside Air Systems (DOAS)***

The slab-integrated hydronic radiant cooling is enhanced by dedicated outside air system for conditioning of ventilation air (Moore, 2008). The sensible loads are controlled by the radiant system to allow for modulating ventilation rates since cooling capacity is decoupled from ventilation rate. The DOAS system is used to remove the latent loads for space and also eliminate the potential for condensation with radiant cooling system (LBNL, 2009).

⑪ ***Automated recommendation based on cost-effective criteria***

The 14 high-performance measures recommended in this study were readily available common technologies; however the costs for implementing these measures vary. Also, utility costs change over time and are different from one location to the other. Integrating these costs can help users of the proposed easy-to-use tool decide best systems and cost-effective technologies as well. A database, which contains regional life-cycle costing data including such costs as initial costs and maintenance costs, can benefit users in different regional areas to select high-performance systems in a cost-effective manner.

⑫ ***An expert system with on-line tutorial***

To better assist the users of the proposed easy-to-use tool, an expert system with on-line tutorial is desirable. The users would be able to find their optimized and customized building systems by answering questions in the expert system. An on-line tutorial would also help quickly understand how to drive the proposed easy-to-use tool.

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APPENDIX A

2006 TRY WEATHER FILE PACKING FOR COLLEGE STATION, TX

For the calibration of the case-study building simulation model, a Test Reference Year (TRY) weather file was developed that contained measured weather data that coincided with the measured energy use and indoor environmental conditions. In this appendix, the TRY weather preparation or “packing” process is presented.

A.1 TRY Weather Data Packing Process

Figure A.1 shows a diagram of the TRY weather packing process. In this process, there were three weather data sources, The National Weather Service (NWS) database, data from the ESL’s National Renewable Energy Laboratory (NREL) solar test station, and data from the Energy Systems Laboratory (ESL) solar test bench. The NREL station is located at TAMU’s riverside campus in Bryan, Texas as shown in Figure A.2. The ESL solar test bench is located on the roof of the Langford Architecture building on the Texas A&M campus in College Station, Texas. The NWS weather data include temperatures (dry-bulb, wet-bulb, and dew-point) and wind speed data. Data from NWS were processed to develop an unpacked TRY data format using the INSTRUCTION input file (INS.INP) and the weather data processor (LS2TRY.FOR) (LBNL, 1981).

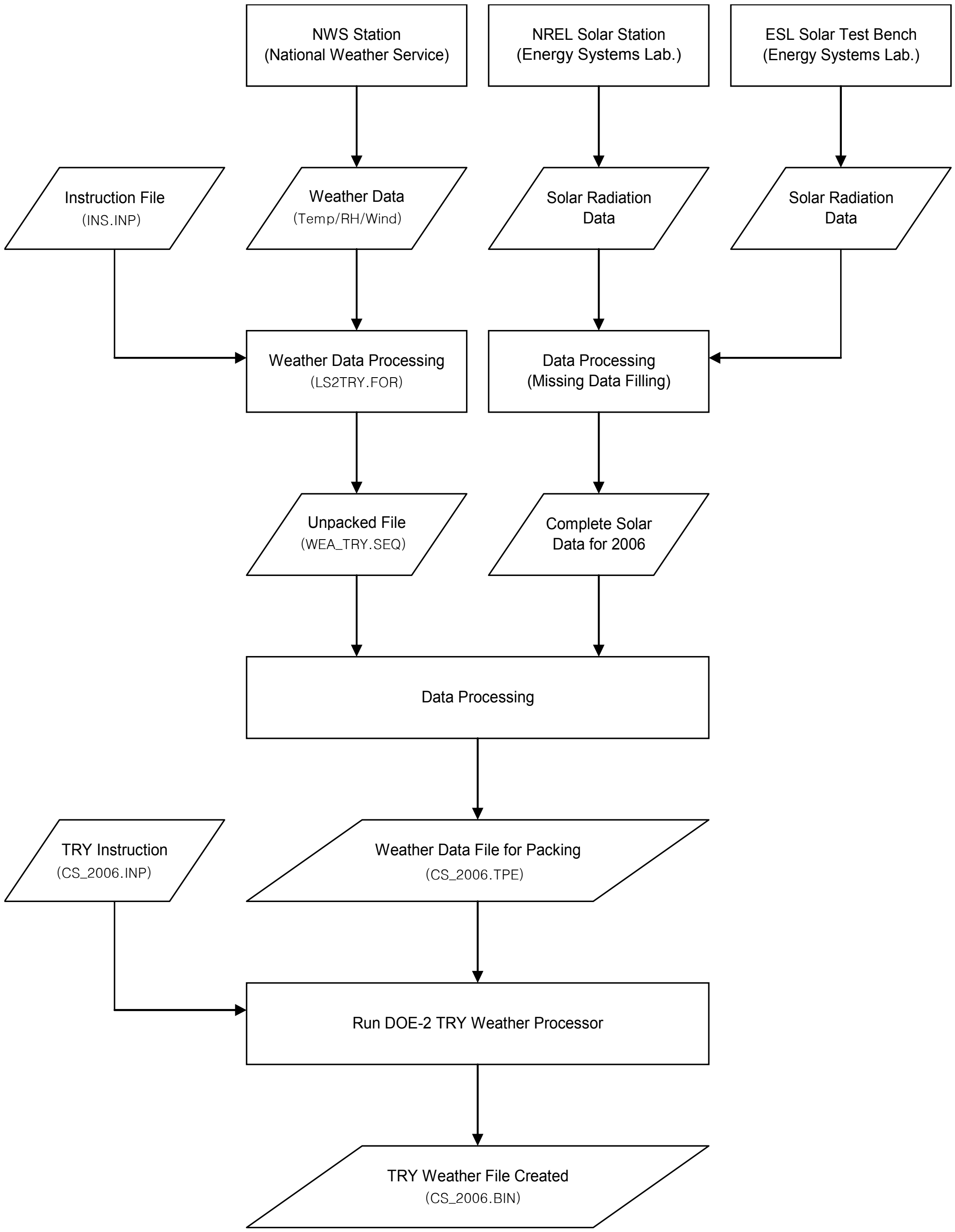

Figure A.1 Flow Chart of the Test Reference Year (TRY) Weather Packing Process for the DOE-2.1e Calibrated Simulation of the Case-Study Building.

This process creates an unpacked weather file, WEA_TRY.SEQ. The ESL solar test bench data were then used to fill the missing gaps that occurred in the NREL solar station database. The complete solar data were then incorporated into the unpacked weather file (WEA_TRY.SEQ). The data file including both NWS weather data and NREL solar data, CS_2006.TPE, was run by the DOE-2 TRY weather packing processor with the TRY instruction file, CS_2006.INP. This process creates the packed TRY weather file, CS_2006.BIN, for use by the DOE-2.1e calibrated simulation of the case-study building.

A.2 Locations of the Weather Stations and the Case-Study Building

The NWS station in College Station is located at the Easterwood Airport in College Station, Texas with the latitude of 30.35 degree North, a longitude of 96.21 degree West, and has an elevation of 321 feet above sea level. Figure A.2 shows the locations of the weather stations and the case-study building. The ESL's NREL solar station (marked as D on the map) is located in seven miles away toward the west direction of the NWS station (marked as C). The ESL solar test bench (marked as B) is less than three miles the northeast direction from the NWS station. The case-study building, John B. Connally building (marked as A), is near the TAMU main campus, which is one and a half miles the northeast from the TAMU campus.

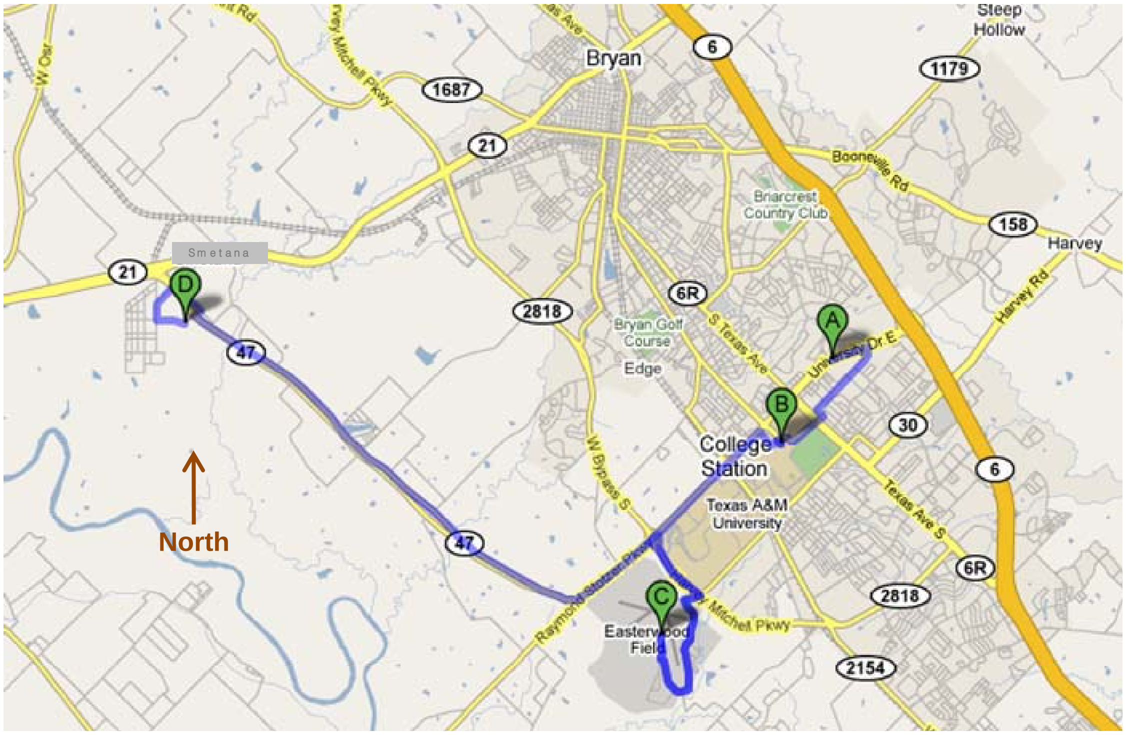

Figure A.2 Google Map Showing Locations of Weather Stations and Case-Study Building: A (Case-Study Building), B (ESL Solar Test Bench), C (NWS Station), and D (NREL Solar Station) (Map Source: http://www.google.com).

A.3 Missing Data and Procedures for Filling Gaps

There were six hours of missing weather data from the NWS in College Station in 2006, which happened from 6 pm to 10 pm on October 3rd and 8 pm on December 5th. These missing data were filled using linear interpolation (Baltazar, 2006). Table A.1 show the missing hours and interpolated data.

Table A.1 Six Hourly Missing Weather Data filled by Linear Interpolation.

Missing Data Replaced by Linear Interpolation						
Month	Day	Hour	Temperature Dry-Bulb (F)	Temperature Wet-Bulb (F)	Temperature Dew-Point (F)	Wind Speed (MPH)
10	3	6pm	85	72	65	9
10	3	7pm	83	72	65	8
10	3	8pm	82	72	66	7
10	3	9pm	80	71	67	5
10	3	10pm	78	71	67	4
12	5	8am	38	33	26	4

Solar radiation data were obtained from the NREL solar test bench installed in the Riverside campus of Texas A&M University located west of Bryan, Texas. However, for the cases where there were missing data during the 2006 year period from the NREL database, the gaps were filled with measured data from another solar test bench (STB) located in the roof of the Langford Architecture building in the Texas A&M university campus, College Station, Texas. Table A.2 shows missing solar data in the NREL solar station database.

Table A.2 Missing Solar Data in the LBNL Solar Station Database.

Missing Period		# of Missing Days	Replaced By
From	To		
1/1/06	1/12/06	12	ESL Solar Test Bench Data
1/22/06	1/31/06	10	ESL Solar Test Bench Data
6/20/06	7/6/06	17	ESL Solar Test Bench Data
8/6/06	8/9/06	4	ESL Solar Test Bench Data
9/15/06	9/15/06	1	ESL Solar Test Bench Data
10/7/06	10/13/06	7	ESL Solar Test Bench Data

Before the STB data were used for filling gaps, a data comparison was conducted to check the uncertainties between the NREL station and the ESL solar test bench data. Figure A.3 shows comparisons performed for four days, 1/16/2006, 2/9/2006, 5/17/2006, and 6/1/2006. As indicated in the figure, the ESL solar test bench (STB) data and the NREL data match well in the morning hours; however, the STB data showed about 10-20% higher values than that of NREL as time approaches to noon and thereafter of a day.

Although there are discrepancies between the NREL and ESL's STB data, it was decided to use the ESL's STB data would be used for filling missing gaps of the NREL data since the total missing days included 51 days (14% of 365 days) and the uncertainties between the NREL and ESL data were less than 10% in a whole day period. The possible impact from these uncertainties will be minimal to the whole-building energy calculation, which is less than 1%.

However, even with the availability of the ESL's STB data for filling the periods in missing days of the NREL data, there were still gaps, which occurred in a whole day (1/3/2006) and several hours on 1/4/2006 (from 8am to 12pm) and on 6/20/2006 (from 2pm to 7pm). These missing hours in the STB data were linearly interpolated except the whole day's missing data on 1/3/2006. To fill the January 3rd missing data, another solar data source, the Habitat solar data, was used. The Habitat data was obtained from a data logger installed in a single Habitat home for research in ESL and located in Bryan, Texas.

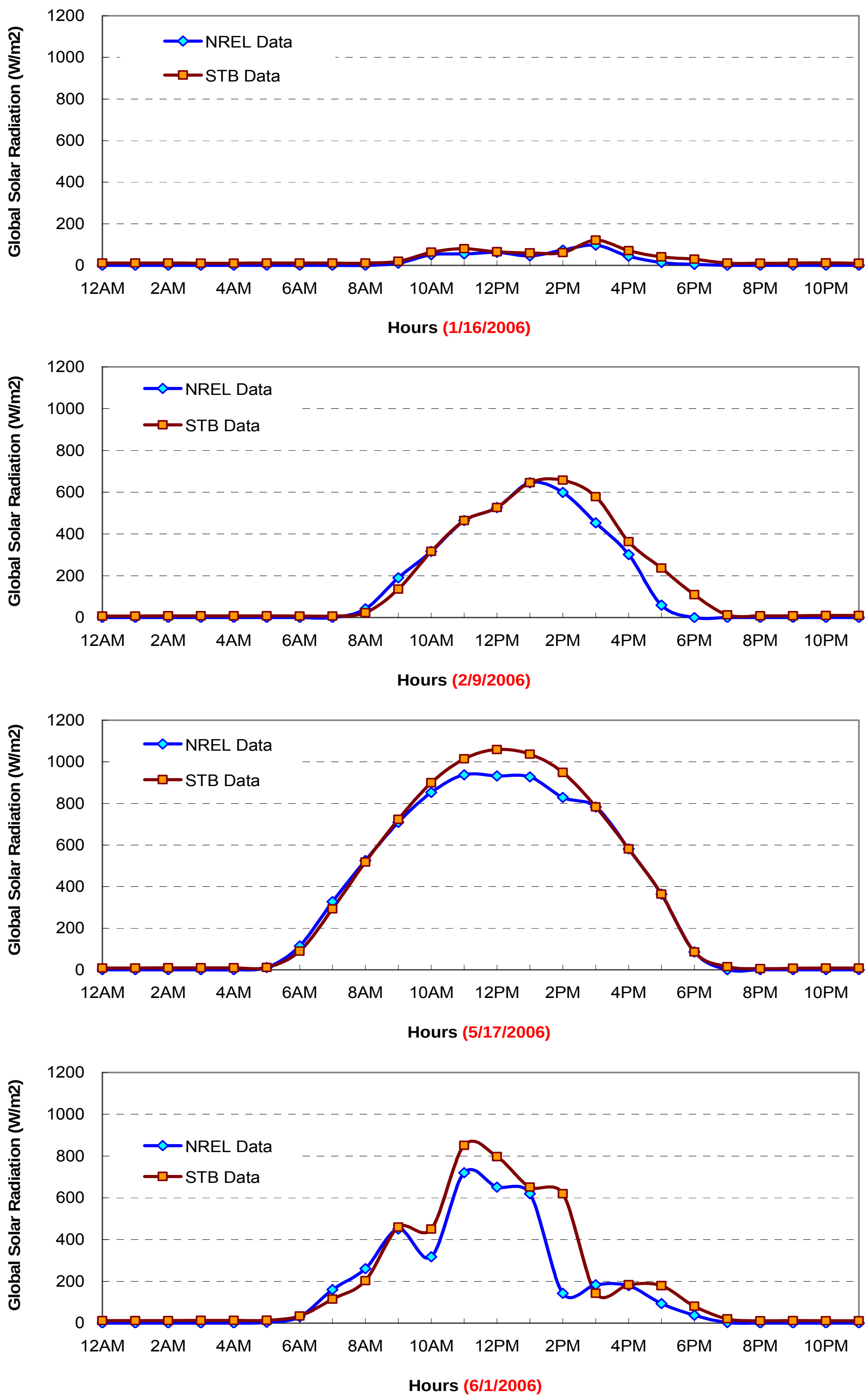

Figure A.3 Data Comparison of Measured Global Solar Radiation Between NREL Station and ESL Solar Test Bench.

Figure A.4 shows a comparison between NREL, STB, and Habitat data for the January 16th. The Habitat solar data appeared in between the NREL and STB data. For the missing data of January 16th of 2006 solar data, the Habitat data were used to develop the complete solar dataset for the TRY weather file.

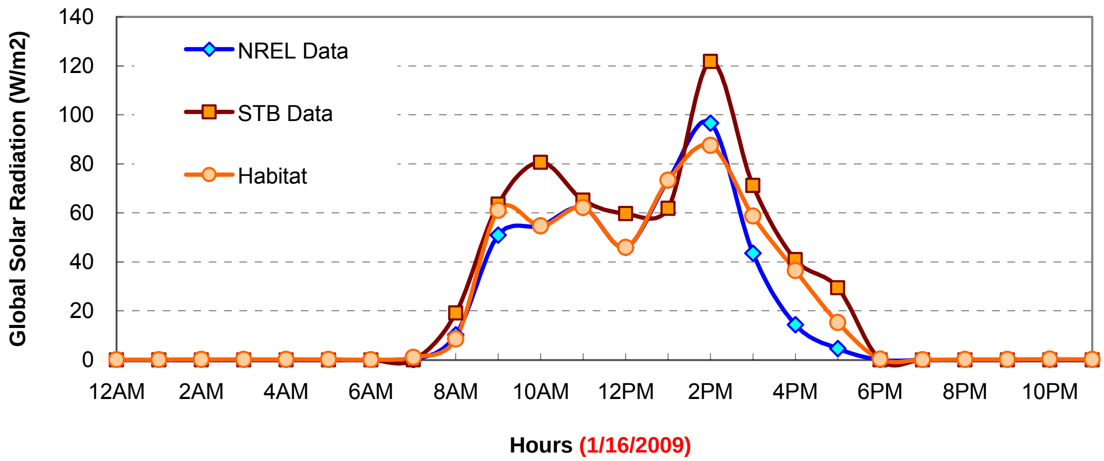

Figure A.4 Data Comparison of Measured Global Solar Radiation Between NREL Station, ESL Solar Test Bench, and Habitat Weather Data Logger.

A.4 Complete (8760 Hours) Weather and Solar Radiation Data for TRY Processing

After filling all the gaps in the weather and solar data, a contiguous set of 8,760 hours of data was created. Figure A.4 through Figure A.9 show the hourly and average daily dry-bulb temperature, wet-bulb temperature, dew-point temperature, wind speed, global solar radiation, and direct normal solar radiation for College Station, Texas in 2006. The figures for temperatures and wind speed include hourly measurement data and daily average values.

The maximum hourly temperature was 100 F for the dry-bulb measurements, 80 F for the wet-bulb measurements, and 77 F for the dew-point temperature. The minimum hourly temperature was 27 F for the dry-bulb temperature, 24 F for the wet-bulb temperature, and 7 F for the dew-point temperature. The annual average temperature was 70 F for the dry-bulb temperature, 62 F for the wet-bulb temperature, and 56 F for the dew-point temperature. The maximum and average wind speeds were 32 and 8 miles per hour, respectively.

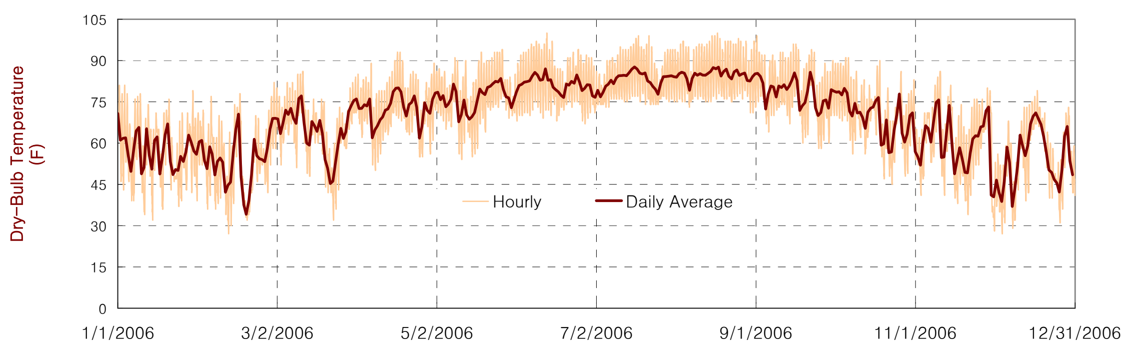

Figure A.4 Hourly and Daily Dry-Bulb Temperature for College Station, TX for 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

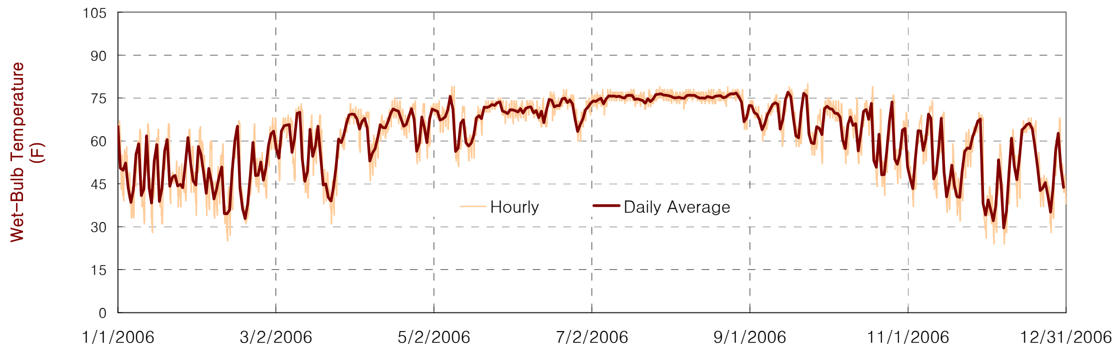

Figure A.5 Hourly and Daily Wet-Bulb Temperature for College Station, TX for 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

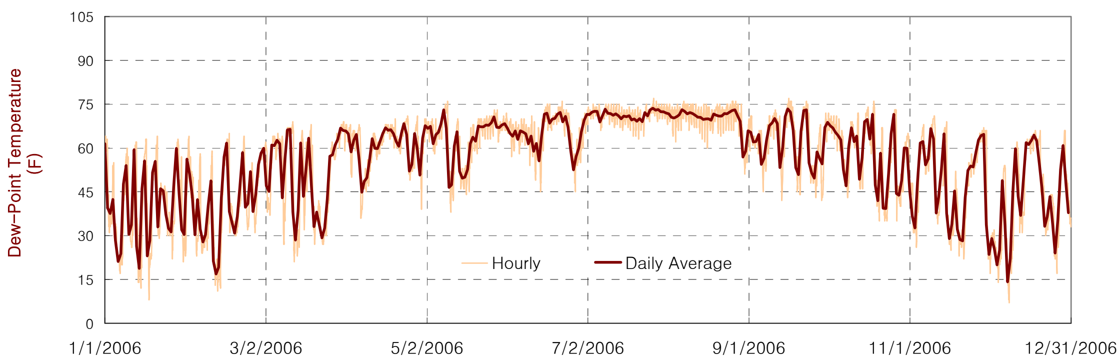

Figure A.6 Hourly and Daily Dew-Point Temperature for College Station, TX, for 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

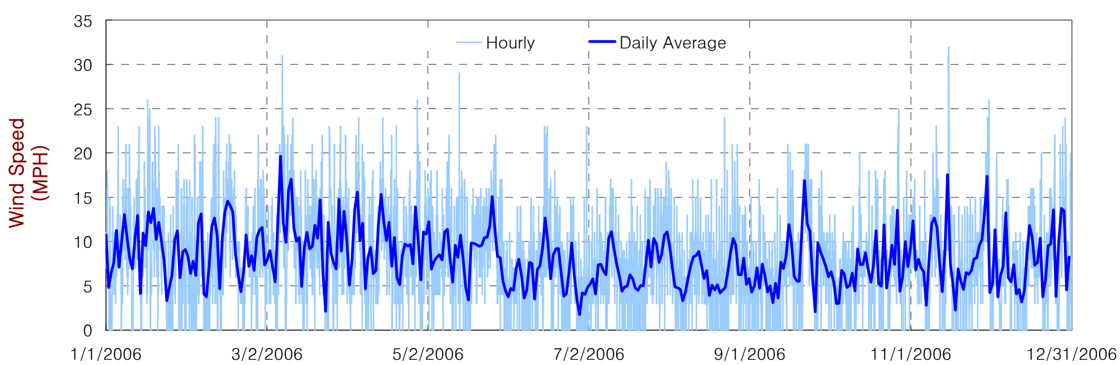

Figure A.7 Hourly and Daily Wind Speed for College Station, TX, for 2006 Obtained from the National Weather Service (NWS) Data Base (NWS, 2007).

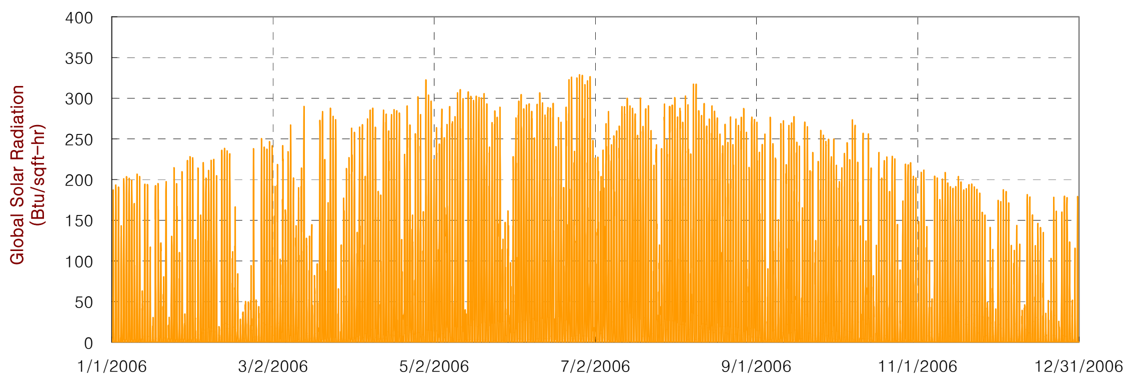

Figure A.8 Hourly Global Solar Radiation for College Station, TX, for 2006 Obtained from the Energy Systems Laboratory (ESL, 2007).

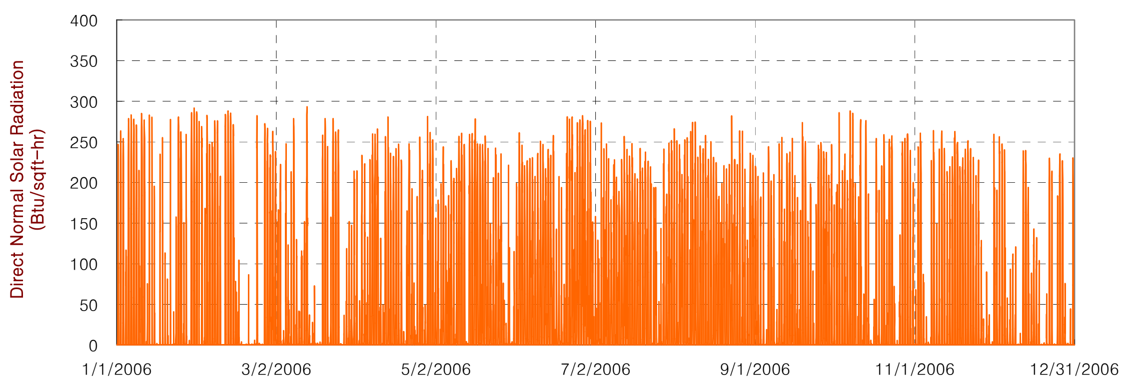

Figure A.9 Hourly Direct Normal Solar Radiation for College Station, TX, for 2006 Calculated Based on the Hourly Global Solar Radiation Data.

APPENDIX B

CALIBRATION OF PORTABLE THERMAL DATA LOGGERS

In this appendix, the calibration procedures are described for the portable data loggers (Onset, 2008). The portable data loggers were calibrated before they were installed in the case-study building to measure the indoor air conditions such as temperature and humidity. The measured temperature and humidity data were then used for the calibration of the DOE-2.1e simulation model of the case-study building.

The portable data loggers were calibrated based on both the standard practice of American Society of Testing and Material (ASTM, 1998) and the National Bureau of Standard (NBS) Monograph 174 and 150 (Wise and Soulen, 1986). The temperature and RH data were measured at three different temperatures (i.e., a three-point measurement: cold, medium, and hot temperatures) using two aqueous, saturated salt solutions; magnesium chloride as RH 23% and sodium chloride as RH 75% (ASTM, 1996). A linear regression analysis was performed to account for RH variations with respect to the temperature changes. The following sections show the calibration procedures and results.

Figure B.1 shows a photo of a portable data logger. It measures relative humidity, dry-bulb temperature, and relative lighting level. It also has an external port that can be used for the measurement of temperature from a remote location using an external probe. The working range of this data logger is between -4 F and 158 F (temperature) and between

5% and 95% for relative humidity. The accuracy is ±0.63 F for the temperature range from 32 F and 122 F and ±2.5% for the relative humidity range from 10% to 90%.

Figure B.1 Photo of a HOBO Portable Data Logger (Onset, 2005).

The calibration process uses a three point calibration against a certified reference. The first step is to calibrate several RTD (Resistance Temperature Detector) sensors against several certified ASTM thermometers (ASTM, 1988). This step is necessary for the RTD sensors to be able to be used for the remainder of the time series calibration of the portable loggers. After the calibration of the RTD sensors, the calibration of the portable loggers is conducted using the certified RTD sensors as the reference.

B.1 RTD Temperature Sensor Calibration against ASTM Certified Thermometers

Figure B.2 shows a picture of an RTD (Resistance Temperature Detector) sensor (1,000 Ohm platinum). The working range of the RTD sensor is from -40 F to 500 F with an accuracy of ±0.1% of span (30 F to 320 F). The RTD sensor can be an accurate temperature sensor if it is properly calibrated.

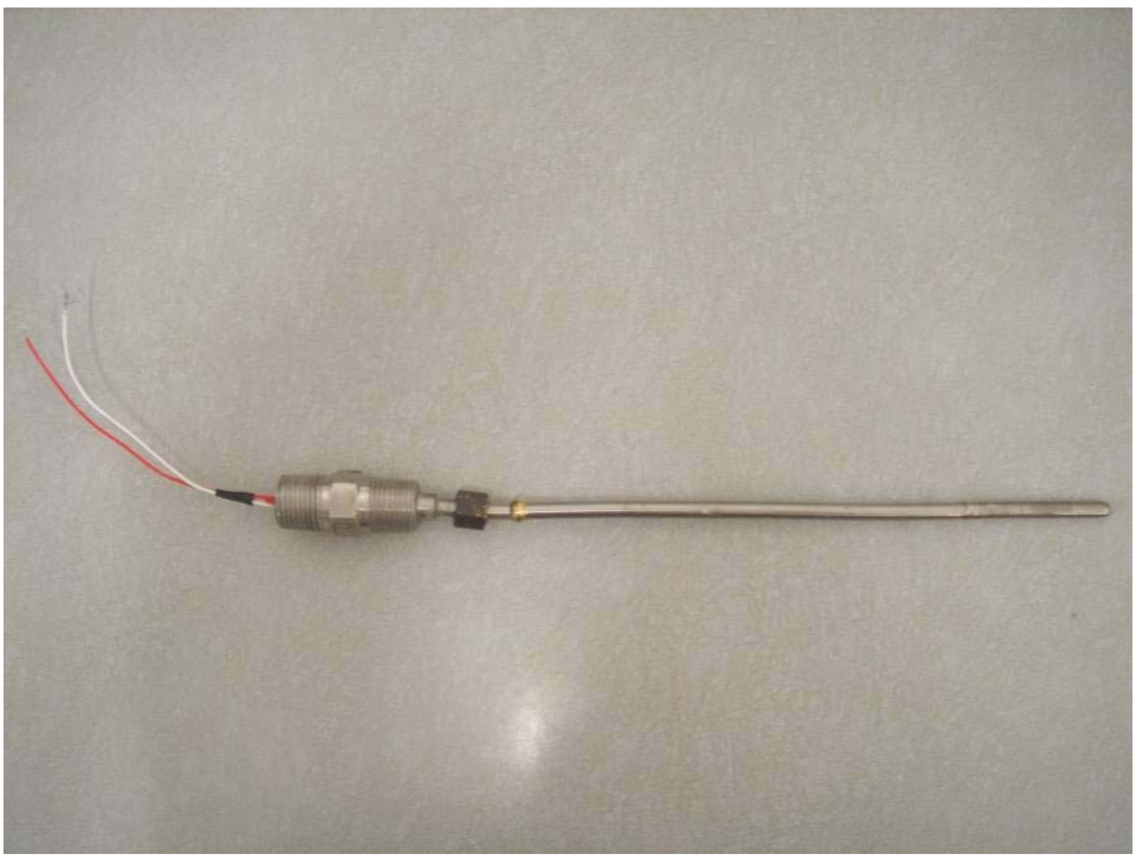

Figure B.2 Photo of a Platinum RTD Sensor (Minco, 2005): Model - S623 PF100Y24T.

As the name implies, RTDs are sensors used to measure temperature by correlating the resistance of the RTD element with measured temperatures from a test bench. The RTD element is made from a pure material or platinum. The material has a predictable change in resistance as the temperature changes. This predictable change is used to determine the temperature.

Figure B.3 ASTM Certified Thermometer (ASTM, 1988): Model - Immersion 108 MM.

Three ASTM certified thermometers (ASTM, 1988), as shown in Figure B.3, were used as transfer references. The working range of these thermometers is between 18 F and 89

F. Two platinum RTD sensors are put into an ice-maker bath in the insulated bottle along with the three ASTM certified thermometers as shown in Figure B.4.

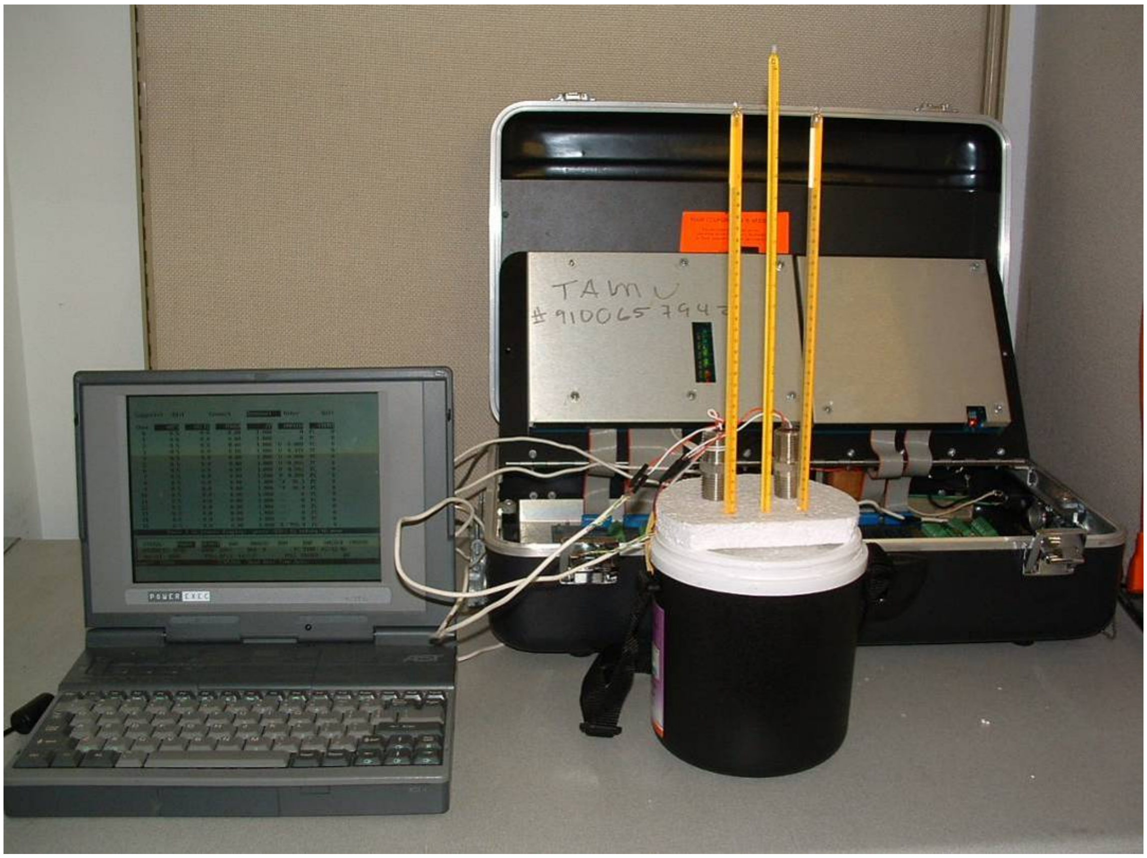

Figure B.4 An Ice-Point Bath with Thermometers and Two Platinum RTD Sensors Connected to A Data Logger (Photo by Permission of Suwon Song) (Song, 2006).

The platinum RTD sensors were connected to a Synergistic data logger (Synergistics, 1994), shown in Figure B.5, that stores the one-minute time series temperature data from the sensors. The stored temperature data were then retrieved using the PARSET program (Synergistics, 1994) installed on a computer connected to the logger. The measured data from the platinum RTD sensors were then compared to the manually read data from the

ASTM certified thermometers with the aid of a magnifier. When there were temperature differences between the manually read measurements from the platinum RTD and ASTM thermometers, a new offset was then calibrated for the Synergistic logger for the correct platinum RTD sensor readings.

Figure B.5 Photo of a Synergistic Logger Model - C180-XP (Serial No.: 1508) (Synergistics, 1994).

B.2 Portable Data Logger Calibration for Temperature and Relative Humidity.

After the platinum RTD sensors were calibrated with the ASTM certified thermometers, they were then used as the reference for the calibration of the portable data loggers.

Figure B.6 Photo of the Refrigerator with the Temperature and Humidity Chamber with a Container Including Two Portable Data Loggers, Two Platinum RTD Sensors, and a Standard Thermometer (Photo by Permission of Suwon Song) (Song, 2006).

Figure B.6 shows the inside of the refrigerator that was used for the calibration. Inside the refrigerator are the portable loggers, platinum RTD sensors, and an ASTM thermometer installed in a specifically-made glass flask, a light fixture with a 40 watt lamp, and a fan to circulate the air inside the refrigerator to help keep temperature uniform.

Below are the details of individual equipment for the experiment.

- Equipment required for the HOBO portable data logger calibration:
  - ASTM certified thermometers (ASTM, 1988)
    - Model: Immersion 108 MM (Figure B.3)
  - Platinum RTD sensors (Minco, 2005)
    - Model: S623 PF100Y24T (Figure B.2)
  - Synergistic logger (Synergistics, 1994)
    - Model: C180-XP (Serial No.: 1508) (Figure B.5)
  - Refrigerator (GE, 2004)
    - Model: TAX4DNCAWH (Figure B.7)
  - Light fixture & bulb (Walmart, 2004)
    - Model: BH-87, 899 (Figure B.8)
  - Portable temperature & RH loggers (Onset, 2005)
    - Model: HOBO (RH,Temp,Light,External) (Figure B.1)
  - MgCL (Alfa, 2004) and NaCL (Merck, 2004) (Figure B.9)
  - Flask with rubber stoppers (TAMU, 2004) (Figure B.10)

Figure B.7 Refrigerator Model - TAX4DNCAWH (GE, 2004).

Figure B.8 Light Fixture and 40 Watt Lamp (Cheyenne): Model - BH-87, 899 (Walmart, 2004).

Figure B.9 MgCL (Alfa, 2004) and NaCL (Merck, 2004).

Figure B.10 Flask with Rubber Stoppers (TAMU, 2004).

A detailed step-by-step calibration procedure is introduced below. These procedures were referenced from earlier publications (ASTM, 1996 and Greenspan, 1977).

A. Steps for temperature calibration against the platinum RTD sensors (refer to Figure B.6)

Step 1. Setup the HOBO loggers (Figure B.1) for the temperature reading. Using the specifically-made flask (Figure B.9), which has five narrow necks, put the platinum RTD and HOBO sensors into the flask and lightly seal with the rubber stoppers.

Step 2. Put the flask including the platinum RTD and portable loggers into the refrigerator (Figure B.6).

Step 3. Change the temperature inside the refrigerator and vary the temperature from 40 F to 130 F using the refrigerator for the cold temperature condition, using the light bulb for the high temperature condition and room temperature for the middle temperature condition (Figure B.6).

Step 4. Put a fan inside the refrigerator (Figure B.5) to circulate the air inside the refrigerator so that everywhere inside the refrigerator has the same temperature condition.

Step 5. Compare the loggers' readings with platinum RTD readings.

Step 6. If the differences between the platinum RTD and portable data logger readings are out of the manufacturer's error range, adjust the differences by adding or subtracting from the measurements.

B. Steps for Relative Humidity (RH) calibration using MgCL and NaCL

Step 1. Put the MgCl (or NaCl) and distilled water into the flask (Figure B.10).

Step 2. Stir the mixed water and the MgCl (or NaCl) until it becomes a saturated salt solution (i.e., a slurry that still has crystals).

Step 3. Setup the loggers for the relative humidity reading. Using the flask, which has five narrow necks, put the loggers into the flask with the MgCl-saturated (or NaCl-saturated) solution and seal lightly with rubber stoppers (Figure B.9). Do not allow the logger to contact the salt solution as this will destroy the logger.

Step 4. Put the flask with the sensors and the saturated solution into the refrigerator.

Step 5. Read the RH values at 3 different temperature points

- Read RH value at a cold temperature (40F) condition.
- Read RH value at a room temperature (85F) condition.
- Read RH value at a hot temperature (130F) condition.

Step 6. Compare the RH readings with the calculated RH values from an equation, $RH = \sum_{i=o}^{3} A_i t^i$ where A is a constant and t is temperature, (Greenspan, 1977).

Step 7. Repeat the steps of '1' through '6' with the other solution.

Step 8. Plot the differences and make an equation for RH offset of readings from the loggers.

B.3 Results of Calibration

Table B.1 and Table B.2 show the results of the three-point temperature measurements for the eight portable data loggers compared to the platinum RTD sensor temperature measurement. Figure B.11 and Figure B.12 show that the portable data loggers were measuring temperature within the manufacturer's error range. Table B.3 and Table B.4 show the results of the relative humidity measurement for the portable loggers with the MgCl solution, while Table B.5 and Table B.6 show the humidity measurement with the NaCl solution. Figure B.13 and Figure B.14 show that the humidity measurement of the portable data loggers is also within the manufacturer's tolerance range.

Table B.1 Temperature Measurements for Platinum RTD Sensor and Portable Loggers 1-4.

Three Points	RTD Sensor	Portable Logger-1		Portable Logger-2		Portable Logger-3		Portable Logger-4	
	Mea. Temp. (F)	Mea. Temp. (F)	Temp. Diff. (F)	Mea. Temp. (F)	Temp. Diff. (F)	Mea. Temp. (F)	Temp. Diff. (F)	Mea. Temp. (F)	Temp. Diff. (F)
Cold	35	34.85	0.15	34.67	0.33	34.74	0.27	34.93	0.07
Medium	75	74.81	0.19	74.57	0.43	74.89	0.11	74.97	0.03
Hot	95	94.79	0.21	94.53	0.47	94.97	0.03	94.99	0.01

Table B.2 Temperature Measurements for RTD Sensor and Portable Loggers 5-8.

Three Points	RTD Sensor	Portable Logger-5		Portable Logger-6		Portable Logger-7		Portable Logger-8	
	Mea. Temp. (F)	Mea. Temp. (F)	Temp. Diff. (F)	Mea. Temp. (F)	Temp. Diff. (F)	Mea. Temp. (F)	Temp. Diff. (F)	Mea. Temp. (F)	Temp. Diff. (F)
Cold	35	34.59	0.41	34.75	0.25	34.76	0.24	34.78	0.22
Medium	75	74.43	0.57	74.59	0.41	74.57	0.43	74.56	0.44
Hot	95	94.36	0.64	94.51	0.49	94.47	0.53	94.45	0.55

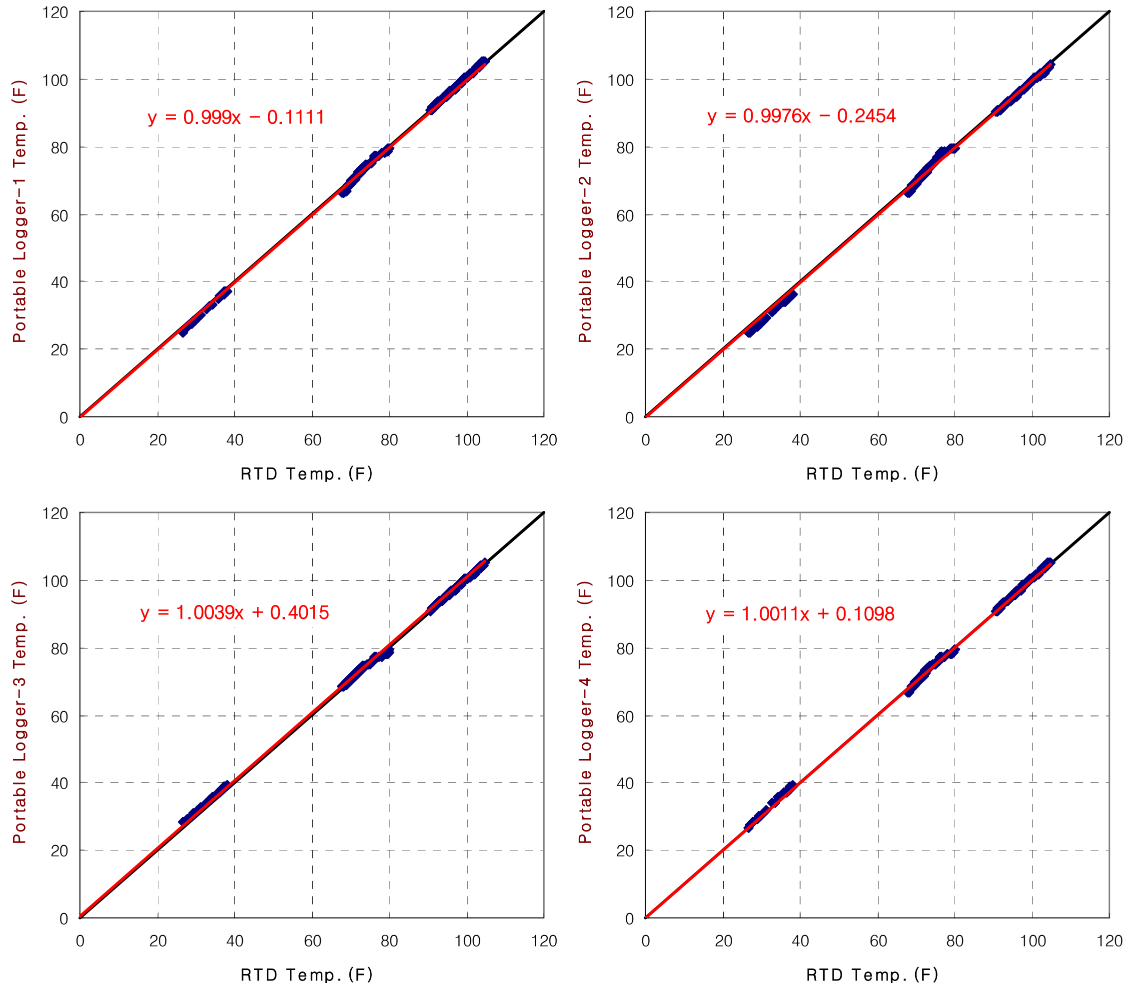

Figure B.11 Temperature Measurement of the Portable Data Loggers with the Reference Temperature from the RTD Sensor: Logger-1 (Top Left), Logger-2 (Top Right), Logger-3 (Lower Left), and Logger-4 (Lower Right).

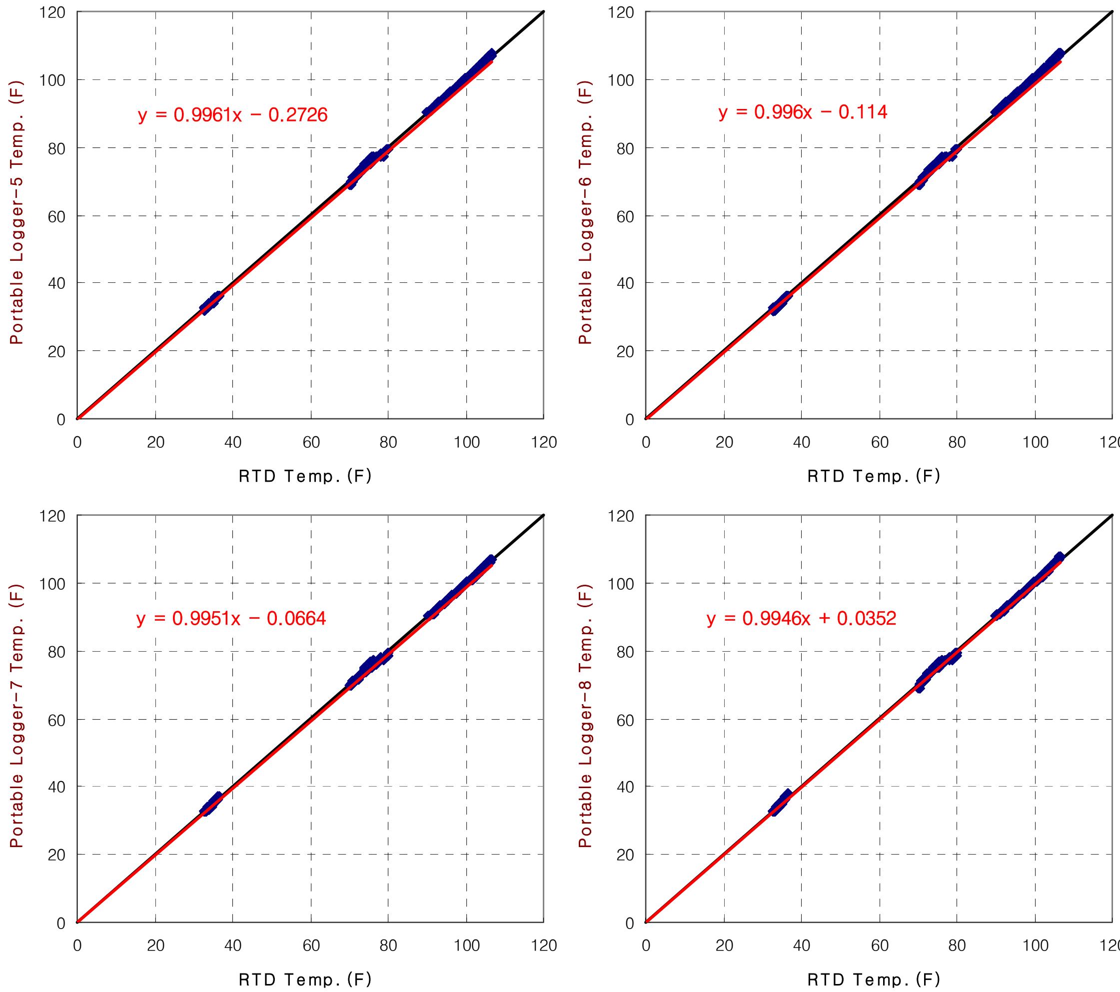

Figure B.12 Temperature Measurement of the Portable Data Loggers with the Reference Temperature from the RTD Sensor: Logger-5 (Top Left), Logger-6 (Top Right), Logger-7 (Lower Left), and Logger-8 (Lower Right).

Table B.3 Relative Humidity Measurements for Portable Loggers 1-4 with the MgCl Solution.

Three Points	MgCl (RH=32%)		Portable Logger-1		Portable Logger-2		Portable Logger-3		Portable Logger-4	
	Mea. Temp. (F)	MgCl RH (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)
Cold	35	33.94	31.25	2.69	31.22	2.72	31.97	1.97	31.77	2.17
Mediu m	75	32.65	31.01	1.64	30.08	2.57	31.01	1.64	31.09	1.56
Hot	95	32.00	30.19	1.81	30.01	1.99	30.98	1.02	29.99	2.01

Table B.4 Relative Humidity Measurements for Portable Loggers 5-8 with the MgCl Solution.

Three Points	MgCl (RH=32%)		Portable Logger-5		Portable Logger-6		Portable Logger-7		Portable Logger-8	
	Mea. Temp. (F)	MgCl RH (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)
Cold	35	33.94	32.99	0.95	32.78	1.16	32.65	1.29	32.87	1.07
Medium	75	32.65	32.02	0.63	31.08	1.57	31.23	1.42	30.11	2.54
Hot	95	32.00	30.99	1.01	30.82	1.18	29.98	2.02	29.56	2.44

Table B.5 Relative Humidity Measurements for Portable Loggers 1-4 with the NaCl Solution.

Three Points	NaCl (RH=75%)		Portable Logger-1		Portable Logger-2		Portable Logger-3		Portable Logger-4	
	Mea. Temp. (F)	NaCl RH (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)
Cold	35	75.81	73.29	2.52	73.45	2.36	75.00	0.81	74.34	1.47
Medium	75	75.18	69.55	5.63	68.00	7.18	69.96	5.22	67.90	7.28
Hot	95	74.87	63.05	11.82	64.06	10.81	66.03	8.84	64.98	9.89

Table B.6 Relative Humidity Measurements for Portable Loggers 5-8 with the NaCl Solution.

Three Points	NaCl (RH=75%)		Portable Logger-5		Portable Logger-6		Portable Logger-7		Portable Logger-8	
	Mea. Temp. (F)	NaCl RH (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)	Mea. RH (%)	RH Diff. (%)
Cold	35	75.81	74.21	1.60	75.30	0.51	74.93	0.88	75.00	0.81
Medium	75	75.18	68.88	6.30	69.66	5.52	70.01	5.17	71.01	4.17
Hot	95	74.87	66.11	8.76	66.93	7.94	66.77	8.10	67.09	7.78

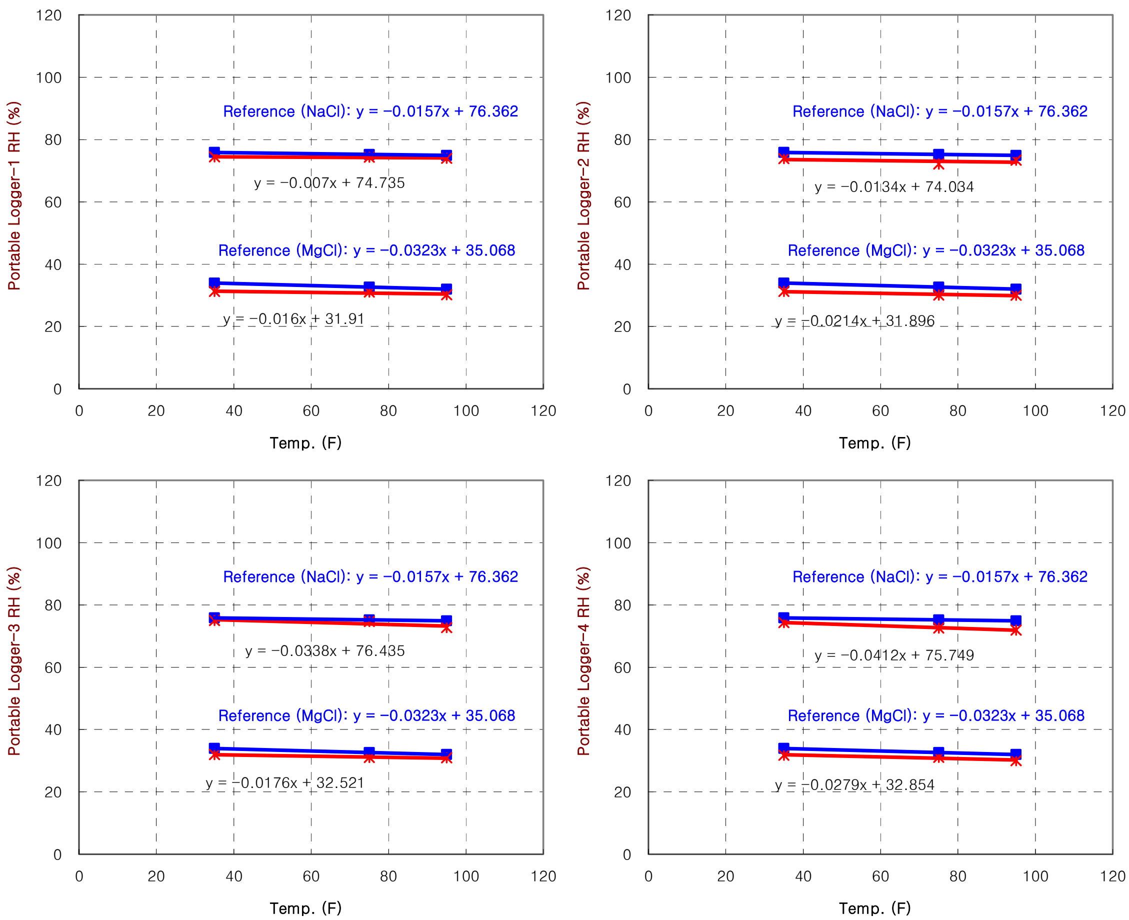

Figure B.13 Relative Humidity Measurement of the Portable Data Loggers with the Reference of MgCl and NaCl Solutions: Logger-1 (Top Left), Logger-2 (Top Right), Logger-3 (Lower Left), and Logger-4 (Lower Right).

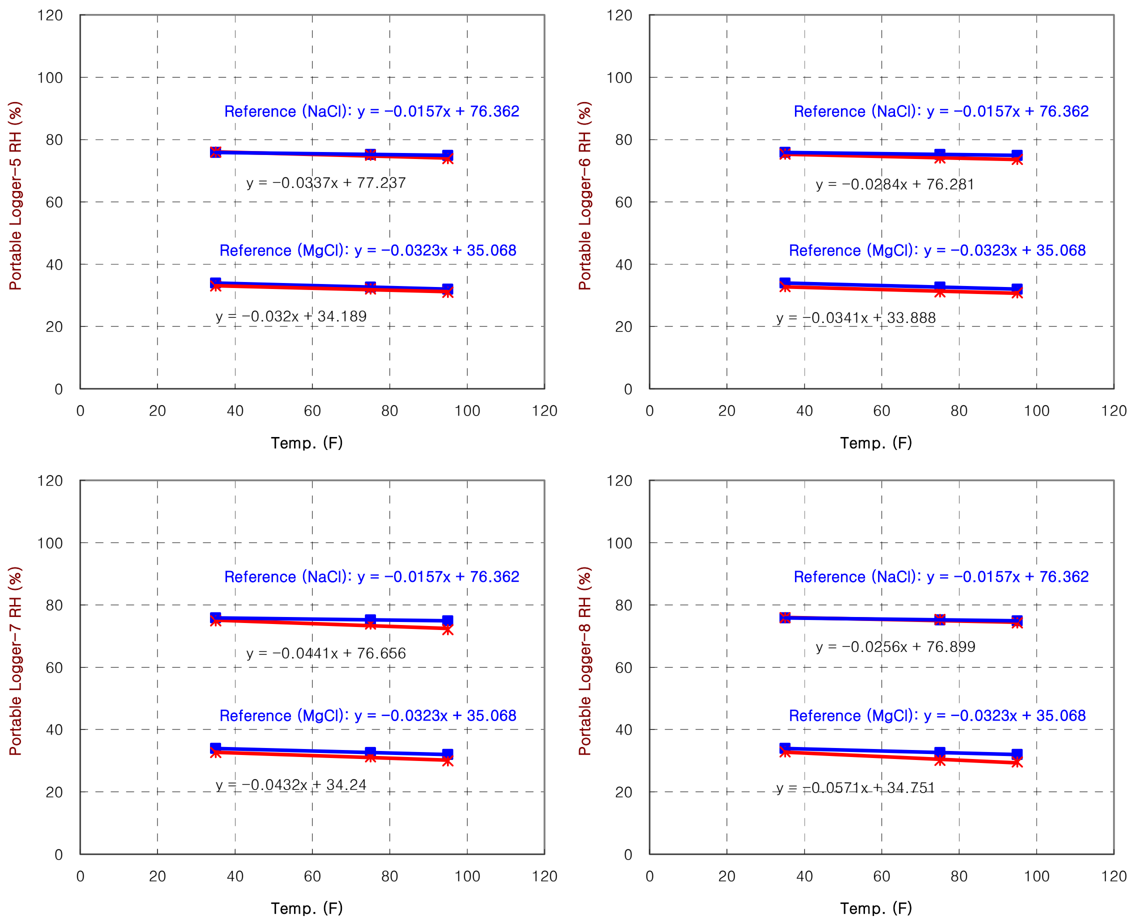

Figure B.14 Relative Humidity Measurement of the Portable Data Loggers with the Reference of MgCl and NaCl Solutions: Logger-5 (Top Left), Logger-6 (Top Right), Logger-7 (Lower Left), and Logger-8 (Lower Right).

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