Modeling Energy Performance of Concrete Buildings for LEED-NC v2.2 Energy and Atmosphere Credit 1

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ABSTRACT

This paper provides information on energy savings in mid-rise commercial buildings due to additional thermal mass and for exceeding thermal performance requirements in the building envelope. The paper also shows how to model the thermal properties of concrete to obtain points for optimizing energy performance under the Energy and Atmosphere (EA) credit of LEED-NC v2.2. Obtaining points for this EA credit using the performance path requires modeling with whole-building energy simulation software; and modeling thermal mass effects requires software that models yearly energy use on an hourly basis.

Five-story prototype buildings with plan dimensions of 105 by 105 sq ft. (32 by 32 m) and a window-to-wall ratio of 0.40 have been modeled using the software program VisualDOE. Since the effects of thermal mass vary with climate, the buildings were modeled in six cities representing the range of climates in the US: Miami, Phoenix, Memphis, Salem (Oregon), Denver, and Chicago. The buildings include: EIFS, precast concrete, and curtain walls meeting ASHRAE 90.1-2004 with either structural steel or reinforced concrete frame; and precast concrete walls exceeding ASHRAE 90.1-2004 with either structural steel or reinforced concrete frame.

The energy modeling shows that the effect of thermal mass in concrete framed buildings, combined with thermal improvements to the building envelopes (including walls and windows), lowers energy cost up to 23% relative to the baseline steel framed EIFS buildings. This energy savings qualifies for up to 4 LEED-NC v2.2 points.

INTRODUCTION

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System is a family of voluntary rating systems for designing, constructing, operating, and certifying green buildings. LEED is administered by the U.S. Green Building Council (USGBC)—a coalition of individuals and groups from across the building industry working to promote buildings that are environmentally responsible, profitable, and healthy places to live and work. The work described in this paper is based on version 2.2 of LEED for new construction and major renovation (LEED-NC) (USGBC 2005).

LEED-NC has gained widespread acceptance across the US. Many states and municipalities require that new public and publicly funded buildings meet the LEED-NC requirements for certification. Many owners and architects are also seeking LEED-NC ratings for privately funded buildings.

The LEED rating systems are point-based systems. Points are awarded for meeting specific requirements, such as energy conservation and using recycled-content materials. Previous work by the authors has shown how concrete can contribute to 20 of the 26 points required for the basic level of LEED-NC certification. For example, concrete is a locally-produced, recyclable, material that often includes recycled materials.

The LEED-NC Energy & Atmosphere (EA) Credit 1 for optimizing energy performance can potentially provide up to 10 points for energy cost savings beyond *ANSI/ASHRAE/IESNA Standard 90.1-2004* (ASHRAE 2004). Obtaining points for EA Credit 1 requires modeling with energy simulation software. The software must be capable of simulating

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yearly energy use on an hourly basis. Hourly simulation is especially important in concrete construction because it is the best practical way to simulate the thermal interaction of concrete with changing outdoor conditions and changes in the operation of building systems. The thermal behavior of a material is a function of its density, thermal conductivity, and specific heat. Materials like concrete, masonry, and stone have a beneficial effect on a building's thermal environment because they moderate and delay extreme changes in temperature resulting in lower energy use. This complex behavior is often simply called thermal mass effect.

Although energy simulation software is readily available, many architects and engineers would like guidance on how the thermal mass of concrete saves energy.

Objective

The objective of this project is to provide information to architects and engineers that will explain how to obtain LEED-NC points related to optimizing energy performance in mid-rise concrete commercial buildings. This paper demonstrates how to model thermal mass in buildings and presents results for several buildings in five climates. The work described in this paper was conducted by the authors with the sponsorship of the Portland Cement Association. The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

METHODOLOGY

Several buildings were modeled in a range of climates to demonstrate how the thermal properties of concrete in buildings can result in energy cost savings beyond *ASHRAE 90.1-2004*. The modeling conforms to the requirements of Informative Appendix G: Performance Rating Method in *ASHRAE 90.1-2004*.

The building performance rating method in Appendix G is intended for rating the energy efficiency of a building whose design exceeds the requirements of the standard. In this method, two buildings are modeled: a baseline building that meets the standard and the proposed above-standard building. The energy costs of two buildings are compared according to Equation 1.

$$\text{Percent improvement} = 100 \times \frac{(\text{baseline building performance} - \text{proposed building performance})}{\text{baseline building performance}} \quad (1)$$

Table 1 shows the number of points available under EA Credit 1 for achieving energy cost savings beyond *ASHRAE Standard 90.1-2004*.

Baseline Building and Proposed Buildings

The buildings in this study are based on the prototype building used by ASHRAE committees and other building industry groups to model the effects of energy. The major difference between this building and buildings in other studies is the five-story height in this study, compared to two stories in other studies.

All buildings in this study are five-story commercial buildings with plan dimensions 105 by 105 ft (32 by 32 m). More detail is provided below in the section called Building Description. The baseline building conforms to the requirements of Appendix G. It consists of an exterior insulation finishing system (EIFS) with steel stud walls, structural steel frame, and metal deck floors with concrete topping slab. In addition to the baseline buildings, there are nine proposed buildings. All are variations of the structure and building envelope of the baseline building. Table 2 provides a summary of the differences between the baseline building and the proposed buildings. The proposed buildings were chosen to explore the effect of different amounts of concrete on energy use in a variety of scenarios. In addition, the curtain wall building was chosen because it is a common building type. In this paper, a curtain wall is a façade that does not carry any dead load from the building other than it's own dead load and consists of an aluminum frame infilled with a combination of glass and insulated metal pans. Further, for a given climate the curtain wall and EIFS have the same U-factor, but the curtain wall has less thermal mass. The modeled scenarios are:

- EIFS and curtain walls meeting *ASHRAE 90.1-2004* with either structural steel or reinforced concrete frame,
- Precast concrete walls meeting *ASHRAE 90.1-2004* with either structural steel or reinforced concrete frame,
- Precast concrete walls exceeding *ASHRAE 90.1-2004* with either structural steel or reinforced concrete frame,
- Precast concrete walls meeting *ASHRAE 90.1-2004*, reinforced concrete frame, and high internal load equipment placed near the central core of the building, and
- Precast concrete walls exceeding *ASHRAE 90.1-2004*, reinforced concrete frame, and high internal load equipment placed near the central core of the building.

The first letter of the abbreviated building designation refers to the exterior wall system: "E" for EIFS, "C" for curtain wall, or "M" for precast concrete (the letter M is used because of the thermal mass effects of concrete). The second letter refers to the structural framing system and interior walls and floors: "L" for light and "M" for mass. The light materials are structural steel framing and metal deck floors with concrete topping slab. The mass materials are reinforced concrete framing and 12-in. (300-mm) concrete floors. Although a common thickness for post-tensioned concrete floors is 8 in. (200 mm), a 12-in. (300-mm) thick floor is investigated in this study because this thickness allows for longer spans and more usable floor space. Other floor thicknesses were modeled to determine their sensitivity to the results. The results, which are discussed in the sensitivity analysis section, shows that floor

Table 1. Points for Optimizing Energy Performance in LEED-NC v2.2 Under Energy and Atmosphere Credit 1 for Energy Cost Savings Beyond *ASHRAE Standard 90.1-2004 (Source: USGBC 2005)*

New Buildings	Existing Buildings	Points
10.5%	3.5%	1
14.0%	7.0%	2
17.5%	10.5%	3
21.0%	14.0%	4
24.5%	17.5%	5
28.0%	21.0%	6
31.5%	24.5%	7
35.0%	28.0%	8
38.5%	31.5%	9
42.0%	35.0%	10

Table 2. Buildings Modeled

Designation[1]	Exterior Walls	Structural Frame	Floors	Interior Walls
EL (Baseline)	EIFS and metal stud	structural steel	concrete on metal deck	metal stud
CL	curtain wall	structural steel	concrete on metal deck	metal stud
ML	precast concrete	structural steel	concrete on metal deck	metal stud
EM	EIFS and metal stud	reinforced concrete	12 in. (300 mm) solid concrete	reinforced concrete
CM	curtain wall	reinforced concrete	12 in. (300 mm) solid concrete	reinforced concrete
MM	precast concrete	reinforced concrete	12 in. (300 mm) solid concrete	reinforced concrete
MLX	precast concrete exceeding code	structural steel	concrete on metal deck	metal stud
MMX	precast concrete exceeding code	reinforced concrete	12. in (300 mm) solid concrete	reinforced concrete
MMI	precast concrete	reinforced concrete	12 in. (300 mm) solid concrete	reinforced concrete
MMXI	precast concrete exceeding code	reinforced concrete	12 in. (300 mm) solid concrete	reinforced concrete

[1] See text for an explanation of the designations.

thicknesses between 7.5 and 12 in. (190 and 300 mm) result in very similar energy use. An “X” indicates that the building envelope exceeds *ASHRAE 90.1-2004* requirements and an “I” indicates that the internal loads are clustered near the central core of the building. Throughout this paper, the word “code” will refer to *ASHRAE 90.1-2004*.

Buildings EM, CM, and MM are like EL, CL, and ML, respectively, except they have more concrete in interior floors and walls. Buildings MLX and MMX are like ML and MM, respectively, except their building envelopes modestly exceed code. Buildings MMI and MMXI are like MM and MMX, respectively, except that internal loads are assumed to be clustered near the central core of the building, where most of the interior concrete is located.

Energy Modeling

Building energy use was modeled using the energy simulation computer program VisualDOE. VisualDOE (AEC 2004a) is a graphic interface to the DOE-2 program modules. DOE2.1E-119 is a set of modules for energy analysis in buildings. Modules are included (1) to calculate the heating and cooling loads of each space in a building for each hour of a year, (2) to simulate operation and response of the equipment and systems that control temperature and humidity and distribute heating, cooling and ventilation to the building, (3) to model energy conversion equipment that uses fuel or electricity to provide the required heating, cooling and electricity, and (4) to compute the cost of energy and building operation based on utility rate schedule and economic parameters (Winkelmann 2002a). The user enters information about the building being modeled on the VisualDOE input screens. When VisualDOE is run, the information on the input screens is translated into a DOE-2 input file. This file is the input for the DOE-2 program modules. The program simulates energy use for every hour of a typical meteorological year. The typical meteorological year is based on 30-year historical weather data. The analyses used the DOE-2 Typical Mean Year Data Set No. 2 (TMY2) for all cities. These weather data consist of the average hourly weather for particular locations, compiled from 1961 to 1990.

Climates

Since thermal mass effects vary with climate, the buildings were modeled in six cities representing the range of climates in the US. The locations selected are those often used by other energy analysts when estimating national energy use in buildings. Five of these cities are representative cities for the U.S. Department of Energy's climate zones in *ASHRAE 90.1-2004* and *2004 International Energy Conservation Code* (IECC 2004). The cities and the climate zone numbers are:

- Miami, Florida—a hot and humid climate (Zone 1A)
- Phoenix, Arizona—a hot and dry climate with large daily temperature swings (Zone 2B)
- Memphis, Tennessee—a mild climate (Zone 3A)
- Salem, Oregon—a cool climate (Zone 4C)
- Denver, Colorado—a cold climate with large daily temperature swings (Zone 5B, but not a representative city)
- Chicago, Illinois—a cold climate (Zone 5A)

BUILDING DESCRIPTION

This section describes the features that are common to all the buildings and the features that differ because of climate or modeling scenario. Greater detail can be found in Marceau and VanGeem (2007).

Common Features

All the buildings in this study are five-story commercial buildings with plan dimensions 105 by 105 ft (32.0 by 32.0 m). They are square in plan with the same amount of glazing equally distributed on each wall to minimize the influence of solar effects due to orientation. The building height, 63 ft (19.2 m), is based on 15 ft (4.6 m) for the first story and 12 ft (3.7 m) for the remaining four stories. The story height is measured from finished floor to finished floor.

Floor Plans and Zones. Each floor is modeled with five zones: four perimeter zones and one central zone. The five zones are shown schematically in Figure 1. The depth of the perimeter zones is 35 ft (10.7 m). The center zone is 35 by 35 ft (10.7 by 10.7 m). The selection of 35-ft perimeter zones is based on the designed zones and the location of interior walls with significant thermal mass in the central core. Appendix G requires 15-foot perimeter zones, unless the zones are defined on HVAC design drawings. VisualDOE automatically includes partition walls between adjacent zones. The user can accept the default partition wall construction or input a new construction.

Windows. Each façade of each story has a strip of ten windows each measuring approximately 5 ft high by 10½ ft wide (1.5 m by 3.2 m). Figure 2 shows the arrangement of windows. Windows are flush-mounted (non-recessed) and are equally spaced. Windows are non-operable and have no blinds or shading devices. The overall window to wall ratio is 0.40.

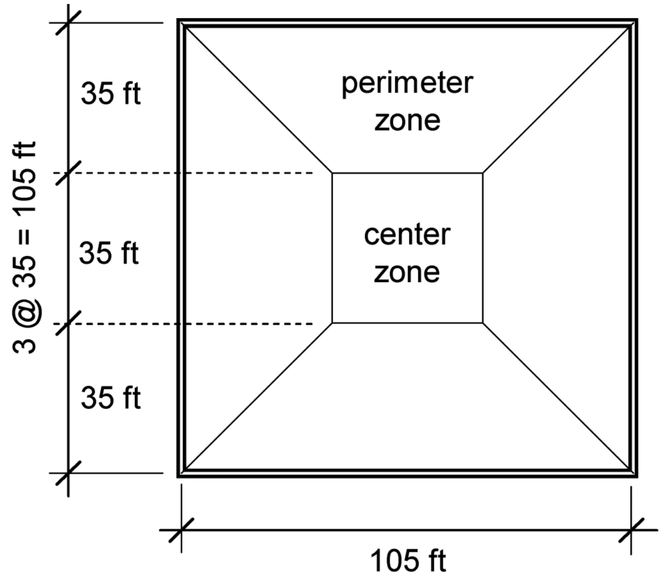

Figure 1 *This schematic shows the five zones per floor, which coincide with the VisualDOE partition walls.*

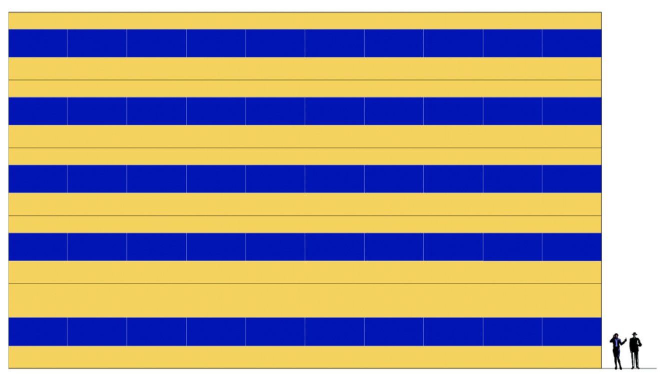

Figure 2 *Each façade consists of bands of windows.*

Orientation. Energy use is dependent on building and window orientation. However, the analyses in this report are not orientation specific since the buildings modeled are symmetrical in plan and have equal amounts of glazing on each orientation. Therefore, the buildings do not need to be modeled in four perpendicular orientations (as required in Appendix G) to eliminate the effect of orientation.

Shading. No exterior shading was assumed around the buildings. This assumption is typical for new construction in rural and suburban locations.

Roofs. The roofs on all the buildings in this study consist of open-web steel joists, ribbed steel deck, 5/8-in. (16-mm) gypsum wallboard, board insulation, and built-up waterproofing membrane. The overall roof U-value is 0.062 Btu/h·ft^2·°F (0.35 W/m^2·K) (including air films) for the building meeting code requirements. The built-up roof is medium-colored and has a coefficient of solar absorptance of 0.70 (this is the default value required in Appendix G).

Slab-on-Ground. The ground-level floor consists of carpet with fibrous pad and 6-in. (15 cm) cast-in-place concrete slab-on-ground. According to *ASHRAE 90.1-2004*, an unheated slab-on-ground floor does not require insulation in the six cities considered in this report. However, in order to accurately model the heat transfer between the slab and the ground, a layer of soil and a fictitious insulation layer need to be considered. The heat transfer was modeled using the effective resistance method (Winkelman 2002b). In this method the floor is also assumed to consist of a 12-in. (30-cm) layer of soil with a thermal resistance of 1.0 h·ft^2·°F/Btu (0.18 m^2·K/W) and a fictitious insulation layer. This thickness of soil is sufficient to account for most of the thermal mass effects of the ground, and the fictitious insulation layer is required to give the correct effective resistance for the floor. The method yields an R-value of 32.5 h·ft^2·°F/Btu (5.72 m^2·K/W) for the fictitious insulation. The inside air-film resistance is omitted from the calculations because VisualDOE adds air film resistances automatically.

Heating Ventilation and Air Conditioning. The heating ventilation and air conditioning (HVAC) system is a packaged variable air volume system. Each building has three packaged units. One unit serves the zones of the ground floor, another serves the zones of the three intermediate floors, and the remaining unit serves the zones of the top floor. In cooling mode, the supply air temperature is constant and the volume of air is varied from minimum to maximum to satisfy the zone requirements. The minimum flow ratio is set at 30% of the maximum. In heating mode, the supply air temperature is varied in response to the zone requirements and the volume of air is set to the minimum (constant). The efficiency of HVAC equipment is identical for all buildings. Cooling is provided by high efficiency direct expansion. The energy-efficiency ratio is 9.5. The energy simulation program sizes the HVAC equipment automatically. The cooling over-sizing ration is 1.15. Heating is provided by a hot water natural gas boiler with a thermal efficiency is 0.8. The heating over-sizing ratio is 1.25. Each zone also has baseboard heaters for zone reheating using hot water from a central plant. The energy simulation program sizes the supply fan. Its energy use is included in the overall energy-efficiency ratio above. Operational schedules, shown in Table 3, are based on *ASHRAE/IESNA 90.1-1989* schedules (ASRAE 1989) and VisualDOE defaults.

Equipment and Lighting. Equipment power density (also called plug or receptacle load) is 0.75 W/ft^2 (5.4 W/m^2). It includes all plug or receptacle loads and two average-efficiency elevators. Lighting power density is 1.0 W/ft^2 (10.8 W/m^2). There is no daylight control. The energy for exterior lighting is not considered. Natural gas water heaters supply domestic hot water.

Air Infiltration and Fresh Air Requirements. The rate of air infiltration through the building envelope is 0.4 air changes per hour (ach). This is close to the infiltration calculated from window and door air leakage (0.37 ach) using ASHRAE Handbook of Fundamentals (ASHRAE 2001). It is also within the normal range for office buildings, that is 0.1 to 0.6 ach (ASHRAE 2001). The air infiltration rate was modified to account for differences in infiltration rates between perimeter zones and the central zone. The infiltration rate was set to 0.42 ach in perimeter zones and zero ach in the central zones. In addition to air infiltration, fresh outside air is supplied at a rate of 20 cfm (10 L/s) per person (ASHRAE 1999).

Occupancy. The occupancy is 275 sq ft (25.5 m^2) per person. The thermostat throttling range is 4°F (2.2°C). The occupancy and operating hours are based on ASHRAE 90.1-1989 (ASHRAE 1989). These schedules, shown in Table 3, are commonly used for modeling energy use in commercial buildings.

Differing Features

Concrete Construction. Concrete is normal weight with density of 145 lb/ft^3 (2320 kg/m^3), conductivity of 1.33 Btu/h·ft·°F (2.31 W/m·K), and specific heat of 0.22 Btu/lb·°F (921 J/kg·K). Buildings ML, EM, CM, MM, MLX, MMX, MMI, and MMXI as noted earlier are the "mass" buildings.

Ceilings and Floors. The interior floors of the steel frame buildings consist of ribbed steel deck, an equivalent concrete thickness of 4 in. (10 cm), and carpet with fibrous pad. Ceiling tiles are attached directly to the bottom of the roof and floor framing. Although this is not a common way of installing ceiling tiles, this simplification is necessary because available energy simulation tools do not accurately model the space between a suspended ceiling and interior floor or roof (plenums). The interior floors of the reinforced concrete frame buildings consist of 12 in. (30 cm) concrete and carpet with fibrous pad.

Exterior Walls. The thermal performance requirements for exterior walls are shown in the tables below. Table 4 shows the minimum requirements for EIFS and curtain walls along with the construction of the walls selected to meet code. Table 5 shows the minimum requirements for concrete walls along with the insulation selected to meet code. Note that the tabulated U-values include the thermal resistance of interior and exterior air films. Table 6 shows the thermal resistance of materials in the concrete wall assemblies that were used to meet and exceed the code requirements.

Interior Partition Walls. The interior partition walls of the steel frame buildings consist of non-structural steel studs and gypsum wallboard. Lateral resistance is provided by the structural frame. The interior partition walls of the concrete frame buildings are structural reinforced concrete. In this case, lateral resistance is provided by the partition walls, that is, the partition walls also act as shear walls. The thickness of the concrete partition walls is discussed in the section, "Modeling Thermal Mass".

Fenestration. The thermal performance requirements for windows are shown in Table 7 along with the properties of the

Table 3. Building Systems Operational Parameters and Schedules[1]

Schedule Type, Unit and Day Type	Hour of Day																		
	1–5	6	7	8	9	10-11	12	13	14	15	16	17	18	19	20	21	22	23	24
Occupancy, %																			
Weekdays	0	0	10	20	95	95	95	50	95	95	95	95	30	10	10	10	10	5	5
Saturday	0	0	10	10	30	30	30	10	10	10	10	10	5	5	0	0	0	0	0
Sunday & Holidays	0	0	5	5	5	5	5	5	5	5	5	5	5	0	0	0	0	0	0
Lighting and Equipment, %																			
Weekdays	5	10	10	30	90	90	90	80	90	90	90	90	50	30	30	20	20	10	5
Saturday	5	5	10	10	30	30	30	15	15	15	15	15	5	5	5	5	5	5	5
Sunday and Holidays	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Infiltration, %																			
Weekdays	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100
Saturday	100	100	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Sunday and Holidays	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Domestic hot water, %																			
Weekdays	5	10	5	20	35	40	45	60	55	35	35	45	25	20	15	15	10	5	5
Saturday	0	0	5	10	15	20	25	20	20	15	10	15	5	0	0	0	0	0	0
Sunday and Holidays	5	5	5	5	5	5	5	5	10	5	5	5	5	5	5	5	5	5	5
Outside air, %																			
Weekdays	0	0	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	0	0
Saturday	0	0	F	F	F	F	F	F	F	F	F	F	F	0	0	0	0	0	0
Sunday and Holidays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HVAC supply fan, %																			
Weekdays	F	F	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Saturday	F	F	100	100	100	100	100	100	100	100	100	100	100	100	F	F	F	F	F
Sunday and Holidays	F	F	100	100	100	100	100	100	100	100	100	100	100	F	F	F	F	F	F
Cooling set point, °F																			
Weekdays	99	99	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75
Saturday	99	99	75	75	75	75	75	75	75	75	75	75	75	75	99	99	99	99	99
Sunday & Holidays	99	99	75	75	75	75	75	75	75	75	75	75	75	99	99	99	99	99	99
Heating set point, °F																			
Weekdays	55	55	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
Saturday	55	55	70	70	70	70	70	70	70	70	70	70	70	70	55	55	55	55	55
Sunday and Holidays	55	55	70	70	70	70	70	70	70	70	70	70	70	55	55	55	55	55	55

[1]Typical schedules based on *ASHRAE 90.1-1989* and VisualDOE defaults.
Note: F is float and % is percent of total.

Table 4a. Thermal Performance Requirements in *ASHRAE 90.1-2004* for EIFS and Curtain Walls

Location	Maximum Code-Required U-Factor[1]	Insulation and Resulting Wall U-Factor to Meet Code	
		Insulation[2]	U-Factor[1]
Miami	0.124	R-13 batts	0.124
Phoenix	0.124	R-13 batts	0.124
Memphis	0.124	R-13 batts	0.124
Salem	0.124	R-13 batts	0.124
Denver	0.084	R-13 batts + R-3.8 boards	0.084
Chicago	0.084	R-13 batts + R-3.8 boards	0.084

[1]These U-factors, in units of Btu/h·ft^2·°F, include the thermal bridging effects of steel stud framing and the thermal resistance of inside and outside air films.
[2]Batt insulation is installed between steel studs, which are 16 in. on center. Board insulation is continuous over the steel studs.

Table 4b. Thermal Performance Requirements in *ASHRAE 90.1-2004* for EIFS and Curtain Walls

Location	Maximum Code-Required U-Factor[1]	Insulation and Resulting Wall U-Factor to Meet Code	
		Insulation[2]	U-factor[1]
Miami	0.704	RSI-2.3 batts	0.704
Phoenix	0.704	RSI-2.3 batts	0.704
Memphis	0.704	RSI-2.3 batts	0.704
Salem	0.704	RSI-2.3 batts	0.704
Denver	0.477	RSI-2.3 batts + RSI-0.7 boards	0.477
Chicago	0.477	RSI-2.3 batts + RSI-0.7 boards	0.477

[1]These U-factors, in units of W/m^2·K, include the thermal bridging effects of steel stud framing and the thermal resistance of inside and outside air films.
[2]Batt insulation is installed between steel studs, which are 400 mm on center. Board insulation is continuous over the steel studs.

Table 5a. Thermal Performance Requirements in *ASHRAE 90.1-2004* for Concrete Walls

Location	Maximum Code-Required U-Factor[1]	Insulation and Resulting Wall U-Factor to Meet Code	
		Insulation[2]	U-Factor[1]
Miami	0.580	None	0.405
Phoenix	0.580	None	0.405
Memphis	0.151	R-13 batts	0.130
Salem	0.151	R-13 batts	0.130
Denver	0.123	R-15 batts with ½ in. air space	0.113
Chicago	0.123	R-15 batts with ½ in. air space	0.113

[1]These U-factors, in units of Btu/h·ft^2·°F, include the thermal bridging effects of steel stud framing and thermal resistance of inside and outside air films.
[2]Batt insulation is installed between steel studs, which are 16 in. on center. Board insulation is continuous over the steel studs.

Table 5b. Thermal Performance Requirements in *ASHRAE 90.1-2004* for Concrete Walls

Location	Maximum Code-Required U-Factor[1]	Insulation and Resulting Wall U-Factor to Meet Code	
		Insulation[2]	U-Factor[1]
Miami	3.293	None	2.300
Phoenix	3.293	None	2.300
Memphis	0.857	RSI-2.3 batts	0.738
Salem	0.857	RSI-2.3 batts	0.738
Denver	0.698	RSI-2.6 batts with 13 mm air space	0.642
Chicago	0.698	RSI-2.6 batts with 13 mm air space	0.642

[1]These U-factors, in units of W/m^2·K, include the thermal bridging effects of steel stud framing and thermal resistance of inside and outside air films.
[2]Batt insulation is installed between steel studs, which are 400 mm on center. Board insulation is continuous over the steel studs.

Table 6a. Concrete Wall Assembly Used to Meet and Exceed Requirements in *ASHRAE Standard 90.1-2004*

Layer	Location			
Thermal Resistance, h·ft^2·°F/Btu	Miami and Phoenix	Memphis and Salem	Denver and Chicago	Exceeding Code, All Cities
Outside Air Film	0.17	0.17	0.17	0.17
Concrete, 6 in.	0.38	0.38	0.38	0.38
Air Space[1]	0	0	0.77	0
Insulation and 3.5 in. Framing[2]	0.79	6.00	6.40	10.00
Gypsum Wallboard, 0.5 in.	0.45	0.45	0.45	0.45
Inside Air Film	0.68	0.68	0.68	0.68
Total R-Value	2.47	7.68	8.85	11.68
U-Factor, Btu/h·ft^2·°F	0.405	0.130	0.113	0.086

[1]Although there is a gap between the steel studs and the precast concrete panels, in most cases the thermal resistance of the air spaces can be ignored. However, in Denver and Chicago, the thermal resistance of the ½-in. air space is needed to meet minimum code requirements.
[2]The effective R-value of insulation and steel studs spaced 16 in. on-center according to *ASHRAE 90.1-2004*, Table A9.2B, assuming: no insulation in Miami and Phoenix, R-13 batt insulation in Memphis and Salem, R-15 batt insulation in Denver and Chicago, and R-13 batt insulation (effectively R-6) plus R-4 board insulation for the wall exceeding code.

Table 6b. Concrete Wall Assembly Used to Meet and Exceed Requirements in *ASHRAE Standard 90.1-2004*

Layer	Location			
Thermal Resistance, m^2·K/W	Miami and Phoenix	Memphis and Salem	Denver and Chicago	Exceeding Code, All Cities
Outside Air Film	0.03	0.03	0.03	0.03
Concrete, 150 mm	0.07	0.07	0.07	0.07
Air Space[1]	0	0	0.14	0
Insulation and 90 mm Framing[2]	0.14	1.06	1.13	1.76
Gypsum Wallboard, 13 mm	0.08	0.08	0.08	0.08
Inside Air Film	0.12	0.12	0.12	0.12
Total R-Value	0.43	1.35	1.56	2.06
U-Factor, W/m^2·K	2.304	0.740	0.642	0.486

[1]Although there is a gap between the steel studs and the precast concrete panels, in most cases the thermal resistance of the air spaces can be ignored. However, in Denver and Chicago, the thermal resistance of the 13-mm air space is needed to meet minimum code requirements.
[2]The effective R-value of insulation and steel studs spaced 400 mm on-center according to *ASHRAE 90.1-2004*, Table A9.2B, assuming: no insulation in Miami and Phoenix, RSI-2.3 batt insulation in Memphis and Salem, RSI-2.6 batt insulation in Denver and Chicago, and RSI-2.3 batt insulation (effectively RSI-1.1) plus RSI-0.7 board insulation for the wall exceeding code.

windows selected to meet code. Table 8 shows the properties of the selected windows that were used to exceed the requirements.

Roofs. The code requires a U-factor no more than 0.063 Btu/h·ft^2·°F (0.358 W/m^2·K) including air films. The thermal performance requirements for roofs are met using R-15 (RSI-2.6) board insulation in all locations. The resulting roof U-factor is 0.062 Btu/h·ft^2·°F (0.352 W/m^2·K) including air films. Table 9 shows the properties of the selected roofs used to exceed the requirements.

HVAC. Each HVAC is equipped with an average-efficiency air-side economizer, as required in Appendix G. The economizer shutoff limits are shown in Table 10. The limits are based on the 1% cooling design wet-bulb temperature.

Energy Costs. The energy costs for each city are shown in Table 11. The costs are averages of the utilities operating in each particular state.

MODELING THERMAL MASS

Custom Weighting Factors

VisualDOE accounts for thermal mass effect in a space using one of two methods: custom weighting factors and precalculated weighting factors. By default, VisualDOE uses the custom weighting factor method. In order to invoke the custom weighting factor method, VisualDOE sets the FLOOR WEIGHT code word equal to zero. The user can verify this in the “Rooms” tab of the “Advanced Edit” dialogue box under the “Alternatives” menu. In general, the custom weighting

Table 7a. Fenestration Requirements in *ASHRAE Standard 90.1-2004*

Location	Code Required		Selected Windows			
	Maximum U-Factor[1]	Maximum SHGC[2]	U-Factor[1]	SHGC[3]	VLT[4]	VisualDOE Identifier and Name
Miami, Phoenix	1.22	0.25	0.88	0.25	0.13	1411 single clear LR13
Memphis	0.57	0.25	0.52	0.23	0.18	2420 double ref-B clear-L air
Salem, Denver, and Chicago	0.57	0.39	0.52	0.30	0.27	2426 double ref-B clear-H air

[1]U-factor in units of Btu/h·ft^2·°F.
[2]Solar heat gain coefficient (SHGC) requirement in a non-north orientation.
[3]Solar heat gain coefficient at a 60° angle of incidence.
[4]Visible light transmittance (VLT) is not a code requirement.

Table 7b. Fenestration Requirements in *ASHRAE Standard 90.1-2004*

Location	Code Required		Selected Windows			
	Maximum U-Factor[1]	Maximum SHGC[2]	U-Factor[1]	SHGC[3]	VLT[4]	VisualDOE Identifier and Name
Miami, Phoenix	6.93	0.25	5.00	0.25	0.13	1411 single clear LR13
Memphis	3.24	0.25	2.95	0.23	0.18	2420 double ref-B clear-L air
Salem, Denver & Chicago	3.24	0.39	2.95	0.30	0.27	2426 double ref-B clear-H air

[1]U-factor in units of W/m^2·K.
[2]Solar heat gain coefficient (SHGC) requirement in a non-north orientation.
[3]Solar heat gain coefficient at a 60° angle of incidence.
[4]Visible light transmittance (VLT) is not a code requirement.

Table 8a. Selected Windows that Exceed Requirements in *ASHRAE Standard 90.1-2001*

Location	U-Factor[1]	SHGC[2]	VLT[3]	VisualDOE Identifier and Name
Miami, Phoenix	0.52	0.23	0.18	2406 double ref A clear-H IG
Memphis, Salem, Denver, and Chicago	0.31	0.15	0.14	2823 double electrochromic ref bleached/colored, 12.7 mm gap

[1]U-factor in units of Btu/h·ft^2·°F.
[2]Solar heat gain coefficient at a 60° angle of incidence.
[3]Visible light transmittance (VLT) is not a code requirement.

Table 8b. Selected Windows that Exceed Requirements in *ASHRAE Standard 90.1-2001*

Location	U-Factor[1]	SHGC[2]	VLT[3]	VisualDOE Identifier and Name
Miami, Phoenix	2.95	0.23	0.18	2406 double ref A clear-H IG
Memphis, Salem, Denver, and Chicago	1.76	0.15	0.14	2823 double electrochromic ref bleached/colored, 12.7 mm gap

[1]U-factor in units of W/m^2·K.
[2]Solar heat gain coefficient at a 60° angle of incidence.
[3]Visible light transmittance (VLT) is not a code requirement.

factor method requires the most amount of user input but produces the most accurate results. The DOE reference manuals suggest using custom weighting factors for masonry buildings and heavy construction (Winkelmann and others 1993). Precalculated weighting factors are not recommended. Custom weighting factors are based on the actual properties of the room being modeled including wall construction, furniture type, furniture fraction, and furniture weight.

Wall Construction. In order to benefit from the thermal properties of the walls, the various layers of the wall must be defined using the VisualDOE Construction Editor. A construction is composed of individual layers of materials. The individual materials should be defined according to their material properties, such as thickness, conductivity, density, and specific heat. When several layers of materials are combined to form a construction, the texture, emissivity, and absorptance must also be specified. For common building materials, the *VisualDOE 4.0 User Manual* gives typical values (AEC, 2004b).

Table 9a. Selected Roof Insulation that Exceeds Requirements in *ASHRAE Standard 90.1-2004*

Location	Insulation and Resulting U-Factor to Exceed Code	
	Insulation	U-Factor[1]
Miami and Phoenix	R-15 board	0.062
Memphis, Salem, Denver, and Chicago	R-20 board	0.047

[1]U-factor in units of $Btu/h \cdot ft^2 \cdot {}^\circ F$.

Table 9b. Selected Roof Insulation that Exceeds Requirements in *ASHRAE Standard 90.1-2004*

Location	Insulation and Resulting U-Factor to Exceed Code	
	Insulation	U-Factor[1]
Miami and Phoenix	RSI-2.6 board	0.35
Memphis, Salem, Denver, and Chicago	RSI-3.5 board	2.31

[1]U-factor in units of $W/m^2 \cdot K$.

Table 10. Control Condition for Economizer in Various Locations

Location	1% Wet-Bulb Temperature, °F (°C)	Shutoff Dry-Bulb Temperature, °F (°C)	
		High Limit	Low Limit
Miami	77 (25)	65 (18)	40 (4)
Phoenix	70 (21)	70 (21)	40 (4)
Memphis	77 (25)	65 (18)	40 (4)
Salem	66 (19)	75 (24)	40 (4)
Denver	59 (15)	75 (24)	40 (4)
Chicago	73 (23)	70 (21)	40 (4)

Table 11. Energy Costs

Location	Electricity,[1] ¢/kWh	Electricity, $/kWh	Natural Gas,[2] $/Thousand cu ft ($/m^3)	Natural Gas, $/Therm ($/GJ)
Miami	7.64	0.0764	10.91 (0.360)	1.091 (10.34)
Phoenix	9.55	0.0955	7.75 (0.274)	0.775 (7.35)
Memphis	7.39	0.0739	8.63 (0.305)	0.863 (8.18)
Salem	5.93	0.0593	7.90 (0.279)	0.790 (7.49)
Denver	8.33	0.0833	5.83 (0.205)	0.583 (5.52)
Chicago	8.07	0.0807	8.23 (0.291)	0.823 (7.80)

[1]Source: Energy User News, April 2004, Ranking of Electricity Prices Commercial, data from September 2003. Used average of a state's utilities. No data was available for Salem, so the average data for the state of Washington was used instead.
[2]Source: http://www.eia.doe.gov/emeu/states/_states.html. Used 2003 averages and 100 cu ft natural gas = 1 Therm (1 GJ = 26.9 m^3).

Interior Partition Walls. Buildings modeled with VisualDOE also contain interior partitions by default. If the partition walls are lightweight, such as steel studs and gypsum wallboard, their thermal mass is insignificant. However, for concrete partition walls, the mass should not be ignored. The mass of the actual concrete partition walls must be compared to the default arrangement of partition walls (see Figure 1). If the mass differs, the thickness of the partition walls should be adjusted to reflect the actual situation. For example, in the modeling scenarios that have interior reinforced concrete walls, these concrete walls are actually the building shear walls. The total volume of the shear walls, 5,447 ft^3 (154.2 m^3), in the building is distributed over the VisualDOE default partition wall area, 19,604 ft^2 (1821.3 m^2), for the entire building. The resulting interior concrete wall thickness of 3.334 in. (84.7 mm) is used in the VisualDOE model.

Interior Thermal Mass. Furniture type describes the thermal response of the furniture. Two values are possible: light and heavy. Light represents a furniture density of 40 lb/ft^3 (640 kg/m^3) and heavy represents a density of 80 lb/ft^3.

Furniture fraction is the fraction of floor area covered by furniture, and furniture weight is the weight of the furniture per unit area of floor. The range of permissible values is 8 to 300 lb/ft^2 (39 to 1500 kg/m^2). The custom weighting factor scenario that was considered for this project is the VisualDOE default amount of thermal mass, which assumes light furniture weighing 8 lb/ft^2 (39 kg/m^2) covering 85% of the floor. This scenario is the most common for office buildings.

RESULTS

The VisualDOE results are summarized in Figure 3 and Tables 12 and 13. The detailed results, including summary charts and tabulated data, are presented in Appendices in Marceau and VanGeem (2007). For each city, the tables show yearly energy use and cost. Energy use is broken down into its components: heating, cooling, pumps, fans, domestic hot water, lighting, and equipment loads. Figure 4 shows energy cost savings compared to the baseline buildng.

Energy Cost Savings. In most scenarios, the effect of a concrete frame with or without precast concrete walls is to lower energy use and energy cost relative to the baseline building (steel frame EIFS, EL). As previously described, the baseline building is defined by *ASHRAE 90.1-2004* Appendix G. In Memphis, Salem, Denver, and Chicago, significant energy cost savings of 6 to 11% are indicated for the three concrete frame buildings meeting code compared to the baseline building (compare EM, CM, and MM to EL). Additional thermal mass in the frame provides at least 6% energy cost savings in

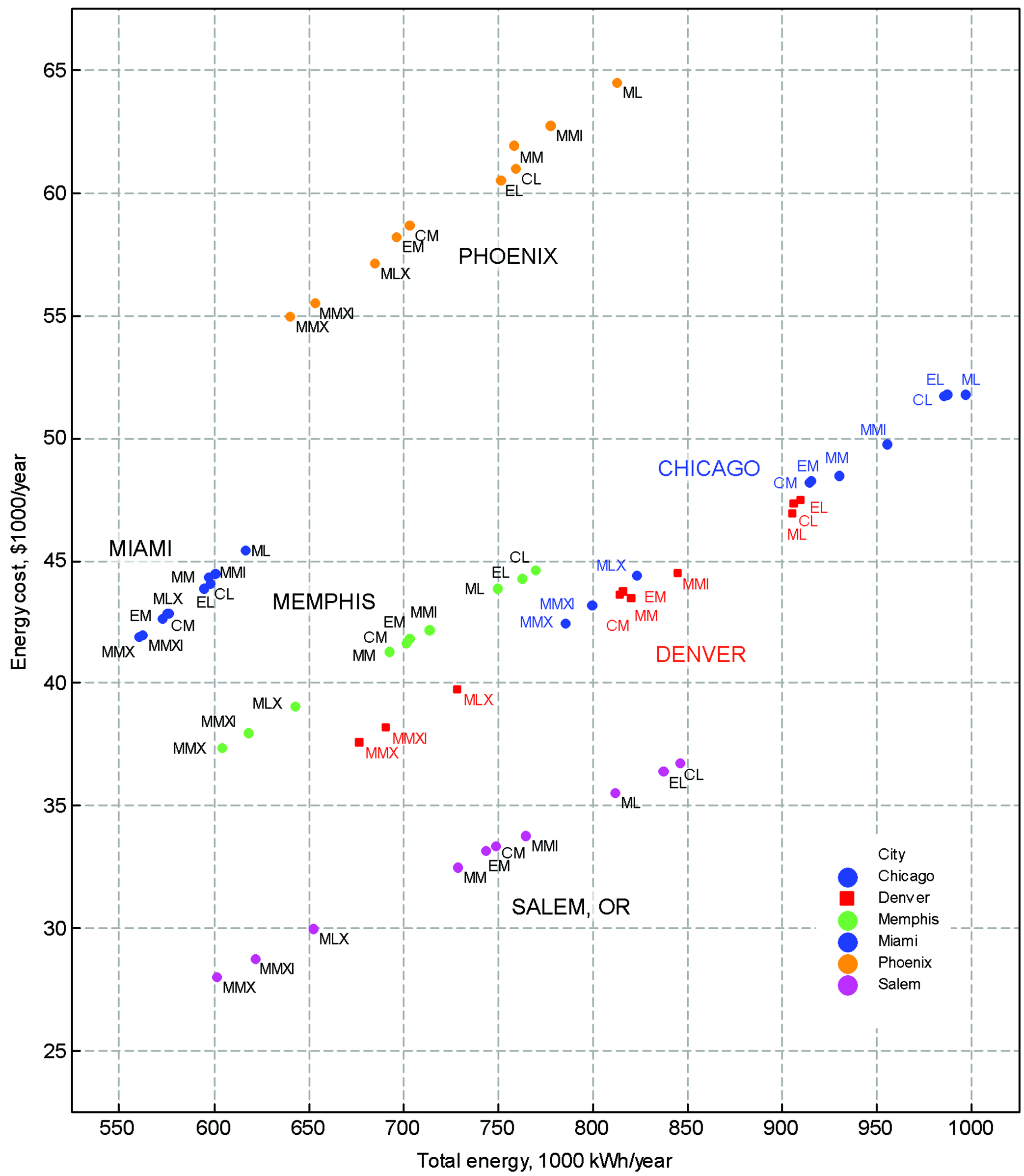

Figure 3 *The relationship between annual energy use and cost varies by city.*

Table 12. VisualDOE Annual Electrical and Fuel End Uses

City	Scenario	Electrical, kWh						Fuel, kWh		Total, kWh
		Lights	Equipment	Heating	Cooling	Pumps/ Auxiliary	Fans	Space Heating	Hot Water Heating	
Miami	EL	156,000	117,000	330	248,000	1,910	34,900	23,000	12,500	594,000
	CL	156,000	117,000	350	250,000	2,040	35,200	24,000	12,500	597,000
	ML	156,000	117,000	370	264,000	2,000	37,500	26,000	12,500	616,000
	EM	156,000	117,000	180	240,000	1,130	33,600	12,000	12,500	573,000
	CM	156,000	117,000	180	241,000	1,190	33,800	13,000	12,500	575,000
	MM	156,000	117,000	240	256,000	1,490	36,400	17,000	12,500	597,000
	MLX	156,000	117,000	210	240,000	1,440	33,800	15,000	12,500	576,000
	MMX	156,000	117,000	110	233,000	880	32,700	7,000	12,500	560,000
	MMI	156,000	117,000	270	257,000	1,630	36,400	19,000	12,500	600,000
	MMXI	156,000	117,000	130	234,000	1,010	32,500	9,000	12,500	562,000
Phoenix	EL	156,000	117,000	2,070	265,000	6,240	42,300	148,000	13,800	751,000
	CL	156,000	117,000	2,130	268,000	6,440	42,700	152,000	13,800	759,000
	ML	156,000	117,000	2,450	295,000	6,520	46,000	175,000	13,800	812,000
	EM	156,000	117,000	1,500	257,000	5,170	40,300	106,000	13,800	696,000
	CM	156,000	117,000	1,530	260,000	5,230	40,700	108,000	13,800	703,000
	MM	156,000	117,000	1,940	281,000	5,800	44,300	138,000	13,800	758,000
	MLX	156,000	117,000	1,490	247,000	5,380	39,200	105,000	13,800	685,000
	MMX	156,000	117,000	1,070	235,000	4,550	37,500	75,000	13,800	640,000
	MMI	156,000	117,000	2,150	286,000	6,020	44,400	152,000	13,800	777,000
	MMXI	156,000	117,000	1,210	237,000	4,910	37,400	85,000	13,800	653,000
Memphis	EL	156,000	117,000	3,450	177,000	7,620	31,300	252,000	17,600	762,000
	CL	156,000	117,000	3,510	179,000	7,830	31,700	256,000	17,600	769,000
	ML	156,000	117,000	3,310	177,000	7,340	30,000	241,000	17,600	749,000
	EM	156,000	117,000	2,890	165,000	6,320	29,100	209,000	17,600	703,000
	CM	156,000	117,000	2,920	161,000	6,410	29,600	211,000	17,600	701,000
	MM	156,000	117,000	2,830	160,000	6,290	28,100	204,000	17,600	692,000
	MLX	156,000	117,000	2,380	148,000	6,170	24,600	171,000	17,600	643,000
	MMX	156,000	117,000	2,050	137,000	5,390	23,200	146,000	17,600	604,000
	MMI	156,000	117,000	3,050	166,000	6,800	28,100	219,000	17,600	714,000
	MMXI	156,000	117,000	2,180	141,000	5,800	23,100	155,000	17,600	618,000
Salem	EL	156,000	117,000	5,360	108,000	11,510	30,300	387,000	21,200	837,000
	CL	156,000	117,000	5,430	111,000	11,590	31,000	392,000	21,200	845,000
	ML	156,000	117,000	5,100	106,000	11,070	28,200	367,000	21,200	812,000
	EM	156,000	117,000	4,420	92,000	9,770	27,000	315,000	21,200	743,000
	CM	156,000	117,000	4,450	94,000	9,840	27,600	318,000	21,200	748,000
	MM	156,000	117,000	4,310	87,000	9,500	25,400	307,000	21,200	728,000
	MLX	156,000	117,000	3,480	78,000	9,350	20,200	247,000	21,200	652,000
	MMX	156,000	117,000	3,020	64,000	8,160	18,300	213,000	21,200	601,000
	MMI	156,000	117,000	4,690	95,000	10,160	25,400	334,000	21,200	764,000
	MMXI	156,000	117,000	3,210	70,000	8,690	18,300	226,000	21,200	621,000
Denver	EL	156,000	117,000	5,740	141,000	11,330	31,800	424,000	22,100	909,000
	CL	156,000	117,000	5,710	140,000	11,240	31,600	422,000	22,100	906,000
	ML	156,000	117,000	5,780	136,000	11,140	30,600	427,000	22,100	905,000
	EM	156,000	117,000	4,940	117,000	9,700	28,600	360,000	22,100	816,000
	CM	156,000	117,000	4,920	117,000	9,670	28,500	359,000	22,100	814,000
	MM	156,000	117,000	5,060	113,000	9,630	27,700	369,000	22,100	820,000
	MLX	156,000	117,000	4,250	90,000	9,530	21,900	308,000	22,100	728,000
	MMX	156,000	117,000	3,820	75,000	8,380	20,000	274,000	22,100	676,000
	MMI	156,000	117,000	5,290	120,000	10,110	27,600	386,000	22,100	844,000
	MMXI	156,000	117,000	3,950	80,000	8,750	19,900	283,000	22,100	691,000
Chicago	EL	156,000	117,000	6,760	139,000	10,670	28,800	506,000	22,200	987,000
	CL	156,000	117,000	6,740	139,000	10,620	28,700	505,000	22,200	985,000
	ML	156,000	117,000	6,940	135,000	10,620	28,000	520,000	22,200	996,000
	EM	156,000	117,000	6,240	114,000	9,040	26,400	464,000	22,200	915,000
	CM	156,000	117,000	6,230	114,000	9,010	26,300	463,000	22,200	914,000
	MM	156,000	117,000	6,470	111,000	9,060	25,700	483,000	22,200	930,000
	MLX	156,000	117,000	5,360	98,000	9,210	20,500	395,000	22,200	823,000
	MMX	156,000	117,000	5,170	82,000	8,230	19,000	375,000	22,200	785,000
	MMI	156,000	117,000	6,670	121,000	9,500	25,700	497,000	22,200	955,000
	MMXI	156,000	117,000	5,280	89,000	8,540	18,900	383,000	22,200	799,000

Table 13. VisualDOE Annual Electrical and Fuel Cost

City	Scenario	Electrical, $						Fuel, $		Total, $
		Lights	Equipment	Heating	Cooling	Pumps Auxiliary	Fans	Space Heating	Hot-Water Heating	
Miami	EL	$11,920	$8,940	$30	$18,900	$150	$2,670	$860	$460	$44,000
	CL	$11,920	$8,940	$30	$19,100	$160	$2,690	$910	$460	$44,200
	ML	$11,920	$8,940	$30	$20,200	$150	$2,870	$980	$460	$45,600
	EM	$11,920	$8,940	$10	$18,300	$90	$2,570	$460	$460	$42,800
	CM	$11,920	$8,940	$10	$18,400	$90	$2,590	$470	$460	$42,900
	MM	$11,920	$8,940	$20	$19,600	$110	$2,780	$620	$460	$44,500
	MLX	$11,920	$8,940	$20	$18,300	$110	$2,580	$560	$460	$42,900
	MMX	$11,920	$8,940	$10	$17,800	$70	$2,490	$280	$460	$42,000
	MMI	$11,920	$8,940	$20	$19,700	$120	$2,780	$710	$460	$44,600
	MMXI	$11,920	$8,940	$10	$17,900	$80	$2,480	$330	$460	$42,100
Phoenix	EL	$14,900	$11,180	$200	$25,300	$600	$4,040	$3,910	$370	$60,500
	CL	$14,900	$11,180	$200	$25,600	$610	$4,080	$4,030	$370	$61,000
	ML	$14,900	$11,180	$230	$28,200	$620	$4,390	$4,640	$370	$64,500
	EM	$14,900	$11,180	$140	$24,500	$490	$3,850	$2,790	$370	$58,200
	CM	$14,900	$11,180	$150	$24,900	$500	$3,890	$2,860	$370	$58,700
	MM	$14,900	$11,180	$190	$26,900	$550	$4,240	$3,650	$370	$61,900
	MLX	$14,900	$11,180	$140	$23,600	$510	$3,740	$2,770	$370	$57,200
	MMX	$14,900	$11,180	$100	$22,400	$430	$3,580	$1,990	$370	$55,000
	MMI	$14,900	$11,180	$210	$27,300	$570	$4,240	$4,030	$370	$62,800
	MMXI	$14,900	$11,180	$120	$22,700	$470	$3,580	$2,240	$370	$55,500
Memphis	EL	$11,530	$8,650	$260	$13,100	$560	$2,310	$7,430	$520	$44,300
	CL	$11,530	$8,650	$260	$13,200	$580	$2,350	$7,550	$520	$44,700
	ML	$11,530	$8,650	$240	$13,100	$540	$2,210	$7,100	$520	$43,900
	EM	$11,530	$8,650	$210	$12,200	$470	$2,150	$6,160	$520	$41,900
	CM	$11,530	$8,650	$220	$11,900	$470	$2,190	$6,210	$520	$41,700
	MM	$11,530	$8,650	$210	$11,800	$460	$2,080	$6,000	$520	$41,300
	MLX	$11,530	$8,650	$180	$10,900	$460	$1,820	$5,040	$520	$39,100
	MMX	$11,530	$8,650	$150	$10,100	$400	$1,710	$4,290	$520	$37,400
	MMI	$11,530	$8,650	$230	$12,300	$500	$2,070	$6,440	$520	$42,200
	MMXI	$11,530	$8,650	$160	$10,500	$430	$1,710	$4,560	$520	$38,000
Salem	EL	$9,250	$6,940	$320	$6,400	$680	$1,800	$10,420	$570	$36,400
	CL	$9,250	$6,940	$320	$6,600	$690	$1,840	$10,570	$570	$36,800
	ML	$9,250	$6,940	$300	$6,300	$660	$1,670	$9,900	$570	$35,600
	EM	$9,250	$6,940	$260	$5,500	$580	$1,600	$8,490	$570	$33,200
	CM	$9,250	$6,940	$260	$5,600	$580	$1,640	$8,570	$570	$33,400
	MM	$9,250	$6,940	$260	$5,200	$560	$1,510	$8,280	$570	$32,500
	MLX	$9,250	$6,940	$210	$4,600	$550	$1,200	$6,660	$570	$30,000
	MMX	$9,250	$6,940	$180	$3,800	$480	$1,090	$5,740	$570	$28,100
	MMI	$9,250	$6,940	$280	$5,700	$600	$1,510	$9,000	$570	$33,800
	MMXI	$9,250	$6,940	$190	$4,200	$520	$1,090	$6,100	$570	$28,800
Denver	EL	$13,000	$9,750	$480	$11,800	$940	$2,650	$8,430	$440	$47,500
	CL	$13,000	$9,750	$480	$11,700	$940	$2,630	$8,390	$440	$47,300
	ML	$13,000	$9,750	$480	$11,300	$930	$2,550	$8,490	$440	$46,900
	EM	$13,000	$9,750	$410	$9,800	$810	$2,380	$7,170	$440	$43,700
	CM	$13,000	$9,750	$410	$9,700	$810	$2,370	$7,150	$440	$43,600
	MM	$13,000	$9,750	$420	$9,400	$800	$2,300	$7,350	$440	$43,500
	MLX	$13,000	$9,750	$350	$7,500	$790	$1,820	$6,120	$440	$39,700
	MMX	$13,000	$9,750	$320	$6,300	$700	$1,660	$5,450	$440	$37,600
	MMI	$13,000	$9,750	$440	$10,000	$840	$2,300	$7,670	$440	$44,500
	MMXI	$13,000	$9,750	$330	$6,600	$730	$1,660	$5,630	$440	$38,200
Chicago	EL	$12,590	$9,440	$550	$11,200	$860	$2,320	$14,210	$620	$51,800
	CL	$12,590	$9,440	$540	$11,200	$860	$2,320	$14,180	$620	$51,700
	ML	$12,590	$9,440	$560	$10,900	$860	$2,260	$14,610	$620	$51,800
	EM	$12,590	$9,440	$500	$9,200	$730	$2,130	$13,030	$620	$48,300
	CM	$12,590	$9,440	$500	$9,200	$730	$2,120	$13,010	$620	$48,200
	MM	$12,590	$9,440	$520	$8,900	$730	$2,080	$13,550	$620	$48,500
	MLX	$12,590	$9,440	$430	$7,900	$740	$1,650	$11,090	$620	$44,400
	MMX	$12,590	$9,440	$420	$6,600	$660	$1,530	$10,540	$620	$42,500
	MMI	$12,590	$9,450	$540	$9,800	$770	$2,070	$13,950	$620	$49,700
	MMXI	$12,590	$9,450	$430	$7,100	$690	$1,530	$10,740	$620	$43,200

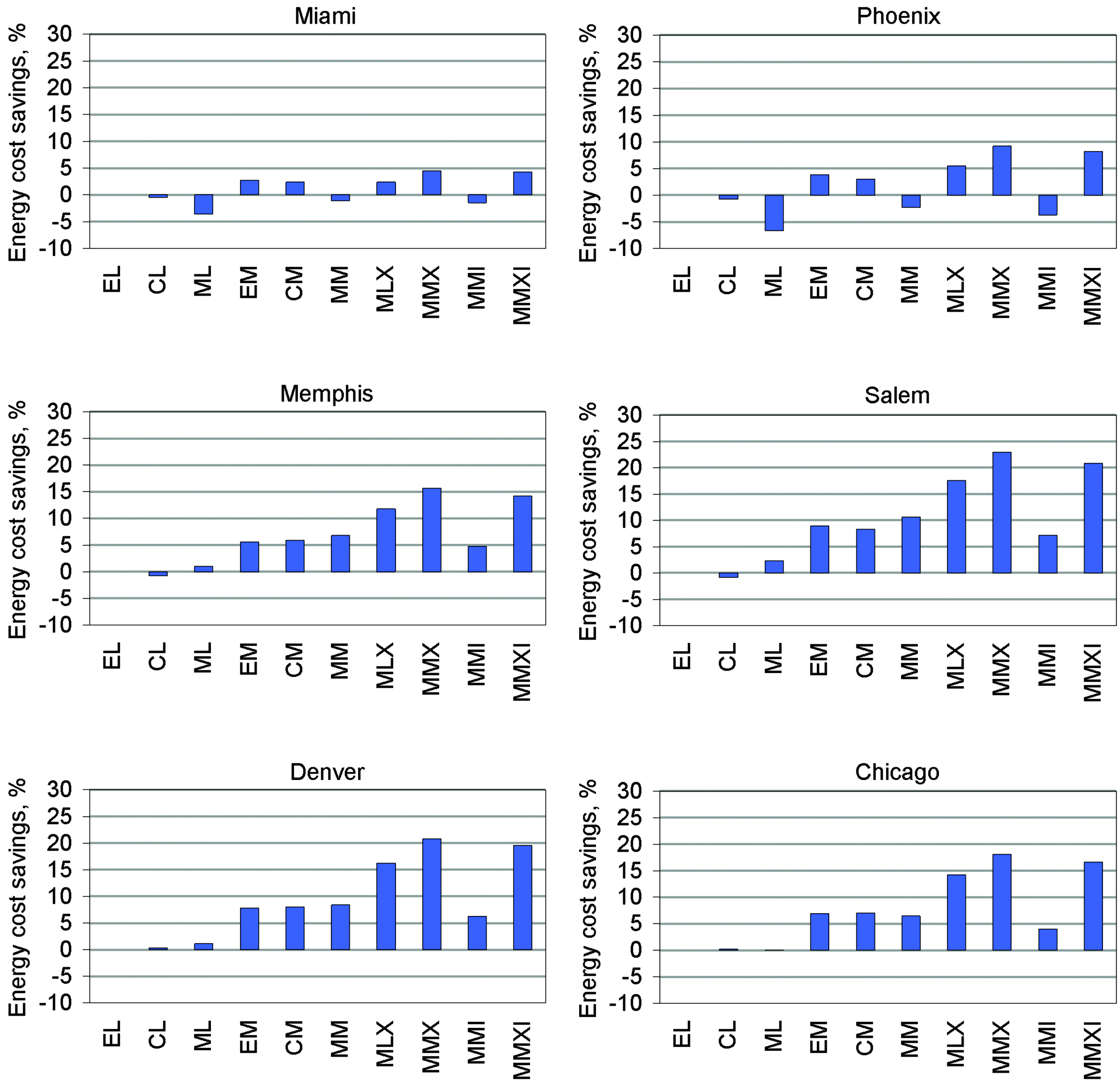

Figure 4 *Energy cost savings as a percent of baseline building (EL). The abbreviated scenario names EL through MMXI are described in the text.*

Memphis, Salem, Denver, and Chicago (compare CL to CM, EL to EM, and ML to MM). In Miami and Phoenix, the variations in energy cost scenarios are small. The additional thermal mass in the frame saves some energy costs (less than 5%: compare CL to CM, EL to EM, and ML to MM), but the buildings with concrete walls have 1 to 7% greater energy costs than the baseline building (compare ML and MM to EL).

Energy Cost Savings Due to the Structural Frame. In Memphis, Salem, Denver, and Chicago, energy cost savings of 6 to 9% are indicated for the three concrete frame buildings meeting code compared to the three steel frame buildings meeting code (compare CL to CM, EL to EM, and ML to MM). The exterior wall construction is identical in each pair of comparisons, that is the exterior walls of CL and CM are identical, as are EL and EM, and ML and MM. So the energy cost savings are due primarily to the concrete shear walls in the concrete frame building.

Energy Cost Savings Due to Walls. Due to thermal mass effects, *ASHRAE 90.1-2004* does not require mass walls to have as high an R-value as low-mass walls (for example, see Tables 4 and 5). Comparing buildings with the same structural frame but different walls shows small differences in energy costs savings (compare EL to CL to ML and compare EM to CM to MM). Energy cost savings range from -3% to 6% and the average is 1%. These results indicate that the reduced R-values for mass walls allowed in energy codes are justified.

For a given structural frame, the EIFS and curtain wall buildings in Miami and Phoenix have less energy cost than the buildings with uninsulated concrete walls (compare EL and CL to ML, and compare EM and CM to MM). In Miami they use about 3% less energy, and in Phoenix they use about 6% less energy. According to the minimum code requirements, concrete walls in Miami and Phoenix do not require added insulation, but EIFS and curtain walls in these same cities require at least R-13 batt insulation. Therefore, the mass walls are more than three times more conductive than the light-weight walls.

Internal Loads Near Central Core. We analyzed the building with precast concrete walls and reinforced concrete frames in two ways. First, with internal loads distributed uniformly across the floor area (this is the usual way to simulate a building), and second, with the internal loads weighted more heavily towards the interior zone. The second case has more energy use for all cases (compare MMI to MM and MMXI to MMX).

Walls Exceeding Energy Code Requirements. VisualDOE shows significant energy cost savings for building envelopes (including walls and windows) exceeding code. The amount of added insulation chosen to make the concrete walls exceed code is not unusual. Even more insulation could have been used, but using a low value shows how even modest improvements can result in significant energy savings. The added insulation in the concrete wall exceeding code is about the same as the amount of insulation in the EIFS and curtains walls meeting code in Denver and Chicago. This shows that the amount of added insulation is realistic and that concrete with insulation saves energy. Energy cost savings are in the range of 9 to 23% for all cities except Miami, where the energy cost savings are about 5% (see Figure 4, compare MMX to EL)

Only two comparisons were made for buildings exceeding code requirements; one with concrete walls and a concrete frame and one with concrete walls and a steel frame. Generally, the savings were 1 to 3% greater for the concrete walls with a steel frame compared to that for the concrete walls with the concrete frame (compare ML to MLX and MM to MMX). However, the concrete walls exceeding code with the concrete frame had the most energy cost savings compared to the baseline builidng (compare MLX and MMX to EL.)

LEED EA Credit 1. In the four cities representing mild, cool, and cold climates, reinforced concrete frame buildings with building envelopes that exceed code will most likely qualify for points under LEED-NC EA Credit 1. In the cold climate category (Denver and Chicago), these buildings will likely qualify for 3 points, that is, at least 17.5% energy cost savings (actual is Denver 21% and Chicago 18%). In the cool climate category (Salem), these buildings will likely qualify for 4 points, that is, at least 21% energy cost savings (actual is 23%). In mild climates, such as Memphis, these buildings will likely qualify for 2 points, that is, at least 14.5% energy cost savings (actual is 16%) (see Figure 4). In addition, the steel frame buildings with concrete walls and windows exceeding code will likely qualify for 2 points, at least 14.5% energy savings, in Salem (actual is 17%) and Denver (actual is 16%). These results are particularly significant because commercial buildings such as the ones modeled in this study have a relatively large window area (0.4 window-to-wall ratio) and very large associated energy loads.

Sensitivity Analysis. A sensitivity analysis was also performed using VisualDOE to determine how energy use and costs vary with concrete floor thickness. The results are summarized in Table 14. The sensitivity analysis considered: (1) floor thicknesses of 7.5, 9, 10.5, and 12 in.; (2) building types CM, MM, and MMX; and (3) cities Phoenix, Salem, and Denver. These cities represent climates where (1) thermal mass is demonstrably effective in saving energy costs (Salem and Denver) and (2) a wide daily temperature swing normally shows positive benefits for thermal mass but because of the energy code requirements and energy cost, results are not as dramatic (Phoenix).

The summary results for Salem and Phoenix are presented in Figures 5 and 6, respectively. The complete results for all three cities are tabulated in Table 14. The results show that regardless of building type or location, increasing the floor thickness in increments of 1.5 in. (38 mm), from 7.5 (190 mm) in to 12 in. (305 mm), increases the energy cost savings by a small amount. For Salem and Denver, increasing the floor thickness by 1.5 in. (38 mm) results in incremental energy costs savings of about 0.1%. For Phoenix it is about 0.05%. These savings are not significant because they represent annual savings in the range of $50 to $150. This is well below the modeling resolution of any simulation program.

Thermal Mass Effects and Energy Simulation. Energy simulation computer programs based on DOE-2, such as VisualDOE, typically do not show as large energy savings due to building thermal mass as BLAST or EnergyPlus (Crawly and others 2005). However, VisualDOE was used due to its relative user friendliness. Until very recently, there have been no user interfaces for EnergyPlus.

SUMMARY AND CONCLUSIONS

This project provides in-depth information on potential energy savings in mid-rise commercial buildings with structural steel or precast concrete frame construction and using EIFS, curtain wall, and precast concrete walls meeting code requirements and precast concrete walls exceeding building envelope thermal performance requirements. It shows how to model the thermal properties of concrete to obtain points in LEED-NC version 2.2 Energy and Atmosphere Credit 1. Using energy simulation software, in most scenarios, the effect of the concrete frame buildings has been shown to lower energy *use* and energy *cost* relative to the baseline steel framed EIFS buildings.

In four of the six cities where buildings were modeled, reinforced concrete frame buildings with concrete walls and building envelopes that exceed code (as described in this report) will most likely qualify for points under EA Credit 1. In the cold climate category (Denver and Chicago), these buildings will likely qualify for 3 points, that is, at least 17.5%

Table 14. Results of Sensitivity Analysis on Floor Thickness

City	Interior Floor Thickness, in.	Scenario[1]	Total Annual Cost, $	Total Annual Energy, kW	Percent Savings Compared to EL		Incremental Cost Savings Compared to Same Scenario[2]	
					Cost, $	Energy, kW	%	Cost, $
Phoenix	4	EL	$60,500	751,000	—	—	—	—
	7.5	CM	$58,800	705,000	2.9%	6.1%	—	—
	7.5	MM	$62,000	760,000	–2.4%	–1.3%	—	—
	7.5	MMX	$55,000	642,000	9.1%	14.5%	—	—
	4	EL	$60,500	751,000	—	—	—	—
	9	CM	$58,700	704,000	3.0%	6.2%	0.10%	$59
	9	MM	$62,000	759,000	–2.4%	–1.1%	0.08%	$47
	9	MMX	$55,000	641,000	9.1%	14.6%	0.08%	$43
	4	EL	$60,500	751,000	—	—	—	—
	10.5	CM	$58,700	703,000	3.0%	6.3%	0.05%	$27
	10.5	MM	$61,900	759,000	–2.3%	–1.1%	0.04%	$25
	10.5	MMX	$55,000	640,000	9.2%	14.7%	0.03%	$15
	4	EL	$60,500	751,000	—	—	—	—
	12	CM	$58,700	703,000	3.0%	6.4%	0.02%	$14
	12	MM	$61,900	758,000	–2.3%	–1.0%	0.02%	$15
	12	MMX	$55,000	640,000	9.2%	14.7%	0.02%	$13
Salem	4	EL	$36,400	837,000	—	—	—	—
	7.5	CM	$33,500	752,000	7.9%	10.1%	—	—
	7.5	MM	$32,700	732,000	10.3%	12.5%	—	—
	7.5	MMX	$28,200	604,000	22.7%	27.9%	—	—
	4	EL	$36,400	837,000	—	—	—	—
	9	CM	$33,400	750,000	8.2%	10.4%	0.2%	$78
	9	MM	$32,600	730,000	10.5%	12.8%	0.2%	$71
	9	MMX	$28,100	602,000	22.8%	28.0%	0.2%	$47
	4	EL	$36,400	837,000	—	—	—	—
	10.5	CM	$33,400	749,000	8.3%	10.5%	0.1%	$36
	10.5	MM	$32,600	729,000	10.6%	12.9%	0.1%	$40
	10.5	MMX	$28,100	601,000	22.9%	28.1%	0.1%	$29
	4	EL	$36,400	837,000	—	—	—	—
	12	CM	$33,400	748,000	8.3%	10.6%	0.1%	$20
	12	MM	$32,500	728,000	10.6%	13.0%	0.1%	$25
	12	MMX	$28,100	601,000	22.9%	28.2%	0.1%	$16
Denver	4	EL	$47,500	909,000	—	—	—	—
	7.5	CM	$43,800	818,000	7.8%	10.1%	—	—
	7.5	MM	$43,600	824,000	8.1%	9.4%	—	—
	7.5	MMX	$37,700	679,000	20.6%	25.3%	—	—
	4	EL	$47,500	909,000	—	—	—	—
	9	CM	$43,700	816,000	7.9%	10.3%	0.2%	$70
	9	MM	$43,500	822,000	8.3%	9.6%	0.2%	$78
	9	MMX	$37,600	678,000	20.7%	25.5%	0.2%	$58
	4	EL	$47,500	909,000			—	—
	10.5	CM	$43,700	815,000	8.0%	10.4%	0.1%	$42
	10.5	MM	$43,500	820,000	8.4%	9.8%	0.1%	$52
	10.5	MMX	$37,600	677,000	20.8%	25.6%	0.1%	$28
	4	EL	$47,500	909,000	—	—	—	—
	12	CM	$43,600	814,000	8.0%	10.5%	0.1%	$22
	12	MM	$43,500	820,000	8.4%	9.9%	0.1%	$25
	12	MMX	$37,600	676,000	20.8%	25.6%	0.04%	$16

[1]Scenario EL, with a floor thickness of 4 in., is included because it is the baseline building to which comparisons must be made to satisfy LEED requirements.
[2]Same scenario in this case is comparing identical building descriptions with the next increment in floor thickness. For example, comparing CM with a 7.5-in. thick floor to CM with a 9-in. thick floor.

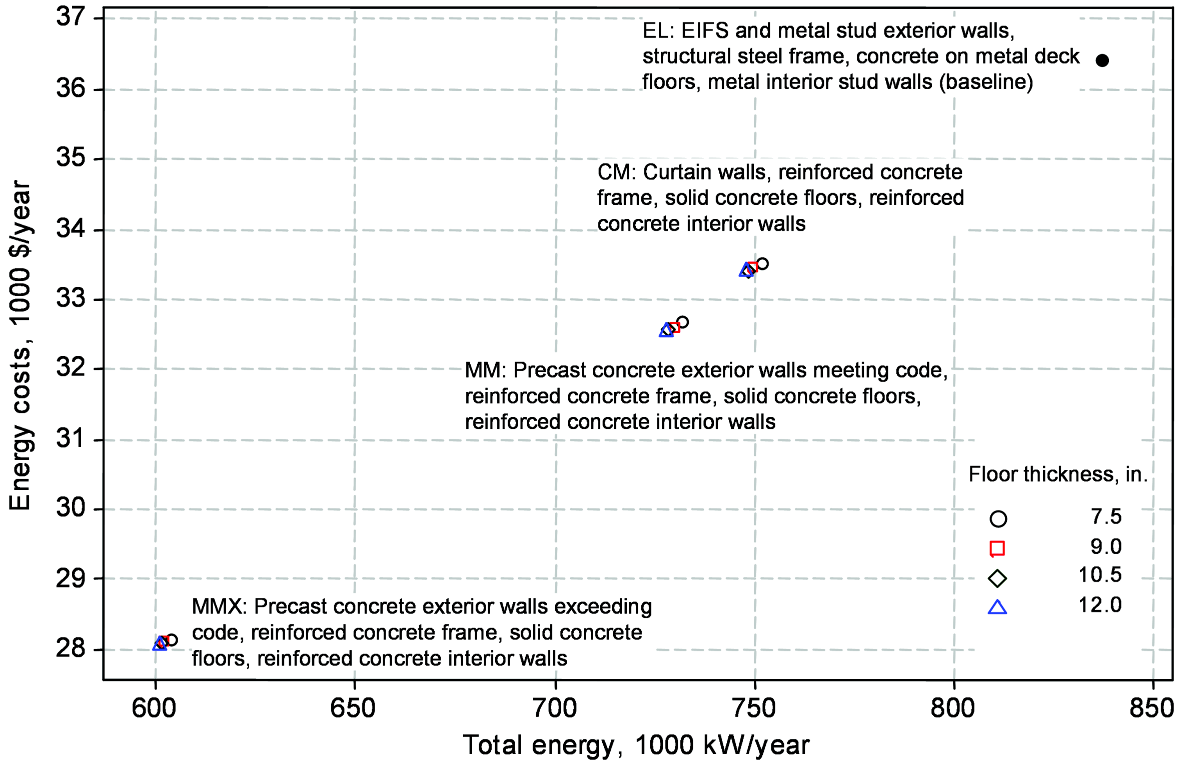

Figure 5 *Concrete floor thickness has a small effect on energy use and cost (Salem).*

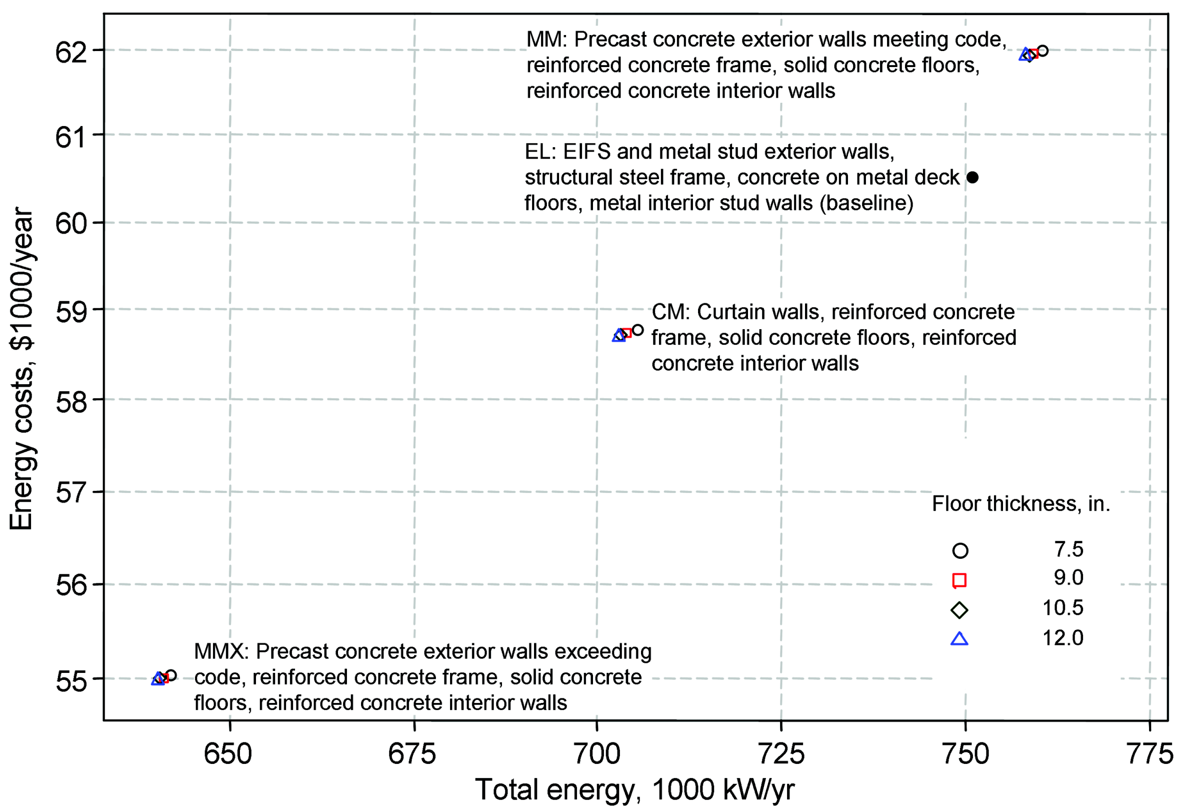

Figure 6 *Concrete floor thickness has a small effect on energy use and cost (Phoenix).*

energy cost savings. In the cool climate category (Salem), these buildings will likely qualify for 4 points, that is, at least 21% energy cost savings. In the mild climate category (Memphis), these buildings will likely qualify for 2 points, that is, at least 14% energy cost savings. In addition, the steel frame buildings with concrete walls and windows exceeding code will likely qualify for 2 points, at least 14% energy savings, in Salem and Denver.

For a given structural frame, the EIFS and curtain wall buildings in Miami and Phoenix used less energy than the buildings with uninsulated mass walls. In Miami they use about 3% less energy, and in Phoenix they use about 6% less energy.

In Memphis, Salem, Denver, and Chicago, energy cost savings of 6 to 9% are indicated for the three concrete frame buildings meeting code compared to the three steel frame buildings meeting code. This energy cost savings is primarily due to the concrete shear walls in the concrete frame building. The exterior wall construction is identical in each pair of comparisons.

The results in this report are for the buildings modeled in the stated cities. Actual energy use and cost will vary depending on climate, building type, use and occupancy, orientation, actual building materials, and fenestration amount and type.

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