

Comparative Life-Cycle Assessment of Precast Concrete Commercial Buildings

Overview/Executive summary

In 2009, the Precast/Prestressed Concrete Institute (PCI)¹ launched a comparative study to better understand precast concrete's environmental life-cycle performance.

The study's primary objectives include:

1. foster a better understanding of the environmental impacts of precast/prestressed concrete components and their use in high-performance structures;
2. better understand precast concrete's environmental life-cycle performance in mid-rise precast concrete buildings compared to alternative structural and envelope systems;
3. benchmark the industry's performance in order to track its improvements; and
4. increase transparency in the marketplace.

The study performed was a cradle-to-grave, comparative life-cycle assessment, or LCA. An LCA is a comprehensive method used to assess and quantify the environmental impact of a product or process over its entire life cycle. Cradle-to-grave LCAs are the most representative accounting of a product's environmental impact because it includes all environmental flows over the full life of the product, such as material and energy resources that go into a product, as well as all emissions to air, water, and land that result from its manufacture and use.

The basis of comparison was a five-story, commercial, office building that meets minimum building and energy code requirements. The service life of the building was assumed to be 73 years. Precast concrete was compared to two other structural systems (steel and cast-in-place concrete), and two envelope systems (curtain wall and brick and steel studs). Precast concrete envelopes were also examined in three variations (solid wall, integral insulated wall, and integral insulated wall with embedded thin brick).

The findings from the study show that in almost all categories the differences are within the margins of error of the analysis. In other words, there is no significant difference in environmental impact between the systems over the full service life of a building. This means that essentially material and system selection can be based on the benefits the materials and system provide, without an environmental tradeoff.

APPROACH & BACKGROUND

The study performed was a cradle-to-grave, comparative life-cycle assessment, or LCA. A cradle-to-grave LCA takes into account the full-life cycle of a product including the extraction of raw materials from nature, any transformation or manufacturing of these raw materials into a product, the product use, and end-of-life scenarios such as recycling or disposal. At the time this research was conducted, it was the most comprehensive comparative study ever undertaken in the construction industry.

This study was administered by an outside consultant hired to perform the analysis of data supplied by PCI in accordance with internationally recognized standards. The methodology employed in this study complied with international standards ISO 14040:2006 and ISO 14044:2006 for conducting life-cycle assessments. The research was conducted by a team comprised of Morrison Hershfield, the Athena Institute, and Venta, Glaser & Associates.

Because the study is a comparative assertion, data for *all products* were treated equally. All buildings were compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary,

¹Project costs were shared among PCI, Canadian Precast/Prestressed Concrete Institute (CPCI) and the National Precast Concrete Association (NPCA) for the product and construction stages of the LCA.



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data quality, allocation procedures, rules on evaluating inputs and outputs, and impact assessment. In comparative assertions, similar data quality (including time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources of the data, and uncertainty of the information) are required to satisfy the ISO requirements on “consistency check” and pass the critical review process.

LCA methodology described in ISO 14040:2006 and ISO 14044:2006 consists of four iterative phases:

- Goal and scope definition: a statement of the functional unit, the system boundary, the assumptions and limitations, the allocation methods used, and the impact categories chosen.
- Life-cycle inventory (LCI): a flow model of the technical system is constructed using data on inputs and outputs.
- Life-cycle impact assessment (LCIA): where the LCI data are characterized in terms of their potential environmental impacts. For example, potential environmental impacts can include acidification, ozone depletion, and global warming.
- Interpretation: The results from the inventory analysis and impact assessment are summarized during the interpretation phase. The outcome of the interpretation is conclusions and recommendations of the study.

This LCA study used the U.S. EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) impact assessment method, which output the following midpoint indicators:

- Global warming potential
- Acidification potential
- Potential respiratory effects
- Eutrophication potential
- Photochemical smog creation potential
- Ozone depletion potential

In addition, the following inventory items were tracked:

- Total primary energy
- Solid waste
- Water use
- Abiotic resource depletion

BASELINE BUILDING

The basis of comparison was a five-story, commercial office building that provides space for 130 people and meets minimum building and energy code requirements of the 2006 International Building Code (IBC) and the 2007 version of ANSI/ASHRAE/IESNA Standard 90.1, respectively. The service life of the building was assumed to be 73 years, the median life for large commercial buildings according to published literature.

In conformance with international standards for comparative studies, the same fundamental design parameters (dimensions, column spacing, and the like) were applied for all cases; the design of the comparison structure was not optimized for any of the structural and envelope systems evaluated.

The building plan dimensions are 27.4 by 36.6 m (90 by 120 ft), with a height of 19.2 m (63 ft), a gross floor area 5017 m² (54,000 ft²) and a column grid spacing of 9.1 by 12.2 m (30 by 40 ft). Story heights are 4.6 m (15 ft) for the first story and 3.7 m (12 ft) for the remaining four stories, with story height measured from finished floor to finished floor. Each façade of each story has a band of windows each measuring approximately 1.5 by 1.5 m (5 by 5 ft). The overall window to wall ratio is 0.40.

SYSTEMS AND CLIMATE ZONES

The study evaluated 15 design cases consisting of five different building envelope systems combined with three different structural systems (Table 1). To consider different climate conditions, all 15 cases were modeled in four U.S. locations (Denver, Memphis, Miami, and Phoenix). The case using precast concrete for both the envelope and structural systems (designated “P-P”) was defined as the baseline for comparison.

Table 1. Summary of the Fifteen Building Types / Assemblies

Building envelope type and abbreviation	Structure type and abbreviation		
	Steel (S)	Cast in place concrete (C)	Precast concrete (P)
Curtain wall (CW)	CW-S	CW-C	CW-P
Brick and steel stud (S)	S-S	S-C	S-P
Precast concrete (P)	P-S	P-C	P-P
Insulated precast concrete (Pi)	Pi-S	Pi-C	Pi-P
Insulated precast concrete and thin-brick veneer (Pib)*	Pib-S	Pib-C	Pib-P

*Thin-brick veneer consists of bricks that are 13 to 16 mm (1/2 to 5/8 in.) thick cast into the precast concrete panels.

LIFE-CYCLE STAGES

The research program considered the full life cycle of a building from cradle to grave.

Product Phase

Within the cradle-to-gate boundary, environmental impacts due to upstream materials, transportation of raw materials to the precast manufacturing facility, and all processes within the plant are included. This means that impacts related to cement manufacture; aggregate production; transportation of fuel, cement, supplementary cementitious materials (for example, fly ash), and aggregates to the plant; and plant operation, which includes forming, reinforcement, and curing processes are included. The upstream profiles of portland cement and aggregates are imported into the concrete system boundary. The energy used to heat, cool, and light plant buildings is included in the plant operations. The upstream profiles of fuels and electricity are also included.

During the product stage of the LCA, manufacturing stage impacts for the constituent precast concrete elements (hollow-core slabs, wall panels, columns, beams, double tees) were evaluated. Unpacking this data revealed some differences among the various element types (about 6%). However, manufacturing stage impacts for all precast concrete element types were driven by a few key factors.

- Portland cement–Portland cement use accounts for the majority of the impact in most environmental impact categories.
- Plant energy–Energy used in the fabrication process accounts for 23% to 25% of the total primary energy (TPE) and 13% to 14% of the global warming potential (GWP) for the manufacturing stage.
- Plant material waste–40% of the solid waste generated in the manufacturing stage is associated with steel reinforcement and steel anchor plates; 44% to 45% is associated with general plant operations.
- Other constituent materials–The extraction processes for fine and coarse aggregates are significant contributors to respiratory effects (21% to 23% combined), due in part to particulate releases during quarrying. The manufacturing and handling of admixtures contribute to ozone depletion and primary energy use.

Construction Phase

The construction life-cycle stage included the full construction of the building, to the point of turnover to the owner. For construction effects, LCI data from a proprietary Athena Institute database was used for the construction of various commercial structural systems (precast concrete, cast-in-place concrete, and structural steel), as well as layers of various envelope materials and interior partitions. These on-site construction LCI data were used to model the requisite on-site construction effects for each of the systems/scenarios evaluated. Data were collected from six precast concrete manufacturing facilities in the United States and Canada.

Use Phase

Annual energy use was calculated using whole-building energy simulation. In whole-building energy simulation, a thermodynamic model of a building is created, and software simulates the operation and response of the building. Whole-building energy software performs these steps:

1. calculates the heating and cooling loads of each space in a building over a defined period such as a typical year,
2. simulates operation and response of the equipment and systems that control temperature and humidity and distribute heating, cooling and ventilation to the building, and
3. models energy conversion equipment that uses fuel and electricity to provide the required heating, cooling, and electricity.

The buildings were modeled with EnergyPlus (version 6.0.0.023) whole-building energy simulation software. In this study, energy use includes space heating and cooling, water heating, ventilation, interior lighting, office equipment, elevator use, and other uses that affect the heating and cooling loads such as air infiltration. The simulation also included the effects of thermal mass in envelope and structural materials, and thermal bridging in wall systems. EnergyPlus was developed by the U.S. Department of Energy and others.

Maintenance, Repair, and Replacement

This section describes how the quantities of energy and materials used in the maintenance stage were calculated. The maintenance stage includes repair and replacement of assemblies and components of assemblies throughout the study building's service life. The following eight assemblies were identified as undergoing maintenance:

1. Interior partitions (all cases)
2. Roof waterproofing system (all cases)
3. Windows (all cases except buildings with curtain wall)
4. Curtain wall (includes the windows in curtain wall)
5. Brick and steel stud wall
6. Conventional precast panel wall
7. Insulated precast panel wall
8. Insulated precast with brick veneer panel wall

The primary source of information is the Athena report, *Maintenance, Repair and Replacement Effects for Envelope Materials* (2002), which describes the following:

- Maintenance stage activities for each assembly
- Material and energy usage, and the rate at which activities occur
- Construction waste factors

Maintenance of precast concrete panels is based on *Architectural Precast Concrete Walls—Best Practice Guide* and Morrison Hershfield's standard recommendations in *Building Envelope Maintenance Manuals* (unpublished). A building envelope maintenance manual provides a schedule of maintenance activities to ensure building envelope components perform as intended throughout their service life. Standard recommendations are based on decades of building envelope experience, manufacturers' installation instructions, material warranties, and industry best practice.

End-of-Life

In general, generic industry associations' data and publications and North American industry practices were taken in consideration to model the end-of-life stage scenarios. A literature review and Internet search was conducted but little detailed information regarding construction and demolition waste management practices in the four U.S. urban centers were found and further considered in this study. End-of-life scenarios are being forecast up to 73 years in the future, thus data generated in the end-of-life stage should be considered in context relative to other life-cycle stages rather a definitive outcome.

RESULTS

The following sections compare the LCIA results among buildings and present graphical summaries of the data. Ten specific environmental impact and life-cycle inventory categories were evaluated for each of the 15 cases, in each of the four cities. To provide a simplified characterization for the purpose of this white paper, the discussion below focuses on the coefficient of variation (COV) of the results for the 15 building cases for each environmental impact and life-cycle inventory category. Refer to **Table 1** for a summary of the 15 building assemblies.

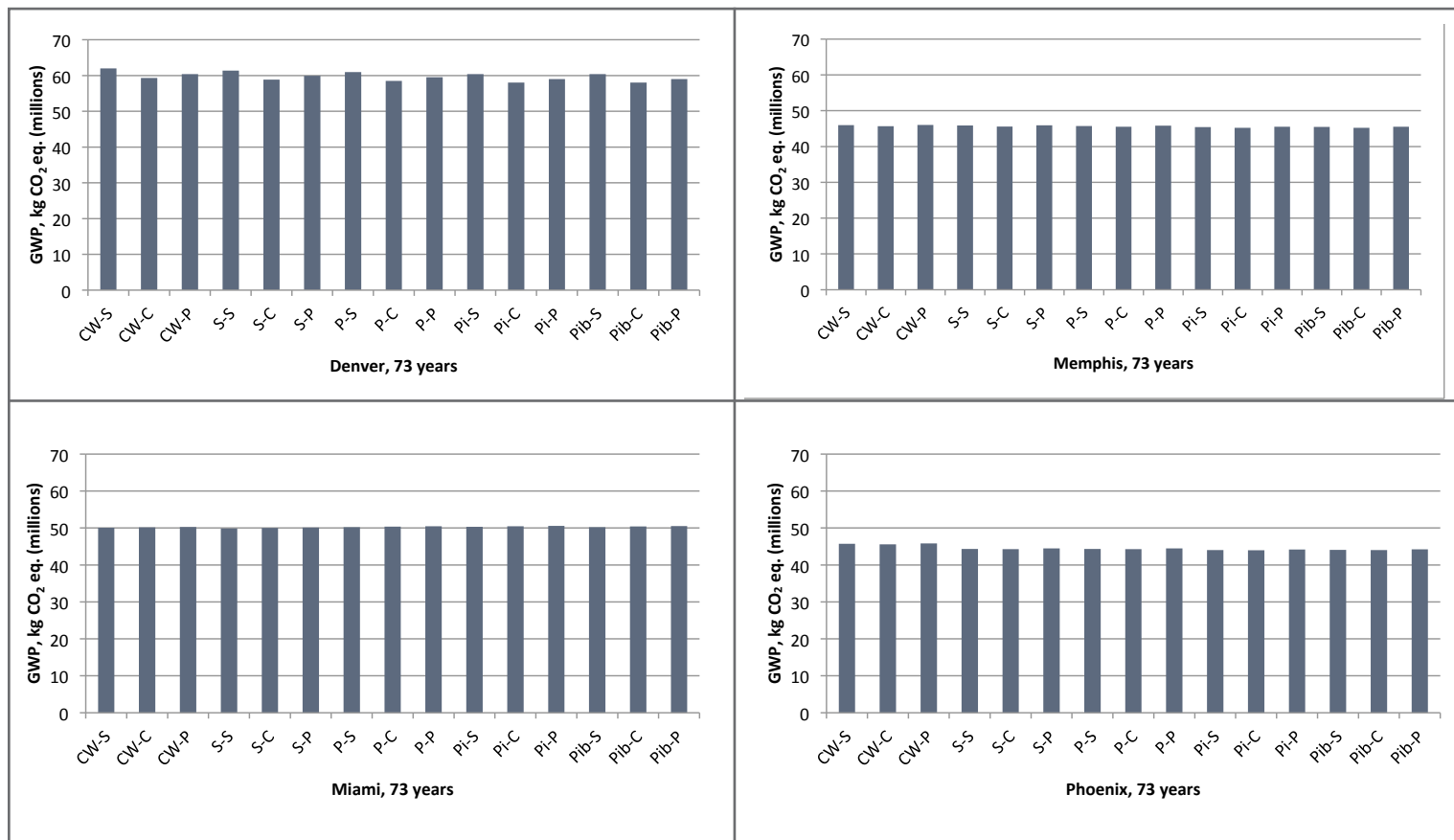
Global Warming Potential

TRACI uses global warming potentials, a midpoint metric proposed by the International Panel on Climate Change (IPCC), for the calculation of the potency of greenhouse gases relative to CO₂. The 100-year time horizons recommended by the IPCC and used by the United States for policy making and reporting are adopted within TRACI. Global warming potential (GWP) is a mainly a function of the energy use of the building and the type (source) of electricity in the particular city. The GWP of electricity from the electricity grid in Denver is more than the GWP of electricity in the other cities because it has much less contribution from nuclear (which is a low CO₂-intensive source of electricity). Therefore, even though the buildings in Denver use the least amount of electricity, they have the highest GWP. Further, the relative difference between the wall U-factors within a city are different between cities because the energy code requirements are different for each city. Therefore the GWP of curtain wall buildings in Miami is lower (better) than their counterparts in Phoenix. For example, compared to curtain walls, the code requires more insulation in concrete walls in Phoenix than in Miami. Figure 1 and the data show:

- In Denver, GWP varies from 58 to 62 million kg CO₂ eq. and the coefficient of variation (COV) is 2%.
- In Memphis, GWP varies from 45 to 46 million kg CO₂ eq. and the COV is 1%.
- In Miami, GWP varies from 50 to 51 million kg CO₂ eq. and the COV is less than 1%.
- In Phoenix, GWP varies from 44 to 46 million kg CO₂ eq. and the COV is 1%.

These small COVs indicate that there is not much relative difference in GWP between the buildings within a given city.

Figure 1. Global warming potential (GWP) of the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 0 to 2%.



*These small COVs indicate that there is not much relative difference in GWP between the buildings within a given city.

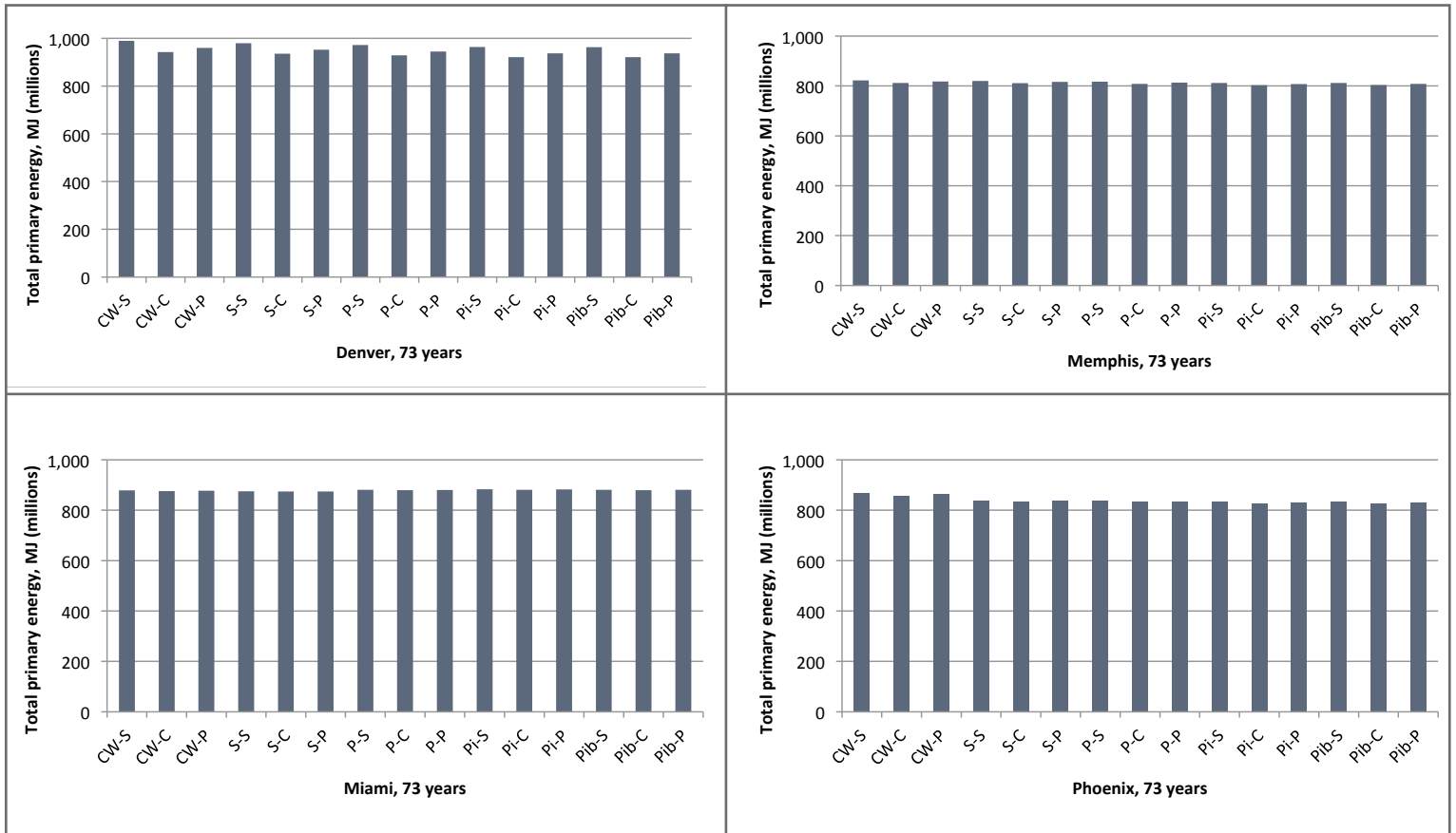
Total Primary Energy

Total primary energy (TPE) is the sum of all energy sources drawn directly from the earth, such as natural gas, oil, coal, biomass, and hydropower energy. Figure 2 and the data show:

- In Denver, TPE varies from 921 to 990 million MJ and the COV is 2%.
- In Memphis, TPE varies from 803 to 822 million MJ and the COV is 1%.
- In Miami, TPE varies from 874 to 883 million MJ and the COV is less than 1%.
- In Phoenix, TPE varies from 827 to 867 million MJ and the COV is 1%.

These small COVs indicate that there is not much relative difference in TPE between the buildings within a given city.

Figure 2. Total primary energy (TPW) of the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 1 to 2%.

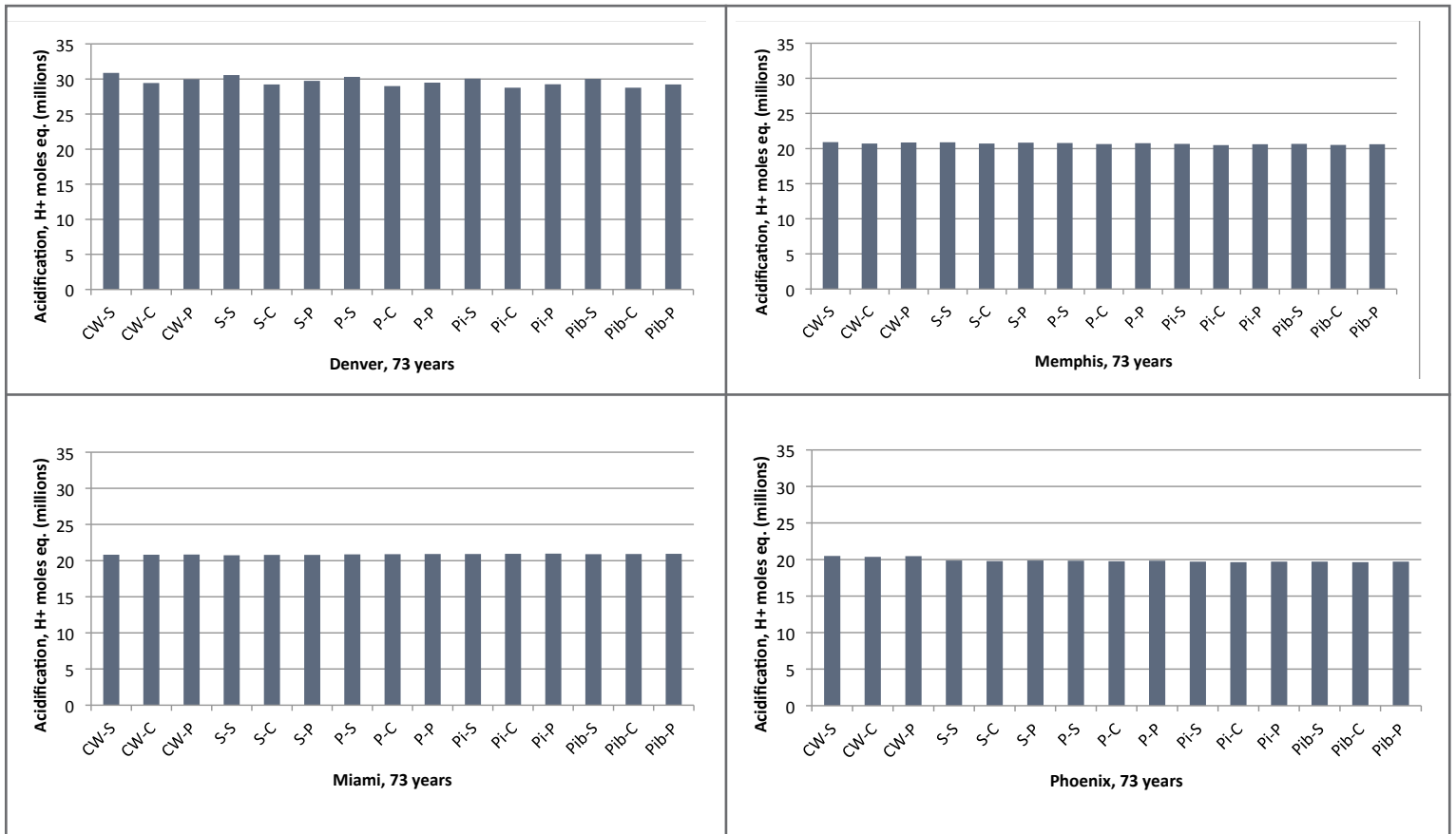


*These small COVs indicate that there is not much relative difference in TPE between the buildings within a given city.

Acidification Potential

Acidification comprises processes that increase the acidity (hydrogen ion concentration, [H+]) of water and soil systems. Acidification is a more regional rather than global impact effecting fresh water and forests as well as human health when high concentrations of SO₂ are attained. Figure 3 and the data show that within a given city, the COV of acidification potential is 2% or less, which shows that there is not much difference between the buildings within a given city.

Figure 3. Acidification potential of the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 0 to 2%.

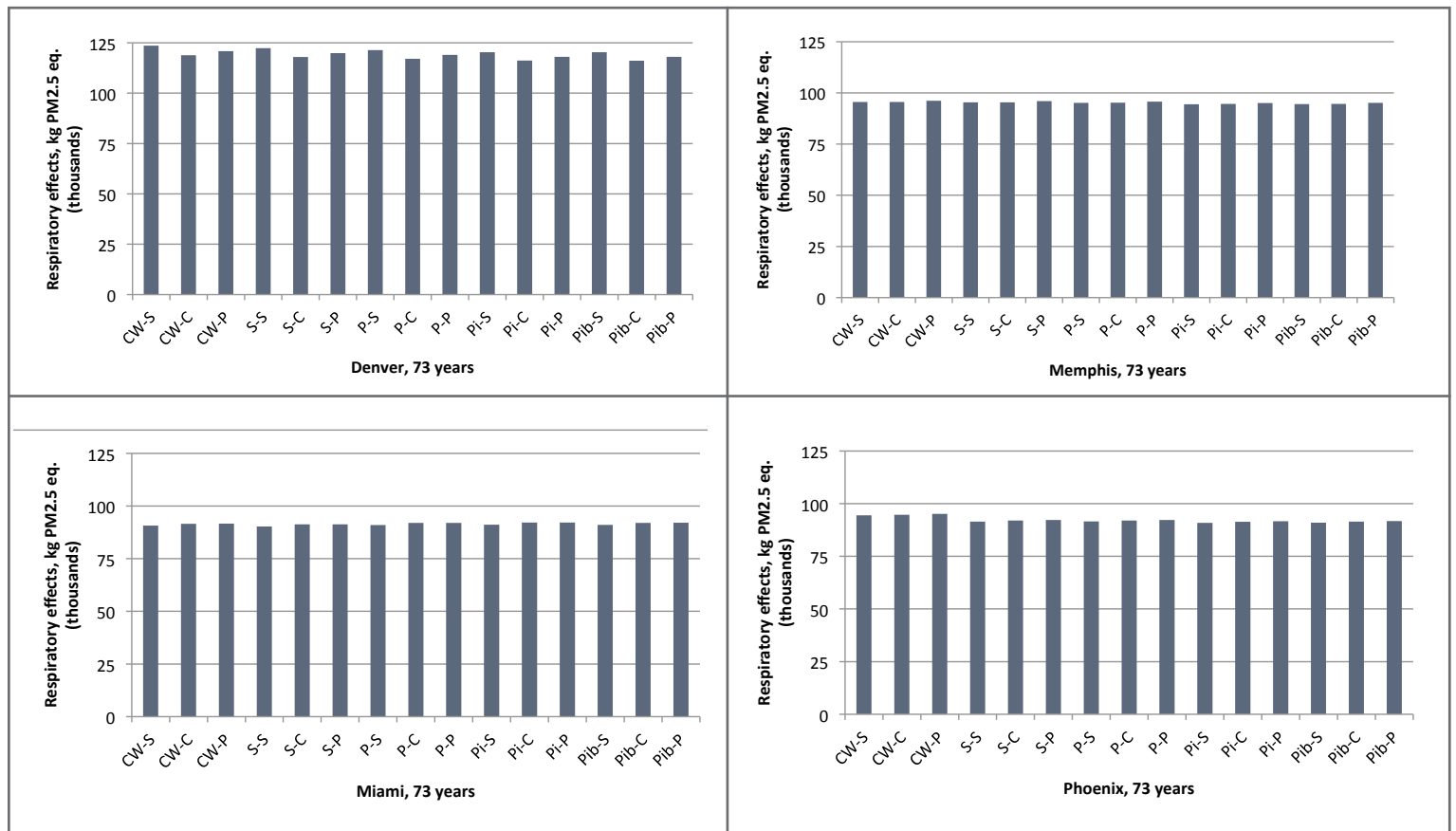


*These small COVs indicate that there is not much relative difference in acidification between the buildings within a given city.

Potential Respiratory Effects

The midpoint level indicator is based on exposure to elevated particulate matter (PM) less than 2.5 micrometers in diameter. Particulate matter is the term for particles found in the air, including dust, dirt, soot, smoke, and liquid droplets. Emissions of SO₂ and NO_x lead to formation of the secondary particulates sulphate and nitrate. Particles can be suspended in the air for long periods of time. Some particles are large or dark enough to be seen as soot or smoke. Others are so small that individually they can only be detected with an electron microscope. Many manmade and natural sources emit PM directly or emit other pollutants that react in the atmosphere to form PM. These solid and liquid particles come in a wide range of sizes. Particles less than 10 micrometers in diameter (PM10) pose a health concern because they can be inhaled into and accumulate in the respiratory system. Particles less than 2.5 micrometers in diameter (PM2.5) are referred to as “fine” particles and are believed to pose the greatest health risks. Because of their small size (approximately 1/30th the average width of a human hair), fine particles can lodge deeply into the lungs. Figure 4 and the data show that within a given city, the COV of potential respiratory effects is 2% or less, which shows that there is not much difference between the buildings within a given city.

Figure 4. Potential respiratory effects due to the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 0 to 2%.

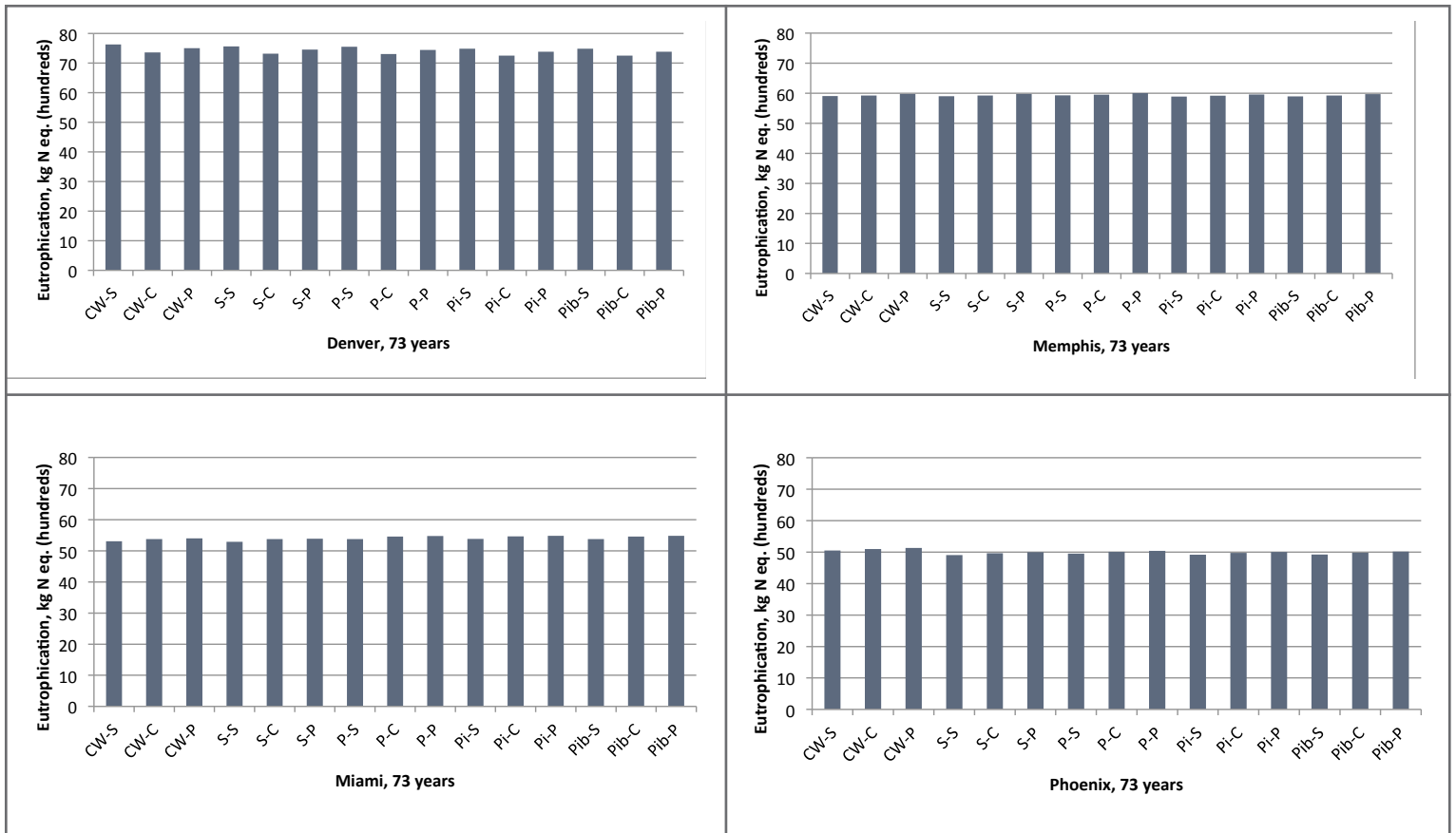


*These small COVs indicate that there is not much relative difference in potential for respiratory effects between the buildings within a given city.

Eutrophication Potential

Eutrophication is defined as the fertilization of surface waters by nutrients that were previously scarce. This measure encompasses the release of mineral salts and their nutrient enrichment effects on waters—typically made up of nitrogen (N) and phosphorous (P) compounds and organic matter flowing into waterways. The result is expressed on an equivalent mass of nitrogen basis. Figure 5 and the data show that within a given city, the COV of eutrophication potential is 2% or less, which shows that there is not much difference between the buildings.

Figure 5. Eutrophication due to the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 0 to 2%.

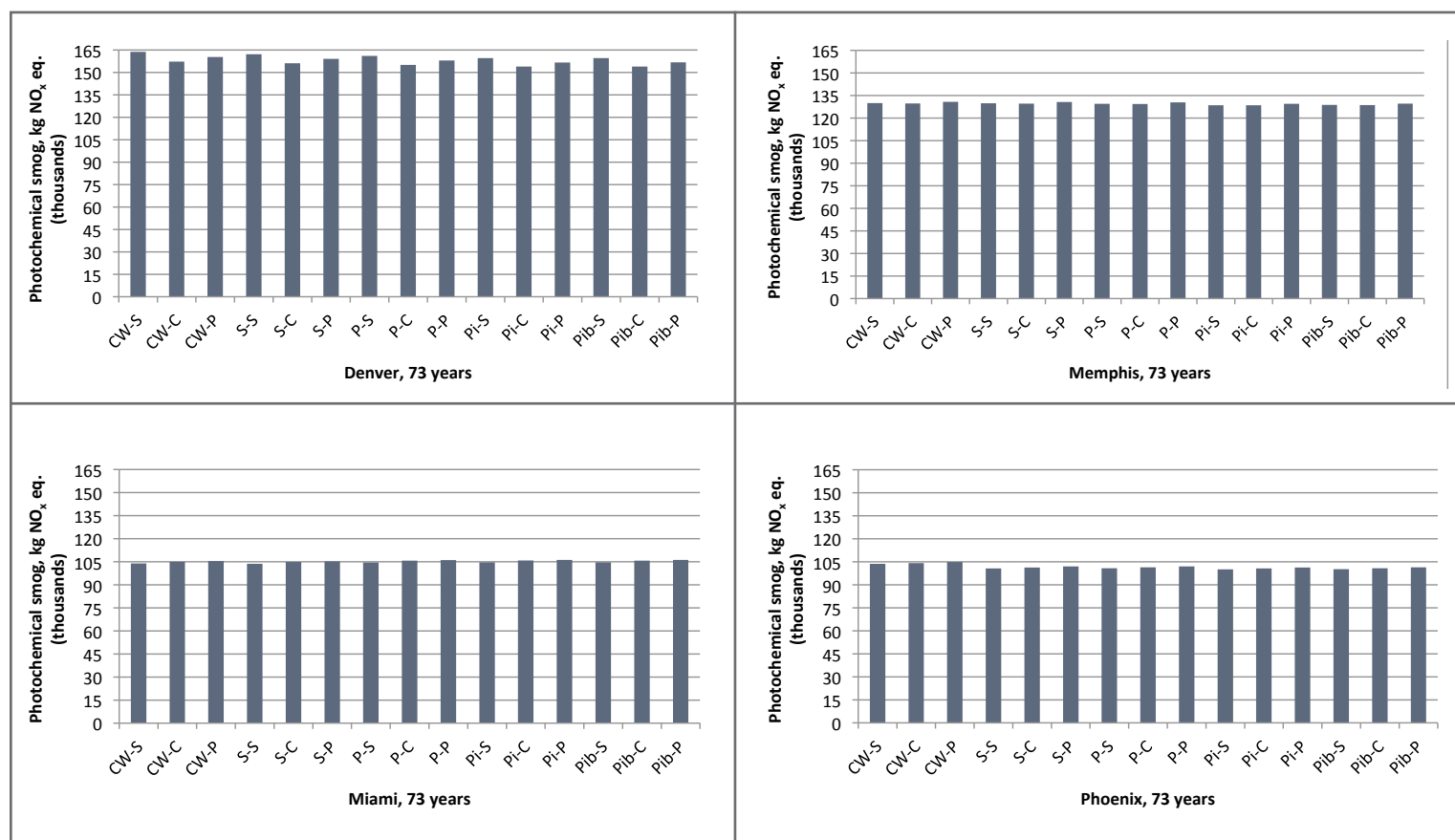


*These small COVs indicate that there is not much relative difference in eutrophication potential between the buildings within a given city.

Photochemical Smog Creation Potential

Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). Figure 6 and the data show that within a given city, the COV of photochemical smog creation potential is 2% or less, which shows that there is not much difference between the buildings.

Figure 6. Photochemical smog creation potential due to the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 0 to 2%.

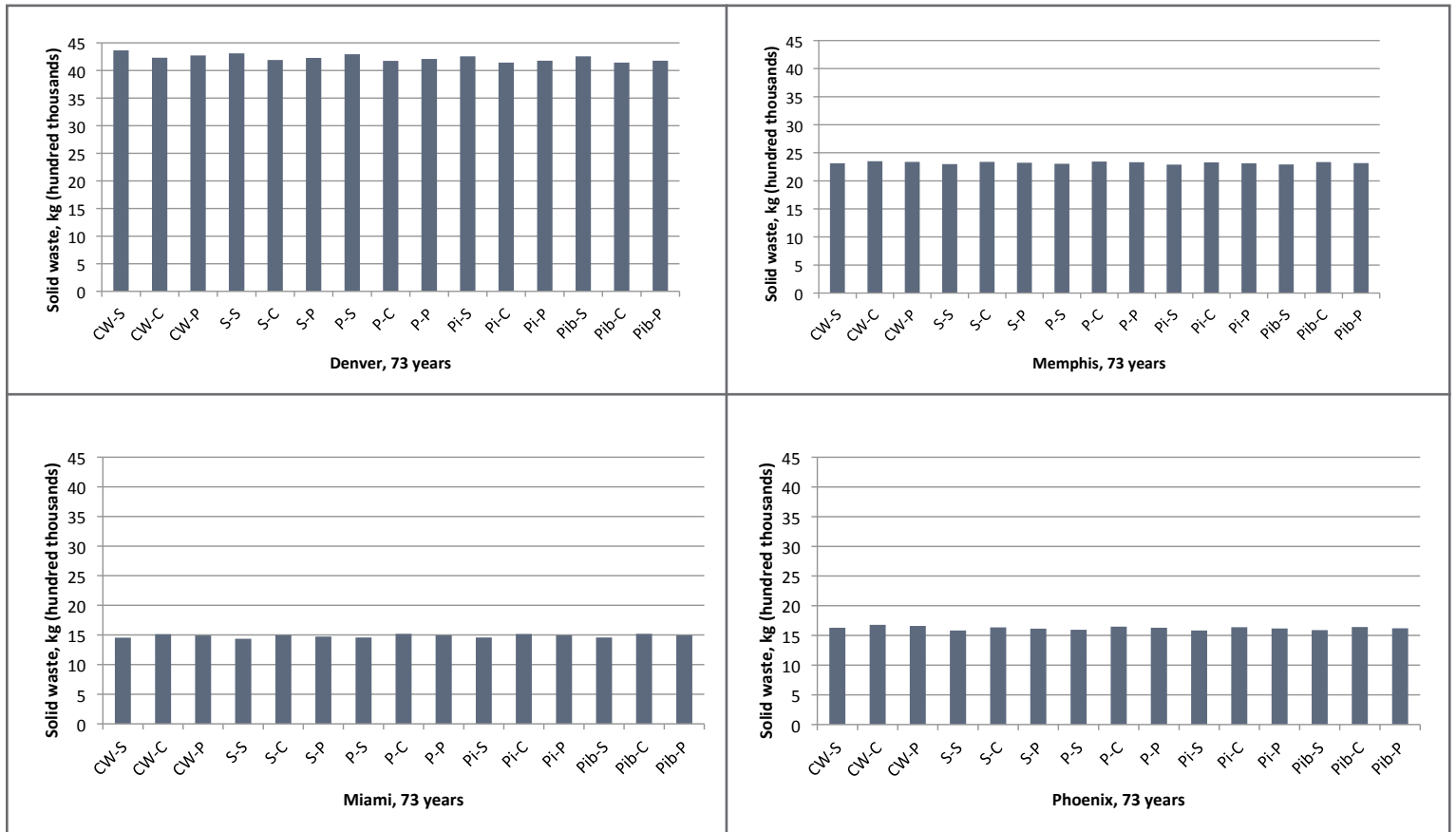


*These small COVs indicate that there is not much relative difference in photochemical smog formation potential between the buildings within a given city.

Solid Waste

This indicator summarizes the cradle-to-gate life-cycle inventory solid waste flows. Figure 7 and the data show that within a given city, the COV of solid waste is 2% or less, which shows that there is not much difference between the buildings.

Figure 7. Solid waste due to the 15 buildings for each of the four cities; coefficient of variation* for the data varies from 0 to 2%.



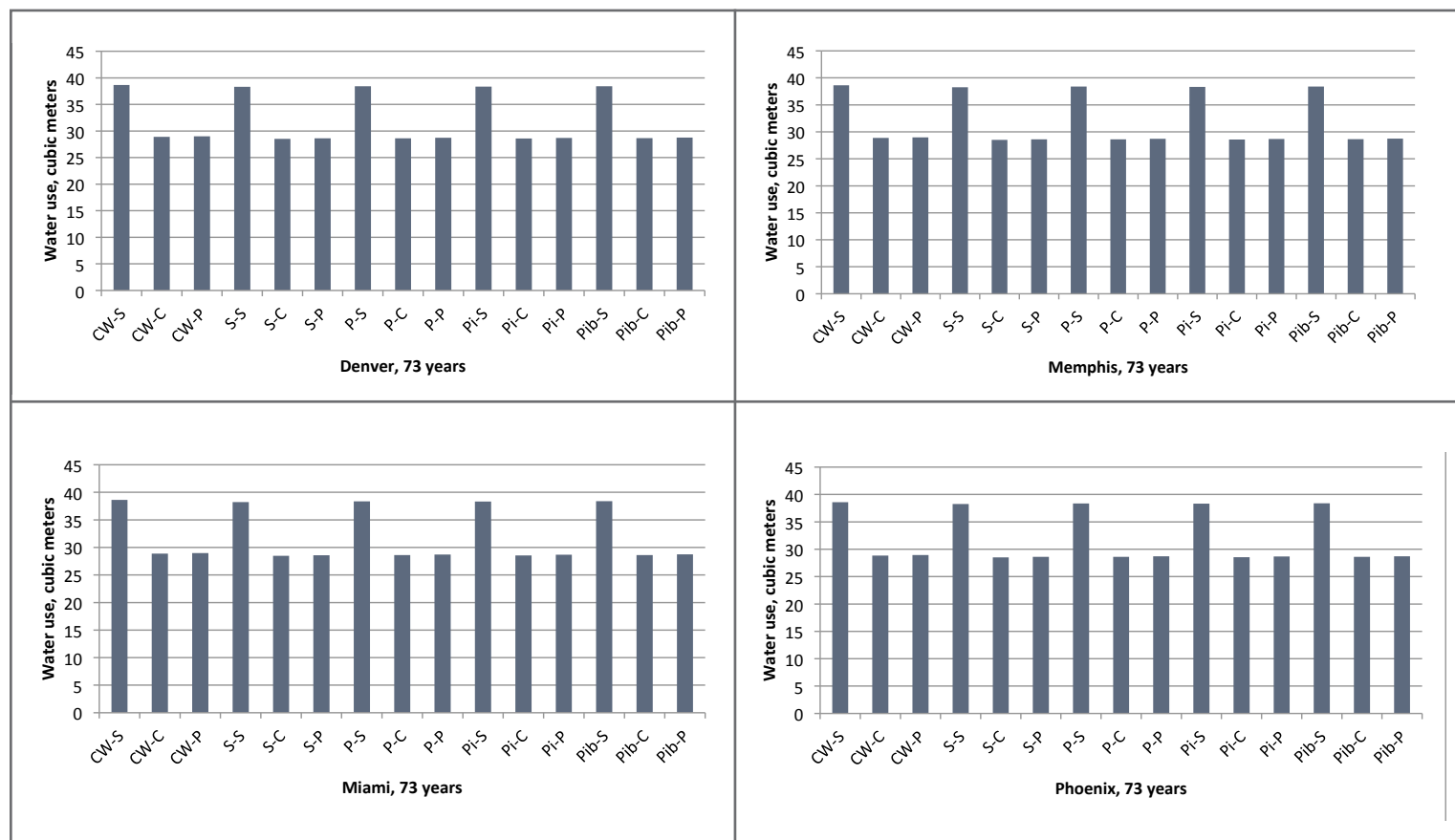
*These small COVs indicate that there is not much relative difference in solid waste between the buildings within a given city.

Water Use

This indicator summarizes the cradle-to-gate life-cycle inventory water usage flows. Figure 8 and the data show:

- Within a given city, the COV of water use is 14%, which shows that there is some difference between the buildings within a given city.
- In all cities, regardless of envelope, the buildings with steel structures have the highest potential water use.
- The reason for the similarity is that most of the water use is during the operating energy stage, and it is the same in all buildings regardless of building or location (23,984 m³).
- The reason for the difference is that in the buildings with steel structures, the elevator and stairwell walls—which are concrete masonry—embody more water use (9882 m³) than all the water the embodied in the buildings with cast-in-place or precast concrete structures (3104 m³ to 4916 m³). The elevator and stairwell walls in the buildings with cast-in-place or precast concrete structures are cast-in-place concrete and embody 175 m³.

Figure 8. Water use due to the 15 buildings for each of the four cities; coefficient of variation for the data is 14%.

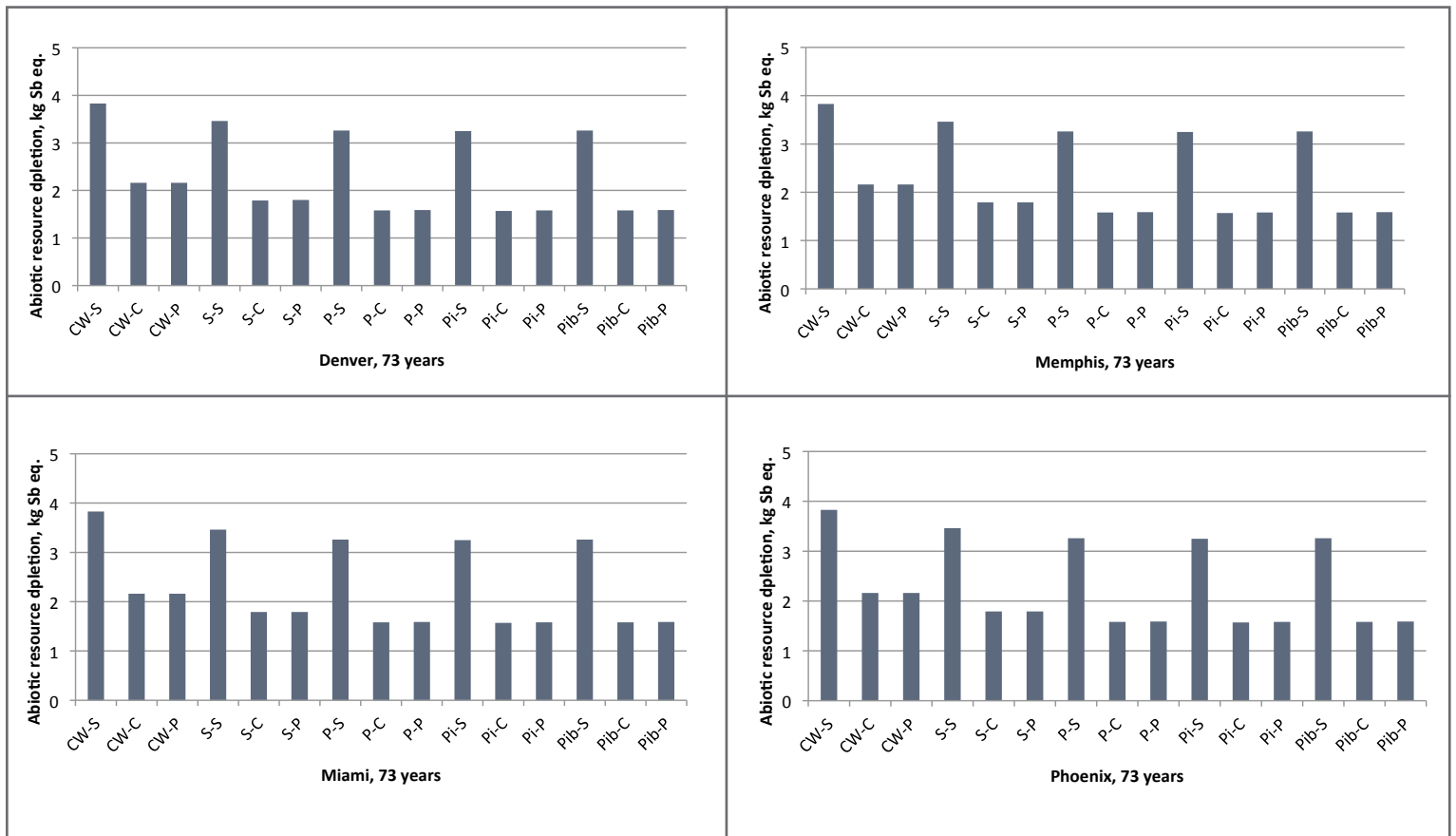


Abiotic Resource Depletion

The abiotic depletion potential (ADP) baseline factors for characterizing abiotic resources are based on ultimate reserves and extraction rates. According to Guinée & Heijungs (1995), a method based on ultimate reserves and rates of extraction is the best option, as these parameters best indicate the seriousness of resource depletion. As the notion of *economic reserves* involves a variety of economic considerations not directly related to the environmental problem of resource depletion, *ultimate reserves* appears to be a more appropriate yardstick. Fossil fuels are excluded because they will be reported under a separate category (total primary energy). Figure 9 and the data show:

- Within a given city, the COV of abiotic resource depletion is 36%, which shows that there is a large difference between the buildings within a given city.
- The majority of the abiotic resource depletion is embodied in the manufacturing stage.
- Regardless of city, the buildings with largest potential for abiotic resource depletion are the buildings with steel structures. Looking deeper into the data, in the buildings with steel structures, the majority of the abiotic resource depletion is embodied in the steel decking of the floors and roof (2.40 kg Sb eq. for the steel floors and roof out of 3.62 kg Sb eq. for the total manufacturing stage). And the total abiotic resource depletion embodied in the manufacturing stage of buildings with cast-in-place concrete or precast concrete structures (1.66 to 2.02 kg Sb eq.) is less than that embodied in just the floors and roof of the buildings with steel structures.

Figure 9. Abiotic resource depletion due to the 15 buildings for each of the four cities; coefficient of variation for the data is 36%.



FINDINGS

1. Precast concrete envelope systems' environmental performance is comparable to that of curtain wall and brick cavity wall envelope systems over the service life of a building.
2. Precast concrete structural systems' environmental performance is comparable to steel and cast-in-place concrete structural systems over the service life of a building.
3. Precast concrete's environmental performance is somewhat better than that of the studied systems in the gate to grave phases of a building's service life.
4. The operating energy stage has the greatest environmental impact, more than 96%.

DISCUSSION AND CONCLUSIONS

This study confirms a basic conclusion of most balanced LCA studies of commercial buildings, such as the MIT Research: Life Cycle Assessment of Commercial Buildings², namely that there is presently not a significant difference in life-cycle impacts between steel, cast-in-place concrete, and precast concrete structural systems. Although concrete is sometimes perceived to have a higher environmental impact, due to energy use and carbon dioxide emissions associated with manufacturing portland cement; the fact is, as shown by this research, precast concrete does not impose *additional environmental burden*.

However, in the operating energy stage, which has the greatest overall impact on environmental performance, precast concrete envelope systems perform better than the other envelope systems that were studied. More than 90% of the impacts relating to global warming, acidification, respiratory effect, eutrophication, photochemical smog, and total primary energy occur in the operating energy stage. While the numbers vary somewhat among the four cities studied, in all cases at least 97% of the total primary energy (TPE) and 96% of the global warming potential (GWP) attributed to the building over its lifetime occurs in the operating energy stage. Therefore, selecting materials and systems that provide energy reducing benefits, such as precast concrete envelope systems, are very important to reducing overall environmental impact.

From a manufacturing perspective, portland cement comprises less than 20% of a typical precast panel, yet is a key aspect of the environmental performance of precast concrete. Environmental improvements in the cement industry, as well as reduced cement usage in precast products, have the potential to improve precast concrete's environmental footprint in the future.

It should also be noted, that comparative LCAs do not optimize a structure for any one material or system; therefore precast concrete would perform even better if a building was optimized for it due to a reduction in total material usage, and optimization of the HVAC system.

HIGH-PERFORMANCE STRUCTURE AND LCA

The United States government defines a high-performance structure as one that ". . .integrates and optimizes on a life-cycle basis all major high-performance attributes including energy and water conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations." (Energy Independence and Security Act of 2007—401 PL 110-140.)

At the heart of this definition is a fundamental shift in perspective from sustainable design and construction to sustainability and performance on a life-cycle basis. The concept of high-performance encompasses the ideas and practices of sustainable design. However it goes beyond a simple comparative approach by requiring optimization of all relevant attributes, over the life of the project. Hence characteristics such as energy and water conservation, safety, security, and durability must be optimized for a specific project; and integrated into a structure's overall design, construction, and performance.

High-performance structures require high-performance materials. These are materials that are inherently versatile, efficient, and resilient. They help designers optimize structures to meet high-performance challenges and requirements, both in the short- and long-term.

²MIT Research: Life Cycle Assessment of Commercial Buildings, National Ready-Mixed Concrete Association, CSR05–September 2011.

Precast concrete inherently offers many high-performance attributes, and is being used to help projects meet and exceed their high-performance goals during design, construction, and operation. *The LCA research shows that the benefits of precast concrete can be utilized to meet high-performance goals with similar environmental burden relative to other materials and systems.*

WHAT'S NEXT?—IMPROVING MANUFACTURING

The precast concrete industry can also improve its environmental performance through more sustainable plant practices. The study identified environmental “hot spots” (energy, waste, recycling, water, and cement use) related to the production of precast concrete. This information has been used in the development of a Sustainable Plant Program for PCI Member Plants. The program includes tracking tools used by participating plants to benchmark and improve manufacturing processes to reduce the environmental impact of the production of precast concrete elements.

In considering ways to reduce the environmental impacts of precast concrete buildings, each life-cycle stage should be examined. While the manufacturing stage might seem to offer the only opportunity for improvement for precast concrete producers, the fact is that refinements in building design, element detailing, plant facilities, manufacturing processes, and materials use can have positive effects in all stages.

For more information on high-performance precast and LCA visit www.pci.org/hpprecast. To read the full LCA report, contact PCI's Jennifer Peters at jpeters@pci.org.