A SURVEY OF HIGH-PERFORMANCE OFFICE BUILDINGS IN THE UNITED STATES

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ABSTRACT

This paper presents the results of a survey of high-performance commercial office buildings to determine the components that could best improve building performance in hot and humid climates. The case studies reviewed include high-performance buildings, high-performance components, and measurement tools. It also includes an analysis of whether or not the building systems and components can be modeled using today's simulation programs. In addition to the general survey, this paper focuses on the most promising characteristics of high-performance office buildings in hot and humid climates.

INTRODUCTION

In the United States, buildings consume more than one-third of the total energy and more than two-thirds of the total electricity use (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 (Torcellini et al., 2004).

Efforts to improve energy efficiency of new commercial buildings have been reported in many studies (Stein et al., 2000; Case and Wingerden, 1998; Brohard et al., 1998; Peterson and Eley, 1996; Kaplan et al., 1992; Diamond et al., 1992 and 1990). However, energy conservation is still the easiest and readily verifiable way to achieve a high performance building. For commercial buildings, energy conservation is a straightforward "green" benefit that can be shared between owner and tenant (Traugott, 2000).

A high performance commercial building is a substantially better building than standard practice in terms of energy, economic, and environmental performance. To build a high performance building, it is necessary to consider the whole-building commercial design concept during the design phase that integrates all the subsystems of the building to work together. To accomplish this, the design team should include architects, engineers, occupants, owners, and energy efficiency specialists (NREL, 2005; EERE, 2003; and Crosbie, 2000).

CASE STUDIES OF HIGH-PERFORMANCE BUILDINGS

High performance buildings have been reported in a number of different climates. All were constructed using high performance building components and systems in all stages of the design, which allowed them to consume considerably less energy than conventional buildings. In this survey, a total of 35 high-performance building case studies were selected, reviewed, and then summarized in Table 1. Table 1 includes information about building characteristics, high-performance strategies, Energy Use Indices (EUIs), and energy savings. Also, climate zones, in which the buildings are located, are included according to the map (USDOE, 2002) in Figure 1.

Currently, the USDOE's Office of Energy Efficiency and Renewable Energy (EERE) contains the largest database of case studies of high performance buildings (EERE, 2005). In this database are more than twenty case studies of high performance commercial buildings in the United States. The energy savings of these case study buildings were calculated mainly with utility bill comparisons or DOE-2 simulations (LBNL, 2002). The savings results varied from study to study, depending upon the unit of measure and the reference buildings.

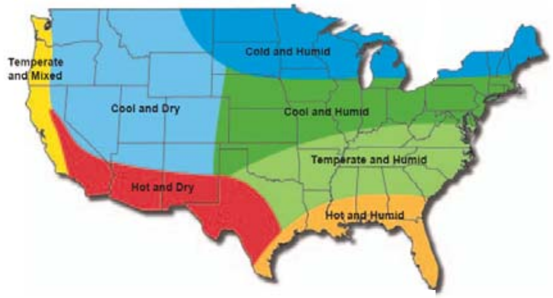

Figure 1: Map of Climate Zones in United States for Energy Design Guidelines (USDOE, 2002)

Table 1: Literature Summary of High-Performance Building Case Studies

No.	Authors	Building Name	Climate Zone	Building Location	Bldg Type	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	Ebensburg, PA	Commercial office	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	Silverthorne, CO	Commercial office, Industrial, Retail	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	Annapolis, MD	Commercial office	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	Springdale, UT	Commercial Office	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	Golden, CO	Office & Laboratory	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	San Francisco, CA	Commercial Office	2002	4	350,000	CEC Title 24 Standards	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
7	Blaevoet (2005)	Hamilton Landing Project (A Retrofit of a 70-year-old Air Force Base Hanger)	Temperate & Mixed	California	Office Complex (7 Hangers)	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	Laguna Niguel, CA	Commercial Office	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	Research Triangle Park, NC	Commercial office, Laboratory	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	Research Triangle Park, NC	Commercial office	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	Reston, VA	Commercial office, Recreation, Interpretive Center, Park	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	Arlington, VA	Commercial office	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	New York, NY	Commercial office, Retail	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	Pittsburgh, PA	Commercial office	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	Harrisburg, PA	Commercial office	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	Allentown, PA	Commercial office, Retail	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	Caribou, ME	Office (24%), Others (76%)	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	Concord, NH	Commercial office	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
19	Miller (1997)	Wampanoag Tribal Headquarters	Cool & Humid	Gay Head, MA	Commercial office, Interpretive Center, Assembly	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	Portland, OR	Commercial office, Restaurant, Retail	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	Port Hueneme, CA	Commercial office, Industrial, Military base	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	Downey, CA	Commercial office, Assembly	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	University Place, WA	Commercial office	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	San Diego, CA	Commercial office	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	San Francisco, CA	Commercial office	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	Golden, CO	Commercial office, Other	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	Chicago, IL	Commercial office, Industrial, Assembly, Other	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	Zeeland, MI	Commercial office	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	Vancouver, BC, Canada	Commercial office, Higher education	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	Mill Run, PA	Commercial office, Interpretive Center	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	Media, PA	Commercial office	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	Hillsboro, OR	Commercial office	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	Oak Ridge, TN	Commercial office, Financial & communications, Laboratory, Campus	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	Falmouth, MA	Commercial office, Laboratory, Other	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	Austin, TX	Commercial Office	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

When 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. Finally, savings of 40-50% were reported for buildings that were compared to California's Title 24 Standards (CEC, 2001).

In one significant study, Torcellini et al. (2004) analyzed the performance of six High-Performance buildings. 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. Torcellini et al. used computer simulation tools (DOE-2 and EnergyPlus) to evaluate the 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.

In terms of EUI, as shown in Figure 2, five of the studies (14%) had EUIs less than 30 kBtu/ft2-yr, eleven studies (31%) had EUIs between 30-50 kBtu/ft2-yr, three studies (9%) had EUIs between 50-70 kBtu/ft2-yr, six studies (17%) had EUIs between 70-90 kBtu/ft2-yr, three studies (9%) had EUIs between 90-110 kBtu/ft2-yr, and four studies (11%) had EUIs greater than 140 kBtu/ft2-yr.

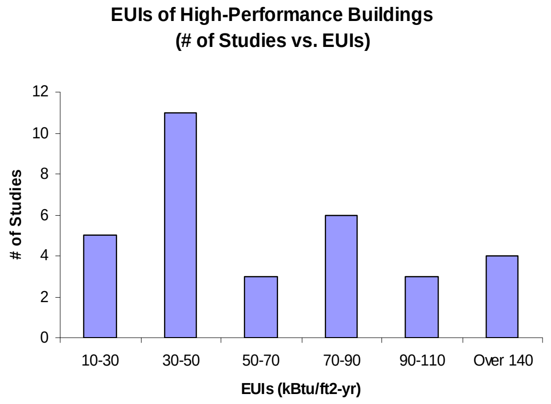

Figure 2: Energy Use Indices (EUIs) of High-Performance Buildings

One of the main reasons for the significant energy savings was the design and selection of the most energy efficient HVAC systems for a specific building (e.g., ground-coupled systems, photovoltaic systems, etc.), which required a detailed analysis involving first costs, replacement costs, utility and operating costs, and maintenance costs analyzed using a life-cycle cost analysis. Moreover, the HVAC systems must also be carefully evaluated and designed for a specific climate and operational requirements, to assure proper Indoor Air Quality (IAQ) and humidity control (Traugott, 2000).

As shown in Table 1, however, no high-performance buildings were identified in hot and humid climates except the Robert E. Johnson Building in Austin, TX (Sylvester et al., 2002). Sylvester et al. developed a baseline simulation model calibrated to the measured whole-building energy consumption to determine the independent and combined effect of the stated efficient components installed in the building. They showed that the energy savings resulting from the new design reduced the energy use by 46% when compared to similar state office buildings. Although there have been studies on energy-efficient buildings in hot and humid climates, 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.

HIGH-PERFORMANCE SYSTEMS AND COMPONENTS

High-Performance systems and system components have also been 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 is a summary of 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 1. In the literature, energy savings were calculated primarily with the DOE-2 simulation program. The results of energy savings by implementing the high-performance systems and components varied from 22% to 80% compared to energy codes or conventional buildings as baselines. The major systems or components implemented in the studies were Under Floor Air Distribution (UFAD) systems, Ground Source Heat Pump (GSHP) systems, natural ventilation systems, photovoltaic systems, dual-path systems, and ground coupled systems. It is interesting to note that most of these systems cannot be simulated with the DOE-2.1e program without modifications.

One noteworthy integrated analysis was performed by Parker et al. in 1997. In this study they presented the energy performance of the new Florida Solar Energy Center (FSEC) building using the DOE-2.1e simulation program to make it a maximum energy efficient building in Florida's hot and humid climate. The DOE-2.1e simulation program calculated the building energy consumption by implementing 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 ten high-performance systems showed an energy reduction of 62% 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 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).

Table 2: 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

In another study, "Energy Consumption Characteristics of Commercial Building HVAC Systems", Roth et al. (2002) reported fifteen high-performance commercial building systems and components that have energy savings potential. The study included a detailed evaluation for each of the fifteen technologies. For example, five of the fifteen technologies used 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 included 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 Displace 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.

There are many high-performance technologies for the construction of high-performance buildings. However, not all high-performance systems and components mentioned in these studies are applicable for high-performance buildings in hot and humid climates. Also, even the technologies, which have been proven to improve building energy performance, need further demonstrations of the benefits of savings. For example, the dual-path system (or DOAS) was verified in a couple of studies (Khattar et al., 2003 and Khattar and Brandemuehl, 1996) as a high-performance system for good humidity control and improved Indoor Air Quality (IAQ); therefore, it should be a good choice for hot and humid climates. However, there is still a need for additional demonstrations for its application to the office buildings in hot and humid climates.

HVAC ENERGY USE OF COMMERCIAL BUILDINGS IN HOT & HUMID CLIMATES

Westphalen and Koszalinski (2001) analyzed total HVAC primary energy use and Energy Use Intensity (EUI) by five regions (Northwest, Midwest, South, Mountain, and Pacific) based on the Commercial Buildings Energy Consumption Survey (CBECS, 1998) report. As shown in Figure 3 and Figure 4, the HVAC energy use was clearly dependent on the geographic regions. The categories here are different from those shown in Figure 1. However, it is reasonable to consider the South region as hot and humid climate area since the climate condition of the South region is mainly hot and humid.

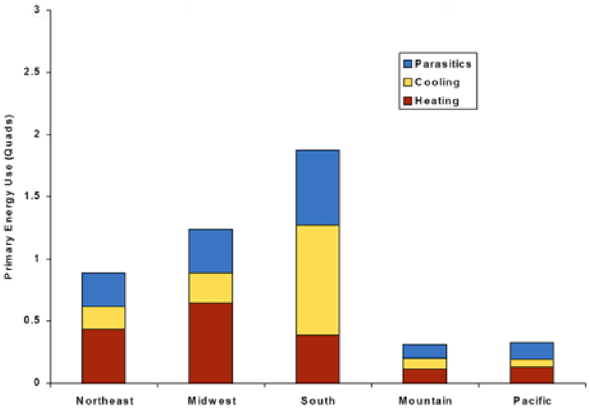

Figure 3: Total HVAC Energy Use by Region (Westphalen and Koszalinski, 2001)

In Figure 3, the South region was the area showing the highest total HVAC energy use since the region has the largest conditioned floor space compared to the other regions. In the South, due to the climatic characteristics (hot and humid), it makes sense that cooling energy use was the major contribution to the total HVAC energy use. Figure 4 shows the average HVAC EUIs by region. Although the South also showed the highest average EUIs, the total EUIs for the five regions did not vary much except one region, the Pacific, which has mild, year-around climate. In the South, however, the cooling portion remains higher than any other regions. It is interesting to note that although there is such a large total HVAC energy use in the South as shown in Figure 3, in Table 1 only a few studies demonstrated specific ideas for reducing energy use in the South.

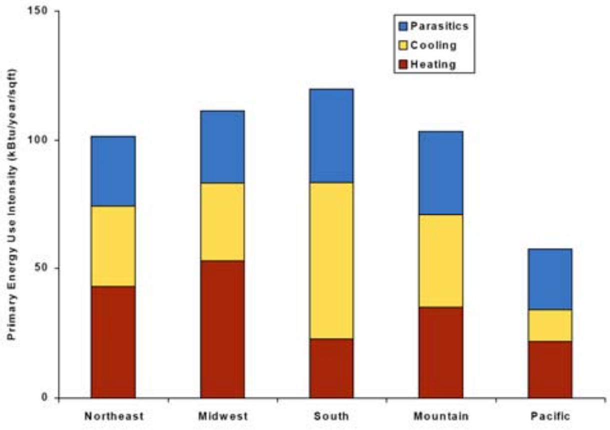

Figure 4: Total HVAC Energy Use Intensity by Region (Westphalen and Koszalinski, 2001)

SUMMARY

In this paper, a literature review revealed not only case studies that deal with high performance buildings, high performance components, and measuring tools, but also experimental research that deals with the development of specific energy-efficient HVAC systems and components in various climates. Based on the survey of high-performance buildings, this study identified 35 case studies of high-performance buildings and 17 papers about high-performance systems and components.

In the case studies of high performance commercial buildings, there were many 'Green' strategies to enhance building performance; e.g., wall insulation, displacement ventilation, ground-coupled system, daylighting, underfloor air distribution system, ventilation system, PV systems, roof insulation, high performance window, and so forth. The energy savings of high-performance buildings were substantial, ranging from 15-83% compared to energy codes or conventional constructions as baseline. The savings from individual systems or components varied from 22-80% compared to the energy consumption of conventional systems or equipment.

For the energy savings analysis, the DOE-2 program has been mainly used as the evaluation tool for the energy performance of case studies. Although DOE-2 is a powerful simulation program that is capable of simulating specific systems and components and showing energy impacts of them on buildings as well, there are still HVAC systems that the DOE-2 (or other) simulation programs cannot simulate (e.g., Under Floor Air Distribution System, Dual Path System, Displacement Ventilation, and Natural Ventilation).

Hot-dry and hot-humid climates consume the most HVAC energy use in United States compared to other climate areas due to the large amount of conditioned floor space and the extreme climatic conditions (hot and humid). Also, the cooling energy use is dominant in the energy use required for HVAC in hot-dry and humid-humid climates. So it is necessary to design and construct high-performance buildings using special high-performance HVAC systems and components for south climates. Unfortunately, however, there were only few high-performance buildings identified and reported publicly in hot and humid climates.

There are many technologies to make a building a high-performance building using high-performance systems and components. However, not all high-performance technologies are applicable for buildings in hot and humid climates. Moreover, even for the technologies applicable in the climates, more demonstrations are needed for designers and engineers to be able to implement them with confidence.

Finally, the most promising characteristics of high-performance office buildings in hot and humid climates are as follows.

- Solar thermal and PV systems
- Dual-Path systems (or dedicated outdoor air systems) to control high humidity
- High efficiency chillers
- High-Albedo roofs
- Daylighting systems
- High-performance glazing

Therefore, there is an opportunity to continue to explore alternatives for high-performance office buildings in hot and humid climates.

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