Portland Cement Association

Research & Development Information

PCA R&D Serial No. 2880a

Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2: Energy and Atmosphere Credit 1

by Medgar L. Marceau and Martha G. VanGeem

5420 Old Orchard Road
Skokie, Illinois 60077-1083
847.966.6200 Fax 847.966.9481

www.cement.org

KEYWORDS

Building, commercial, concrete, energy, interior thermal mass, LEED, office

ABSTRACT

The objective of this project is to provide information to architects and engineers on the design of concrete buildings to obtain LEED points for optimizing energy performance. 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. This project is based on LEED for new construction and major renovation (LEED-NC). Many states and municipalities require that new buildings built with public funds meet the LEED-NC requirements for certification. Many owners, architects, and designers are also seeking LEED-NC ratings for privately funded buildings.

This report provides in-depth information on energy savings in mid-rise buildings due to thermal mass and for exceeding building envelope thermal performance requirements. We also show how to model the thermal properties of concrete to obtain LEED-NC version 2.2 points. The LEED Energy & Atmosphere (EA) Credit 1 on optimizing energy performance provides up to 10 points for energy savings beyond *ASHRAE/IESNA Standard 90.1-2004*. A total of 26 points are required for a basic level of certification. Obtaining points for the EA Credit 1 requires modeling with energy simulation software, and modeling thermal mass effects requires software that models yearly energy use on an hourly basis.

CTLGroup has modeled several five-story prototype buildings with plan dimensions of 105x105 sq ft and a window-to-wall ratio of 0.40. The buildings were modeled using two software programs: VisualDOE and Energy-10. Since the effects of thermal mass vary with climate, the buildings were modeled in six cities representing the range of climates in the United States: Miami, Phoenix, Memphis, Salem (Oregon), Denver, and Chicago. These cities and the building floor plans correspond with those used by ASHRAE committees and various industries to model the effects of materials and energy use. The buildings were modeled using five scenarios:

- 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
- Precast concrete walls exceeding *ASHRAE 90.1-2004*, reinforced concrete frame, and high internal load equipment placed near the central core of the building

In most scenarios, the energy modeling shows that the effect of thermal mass is to lower both energy *use* and *cost* relative to the baseline steel framed EIFS buildings.

In Memphis, Salem, Denver, and Chicago, the three concrete frame buildings meeting basic code requirements have energy cost savings of 6% to 9% compared to the three steel frame buildings meeting code. This energy cost savings is due to the concrete shear walls and increased thickness of the concrete floors in the concrete frame building.

In all cities except Miami and Phoenix, reinforced concrete frame buildings with concrete walls and building envelopes exceeding code will most likely qualify for points in LEED-NC EA Credit 1. The amount of insulation used to exceed code is the same as the amount of insulation in the EIFS and curtain walls meeting code in Denver and Chicago. In cold climates (Denver and Chicago), reinforced concrete frame buildings with concrete walls and building envelopes exceeding code show at least 17.5% energy cost savings, thus qualifying for 3 points. In cool climates (Salem), these buildings show at least 21% energy cost savings, thus qualifying for 4 points. In mild climates (Memphis), these buildings show at least 14% energy cost savings, thus qualifying for 2 points.

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. However, in these climates, the reinforced concrete frame buildings with uninsulated concrete walls have comparable performance to the steel frame buildings with R-13 insulated EIFS and curtain walls.

A sensitivity analysis was also performed to determine how energy use and costs vary with concrete floor thickness. The sensitivity analysis considered:

- floor thicknesses of 7.5, 9, 10.5, and 12 in.;
- three building types: curtain walls meeting code with reinforced concrete frame, precast concrete walls meeting code with reinforced concrete frame, and precast concrete walls exceeding code with reinforced concrete frame; and
- cities Phoenix, Salem, and Denver.

The results show that regardless of building type or location, increasing the floor thickness in increments of 1.5 in., from 7.5 in to 12 in., increases the energy cost savings by a small amount. For Salem and Denver, increasing the floor thickness by 1.5 in. results in incremental energy cost savings of about 0.1%. For Phoenix, it is about 0.05%. These savings, though real, are not significant because they are well below the modeling resolution of any simulation program.

REFERENCE

Marceau, Medgar L. and VanGeem, Martha G., "Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2: Energy and Atmosphere Credit 1," R&D Serial No. 2880a, Portland Cement Association, Skokie, Illinois, USA, 2007, 55 pages.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2 Energy and Atmosphere Credit 1

by Medgar L. Marceau and Martha G. VanGeem[1]

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. This project is based on version 2.2 of LEED for new construction and major renovation (LEED-NC).[2]

LEED-NC has gained widespread acceptance across the United States. 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 certain requirements, such as energy conservation and using recycled-content materials. Previous work by CTLGroup has shown how concrete can contribute to 20 of the 26 points required for the basic level of LEED-NC certification.

The LEED-NC Energy & Atmosphere (EA) Credit 1 on optimizing energy performance can potentially provide up to 10 points for energy cost savings beyond *ASHRAE Standard 90.1-2004*.[3] Obtaining points for EA Credit 1 requires modeling with energy simulation software. The software must be capable of simulating 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 tend to moderate and delay extreme changes in temperature, resulting in lower energy use. This complex behavior is often simply called thermal mass effect.

---

[1] Building Science Engineer and Principal Engineer, respectively, CTLGroup, 5400 Old Orchard Road, Skokie, IL, 60077, (847) 965-7500, www.CTLGroup.com.

[2] *Leadership in Energy and Environmental Design for New Construction and Major Renovations, Version 2.2*, United States Green Building Council, October 2005, www.usgbc.org.

[3] *ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-rise Residential Buildings*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2004, www.ashrae.org.

Although energy simulation software is readily available, many architects and engineers would like guidance on taking full advantage of the EA points available from the inherent beneficial thermal properties of concrete construction.

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 report demonstrates how to model thermal mass in buildings and presents results for several buildings in five climates.

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 Informative 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 using the formula:

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

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

Table 1. Points for Optimizing Energy Performance in LEED-NC Version 2.2 Energy and Atmosphere Credit 1

Energy cost savings beyond *ASHRAE Standard 90.1-2004*		**Points**
New buildings	**Existing buildings**	
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

Baseline Building and Proposed Buildings

In this study, the buildings are based on the prototype building used by ASHRAE committees and other building industry groups to model the effects of materials and energy use. Wherever possible, the work described in this report is consistent with energy analyses that support the criteria in *ASHRAE Standard 90.1-2004* and the *2003 International Energy Conservation Code*.

All the buildings in this study are five-story commercial buildings with plan dimensions 105x105 ft. More detail is provided below in the section called Building Description. The baseline building generally conforms to the requirements of Informative Appendix G. It consists of an exterior insulation finishing system (EIFS) with steel stud walls,[4] 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. 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
- 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. concrete floors. An "X" indicates that the building envelope exceeds code requirements and an "I" indicates that the internal loads are clustered near the central core of the building.

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 high internal loads are assumed to be clustered near the central core of the building, where most of the interior concrete is located.

[4] Steel studs are light gauge cold formed steel framing (American Iron and Steel Institute, www.steel.org).

Table 2. Buildings Modeled

Designation*	Exterior walls	Structural frame	Floors	Interior walls
EL (baseline)	EIFS & 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 & metal stud	reinforced concrete	12" solid concrete	reinforced concrete
CM	curtain wall	reinforced concrete	12" solid concrete	reinforced concrete
MM	precast concrete	reinforced concrete	12" 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" solid concrete	reinforced concrete
MMI	precast concrete	reinforced concrete	12" solid concrete	reinforced concrete
MMXI	precast concrete exceeding code	reinforced concrete	12" solid concrete	reinforced concrete

*See text for an explanation of the designations.

Energy Modeling

Building energy use was modeled using two energy simulation computer programs: VisualDOE and Energy-10.

VisualDOE[5] is a graphic interface to the DOE-2 program modules.[6] On the VisualDOE input screens, the user enters information about the building being modeled. 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. These modules (1) calculate the heating and cooling loads of each space in a building for each hour of a year and (2) simulate operation and response of the equipment and systems that control temperature and distribute heating, cooling, and ventilation to the building. 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.[7] Energy use and demand in response to thermal mass effect are accurately predicted because the program performs hourly simulation.

[5] VisualDOE, version 4.0.0, Architectural Energy Corporation, San Francisco, CA, 2004.

[6] 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 2002).

[7] 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.

Energy-10 is a conceptual design tool for small (less than 10,000 sq ft) low-energy buildings that can be characterized by two thermal zones. It was used in this project primarily as a consistency check in the results. However, Energy-10 is not intended for buildings like the ones in this project, nor does it meet the requirements[8] of Informative Appendix G. Therefore, the results from modeling with Energy-10 are not discussed in detail in this report, but the results are shown in the Appendices.

Climates

Since thermal mass effects vary with climate, the buildings were modeled in six cities representing the range of climates in the United States. 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 the *ASHRAE 90.1- 2004* and *2004 International Energy Conservation Code*. 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.

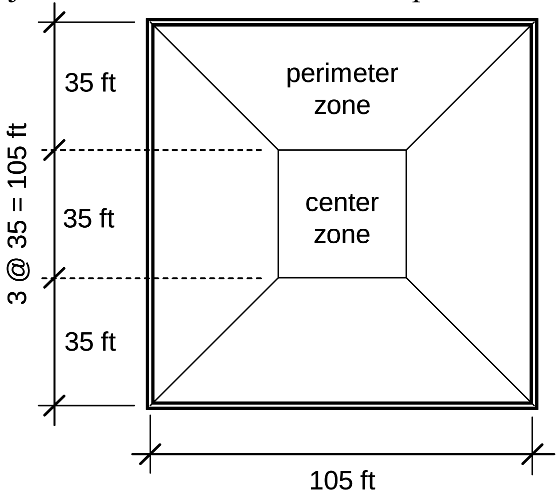
Common Features

All the buildings in this study are five-story commercial buildings with plan dimensions 105x105 ft. 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) is based on 15 ft for the first story and 12 ft 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. The center zone is 35x35 ft. VisualDOE automatically includes partition walls

[8] The requirements are listed in Informative Appendix G, section G2.2, page 169. Energy-10 does not meet the requirements because it can only model two zones.

between adjacent zones. The user can accept the default partition wall construction or input a



new wall.

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

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

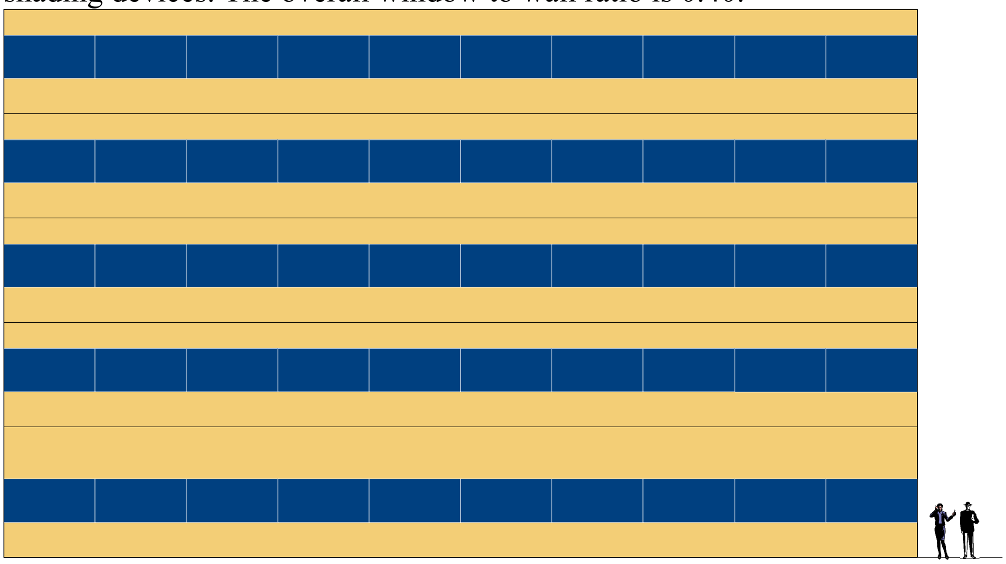


Figure 2. Each façade consists of bands of windows.

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 Informative 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, ⅝-in. gypsum wallboard, board insulation, and built-up waterproofing membrane. The overall roof U-value is 0.062 Btu/h·ft^2·°F (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 (the default value required in Informative Appendix G).

Slab-on-ground. The ground-level floor consists of carpet with fibrous pad and 6-in. 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 2002). In this method the floor is also assumed to consist of a 12-in. layer of soil with a thermal resistance[9] of 1.0 h·ft^2·°F/Btu 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 32.545 h·ft^2·°F/Btu 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 of 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 parameters are shown in Table 3. These operational parameters are based on *ASHRAE 90.1-1989* schedules and VisualDOE defaults.

Equipment and lighting. Equipment power density (also called plug or receptacle load) is 0.75 watt/ft^2. It includes all plug or receptacle loads and two average-efficiency[10] elevators. Lighting power density is 1.0 watt/ft^2. There is no daylight control. The energy for exterior lighting is not considered. Natural gas water heaters supply domestic hot water.

---

[9] The thermal resistance of soil is taken from Winkelmann (2002), section A6, page 99, rather than from *ASHRAE 90.1-2004*.

[10] Using the Otis Energy Expense Calculator assuming two 8-person capacity cars, the resulting energy use is less than 1% of the total equipment power density (http://www.aobr.on.com.br/Rac_energia/New_Zealand/internet_pages/Info_Calc.asp).

Table 3. Building Systems Operational Parameters and Schedules*

Schedule type, unit	Hour of day																	
Day type	**1-5**	**6**	**7**	**8**	**9**	**10-11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Occupancy, %																			
Weekday	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, %																			
Weekday	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 & holidays	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Infiltration, %																			
Weekday	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 & holidays	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Domestic hot water, %																			
Weekday	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 & holidays	5	5	5	5	5	5	5	5	10	5	5	5	5	5	5	5	5	5	5
Outside air, %																			
Weekday	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 & holidays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HVAC supply fan, %																			
Weekday	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 & holidays	F	F	100	100	100	100	100	100	100	100	100	100	100	F	F	F	F	F	F
Cooling set point, °F																			
Weekday	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																			
Weekday	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 & holidays	55	55	70	70	70	70	70	70	70	70	70	70	70	55	55	55	55	55	55

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

Air infiltration and fresh air requirements. The overall 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-90.1-2004*. It is also within the

normal range for office buildings, that is 0.1 to 0.6 ach.[11] 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/person.[12]
Occupancy. The occupancy is 275 sq ft/person.[13] The thermostat throttling range is 4°F. The operating hours are based on *ASHRAE 90.1-1989*.[14] The schedules are shown in Table 3. These schedules 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, conductivity of 1.333 Btu/h·ft·°F, and specific heat of 0.22 Btu/lb °F. Buildings ML, EM, CM, MM, MLX, MMX, MMI, and MMXI as noted earlier are the "mass" buildings.

Floors. The interior floors of the steel frame buildings consist of ribbed steel deck, an equivalent concrete thickness of 4 in., 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. 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 nonstructural 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."

---

[11] *2001 ASHRAE Fundamentals Handbook IP*, page 27.23 (ASHRAE, 2001).

[12] Table 2, page 8 in *ASHRAE Standard 62-1999, Ventilation for Acceptable Indoor Air Quality*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 2001, www.ashrae.org.

[13] *ASHRAE Standard 90.1-1989*, Table 13.2, page 110.

[14] *ASHRAE Standard 90.1-1989,* Table 13.3, page 111.

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

Location	Maximum code-required U-factor*	Insulation and resulting wall U-factor to meet code	
		Insulation**	U-factor*
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

*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.
**Batt insulation is installed between steel studs, which are 16 in. on-center. Board insulation is continuous over the steel studs.

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

Location	Maximum code-required U-factor*	Insulation and resulting wall U-factor to meet code	
		Insulation**	U-factor*
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

*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.
**Batt insulation is installed between steel studs, which are 16 in. on-center. Board insulation is continuous over the steel studs.

Table 6. 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 & Phoenix	Memphis & Salem	Denver & 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*	0	0	0.77	0
Insulation and 3.5-in. framing**	0.79	6.0	6.4	10
Gypsum wallboard, ½ 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**

*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.
**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.

Fenestration. The thermal performance requirements for windows are shown in Table 7 along with the properties of the 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 (including air films). The thermal performance requirements for roofs are met using R-15 board insulation in all locations. The resulting roof U-factor is 0.062 Btu/h·ft^2·°F (including air films). In addition, Table 9 shows the properties of the selected roofs used to exceed the requirements.

Table 7. Fenestration Requirements in ASHRAE Standard 90.1-2004

Location	Code-required		Selected windows			
	Maximum U-factor*	Maximum SHGC**	U-factor*	SHGC†	VLT††	VisualDOE identifier & 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 & Chicago	0.57	0.39	0.52	0.30	0.27	2426 Double Ref-B Clear-H Air

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

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

Location	U-factor*	SHGC**	VLT†	VisualDOE identifier & name
Miami, Phoenix	0.52	0.23	0.18	2406 Double ref A clear-H IG
Memphis, Salem, Denver & Chicago	0.31	0.15	0.14	2823 Double Electrochromic Ref Bleached/Colored, 12.7-mm Gap

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

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

Location	Insulation and resulting U-factor to exceed code	
	Insulation	U-factor*
Miami & Phoenix	R-15 board	0.062
Memphis, Salem, Denver & Chicago	R-20 board	0.047

*U-factor in units of Btu/h·ft^2·°F.

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

Table 10. Control Condition for Economizer in Various Locations

Location	1% wet-bulb temperature, °F	Shutoff dry bulb temperature, °F	
		High-limit	Low-limit
Miami	77	65	40
Phoenix	70	70	40
Memphis	77	65	40
Salem	66	75	40
Denver	59	75	40
Chicago	73	70	40

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

Table 11. Energy Costs

Location	Electricity* ¢/kWh	Electricity $/kWh	Natural gas** $/thousand cu ft	Natural gas $/therm
Miami	7.64	0.0764	10.91	1.091
Phoenix	9.55	0.0955	7.75	0.775
Memphis	7.39	0.0739	8.63	0.863
Salem	5.93	0.0593	7.90	0.790
Denver	8.33	0.0833	5.83	0.583
Chicago	8.07	0.0807	8.23	0.823

*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.
**Source: http://www.eia.doe.gov/emeu/states/_states.html. Used 2003 averages and 100 cu ft natural gas = 1 Therm.

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.[15] In general, the custom weighting 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.[16] 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.

[15] 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.

[16] See page III.A.4 of the DOE-2 Supplement (Winkelmann and others 1993).

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 screen shot of the Construction Editor is shown in Figure 3. 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 (Architectural Energy Corporation, 2004).

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 in the building (5,447 ft^3) is distributed over the VisualDOE default partition wall area (19,604 ft^2 for the entire building). The resulting interior concrete wall thickness of 3.334 in. 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 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. 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 covering 85% of the floor. This scenario is the most common for office buildings.

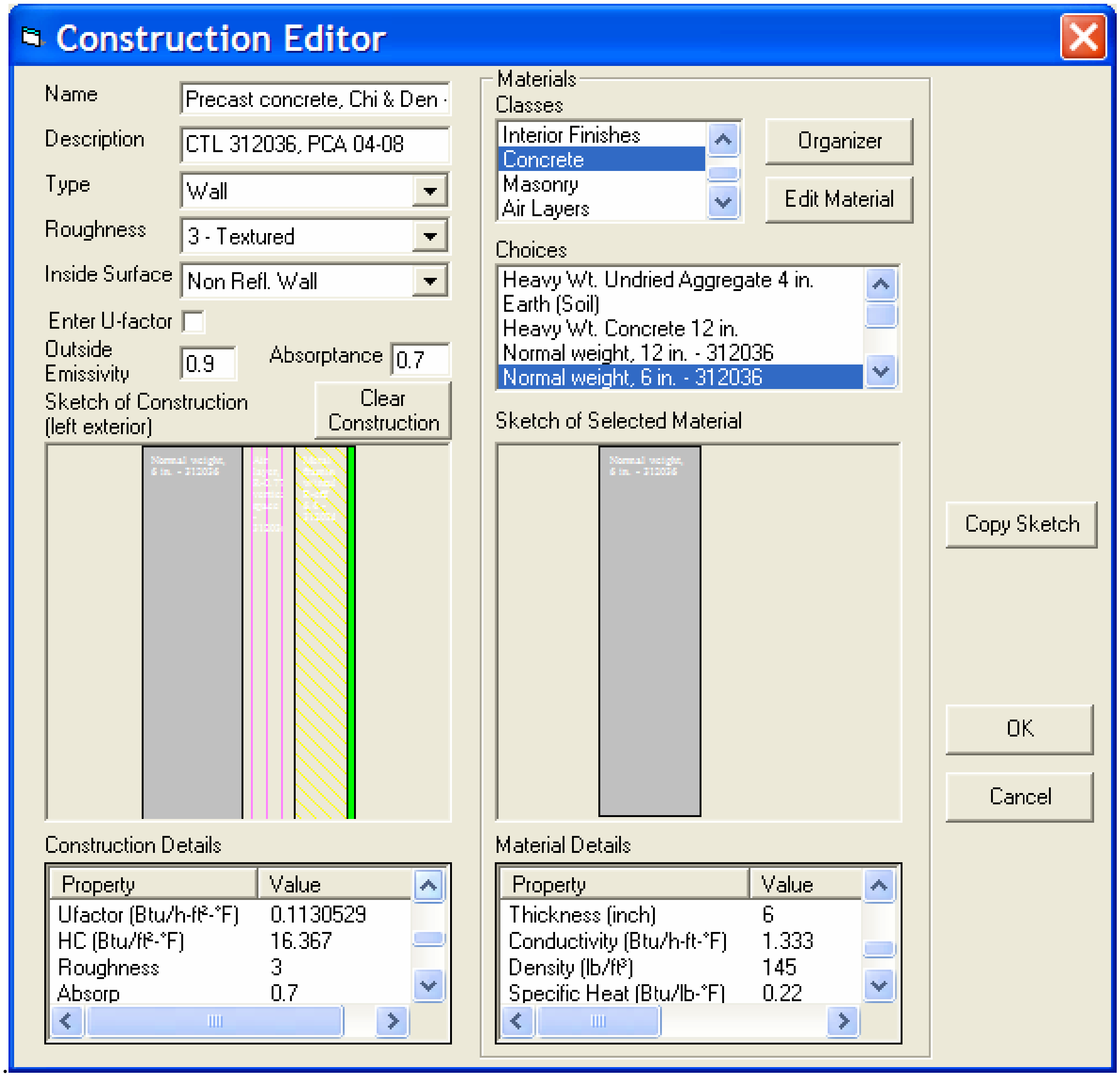


Figure 3. Screen shot of VisualDOE Construction Editor shows that layers of materials are assembled into constructions in order: in this case a 6-in. precast concrete wall.

RESULTS

The VisualDOE results are summarized in Figure 4, and the Energy-10 data are summarized in Figure 5. The detailed results are presented in Appendices A through D. As was mentioned earlier, since Energy-10 does not meet the requirements of Informative Appendix G, the Energy-10 results are not discussed in detail in this report. However, Energy-10 was useful to check that the VisualDOE results were reasonable. For example, Figures 4 and 5 show that the patterns and trends of energy use versus cost are similar using either software. Summary charts and tabulated data from VisualDOE are presented in Appendices A and B, respectively; and summary charts and tabulated data from Energy-10 are presented in Appendices C and D, respectively. For each city, the charts 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.

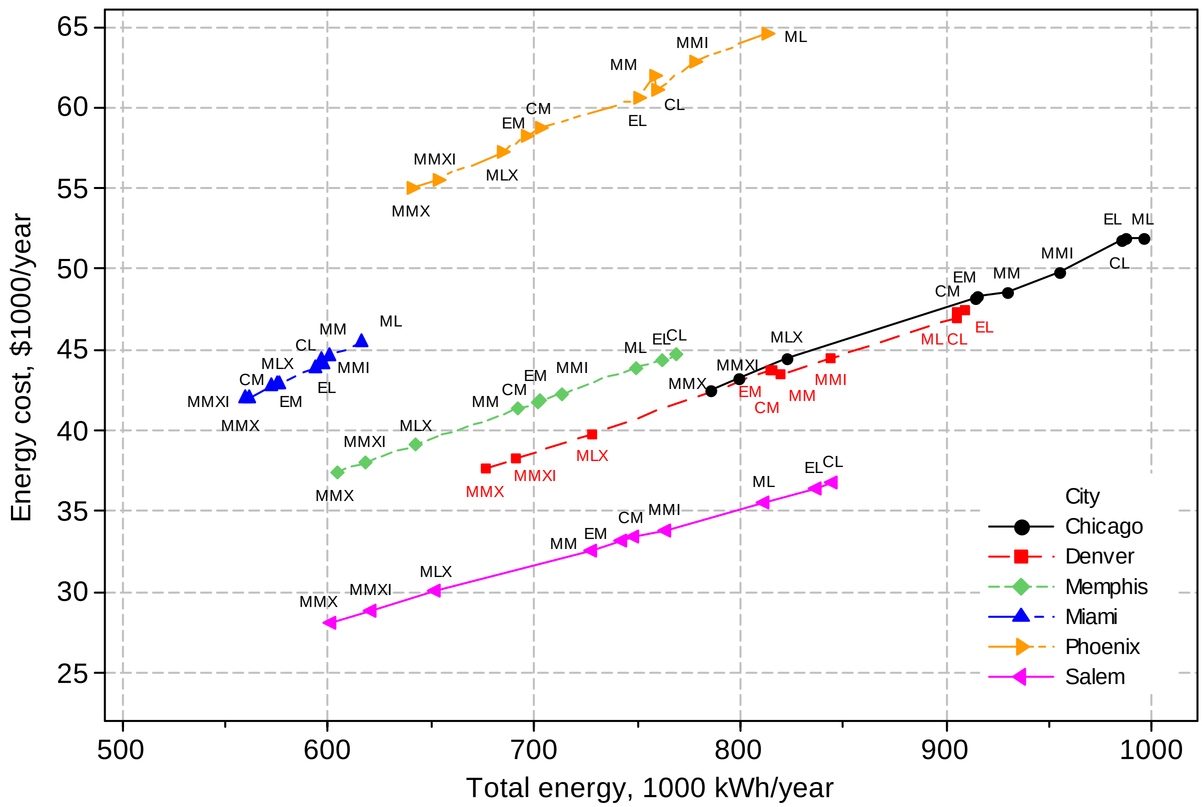


Figure 4. The relationship between annual energy use and cost varies by city (VisualDOE results).

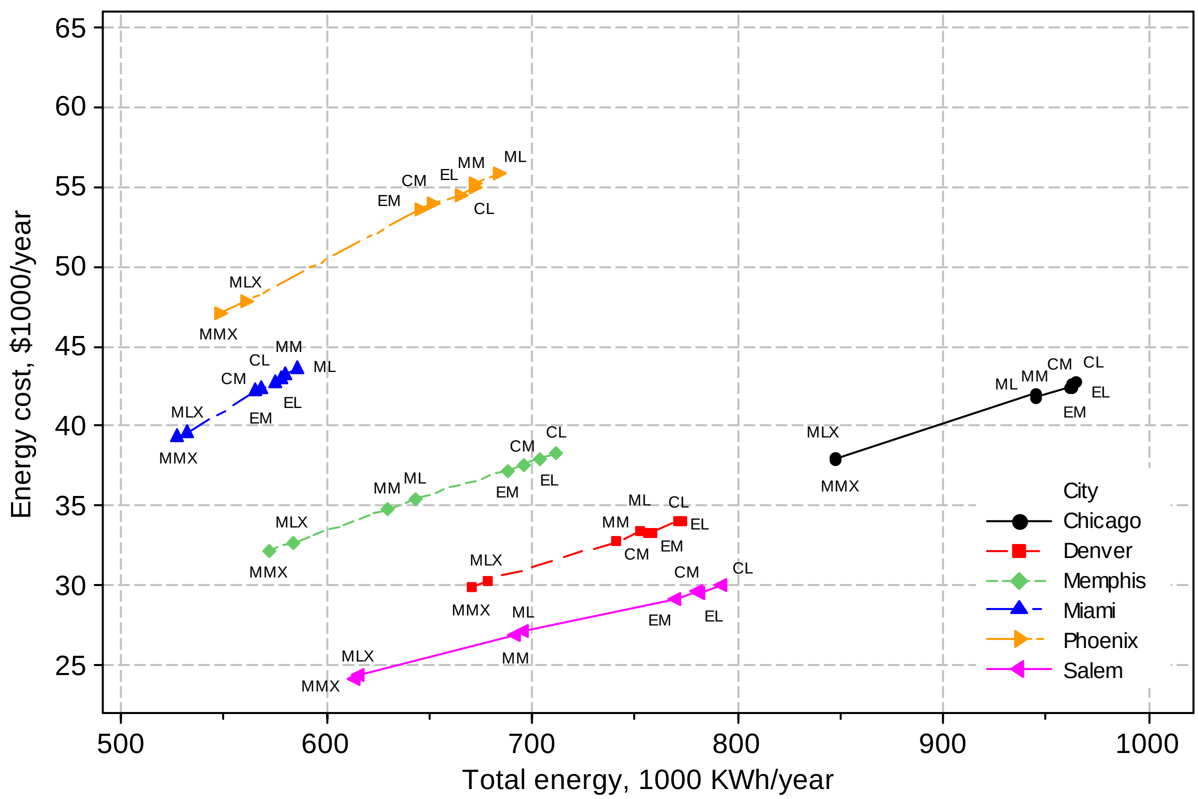


Figure 5. The relationship between annual energy use and cost varies by city (Energy-10 results).

Energy cost savings due to thermal mass effects. In most scenarios, the effect of thermal mass is to lower energy *use* and energy *cost* relative to the baseline building. In Miami, the climate is mild, so the variation in energy cost among scenarios is small; therefore, the difference among scenarios is not as apparent as it is in the other climates. 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. However, in these climates, the reinforced concrete frame buildings with uninsulated concrete walls have comparable performance to the steel frame buildings with insulated EIFS and curtain walls (see Figure 4). 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. Additional thermal mass in the frame and walls will provide at least 5% energy cost savings in Memphis, Salem, Denver, and Chicago (see Figure A8 in Appendix A).

Energy cost savings due to thermal mass in 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 (see Figure A7 in Appendix A). 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 to the concrete shear walls and increased thickness of the concrete floors in the concrete frame building.

Thermal mass in the 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. These results indicate that the reduced R-values for mass walls allowed in energy codes are justified.

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 toward the interior zone. The second case has more energy use for all cases. This means the thermal mass in or near the building envelope helps offset internal loads more than thermal mass in the core. This analysis was done using VisualDOE. Energy-10 was not used because it cannot model more than two zones.

Walls exceeding energy code requirements. VisualDOE shows significant energy cost savings for concrete walls exceeding code. The amount of added insulation chosen to make the 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%.

LEED EA Credit 1. In the four cities representing mild, cool, and cold climates, reinforced concrete frame buildings with concrete walls 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. In the cool climate category (Salem), these buildings will likely qualify for 4 points, that is, at least 21% energy cost savings. In mild climates, such as Memphis, these buildings will likely qualify for 2 points, that is, at least 14.5% energy cost savings (see Figure A8 in Appendix A). 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 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 structure, results are not as dramatic (Phoenix). The summary results for Salem and Phoenix are presented in Figure 6 and Figure 7, respectively. The complete results for all three cities are tabulated in Appendix E. The results show that regardless of building type or location, increasing the floor thickness in increments of 1.5 in., from 7.5 in to 12 in., increases the energy cost savings by a small amount. For Salem and Denver, increasing the floor thickness by 1.5 in. results in incremental energy costs savings of about 0.1%. For Phoenix, it is about 0.05%. These savings, though real, 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.

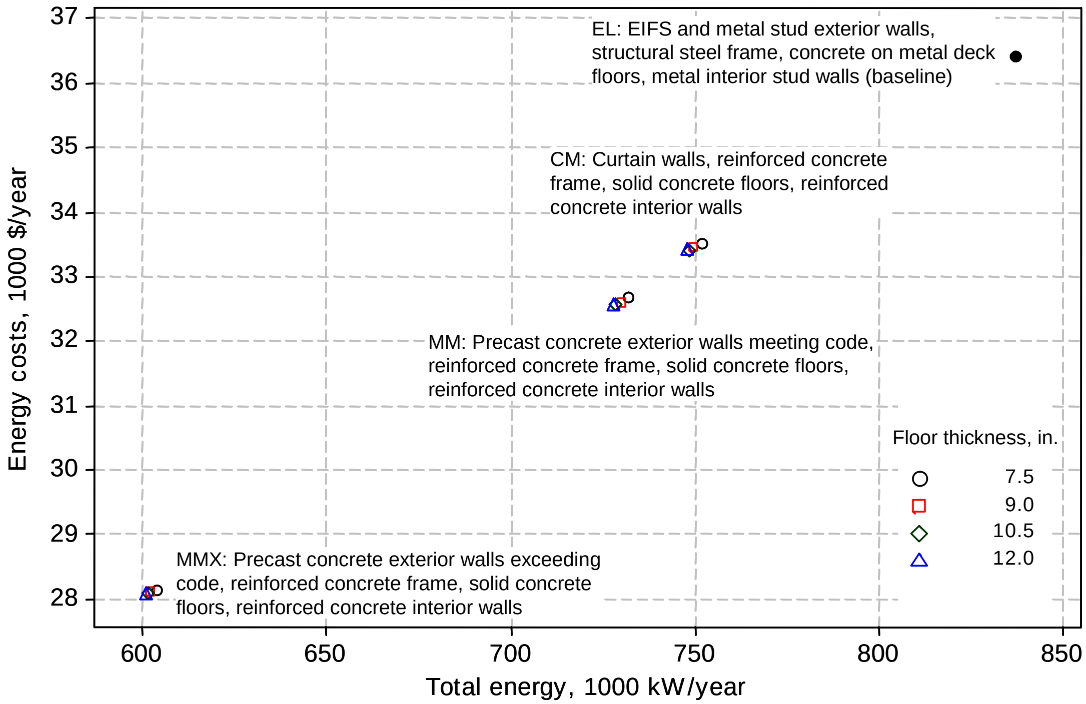


Figure 6. Concrete floor thickness has a small effect on energy use and cost (Salem).

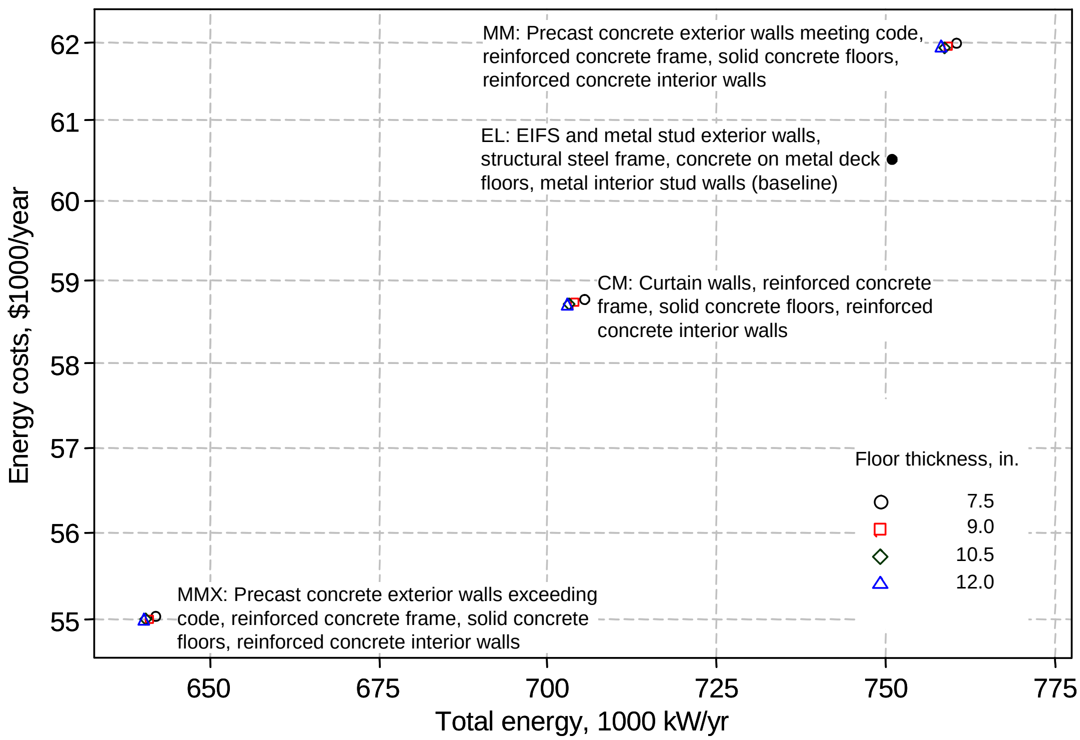


Figure 7. Concrete floor thickness has a small effect on energy use and cost (Phoenix).

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 energy savings in mid-rise commercial buildings from additional thermal mass and for exceeding building envelope thermal performance requirements. It shows how to model the thermal properties of concrete to accurately obtain LEED-NC version 2.2 Energy and Atmosphere Credit 1 points. Using energy simulation software, in most scenarios, the effect of thermal mass in concrete frame buildings has been shown to lower energy *use*, and the overall effect of thermal mass in concrete framed buildings is to lower energy *cost* relative to the baseline steel framed EIFS buildings.

In all cities except Miami, 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% 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 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 due to the concrete shear walls and increased thickness of the concrete floors 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 and occupancy, orientation, actual building materials, and fenestration amount and type.

REFERENCES

ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Georgia, 2004, www.ashrae.org.

ANSI/ASHRAE/IESNA Standard 90.1-2001, Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Georgia, 2001, www.ashrae.org.

ANSI/ASHRAE/IESNA Standard 90.1-1999, Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Georgia, 1999, www.ashrae.org.

ASHRAE/IESNA Standard 90.1-1989, Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Georgia, 1989, www.ashrae.org.

ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Georgia, 1989.

2004 ASHRAE Handbook of Fundamentals IP, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Georgia, 2001, www.ashrae.org.

Architectural Energy Corporation, *VisualDOE 4.0 User Manual*, Architectural Energy Corporation, San Francisco, California, 2004.

Crawly, Drury B.; Hand, Jon W.; Kummert, Michaël, and Griffith, Brent T., *Contrasting the Capabilities of Building Energy Performance Simulation Programs*, a joint report by U.S. Department of Energy, Washington, DC; University of Strathclyde, Glasgow, Scotland; University of Wisconsin-Madison, Madison, Wisconsin; and National Renewable Energy Laboratory, Golden, Colorado, July 2005, 59 pages, www.eere.energy.gov/buildings/tools_directory/

LEED Green Building Rating System for New Construction and Major Renovations (LEED-NC) Version 2.2, United Stated Green Building Council, Washington, DC, 2005, www.usgbc.org.

2004 Supplement to the International Energy Conservation Code, International Code Council, Inc., Country Club Hills, Illinois, 2001, www.iccsafe.org.

2003 International Energy Conservation Code, International Code Council, Inc., Country Club Hills, Illinois, 2003, www.iccsafe.org.

Winkelmann, F.C., "Underground Surfaces: How to get a Better Underground Surface Heat Transfer Calculation in DOE-2.1E," Building Energy Simulation Users News, Vol. 23, No. 6, November/December 2002.

Winkelmann, F.C., "DOE2.1E-119," U.S. Department of Energy, Energy Science and Technology Software Center, Oak Ridge, Tennessee, 2002.

Winkelmann, F.C.; Birdsall, B.E.; Buhl, W.F.; Ellington, K.L.; Erdem, A.E.; Hirsch, J.J., and Gates, S., *DOE-2 Supplement, Version 2.1E*, Regents of the University of California, Lawrence Berkeley Laboratory, Berkeley, California, 1993.

ACKNOWLEDGEMENTS

The research reported in this paper (PCA R&D Serial No. 2880a) was conducted by CTLGroup with the sponsorship of the Portland Cement Association (PCA Project Index No. 04-08). 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.

APPENDIX A – VISUALDOE DATA PLOTS

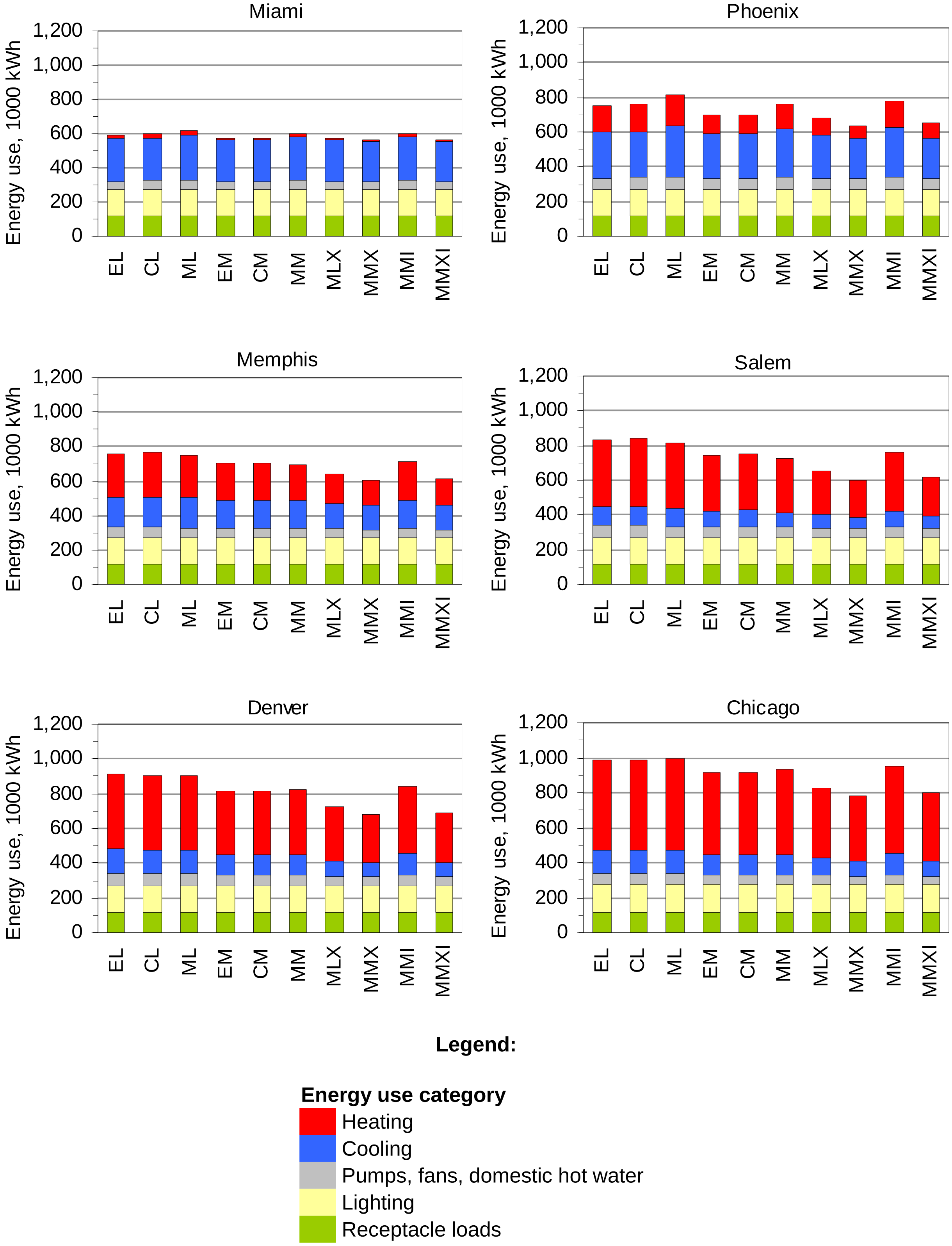


Figure A1. Yearly building energy use by category in six cities from VisualDOE. The abbreviated scenario names EL through MMXI are described in the text.

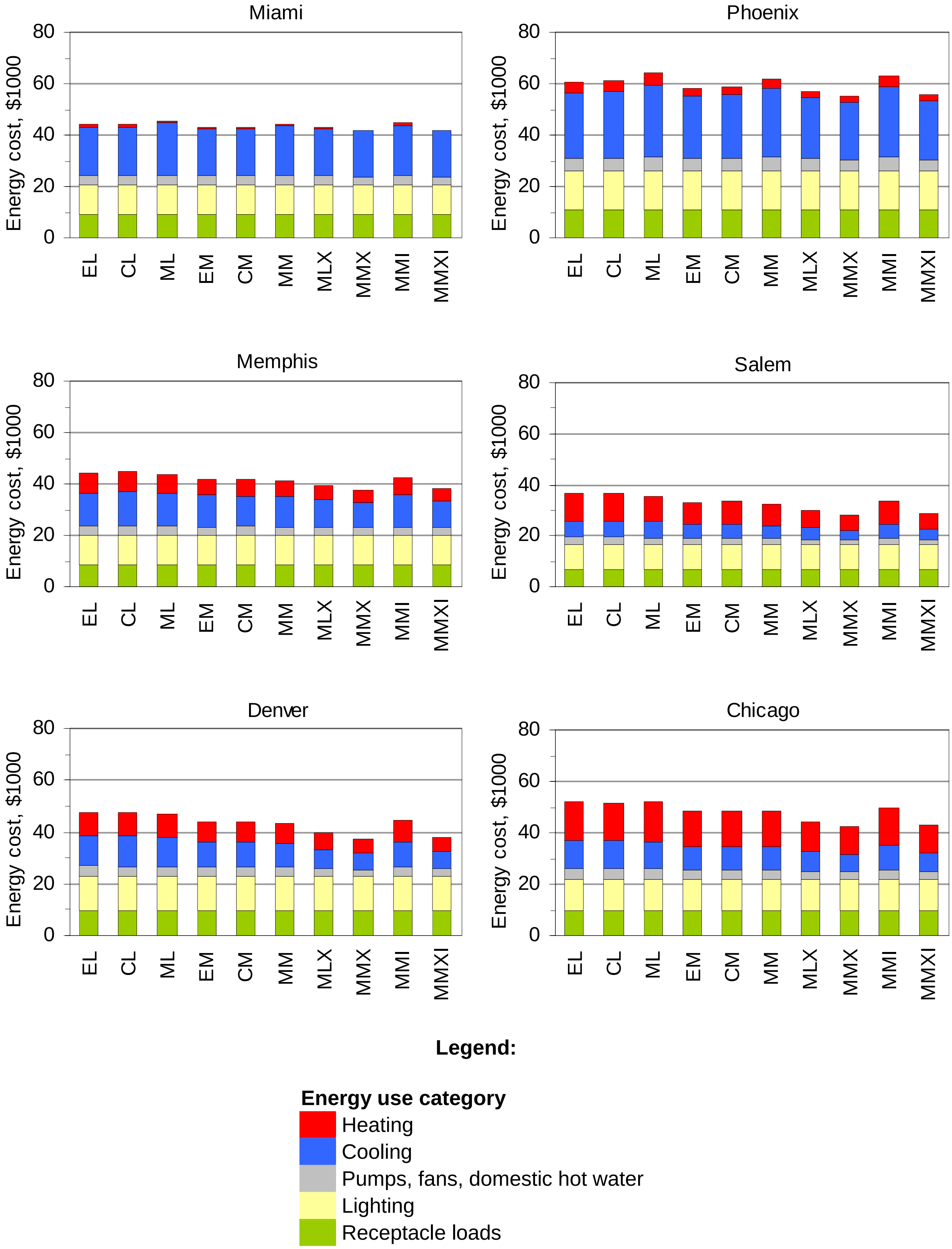


Figure A2. Yearly building energy cost by category in six cities from VisualDOE. The abbreviated scenario names EL through MMXI are described in the text.

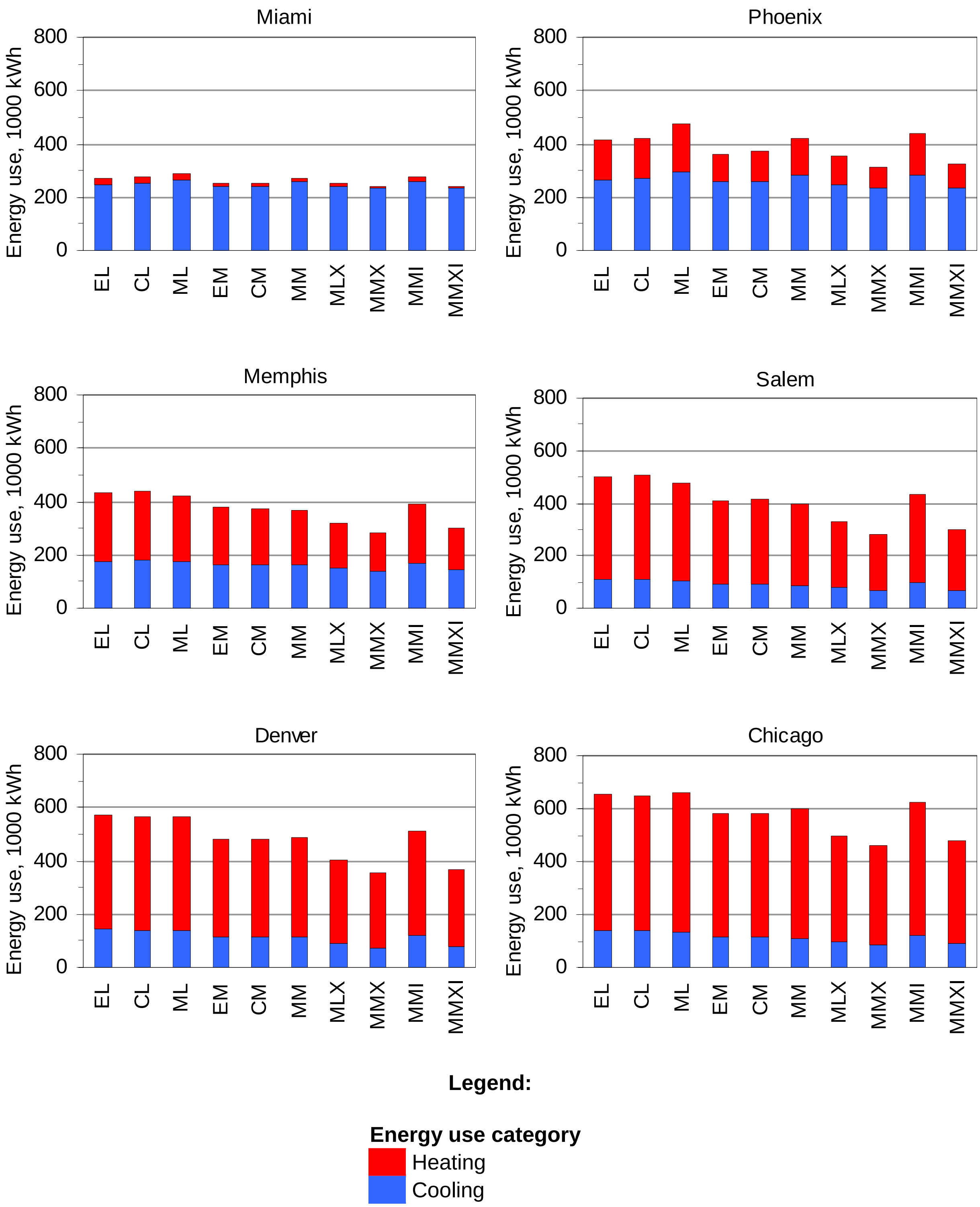


Figure A3. Yearly heating and cooling energy in six cities from VisualDOE. The abbreviated scenario names EL through MMXI are described in the text.

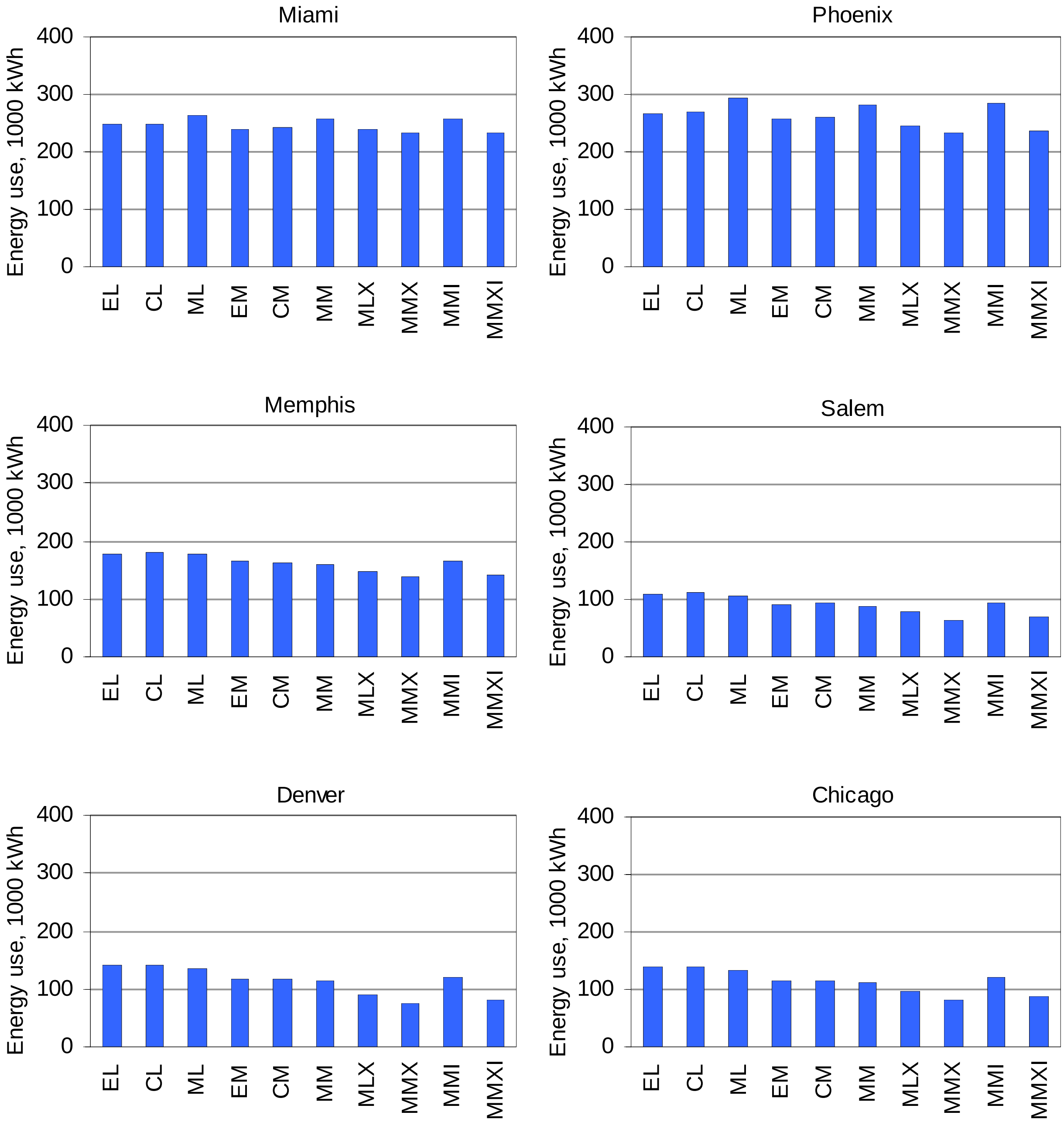


Figure A4. Yearly cooling energy in six cities from VisualDOE. The abbreviated scenario names EL through MMXI are described in the text.

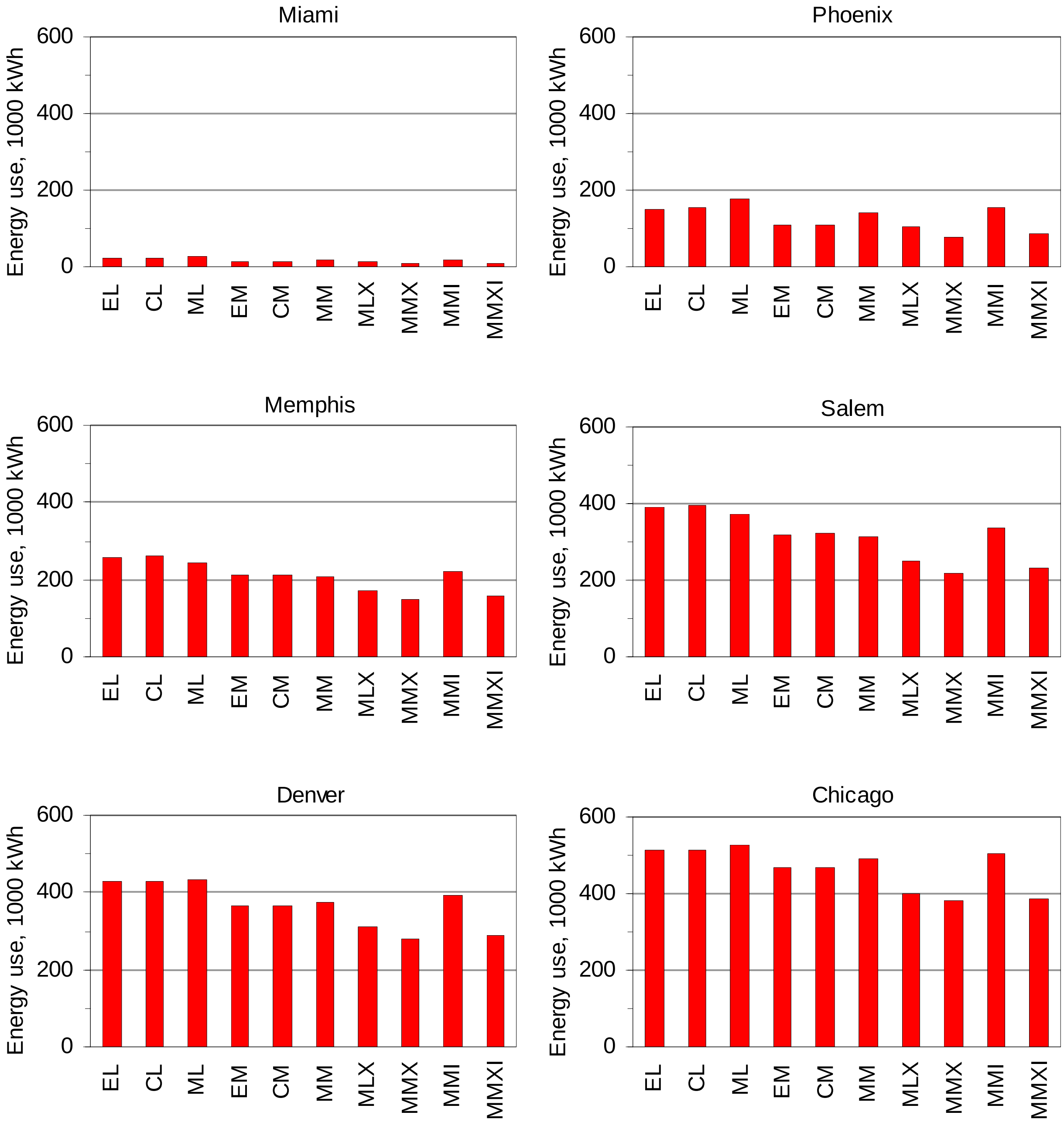


Figure A5. Yearly heating energy in six cities from VisualDOE. The abbreviated scenario names EL through MMXI are described in the text.

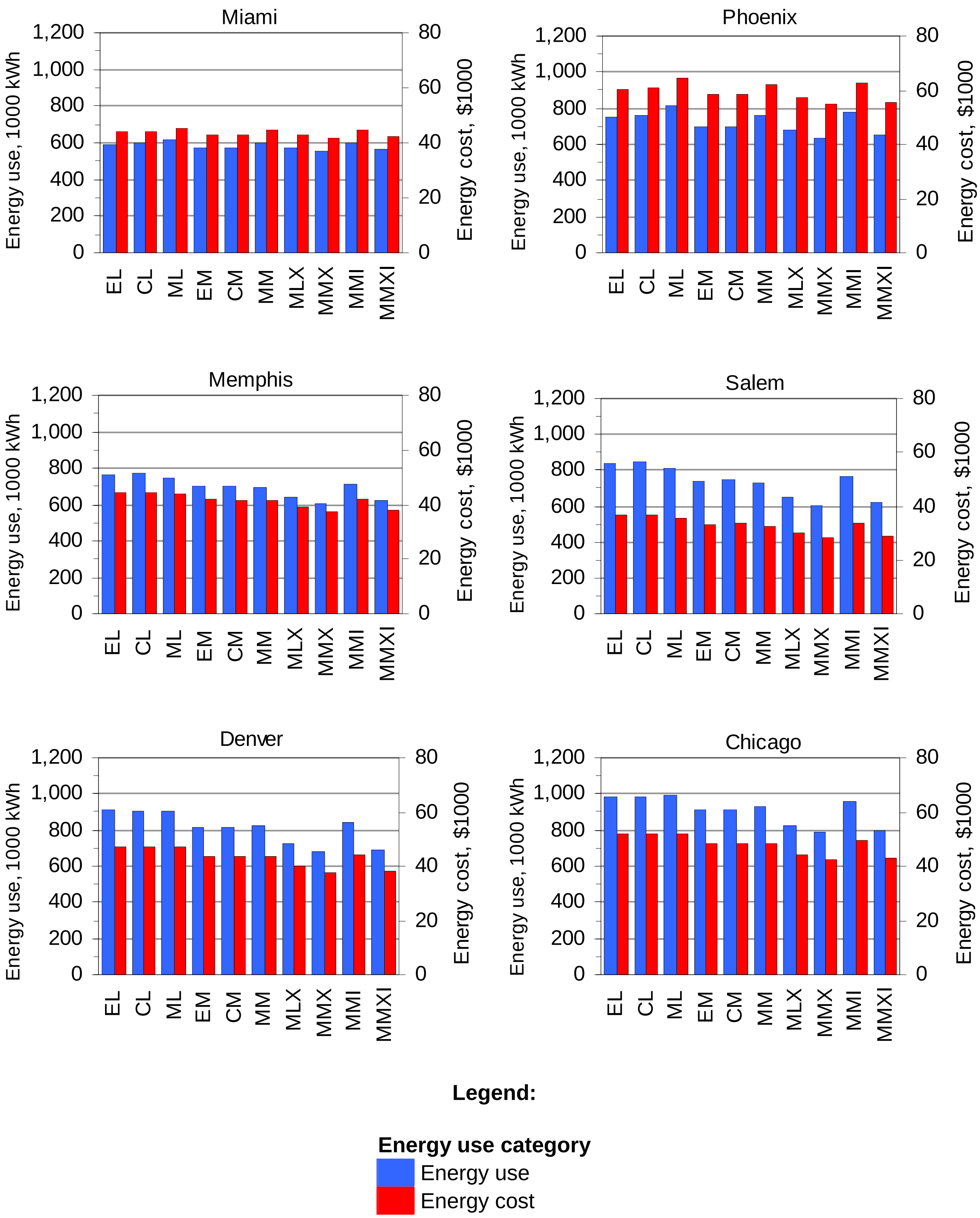


Figure A6. Yearly energy use and cost in six cities from VisualDOE. The abbreviated scenario names EL through MMXI are described in the text.

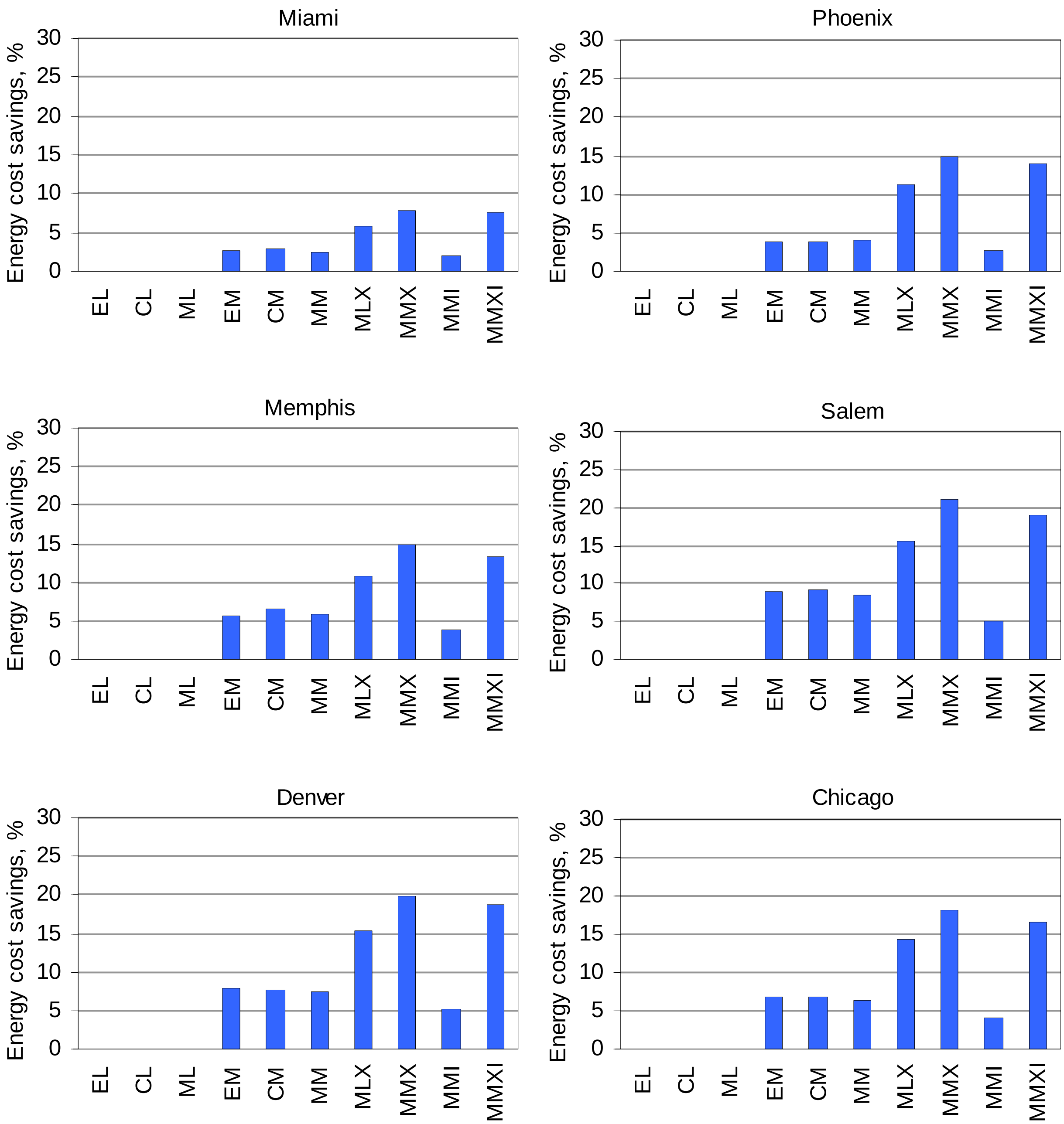


Figure A7. Energy cost savings (from VisualDOE) as a percent of structural frame base case: EM compared to EL, CM compared to CL, and MM to MMXI compared to ML. The abbreviated scenario names EL through MMXI are described in the text.

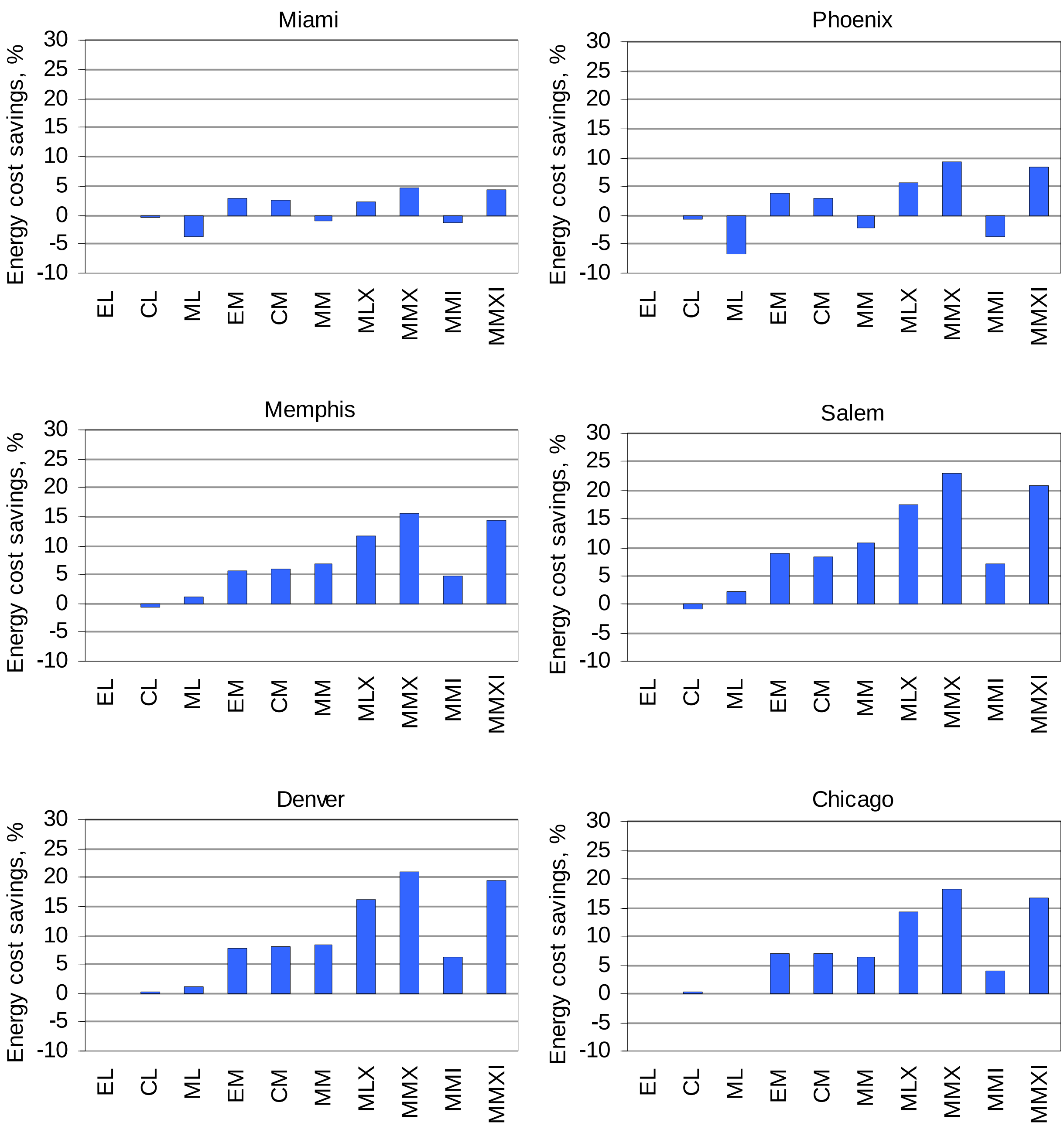


Figure A8. Energy cost savings (from VisualDOE) as a percent of baseline building (EL). The abbreviated scenario names EL through MMXI are described in the text.

APPENDIX B – VISUALDOE DATA TABLES

Table B1. 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	156,023	117,026	328	247,934	1,911	34,935	23,182	12,485	593,824
	CL	156,023	117,026	345	249,832	2,039	35,198	24,384	12,485	597,331
	ML	156,023	117,026	373	264,479	1,995	37,530	26,435	12,485	616,346
	EM	156,023	117,026	176	239,666	1,132	33,632	12,397	12,485	572,537
	CM	156,023	117,026	181	241,136	1,185	33,846	12,749	12,485	574,630
	MM	156,023	117,026	238	256,378	1,492	36,436	16,734	12,485	596,812
	MLX	156,023	117,026	213	239,920	1,442	33,802	14,947	12,485	575,857
	MMX	156,023	117,026	106	233,208	882	32,657	7,444	12,485	559,831
	MMI	156,023	117,054	269	257,290	1,631	36,368	18,962	12,485	600,082
	MMXI	156,023	117,054	126	233,689	1,005	32,514	8,851	12,485	561,747
Phoenix	EL	156,023	117,026	2,070	265,366	6,244	42,334	147,766	13,833	750,662
	CL	156,023	117,026	2,134	268,264	6,435	42,746	152,456	13,833	758,917
	ML	156,023	117,026	2,445	295,312	6,522	45,972	175,286	13,833	812,419
	EM	156,023	117,026	1,495	256,653	5,169	40,265	105,623	13,833	696,087
	CM	156,023	117,026	1,529	260,290	5,233	40,741	108,114	13,833	702,789
	MM	156,023	117,026	1,943	281,235	5,804	44,349	137,978	13,833	758,191
	MLX	156,023	117,026	1,485	246,774	5,376	39,161	104,890	13,833	684,568
	MMX	156,023	117,026	1,073	234,755	4,547	37,493	75,319	13,833	640,069
	MMI	156,023	117,054	2,148	285,516	6,018	44,392	152,309	13,833	777,293
	MMXI	156,023	117,054	1,205	237,459	4,914	37,441	84,610	13,833	652,539
Memphis	EL	156,023	117,026	3,451	176,718	7,617	31,282	252,276	17,614	762,006
	CL	156,023	117,026	3,507	178,971	7,829	31,742	256,291	17,614	769,002
	ML	156,023	117,026	3,308	176,923	7,337	29,956	241,168	17,614	749,355
	EM	156,023	117,026	2,894	164,642	6,321	29,122	209,136	17,614	702,777
	CM	156,023	117,026	2,916	161,095	6,410	29,601	210,747	17,614	701,432
	MM	156,023	117,026	2,830	160,068	6,285	28,145	203,890	17,614	691,880
	MLX	156,023	117,026	2,377	147,661	6,166	24,603	171,066	17,614	642,535
	MMX	156,023	117,026	2,049	136,844	5,387	23,183	145,774	17,614	603,899
	MMI	156,023	117,054	3,045	166,116	6,800	28,068	218,865	17,614	713,585
	MMXI	156,023	117,054	2,178	141,471	5,800	23,101	154,771	17,614	618,011
Salem	EL	156,023	117,026	5,360	108,489	11,511	30,293	386,649	21,248	836,598
	CL	156,023	117,026	5,432	110,854	11,588	30,977	392,012	21,248	845,160
	ML	156,023	117,026	5,097	105,744	11,067	28,244	367,159	21,248	811,608
	EM	156,023	117,026	4,416	92,165	9,766	27,029	315,139	21,248	742,812
	CM	156,023	117,026	4,453	93,984	9,841	27,633	317,777	21,248	747,985
	MM	156,023	117,026	4,313	87,115	9,497	25,418	307,314	21,248	727,954
	MLX	156,023	117,026	3,479	77,720	9,351	20,238	247,205	21,248	652,290
	MMX	156,023	117,026	3,021	64,126	8,164	18,343	213,063	21,248	601,013
	MMI	156,023	117,054	4,693	95,397	10,162	25,388	333,896	21,248	763,861
	MMXI	156,023	117,054	3,212	70,165	8,688	18,297	226,397	21,248	621,084
Denver	EL	156,023	117,026	5,737	141,366	11,329	31,782	423,898	22,098	909,259
	CL	156,023	117,026	5,705	140,415	11,242	31,581	421,524	22,098	905,614
	ML	156,023	117,026	5,779	135,720	11,137	30,592	426,829	22,098	905,203
	EM	156,023	117,026	4,938	117,290	9,700	28,614	360,214	22,098	815,902
	CM	156,023	117,026	4,924	116,768	9,665	28,475	359,188	22,098	814,166
	MM	156,023	117,026	5,058	112,883	9,634	27,661	369,299	22,098	819,681
	MLX	156,023	117,026	4,253	89,702	9,531	21,897	307,637	22,098	728,166
	MMX	156,023	117,026	3,821	75,130	8,383	19,985	273,934	22,098	676,399
	MMI	156,023	117,054	5,294	120,429	10,105	27,649	385,594	22,098	844,245
	MMXI	156,023	117,054	3,953	79,760	8,745	19,941	283,107	22,098	690,680
Chicago	EL	156,023	117,026	6,757	139,112	10,673	28,795	506,104	22,215	986,705
	CL	156,023	117,026	6,739	138,609	10,616	28,692	504,815	22,215	984,735
	ML	156,023	117,026	6,936	134,786	10,618	27,978	520,348	22,215	995,929
	EM	156,023	117,026	6,241	114,105	9,039	26,371	464,019	22,215	915,039
	CM	156,023	117,026	6,232	113,818	9,009	26,301	463,316	22,215	913,940
	MM	156,023	117,026	6,468	110,788	9,059	25,728	482,571	22,215	929,878
	MLX	156,023	117,026	5,364	97,506	9,212	20,501	394,972	22,215	822,819
	MMX	156,023	117,026	5,171	82,249	8,228	18,959	375,483	22,215	785,353
	MMI	156,023	117,054	6,674	120,931	9,495	25,693	496,638	22,215	954,723
	MMXI	156,023	117,054	5,277	88,598	8,535	18,923	382,604	22,215	799,229

Table B2. 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	8,941	25	18,942	146	2,669	863	465	43,971
	CL	11,920	8,941	26	19,087	156	2,689	908	465	44,192
	ML	11,920	8,941	28	20,206	152	2,867	984	465	45,564
	EM	11,920	8,941	13	18,310	86	2,569	461	465	42,767
	CM	11,920	8,941	14	18,423	91	2,586	475	465	42,913
	MM	11,920	8,941	18	19,587	114	2,784	623	465	44,452
	MLX	11,920	8,941	16	18,330	110	2,582	556	465	42,921
	MMX	11,920	8,941	8	17,817	67	2,495	277	465	41,990
	MMI	11,920	8,943	21	19,657	125	2,779	706	465	44,614
	MMXI	11,920	8,943	10	17,854	77	2,484	329	465	42,082
Phoenix	EL	14,900	11,176	198	25,342	596	4,043	3,908	366	60,529
	CL	14,900	11,176	204	25,619	615	4,082	4,032	366	60,993
	ML	14,900	11,176	233	28,202	623	4,390	4,635	366	64,526
	EM	14,900	11,176	143	24,510	494	3,845	2,793	366	58,227
	CM	14,900	11,176	146	24,858	500	3,891	2,859	366	58,695
	MM	14,900	11,176	186	26,858	554	4,235	3,649	366	61,924
	MLX	14,900	11,176	142	23,567	513	3,740	2,774	366	57,178
	MMX	14,900	11,176	102	22,419	434	3,581	1,992	366	54,970
	MMI	14,900	11,179	205	27,267	575	4,239	4,028	366	62,758
	MMXI	14,900	11,179	115	22,677	469	3,576	2,237	366	55,519
Memphis	EL	11,530	8,648	255	13,059	563	2,312	7,429	519	44,315
	CL	11,530	8,648	259	13,226	579	2,346	7,547	519	44,653
	ML	11,530	8,648	244	13,075	542	2,214	7,102	519	43,874
	EM	11,530	8,648	214	12,167	467	2,152	6,158	519	41,856
	CM	11,530	8,648	215	11,905	474	2,188	6,206	519	41,684
	MM	11,530	8,648	209	11,829	464	2,080	6,004	519	41,283
	MLX	11,530	8,648	176	10,912	456	1,818	5,037	519	39,096
	MMX	11,530	8,648	151	10,113	398	1,713	4,293	519	37,365
	MMI	11,530	8,650	225	12,276	503	2,074	6,445	519	42,222
	MMXI	11,530	8,650	161	10,455	429	1,707	4,558	519	38,008
Salem	EL	9,252	6,940	318	6,433	683	1,796	10,422	573	36,417
	CL	9,252	6,940	322	6,574	687	1,837	10,567	573	36,751
	ML	9,252	6,940	302	6,271	656	1,675	9,897	573	35,566
	EM	9,252	6,940	262	5,465	579	1,603	8,495	573	33,169
	CM	9,252	6,940	264	5,573	584	1,639	8,566	573	33,390
	MM	9,252	6,940	256	5,166	563	1,507	8,284	573	32,541
	MLX	9,252	6,940	206	4,609	555	1,200	6,664	573	29,998
	MMX	9,252	6,940	179	3,803	484	1,088	5,743	573	28,062
	MMI	9,252	6,941	278	5,657	603	1,506	9,000	573	33,810
	MMXI	9,252	6,941	190	4,161	515	1,085	6,103	573	28,820
Denver	EL	12,997	9,748	478	11,776	944	2,647	8,433	440	47,462
	CL	12,997	9,748	475	11,697	936	2,631	8,385	440	47,309
	ML	12,997	9,748	481	11,305	928	2,548	8,491	440	46,938
	EM	12,997	9,748	411	9,770	808	2,384	7,166	440	43,723
	CM	12,997	9,748	410	9,727	805	2,372	7,145	440	43,644
	MM	12,997	9,748	421	9,403	803	2,304	7,346	440	43,462
	MLX	12,997	9,748	354	7,472	794	1,824	6,120	440	39,749
	MMX	12,997	9,748	318	6,258	698	1,665	5,449	440	37,574
	MMI	12,997	9,751	441	10,032	842	2,303	7,671	440	44,475
	MMXI	12,997	9,751	329	6,644	728	1,661	5,632	440	38,182
Chicago	EL	12,591	9,444	545	11,226	861	2,324	14,212	624	51,828
	CL	12,591	9,444	544	11,186	857	2,315	14,176	624	51,737
	ML	12,591	9,444	560	10,877	857	2,258	14,612	624	51,823
	EM	12,591	9,444	504	9,208	729	2,128	13,031	624	48,259
	CM	12,591	9,444	503	9,185	727	2,122	13,011	624	48,207
	MM	12,591	9,444	522	8,941	731	2,076	13,552	624	48,480
	MLX	12,591	9,444	433	7,869	743	1,654	11,092	624	44,450
	MMX	12,591	9,444	417	6,637	664	1,530	10,544	624	42,452
	MMI	12,591	9,446	539	9,759	766	2,073	13,947	624	49,745
	MMXI	12,591	9,446	426	7,150	689	1,527	10,744	624	43,197

Table B3. VisualDOE Percent Cost Savings

City	Scenario	Cost savings: Compared to similar building, %	Compared to EL, %
Miami	EL	0.0	0.0
	CL	0.0	-0.5
	ML	0.0	-3.6
	EM	2.7	2.7
	CM	2.9	2.4
	MM	2.4	-1.1
	MLX	5.8	2.4
	MMX	7.8	4.5
	MMI	2.1	-1.5
	MMXI	7.6	4.3
Phoenix	EL	0.0	0.0
	CL	0.0	-0.8
	ML	0.0	-6.6
	EM	3.8	3.8
	CM	3.8	3.0
	MM	4.0	-2.3
	MLX	11.4	5.5
	MMX	14.8	9.2
	MMI	2.7	-3.7
	MMXI	14.0	8.3
Memphis	EL	0.0	0.0
	CL	0.0	-0.8
	ML	0.0	1.0
	EM	5.5	5.5
	CM	6.6	5.9
	MM	5.9	6.8
	MLX	10.9	11.8
	MMX	14.8	15.7
	MMI	3.8	4.7
	MMXI	13.4	14.2
Salem	EL	0.0	0.0
	CL	0.0	-0.9
	ML	0.0	2.3
	EM	8.9	8.9
	CM	9.1	8.3
	MM	8.5	10.6
	MLX	15.7	17.6
	MMX	21.1	22.9
	MMI	4.9	7.2
	MMXI	19.0	20.9
Denver	EL	0.0	0.0
	CL	0.0	0.3
	ML	0.0	1.1
	EM	7.9	7.9
	CM	7.7	8.0
	MM	7.4	8.4
	MLX	15.3	16.3
	MMX	20.0	20.8
	MMI	5.2	6.3
	MMXI	18.7	19.6
Chicago	EL	0.0	0.0
	CL	0.0	0.2
	ML	0.0	0.0
	EM	6.9	6.9
	CM	6.8	7.0
	MM	6.5	6.5
	MLX	14.2	14.2
	MMX	18.1	18.1
	MMI	4.0	4.0
	MMXI	16.6	16.7

APPENDIX C – ENERGY-10 DATA PLOTS

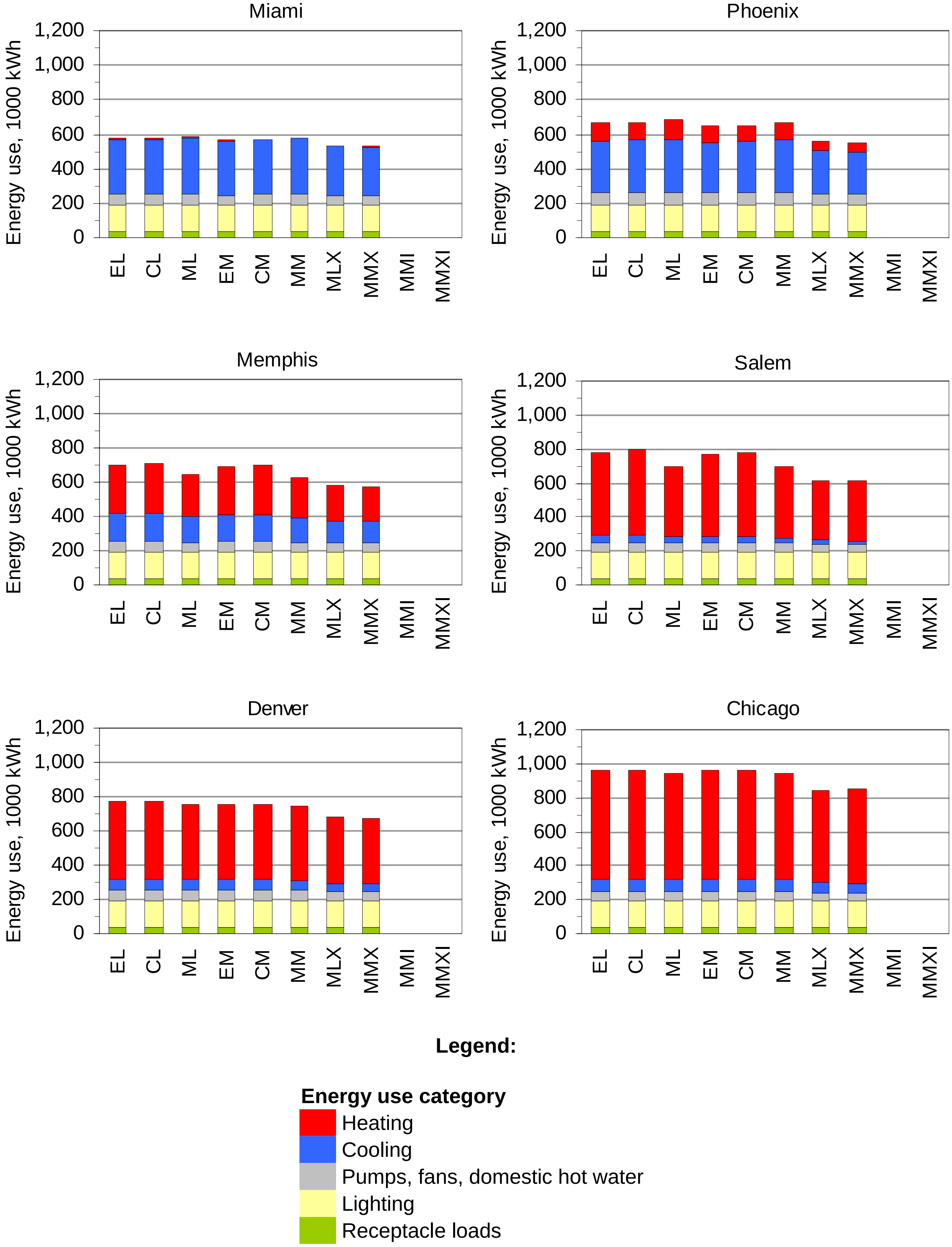


Figure C1. Yearly building energy use by category in six cities from Energy-10. The abbreviated scenario names EL through MMXI are described in the text.

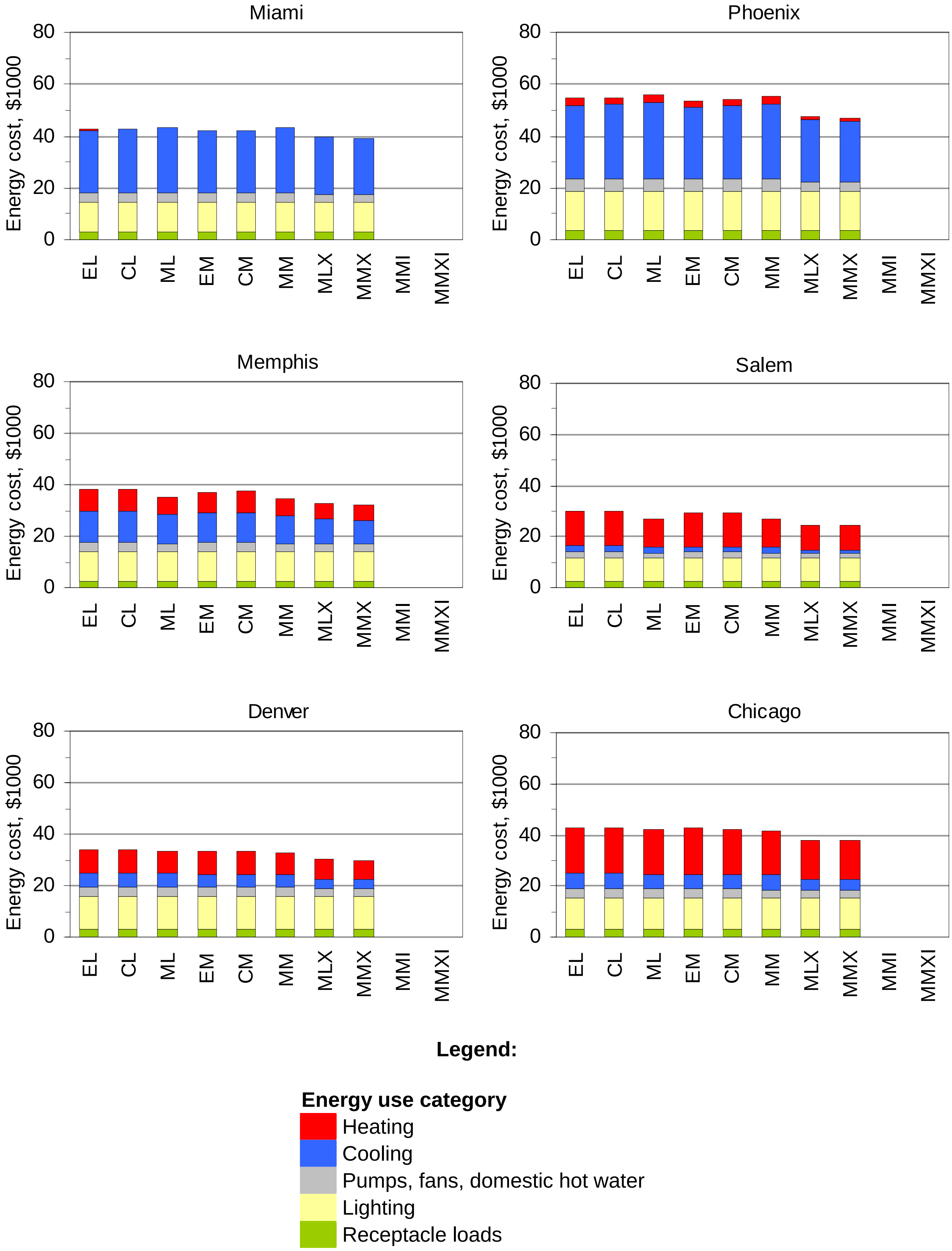


Figure C2. Yearly building energy cost by category in six cities from Energy-10. The abbreviated scenario names EL through MMXI are described in the text.

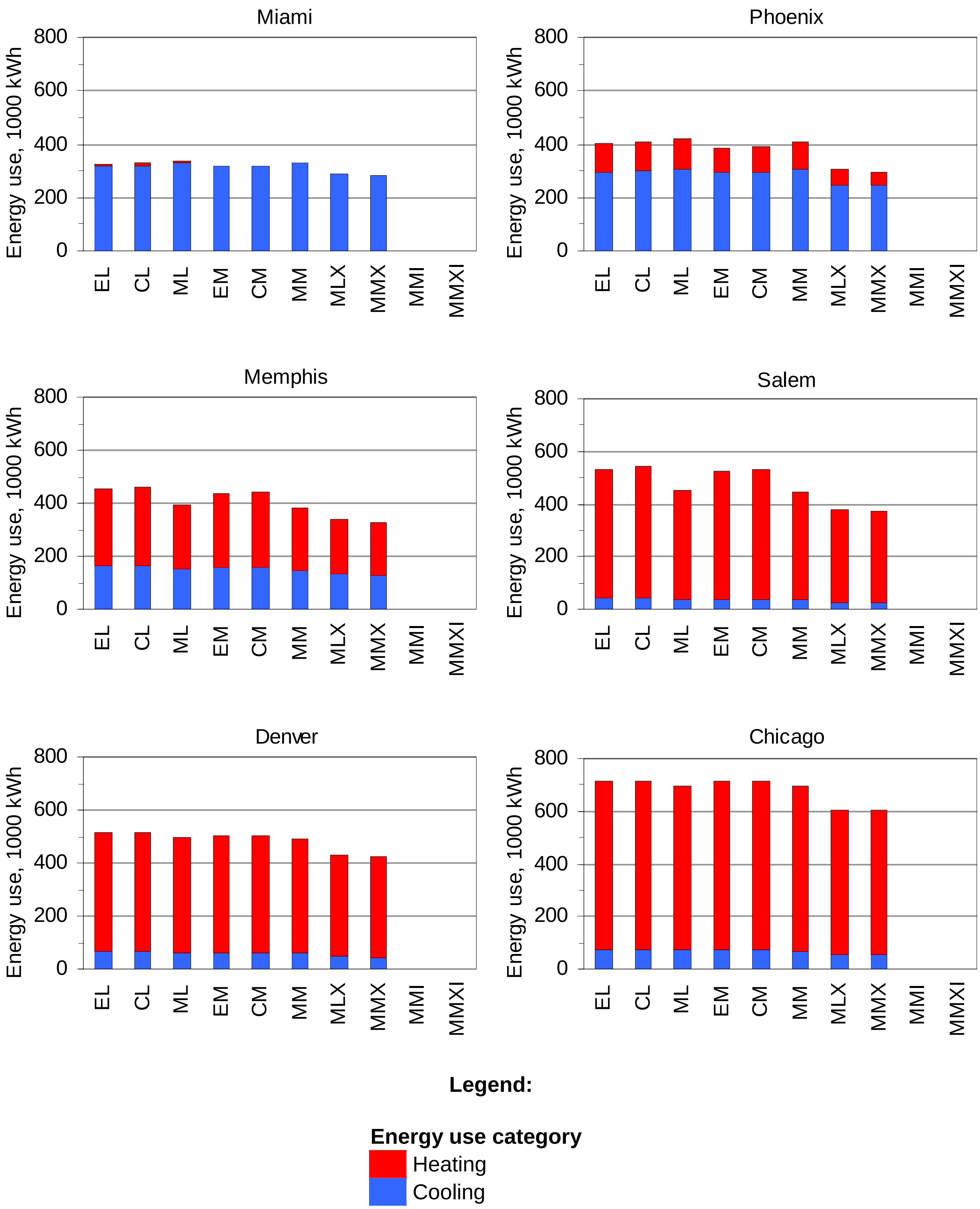


Figure C3. Yearly heating and cooling energy in six cities from Energy-10. The abbreviated scenario names EL through MMXI are described in the text.

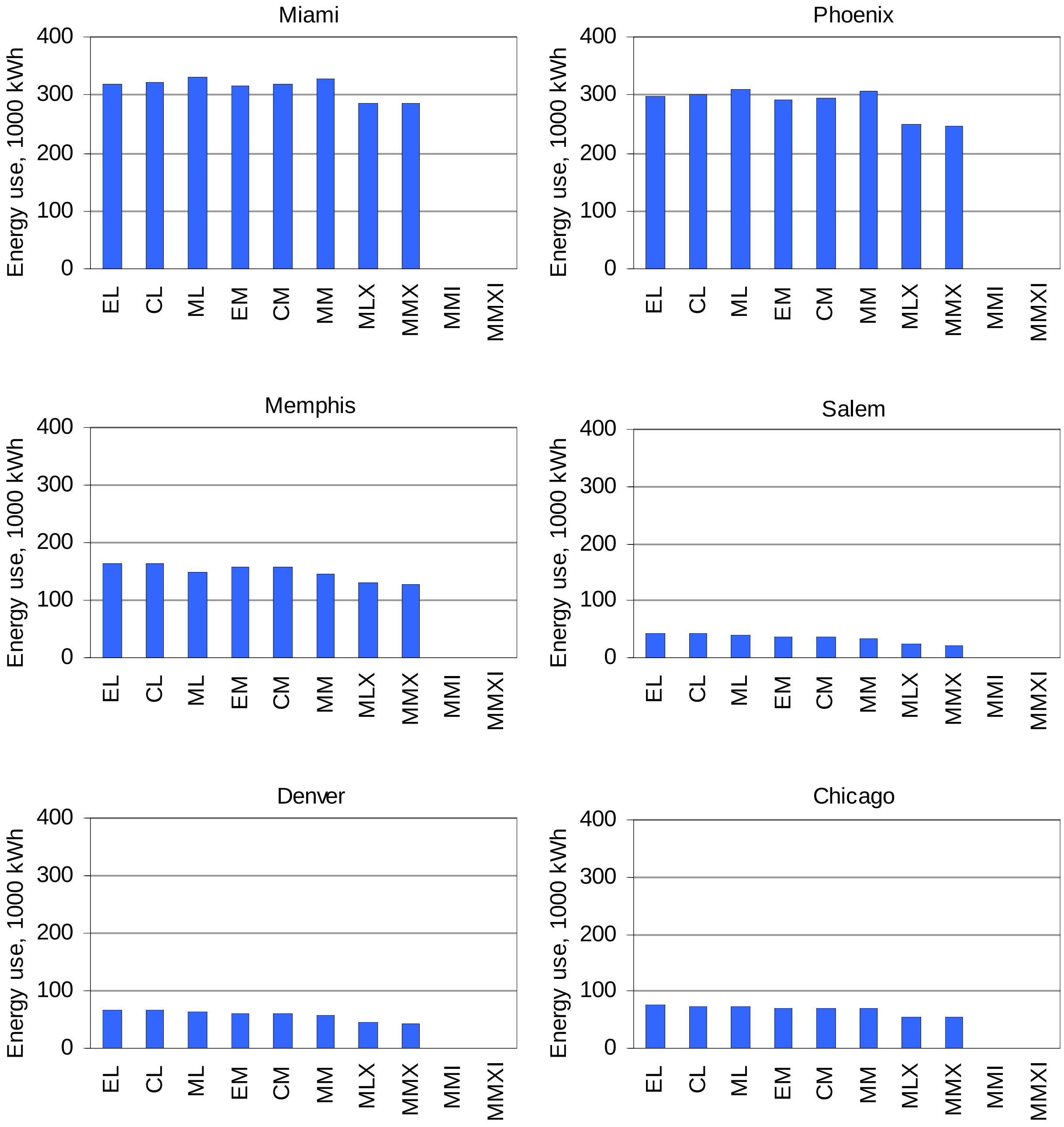


Figure C4. Yearly cooling energy in six cities from Energy-10. The abbreviated scenario names EL through MMXI are described in the text.

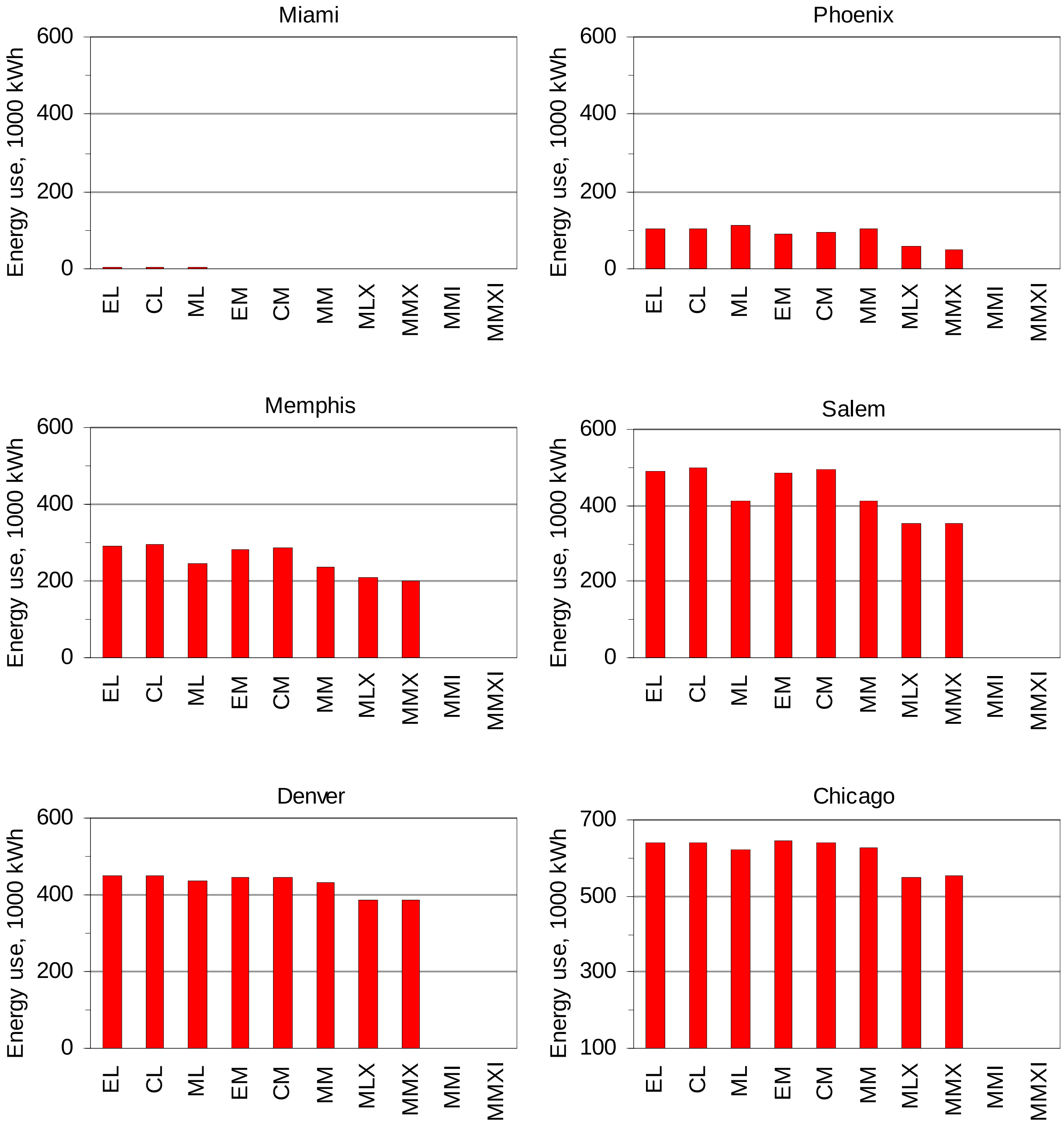


Figure C5. Yearly heating energy in six cities from Energy-10. The abbreviated scenario names EL through MMXI are described in the text.

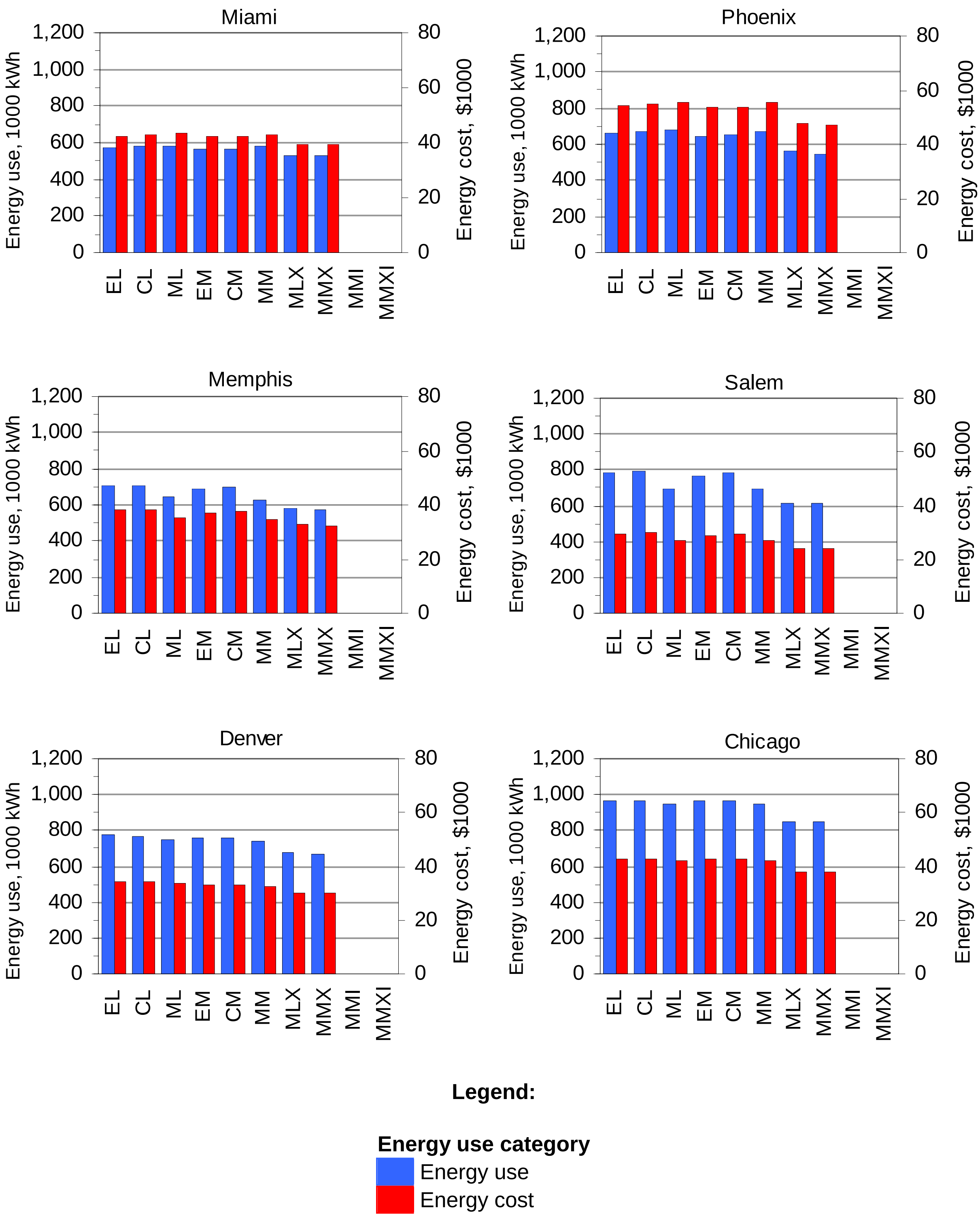


Figure C6. Yearly energy use and cost in six cities from Energy-10. The abbreviated scenario names EL through MMXI are described in the text.

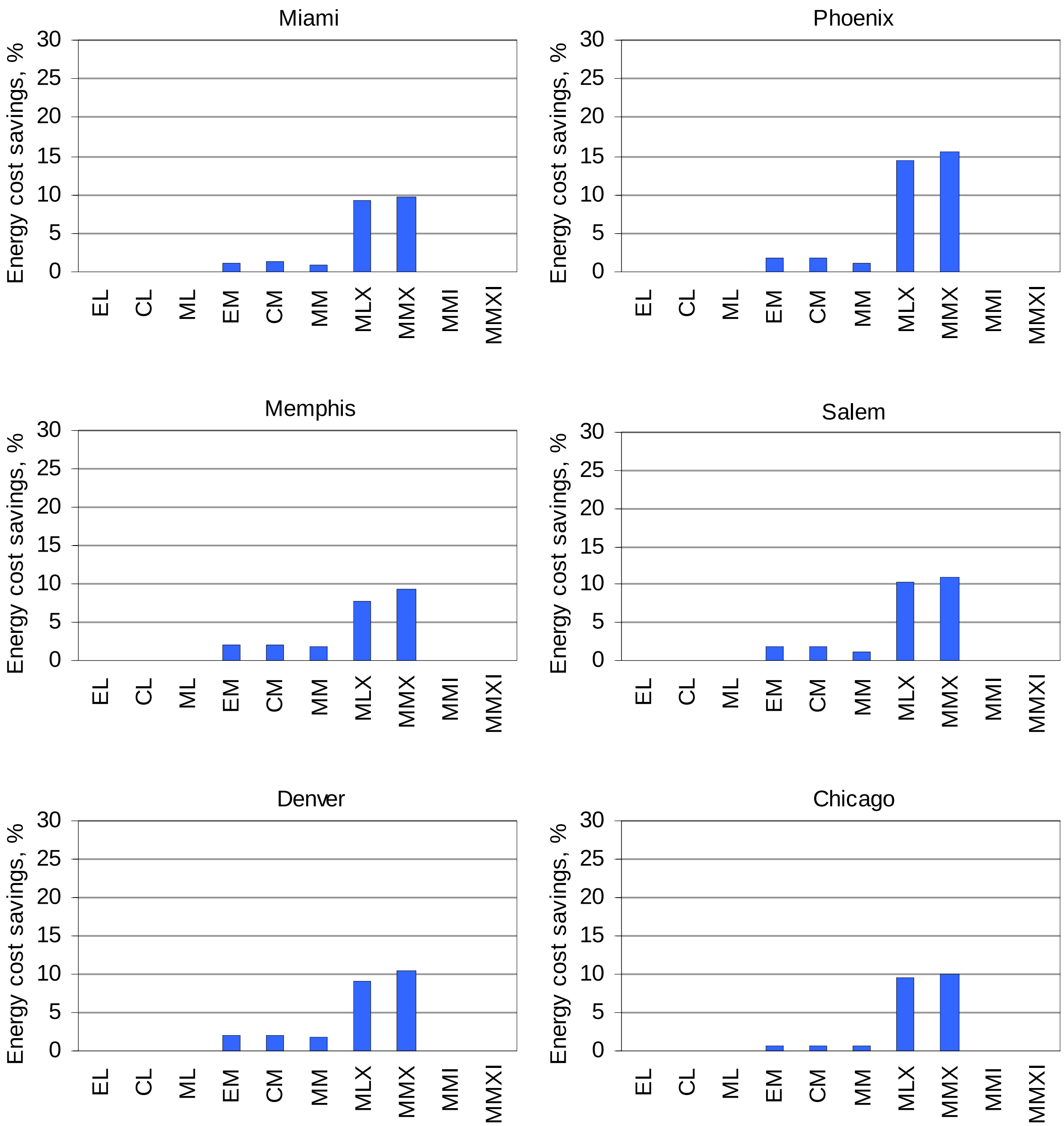


Figure C7. Energy cost savings (from Energy-10) as a percent of structural frame base case: EM compared to EL, CM compared to CL, and MM to MMXI compared to ML. The abbreviated scenario names EL through MMXI are described in the text.

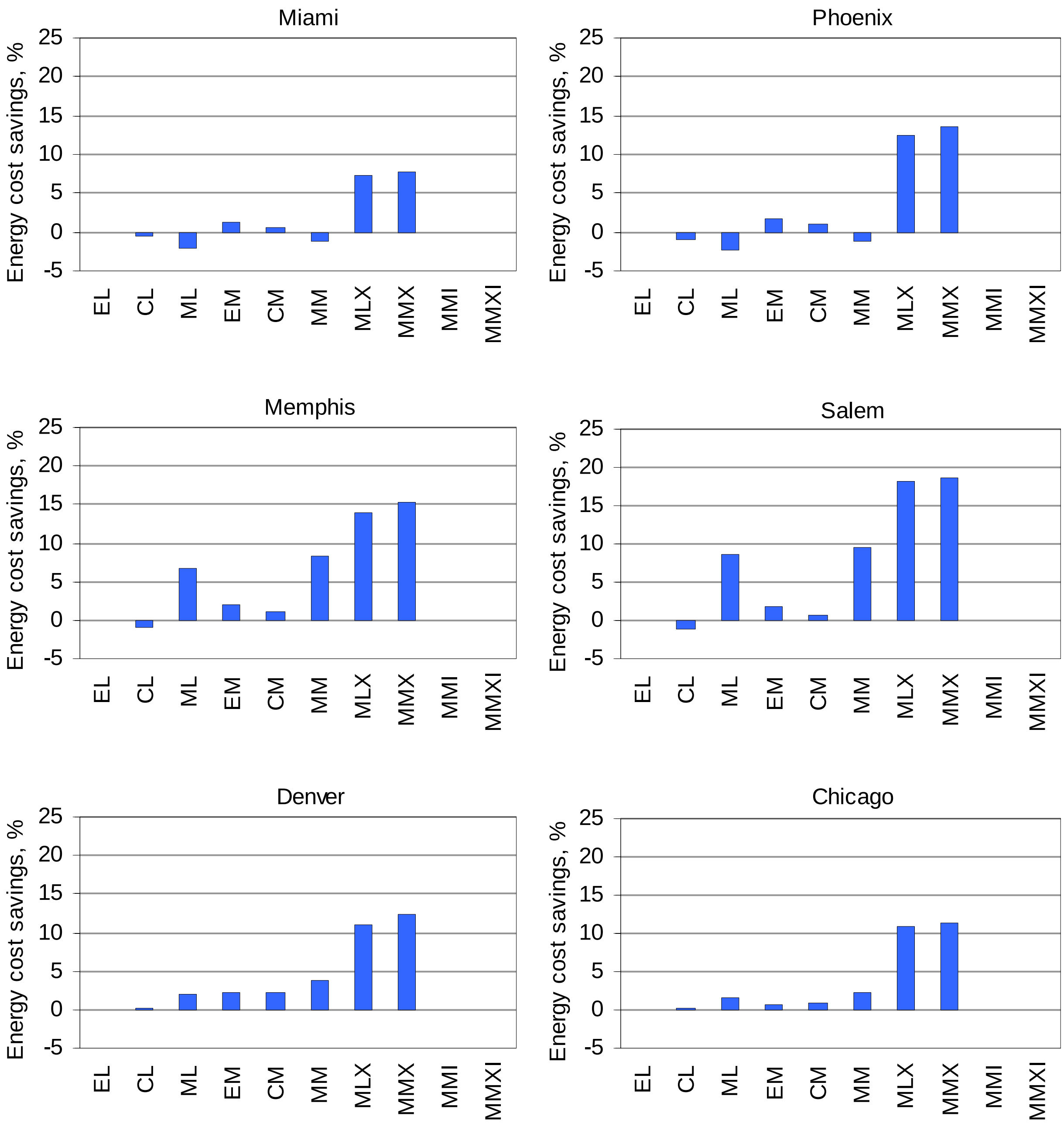


Figure C8. Energy cost savings (from Energy-10) as a percent of baseline building (EL). The abbreviated scenario names EL through MMXI are described in the text.

z

APPENDIX D – ENERGY-10 DATA TABLES

Table D1. Energy-10 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	156,023	36,217	-	319,127	-	31,001	6,379	26,019	574,766
	CL	156,023	36,217	-	321,603	-	31,900	6,644	26,019	578,406
	ML	156,023	36,217	-	330,602	-	31,785	5,748	26,019	586,394
	EM	156,023	36,217	-	315,869	-	29,724	1,849	26,019	565,701
	CM	156,023	36,217	-	317,860	-	30,553	1,931	26,019	568,603
	MM	156,023	36,217	-	328,965	-	30,508	1,862	26,019	579,595
	MLX	156,023	36,217	-	286,233	-	25,868	1,874	26,019	532,235
	MMX	156,023	36,217	-	284,720	-	24,635	254	26,019	527,869
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Phoenix	EL	156,023	36,217	-	297,563	-	44,982	104,416	26,019	665,220
	CL	156,023	36,217	-	301,141	-	46,005	105,902	26,019	671,308
	ML	156,023	36,217	-	308,878	-	45,475	110,678	26,019	683,290
	EM	156,023	36,217	-	291,888	-	43,995	91,405	26,019	645,547
	CM	156,023	36,217	-	295,339	-	44,766	92,857	26,019	651,221
	MM	156,023	36,217	-	305,891	-	44,490	102,728	26,019	671,368
	MLX	156,023	36,217	-	249,147	-	35,586	57,850	26,019	560,842
	MMX	156,023	36,217	-	245,732	-	34,368	49,130	26,019	547,490
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Memphis	EL	156,023	36,217	-	162,223	-	33,244	289,905	26,019	703,631
	CL	156,023	36,217	-	164,035	-	33,808	295,472	26,019	711,574
	ML	156,023	36,217	-	149,587	-	29,172	246,014	26,019	643,032
	EM	156,023	36,217	-	157,034	-	32,028	280,834	26,019	688,156
	CM	156,023	36,217	-	158,420	-	32,568	286,509	26,019	695,756
	MM	156,023	36,217	-	145,350	-	27,956	238,407	26,019	629,972
	MLX	156,023	36,217	-	131,609	-	24,812	208,889	26,019	583,569
	MMX	156,023	36,217	-	128,043	-	23,744	202,003	26,019	572,049
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Salem	EL	156,023	36,217	-	43,150	-	31,460	488,591	26,019	781,460
	CL	156,023	36,217	-	43,829	-	31,864	498,909	26,019	792,861
	ML	156,023	36,217	-	38,626	-	27,628	411,675	26,019	696,188
	EM	156,023	36,217	-	37,370	-	29,729	485,453	26,019	770,812
	CM	156,023	36,217	-	37,732	-	30,110	495,635	26,019	781,736
	MM	156,023	36,217	-	34,648	-	26,179	412,979	26,019	692,065
	MLX	156,023	36,217	-	25,619	-	21,057	350,836	26,019	615,771
	MMX	156,023	36,217	-	22,636	-	20,032	352,862	26,019	613,789
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Denver	EL	156,023	36,217	-	65,945	-	36,641	451,999	26,019	772,844
	CL	156,023	36,217	-	65,828	-	36,582	450,557	26,019	771,226
	ML	156,023	36,217	-	63,433	-	34,773	436,081	26,019	752,546
	EM	156,023	36,217	-	60,619	-	34,870	444,758	26,019	758,506
	CM	156,023	36,217	-	60,564	-	34,818	443,249	26,019	756,891
	MM	156,023	36,217	-	58,662	-	32,943	431,397	26,019	741,261
	MLX	156,023	36,217	-	46,151	-	26,911	387,013	26,019	678,334
	MMX	156,023	36,217	-	42,582	-	25,609	384,540	26,019	670,990
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Chicago	EL	156,023	36,217	-	74,834	-	31,339	639,867	26,019	964,299
	CL	156,023	36,217	-	74,759	-	31,293	638,193	26,019	962,504
	ML	156,023	36,217	-	73,045	-	29,970	623,765	26,019	945,039
	EM	156,023	36,217	-	71,182	-	29,874	643,687	26,019	963,002
	CM	156,023	36,217	-	71,140	-	29,829	641,930	26,019	961,158
	MM	156,023	36,217	-	69,938	-	28,342	628,735	26,019	945,274
	MLX	156,023	36,217	-	56,195	-	23,392	549,385	26,019	847,231
	MMX	156,023	36,217	-	53,741	-	22,192	553,378	26,019	847,570
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-

Table D2. Energy-10 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	2,767	-	24,381	-	2,368	237	969	42,643
	CL	11,920	2,767	-	24,570	-	2,437	247	969	42,911
	ML	11,920	2,767	-	25,258	-	2,428	214	969	43,556
	EM	11,920	2,767	-	24,132	-	2,271	69	969	42,128
	CM	11,920	2,767	-	24,285	-	2,334	72	969	42,346
	MM	11,920	2,767	-	25,133	-	2,331	69	969	43,189
	MLX	11,920	2,767	-	21,868	-	1,976	70	969	39,570
	MMX	11,920	2,767	-	21,753	-	1,882	9	969	39,300
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Phoenix	EL	14,900	3,459	-	28,417	-	4,296	2,761	688	54,521
	CL	14,900	3,459	-	28,759	-	4,393	2,800	688	55,000
	ML	14,900	3,459	-	29,498	-	4,343	2,927	688	55,814
	EM	14,900	3,459	-	27,875	-	4,202	2,417	688	53,541
	CM	14,900	3,459	-	28,205	-	4,275	2,456	688	53,983
	MM	14,900	3,459	-	29,213	-	4,249	2,717	688	55,225
	MLX	14,900	3,459	-	23,794	-	3,398	1,530	688	47,769
	MMX	14,900	3,459	-	23,467	-	3,282	1,299	688	47,096
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Memphis	EL	11,530	2,676	-	11,988	-	2,457	8,537	766	37,954
	CL	11,530	2,676	-	12,122	-	2,498	8,701	766	38,294
	ML	11,530	2,676	-	11,054	-	2,156	7,244	766	35,427
	EM	11,530	2,676	-	11,605	-	2,367	8,270	766	37,214
	CM	11,530	2,676	-	11,707	-	2,407	8,437	766	37,524
	MM	11,530	2,676	-	10,741	-	2,066	7,020	766	34,800
	MLX	11,530	2,676	-	9,726	-	1,834	6,151	766	32,683
	MMX	11,530	2,676	-	9,462	-	1,755	5,948	766	32,138
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Salem	EL	9,252	2,148	-	2,559	-	1,866	13,170	701	29,696
	CL	9,252	2,148	-	2,599	-	1,890	13,449	701	30,038
	ML	9,252	2,148	-	2,291	-	1,638	11,097	701	27,127
	EM	9,252	2,148	-	2,216	-	1,763	13,086	701	29,166
	CM	9,252	2,148	-	2,238	-	1,786	13,360	701	29,485
	MM	9,252	2,148	-	2,055	-	1,552	11,132	701	26,840
	MLX	9,252	2,148	-	1,519	-	1,249	9,457	701	24,326
	MMX	9,252	2,148	-	1,342	-	1,188	9,512	701	24,143
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Denver	EL	12,997	3,017	-	5,493	-	3,052	8,992	518	34,068
	CL	12,997	3,017	-	5,483	-	3,047	8,963	518	34,025
	ML	12,997	3,017	-	5,284	-	2,897	8,675	518	33,387
	EM	12,997	3,017	-	5,050	-	2,905	8,847	518	33,333
	CM	12,997	3,017	-	5,045	-	2,900	8,817	518	33,294
	MM	12,997	3,017	-	4,887	-	2,744	8,582	518	32,744
	MLX	12,997	3,017	-	3,844	-	2,242	7,699	518	30,316
	MMX	12,997	3,017	-	3,547	-	2,133	7,650	518	29,861
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-
Chicago	EL	12,591	2,923	-	6,039	-	2,529	17,969	731	42,781
	CL	12,591	2,923	-	6,033	-	2,525	17,922	731	42,725
	ML	12,591	2,923	-	5,895	-	2,419	17,517	731	42,074
	EM	12,591	2,923	-	5,744	-	2,411	18,076	731	42,476
	CM	12,591	2,923	-	5,741	-	2,407	18,027	731	42,419
	MM	12,591	2,923	-	5,644	-	2,287	17,656	731	41,832
	MLX	12,591	2,923	-	4,535	-	1,888	15,428	731	38,095
	MMX	12,591	2,923	-	4,337	-	1,791	15,540	731	37,912
	MMI	-	-	-	-	-	-	-	-	-
	MMXI	-	-	-	-	-	-	-	-	-

Table D3. Energy-10 Percent Cost Savings

City	Scenario	Cost savings	
		Compared to similar building, %	Compared to EL, %
Miami	EL	0.0	0.0
	CL	0.0	-0.6
	ML	0.0	-2.1
	EM	1.2	1.2
	CM	1.3	0.7
	MM	0.8	-1.3
	MLX	9.2	7.2
	MMX	9.8	7.8
	MMI	-	-
	MMXI	-	-
Phoenix	EL	0.0	0.0
	CL	0.0	-0.9
	ML	0.0	-2.4
	EM	1.8	1.8
	CM	1.8	1.0
	MM	1.1	-1.3
	MLX	14.4	12.4
	MMX	15.6	13.6
	MMI	-	-
	MMXI	-	-
Memphis	EL	0.0	0.0
	CL	0.0	-0.9
	ML	0.0	6.7
	EM	2.0	2.0
	CM	2.0	1.1
	MM	1.8	8.3
	MLX	7.7	13.9
	MMX	9.3	15.3
	MMI	-	-
	MMXI	-	-
Salem	EL	0.0	0.0
	CL	0.0	-1.2
	ML	0.0	8.7
	EM	1.8	1.8
	CM	1.8	0.7
	MM	1.1	9.6
	MLX	10.3	18.1
	MMX	11.0	18.7
	MMI	-	-
	MMXI	-	-
Denver	EL	0.0	0.0
	CL	0.0	0.1
	ML	0.0	2.0
	EM	2.2	2.2
	CM	2.1	2.3
	MM	1.9	3.9
	MLX	9.2	11.0
	MMX	10.6	12.3
	MMI	-	-
	MMXI	-	-
Chicago	EL	0.0	0.0
	CL	0.0	0.1
	ML	0.0	1.7
	EM	0.7	0.7
	CM	0.7	0.8
	MM	0.6	2.2
	MLX	9.5	11.0
	MMX	9.9	11.4
	MMI	-	-
	MMXI	-	-

APPENDIX E – SENSITIVITY ANALYSIS ON FLOOR THICKNESS

Table E1. Results of Sensitivity Analysis on Floor Thickness

City	Interior floor thickness, in.	Scenario*	Total annual cost, $	Total annual energy, kW	Percent savings compared to EL		Incremental cost savings compared to same scenario	
					Cost, $	Energy, kW	%	Cost, $
Phoenix	4	EL	$60,528	750,662	-	-	-	-
	7.5	CM	$58,794	705,158	2.9%	6.1%	-	-
	7.5	MM	$62,010	760,393	-2.4%	-1.3%	-	-
	7.5	MMX	$55,042	641,883	9.1%	14.5%	-	-
	4	EL	$60,528	750,662	-	-	-	-
	9	CM	$58,735	703,846	3.0%	6.2%	0.10%	$59
	9	MM	$61,963	759,237	-2.4%	-1.1%	0.08%	$47
	9	MMX	$54,999	640,909	9.1%	14.6%	0.08%	$43
	4	EL	$60,528	750,662	-	-	-	-
	10.5	CM	$58,708	703,186	3.0%	6.3%	0.05%	$27
	10.5	MM	$61,938	758,601	-2.3%	-1.1%	0.04%	$25
	10.5	MMX	$54,984	640,400	9.2%	14.7%	0.03%	$15
	4	EL	$60,528	750,662	-	-	-	-
	12	CM	$58,694	702,789	3.0%	6.4%	0.02%	$14
	12	MM	$61,923	758,191	-2.3%	-1.0%	0.02%	$15
	12	MMX	$54,971	640,069	9.2%	14.7%	0.02%	$13
Salem	4	EL	$36,417	836,598	-	-	-	-
	7.5	CM	$33,524	751,703	7.9%	10.1%	-	-
	7.5	MM	$32,676	731,711	10.3%	12.5%	-	-
	7.5	MMX	$28,153	603,552	22.7%	27.9%	-	-
	9	EL	$36,417	836,598	-	-	-	-
	9	CM	$33,446	749,599	8.2%	10.4%	0.2%	$78
	9	MM	$32,605	729,797	10.5%	12.8%	0.2%	$71
	9	MMX	$28,106	602,281	22.8%	28.0%	0.2%	$47
	4	EL	$36,417	836,598	-	-	-	-
	10.5	CM	$33,410	748,597	8.3%	10.5%	0.1%	$36
	10.5	MM	$32,565	728,650	10.6%	12.9%	0.1%	$40
	10.5	MMX	$28,077	601,463	22.9%	28.1%	0.1%	$29
	4	EL	$36,417	836,598	-	-	-	-
	12	CM	$33,390	747,985	8.3%	10.6%	0.1%	$20
	12	MM	$32,540	727,954	10.6%	13.0%	0.1%	$25
	12	MMX	$28,061	601,013	22.9%	28.2%	0.1%	$16
Denver	4	El	$47,461	909,259	-	-	-	-
	7.5	CM	$43,778	817,744	7.8%	10.1%	-	-
	7.5	MM	$43,617	823,684	8.1%	9.4%	-	-
	7.5	MMX	$37,675	679,195	20.6%	25.3%	-	-
	4	El	$47,461	909,259	-	-	-	-
	9	CM	$43,708	815,886	7.9%	10.3%	0.2%	$70
	9	MM	$43,539	821,707	8.3%	9.6%	0.2%	$78
	9	MMX	$37,617	677,656	20.7%	25.5%	0.2%	$58
	4	El	$47,461	909,259			-	-
	10.5	CM	$43,666	814,762	8.0%	10.4%	0.1%	$42
	10.5	MM	$43,487	820,441	8.4%	9.8%	0.1%	$52
	10.5	MMX	$37,589	676,906	20.8%	25.6%	0.1%	$28
	4	EL	$47,461	909,259	-	-	-	-
	12	CM	$43,644	814,166	8.0%	10.5%	0.1%	$22
	12	MM	$43,462	819,681	8.4%	9.9%	0.1%	$25
	12	MMX	$37,573	676,399	20.8%	25.6%	0.04%	$16

*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.