# DOE's Commercial Building Benchmarks: Development of Typical Construction Practices for Building Envelope and Mechanical Systems from the 2003 Commercial Building Energy Consumption Survey

*David Winiarski, Mark. Halverson, and Wei Jiang, Pacific Northwest National Laboratory*


## ABSTRACT

The U.S. Department of Energy (DOE) developed a series of prototypical commercial building models in 2007. These models, referred to as DOE Benchmarks, are intended for both internal DOE use in tracking progress toward zero-energy buildings and for external use by other stakeholders in the commercial buildings sector. These models are currently being used in the development of new requirements in building codes and standards, for tracking progress of building codes and standards, and to provide guidance to states contemplating adoption of new building codes and standards. One important aspect of the DOE Benchmarks is that they attempt to replicate "typical" construction practices. With regard to "typical" construction practice in building envelope and mechanical systems, the primary source of information analyzed was the 2003 Commercial Building Energy Consumption Survey (CBECS). The 2003 CBECS provides considerable information related to the appearance of the building envelope, but relatively little in terms of how the building envelope is constructed. The 2003 CBECS also provides limited data on building shapes and ranges (rather than actual) of window-to-wall area values for buildings. CBECS also provides detailed information on building mechanical systems that can be used directly in the Benchmarks, but only after careful consideration of the diversity of systems used in commercial buildings. This paper discusses the analysis of the 2003 CBECS dataset in determining "typical" construction practice in commercial buildings.


## Background

In 2005, the U.S. Department of Energy (DOE) began creating a series of commercial building prototypes called Commercial Benchmarks that were intended for use in tracking the progress of all commercial programs in DOE's Building Technologies program. These Benchmarks were intended to provide a consistent set of building prototypes that could be used to evaluate the effectiveness of DOE's research and development activities as well as provide the basis for proposing new activities. DOE has developed a set of standard Benchmark building descriptions for both new construction and for existing buildings (representing both pre-1980 and post-1980 building stock). These are a complete revision of the DOE Benchmark buildings originally developed in 2006, with building shape, thermal zoning, and operation of the models more indicative of real buildings than those provided in the initial 2006 Benchmark buildings. The development of these commercial Benchmarks was conducted by staff from three of DOE's national laboratories—Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL).

The Benchmarks are being developed in DOE's EnergyPlus simulation tool and are accompanied by documentation of each Benchmark building in the form of spreadsheet "scorecards" that provide descriptions, parameter values, and source data for all parts of the simulation model. This paper deals solely with choosing the building envelope and building heating, ventilating, and air conditioning (HVAC) system parameters needed for each Benchmark model. A companion paper is available in this ACEEE Summer Study that covers additional aspects of the Benchmark-development process, which includes the intended uses of the Benchmark buildings by DOE, development of the efficiency criteria assumed for the building components, and selection of climates for modeling

DOE defined 15 Benchmark buildings, as shown in Table 1. See Deru and Griffith (2006) for detailed discussion of the definitions. The number of Benchmarks chosen was kept intentionally small in an effort to provide a base set of simulation models to help DOE in assessing program performance in a consistent manner without being overly burdensome. The Benchmarks should be considered as "typical buildings" for this level of analysis. It is recognized that any small set of buildings cannot represent fully the diversity of construction and design of commercial buildings built in the U.S., and how these Benchmarks get applied and used for particular programs will depend on the particular questions being asked. It should also be recognized that this small subset of buildings can only provide a rough estimate of typical design energy consumption for the building stock being represented. It is not adequate for assessing or benchmarking relative performance for individual buildings with size and construction characteristics that deviate significantly from those used for the Benchmark buildings.

The Benchmark buildings were defined first by commercial use, which can provide insight into typical internal loads, typical end uses, and schedules, and second—by size—for more significant building use types. For the most part, a Benchmark type corresponds directly with a single, or set of, Detailed Principal Building Activity (PBA) definition(s) in the 2003 Commercial Building Energy Consumption Survey (CBECS). In addition, for this analysis, office buildings were divided into the categories of small, medium, and large based on definitions originally proposed by NREL. Small is defined as single story, medium as two to four stories, and large as greater than four stories. Overall, the building-use types identified represent approximately 70 percent of total square footage of commercial building stock according to CBECS.

**Table 1. Benchmark Building Types**

| | Benchmark Building Type | | Benchmark Building Type | | Benchmark Building Type |
|---|---|---|---|---|---|
| 1 | Large Office | 6 | Strip Mall | 11 | Restaurant |
| 2 | Medium Office | 7 | Primary School | 12 | Hospital |
| 3 | Small Office | 8 | Secondary School and University | 13 | Outpatient Health Care |
| 4 | Warehouse | 9 | Grocery Store | 14 | Motel |
| 5 | Stand-Alone Retail | 10 | Fast Food | 15 | Hotel |

## Development of Envelope Characteristics

This section presents the methodology and results of an analysis of the building envelope characteristics reported in the 2003 CBECS, aggregated to DOE's Commercial Benchmark definitions, and used to inform the selection of envelope components. Only results for buildings constructed after 1980 are discussed in this paper as this time period was used to characterize recent construction practice in commercial buildings. Due to the need for "economy" in these proceedings, this paper focuses on recommendations for only 5 of the 15 Benchmarks—large office, small office, warehouse, stand-alone retail, and fast food. Complete results for the analysis of envelopes for buildings constructed after 1980 may be found in Winiarski, Jiang, and Halverson (2007). A separate study, dealing with *pre-1*980 buildings and used to help characterize older building stock, is found in Winiarski, Halverson, and Jiang (2007). A complete summary of Benchmark envelope and mechanical system characteristics may also be found in Deru et al. (2008).

The starting data source for this effort was a review of the 2003 CBECS, which was undertaken by the DOE's Energy Information Agency (EIA). CBECS is conducted every 4 years by the EIA to provide basic statistical information about energy-related characteristics, consumption, and expenditures in U.S. commercial buildings. Details on the CBECS 2003 survey can be found in EIA (2006).

While the 2003 CBECS is DOE's most current collection of reported commercial building characteristics, the survey data have a number of shortcomings when used for the type of analysis conducted for this paper (See Table 2). Also listed below are the approaches used to address these shortcomings. These approaches are also discussed in more detail in the text of this paper.

**Table 2. 2003 CBECS Shortcomings and Approaches Taken to Address Those Shortcomings**

| 2003 CBECS Shortcomings | Approach Taken in Developing Benchmarks |
|---|---|
| Wall and roof descriptions describe only the appearance or facade of the building, not the underlying wall or roof structure | Appearance or façade descriptions are mapped to probable underlying wall or roof structure |
| No specific building aspect ratio data | 1992 CBECS data used |
| Specific number of stories not available for buildings above 14 stories (data is withheld to protect the identity of specific buildings) | Data from an inventory of U.S. skyscrapers used to estimate relative frequency of number of stories |
| Specific window area or window area fraction not provided | Window area estimated from categorical data provided, using midpoints of categories. |

Final recommendations for wall and roof types are made in terms of the wall and roof assembly descriptions used in ANSI/ASHRAE/IESNA Standard 90.1-2004. This standard, in conjunction with the assembly descriptions, provides the basis for developing the component efficiency levels in DOE's new-construction Benchmarks.

The data was extracted from the 2003 CBECS microdata that have characteristics for each building surveyed (a total of 5215 commercial buildings) and mapped that data to the commercial Benchmark building type using the Detailed Principal Building Activity variable (PBAplus) information.

## Form Factor Characteristics

For the purpose of this analysis, each building in the 2003 CBECS dataset is treated as a rectangular block, with a defined aspect ratio and constant cross-sectional area from bottom floor to top floor. The building footprint is used as a surrogate for roof area. To determine the total roof area of the building, the footprint of the building is calculated from the reported floor area of the building and the number of stories. The footprint, the shape, the number of stories, and the floor-to-floor height are used to estimate the total wall area for each building. The window-to-wall ratio (WWR) can then be used to estimate the window area and the total opaque wall area of the building. All building stories reported by CBECS were assumed to be above grade for the calculation of total wall area.

### Aspect Ratio

The 2003 CBECS contains questions about building shape (square, rectangular, and other) but does not directly ask about the aspect ratio[1] of the building footprint. The 1992 CBECS (EIA 2004) was the last CBECS to collect aspect ratio data (for square and rectangular buildings), and average results from the 1992 data are used in this analysis for corresponding building shapes. Based on these data, the aspect ratio used for each 2003 CBECS building is calculated as: (a) 1.0 for square building shape, (b) the average aspect ratio data reported for the PBA category for rectangle building shapes based on 1992 CBECS, and (c) 4.0 for all other building shapes (T-shaped, L-shaped, H-shaped, E-shaped, U-shaped, and 'other' shaped buildings. Details are found in Winiarski, Jiang, and Halverson (2007). The 1992 CBECS aspect ratio data for the five building types considered here are listed below in Table 3.

**Table 3. 1992 CBECS Aspect Ratio Data**

| 1992 CBECS PBA | Aspect Ratio |
|---|---|
| Office/Professional (Large and Small) | 2.01 |
| Warehouse (Non-Refrigerated) | 2.56 |
| Mercantile/Services | 2.07 |
| Food Services (Restaurants) | 1.88 |

### Number of Stories

The 2003 CBECS provides number–of-stories data for individual buildings. For buildings between 1 and 14 stories, the actual number of stories is reported. However, for buildings greater than 14 stories, the information is provided only as to whether the building falls in which of two ranges: 15 to 25 stories and greater than 25 stories. To provide an estimate of actual number of stories in these buildings, data from an online database were used (Skyscraper Source Media, 2007). The Tall Buildings database contains a repository of data and drawings of tall buildings from all over the world, maintained by tall-building enthusiasts and others interested in architectural issues.

A distribution of buildings was developed by roof height for the tallest 4548 U.S. buildings, as determined by building-roof height and down to 67.4 m (219 ft)[2]. The building data were binned in 10-meter-height bins, and the number of buildings in each bin tabulated. A probability distribution for a building being in each bin was developed using an exponential curve fit of the probability of being in each bin. PNNL calculated the average floor–to-floor height for all buildings in the data subset as 3.95 meters (13 ft)[3]. A relative-probability distribution of the number buildings with a given number of stories was then developed for all

[1] For a rectangular building, aspect ratio is the ratio of the long dimension of the building on the horizontal plane to the short dimension of the building in the same plane. For other building shapes, an "effective" aspect ratio is developed which provides an equivalent ratio of building perimeter to footprint area.

[2] This sample included 2281 offices, 426 hotels, and 1492 high-rise residential buildings.

[3] The average floor-to-floor heights were 4.2m (13.8 ft) for offices, 3.3 m (10.8 ft) for high-rise multi-family residential, and 3.6m (11.8 ft) for hotels included in the dataset.

buildings 15 stories and higher, where the sum of the relative probabilities of all buildings 15 stores or greater in height was 1.0. These relative probabilities were then used as weighting factors to develop average number of floors for buildings in the 15–25 story and greater-than-25-story bins used by CBECS. For buildings 15–25 stories, the average number of stories was calculated to be 19. For buildings 26 or more stories, the average number of stories was calculated to be 35 stories.

### Building Footprint

The footprint of each building was estimated as the reported building floor area divided by the number of stories (reported or estimated as above).

### Window-to-Wall Ratio

The 2003 CBECS reports data on estimated window area using window-area-fraction bins of 0–10 percent, 11–25 percent, 26–50 percent, 51–75 percent, and 76–100 percent. The WWR for each individual building was calculated as the midpoint of the CBECS window fraction bins.

From development of the building aspect ratio number of stories and footprint, estimates of the total wall area for each building in the CBECS dataset. This allowed calculation of total area by opaque envelope construction as well as calculation of total window area (using CBECS window fraction data) for each Benchmark building type.

### Roof Construction

CBECS provides seven categories of roof construction material, plus an "other" category and a "not one major type" category. For each Benchmark building type, PNNL first identified the top five most common roof descriptions listed in decreasing order of occurrence by fraction of total roof area and by fraction of buildings. A subset is provided in Table 4 for five Benchmark categories. Roof area is assumed to correspond to the horizontal projection (footprint) of the building and does not take into account roof slope. The presence of or area covered by skylights is not identified in the CBECS dataset.

ASHRAE Standard 90.1-2004 defines three primary roof types based on the location of insulation relative to the roof: Insulation Entirely Above Deck, Metal Building, and Attic and Other. Our primary assumption is that Insulation Entirely Above Deck has continuous insulation above the structural roof deck, and Metal Building has insulation compressed between structural members. In Attic and Other, the insulation is assumed to be laid between roof joists. A fourth secondary option for determining roof insulation levels in Standard 90.1-2004 is defined as single-rafter roofs, a subclass of Attic and Other, where the roof above and the ceiling below is attached to the same rafter. For the purposes of this document, single-rafter roofs are considered in the Attic and Other classification.

Comparison of the three ASHRAE Standard 90.1-2004 roof types with the 2003 CBECS roof descriptions indicates that the only description that can be unambiguously mapped to a Standard 90.1 roof type is CBECS built-up classification mapping to Standard 90.1's roof with insulation entirely above deck. For example, the CBECS metal surface category may be mapped to 90.1's metal building roof, or it may simply indicate that a metal roof has been used in place of shingles over an attic roof structure. The CBECS PRS—Plastic, Rubber, Synthetic (PRS)—category most likely maps, in our judgment, to the insulation above deck category (most commonly where a synthetic membrane is placed over foam), although there are also commercially available recycled rubber and plastic shingles that would be installed over an attic, and the CBECS AFO—Asphalt, Fiberglass, Other Shingles—classification may in some instances include a built-up tar roof with an asphalt top coat. However, we conclude that the sum of the Built-Up and PRS categories provides an estimate of the total roof area/fraction of roofs with insulation entirely above deck. Metal surfacing may indicate metal building roofs or metal roofing over an attic, depending on building type. All other CBECS roof descriptions are indicative of an attic roof.

Table 4 provides the distribution of roof descriptions for the five Benchmark building types covered in this paper.

To categorize the roof data, we also made the following additional assumptions:

- For warehouses, we assume that metal surfacing is simply a traditional metal building roof. This is the dominant roof type by area and by building in warehouses.
- For restaurants and small offices, we assume that metal surface would generally indicate metal roofing over an attic and assign these observations to the attic category.
- For fast food, the sum of PRS and built-up is 55 percent, but, intuitively, a flat roof with insulation entirely above deck does not appear to be typical for the fast-food category. Many fast-food roofs are mansard roofs, which essentially have an attic space covered with a synthetic material. This is essentially what we see in Table 4 with a high amount of PRS and relatively low amounts of built-up roofing. For this reason, we would categorize fast food as having an attic.
- For stand-alone retail, it is possible that the metal surface roof descriptor could refer to either a traditional metal building or to metal roofing over an attic. Because this is the single largest descriptor by building area and building count, whatever assumption is made on splitting the population of buildings reporting this descriptor will impact the overall choice of roof construction. There does appear to be approximately 40 percent of the roof area in built-up roofs and another 12 percent that would probably be attic, but the vast majority is either metal building or metal roofing over attics. Given that there are metal buildings that are stand-alone retail—but probably not a significant amount—most of the metal surface is probably over attics. This would indicate a split between built-up roofs and roofs with attics that is too close to call definitively.

**Table 4. Roof Descriptions by Benchmark Building Category (Post-1980 Buildings, Example for Five Benchmark Types)**

| Benchmark Number | Benchmark Building Type | Roof Descriptions By Fraction of Roof Area | Roof Descriptions by Fraction of Buildings |
|---|---|---|---|
| 1 | Large Office | Built-Up 48%<br>PRS 34%<br>Concrete 6%<br>AFO 6%<br>STS 2% | PRS 41%<br>Built-Up 40%<br>AFO 6%<br>Concrete 5%<br>STS 4% |
| 3 | Small Office | Metal 34%<br>Built-Up 21%<br>AFO 18%<br>PRS 15%<br>STS 7% | AFO 29%<br>Metal 29%<br>Built-Up 19%<br>STS 9%<br>PRS 8% |
| 4 | Warehouse | Metal 57%<br>Built-Up 21%<br>PRS 12%<br>AFO 6%<br>Other 1% | Metal 76%<br>AFO 10%<br>Built-Up 7%<br>PRS 3%<br>Concrete 1% |
| 5 | Stand-Alone Retail | Metal 46%<br>PRS 22%<br>Built-Up 19%<br>AFO 6%<br>Concrete 6% | Metal 42%<br>Built-Up 20%<br>AFO 16%<br>PRS 8%<br>STS 5% |
| 10 | Fast Food | PRS 41%<br>AFO 23%<br>Metal 18%<br>Built-Up 14%<br>Concrete 4% | PRS 41%<br>AFO 23%<br>Built-Up 16%<br>Metal 10%<br>Concrete 6% |

PRS – Plastic, Rubber, Synthetic
AFO – Asphalt, Fiberglass, Other Shingles
STS – Slate, Tile Shingles
WSSO – Wood Shingles, Shakes, Other
Metal – Metal Surfacing
Built-Up – Built-Up roofing

Even when combining the CBECS data with the assumptions above, sufficient guidance may not be available to assign a Benchmark building type to a particular roof construction. At that point, our recourse is to the use of other sources of information and professional judgment.

Where the most typical selection cannot be based purely on available data, a policy can be used to define the construction used. For instance, one way for DOE to choose a roof construction is to have a policy of selecting either the most-stringent or least-stringent roof type when a predominant roof type cannot be determined from available data. Roofs with insulation entirely above deck are all always subject to less -stringent requirements than roofs with attics in ASHRAE 90.1-2004. The result is that the insulation entirely above deck has the highest U-factors and, therefore, the selection of Benchmarks with this type of roof will have slightly higher energy usage (all other things being equal) than for the same Benchmarks building with other roof choices. Since we know there are limitations to the representativeness of any small subset of buildings, one advantage of defining a policy like this is that it helps provide bounds on the representativeness of the energy-consumption estimates. Table 5 shows CBECS-based recommendations for roof types for this subset of Benchmark buildings.

**Table 5. Recommended Roof Constructions by Building Type**

| DOE Commercial Benchmark Building Type | ASHRAE Standard 90.1-2004 Roof Construction |
|---|---|
| Large Office | Insulation Entirely Above Deck |
| Small Office, Fast Food | Attic and Other |
| Warehouse | Metal Building Roof |
| Stand-Alone Retail | Professional Judgment Needed – Insulation Entirely Above Deck OR Attic and Other |

## Wall Construction

The 2003 CBECS provides the wall construction (WLCNS) statistic as a classification of the major wall construction type for each building. The CBECS WLCNS categories are (a) brick, stone, or stucco; (b) concrete block or poured concrete; (c) decorative or construction glass; (d) pre-cast concrete panels; (e) sheet-metal panels; (f) siding, shingles, tiles, or shakes; and (g) window or vision glass. CBECS also has classifications of (h) no one major type and (i) other. Table 6 lists the top five CBECS wall construction choices for five building types in decreasing order of occurrence by percentage of calculated total opaque wall area or number of buildings. Note that in determining the percentage of total opaque wall area, the window area for the building has been removed from the frequency statistic (i.e., total wall area). Some buildings have their primary wall construction in CBECS characterized as vision or construction glass, which is not an opaque wall construction. Thus, these buildings tend to rank low on this list (compared to buildings ranked by total wall area including glazed area).

ASHRAE Standard 90.1-2004 defines four wall types based on the structural design of the wall. The four types are mass wall, metal building wall, steel-framed wall, and wood-framed and other wall. ASHRAE's primary assumption in setting the 90.1 U-factor requirements is that mass wall has continuous insulation, and metal building wall has insulation compressed between metal members, possibly augmented by continuous insulation to decrease the overall U-factor. Steel-framed and wood-framed and other walls are simply frame walls with different structural members—and, therefore, different thermal bypass factors. It is important that the definition of mass wall in ASHRAE 90.1-2004 is a wall with a heat capacity exceeding (1) 7 Btu/ft$^2$·°F for any weight wall or (2) 5 Btu/ft$^2$·°F provided that the wall has a material unit weight not greater than 120 lb/ft$^3$. Thus, regardless of the actual type and placement of insulation, walls exceeding this level of heat capacity are treated as mass wall for setting of minimum U-Factor requirements. The definition of mass wall is such that a 4-inch brick facing on a frame wall construction does not create a mass wall under ASHRAE 90.1's definition.

Comparing the four ASHRAE Standard 90.1-2004 wall types with the 2003 CBECS wall descriptions indicates that the Brick, Stone, and Stucco description could conceivably be mapped to any one of the four ASHRAE 90.1 wall constructions. This is problematic because the Brick, Stone, and Stucco description is the single most common description in the 2003 CBECS for all Benchmarks. These relationships between the ASHRAE Standard 90.1-2004 roof types and the 2003 CBECS wall descriptions are shown in Table 7.

**Table 6. Wall Descriptions by Benchmark (Post-1980 Buildings)**

| Benchmark Number | Benchmark Building Type | Wall Descriptions by Fraction of Opaque Wall Area | | Wall Descriptions by Fraction of Buildings | |
|---|---|---|---|---|---|
| 1 | Large Office | BSS | 44% | BSS | 48% |
| | | PCCP | 40% | PCCP | 30% |
| | | Vis. Glass | 4% | Vis. Glass | 8% |
| | | CBP | 4% | CBP | 6% |
| | | Cons. Glass | 3% | Cons. Glass | 5% |
| 3 | Small Office | BSS | 52% | BSS | 50% |
| | | SSTS | 19% | SSTS | 26% |
| | | SMP | 17% | SMP | 15% |
| | | CBP | 5% | CBP | 4% |
| | | PCCP | 4% | PCCP | 2% |
| 4 | Warehouse | SMP | 53% | SMP | 57% |
| | | PCCP | 14% | SSTS | 13% |
| | | BSS | 11% | BSS | 13% |
| | | CBP | 11% | CBP | 8% |
| | | SSTS | 10% | PCCP | 7% |
| 5 | Stand-Alone Retail | SMP | 36% | CBP | 33% |
| | | CBP | 28% | SMP | 28% |
| | | BSS | 19% | BSS | 20% |
| | | SSTS | 9% | SSTS | 14% |
| | | PCCP | 6% | PCCP | 3% |
| 10 | Fast Food | BSS | 71% | BSS | 66% |
| | | SSTS | 13% | CBP | 14% |
| | | CBP | 10% | SSTS | 12% |
| | | Vis. Glass | 3% | Other | 3% |
| | | Other | 3% | PCCP | 3% |

BSS – Brick, Stone, Stucco
CBP – Concrete, Block or Poured
SMP – Sheet Metal Panels
Cons. Glass – Construction Glass
PCCP – Pre-Cast Concrete Panel
SSTS – Siding, Shingles, Tiles, Shakes
Vis. Glass – Vision Glass

**Table 7. Crosswalk Matrix - CBECS Wall *Descriptions* and ASHRAE Standard 90.1 Wall *Constructions***

| CBECS Wall Descriptions | ASHRAE Standard 90.1 Wall Construction | | | |
|---|---|---|---|---|
| | **Mass Wall** | **Metal Building Wall** | **Steel-Framed Wall** | **Wood-Framed and Other Wall** |
| Brick, Stone, Stucco (BSS) | X | X | X | X |
| Concrete, Block, or Poured (CBP) | X | | | |
| Pre-Cast Concrete Panels (PCCP) | X | | | |
| Sheet Metal Panels (SMP) | | X | | |
| Siding, Shingles, Tiles, Shakes (SSTS) | | | X | X |
| Decorative or Construction Glass | | | X | |
| Window or Vision Glass | | | X | |
| No Major Type | Unknown | Unknown | Unknown | Unknown |
| Other | Unknown | Unknown | Unknown | Unknown |

The only wall descriptions that appear to be unambiguously mapped to the underlying construction are concrete, block, or poured and pre-cast concrete panels, all of which are expected to fall under Standard 90.1's mass wall construction and sheet-metal panels that can generally be assumed to indicate metal building walls. Buildings that report the use of "decorative or construction glass" or "window or vision glass" are believed to be very high WWR buildings. Many of these buildings are likely some type of curtain-wall construction. Curtain-wall construction falls under the 90.1 construction category of steel-framed wall.

Unfortunately, the single most common opaque wall category in CBECS is brick, stone, and stucco (BSS), which is also the most ambiguous category insofar as mapping to the 90.1 construction categories. Brick, stone, and stucco are all commonly used as material to dress up the façade of a building, and although brick and stone can both be the primary supporting construction material used in a building, we believe that to be a less-common approach for recent buildings because of cost. The question of what is the underlying 90.1 construction is most important for establishing the baseline 90.1-2004 U-factor requirements. However, any attempt to assign these CBECS wall types to 90.1 wall constructions used for the DOE Benchmarks will undoubtedly be laden with professional judgment. Our expectation is that the relative fraction of brick or stone over metal building construction would be small, and the primary question is whether these brick, stone, or stucco façades are over masonry or metal or wood frame walls.

Looking at the CBECS descriptions for specific Benchmarks, as in the Table 6 example, we see the following:

- For large office buildings, the high fraction of pre-cast concrete use, along with some fraction of mass underlying the BSS, seems to imply a near-even split between a metal frame wall- (curtain wall-) type construction and a mass wall construction.
- For small office buildings, it is clear that BSS predominates and that the obvious mass wall construction of Concrete, Brick or Poured (CBP) and Pre-Cast Concrete Panel (PCCP) represents a small fraction of opaque wall area. (< 20 percent for medium office and <10 percent for small offices).
- For warehouse buildings, it appears that metal panels, indicative of metal building construction, would represent the most common post-1980 construction.
- For stand-alone retail buildings, no underlying single recommendation is forthcoming from CBECS. Metal panels appear to be the most common single descriptor by total opaque wall area, although concrete block and/or poured concrete is the most common by number of buildings. Personal experience suggests that a BSS façade (commonly brick) over a metal frame construction is a very common example for the BSS category and that steel frame underlying siding is also common for small retail. Thus, this category as a whole seems to be nearly evenly split into thirds as metal buildings, steel frame (with BSS or siding façade) and mass wall (CBP or PCCP). This may partially be because of the wide range of building sizes in this category.
- For fast food restaurants, the very high fraction of BSS suggests that little guidance as to underlying wall construction can come from CBECS.

Table 8, Column 3 summarizes the characteristics of our CBECS analysis for wall type. In an attempt to improve the wall construction data for new buildings, data from the New Commercial Construction Characteristics (NC3) dataset (Richman et al. 2004) were extracted.

(The NC3 dataset provides data taken from building plans for proposed building designs being put out for bid and, therefore, is not subject to the same issues as CBECS wall description data.) Table 8 column 4 presents the results of that extraction by most common wall type by percent of wall area from NC3. While the sample size of NC3 is currently fairly low for most Benchmark building types (but being expanded), the results do provide some useful data. The final recommendations for wall types are show in **bold font** in columns 3 and 4 of Table 8. NC3 results were used to provide wall types for Benchmarks where it was unclear what CBECS would recommend. Where CBECS was clearer about wall types, we went with them; no attempt was made to override CBECS (column 3) with NC3 (column 4).

**Table 8. Wall Constructions Conclusion by Benchmark from CBECS and NC3**

| Benchmark Number | Benchmark Building Type | Wall Construction (CBECS) | Wall Construction (NC3) |
|---|---|---|---|
| 1 | Large Office | **Steel Frame Wall or Mass Wall** | NA |
| 3 | Small Office | No Recommendation | **Mass Wall** |
| 4 | Warehouse | **Metal Building Wall** | Mass Wall |
| 5 | Stand-Alone Retail | No Recommendation | **Mass Wall** |
| 10 | Fast Food | No Recommendation | **Wood Frame Wall** |

### Window-to-Wall Ratio

As noted previously, CBECS uses five different bins for classifying the percent exterior glass for each building (WWR bin) for those buildings reporting this statistic. Table 9 shows the fraction of total wall area (opaque and glass area) reported as glass calculated for all buildings that fall into each Benchmark category by WWR bin, again using the percent exterior glass assumptions from Table 2 (the midpoint of each range), and ignoring buildings where the window-to-wall area statistic was not reported. Table 9 also shows the average window area to total-wall-area ratio calculated for each Benchmark category considering all observations in that category. In establishing the relative impact of exterior glazing to opaque wall for an entire Benchmark category, this is possibly the most relevant statistic. What is important is that the average window-to-wall area fraction calculated for the entire building category is often higher than that typical of the most common bin.

**Table 9. Calculated Window-to-Wall Area Fraction for Post-1980 CBECS Buildings (Total Window Area Divided by Total Wall Area)***

| Benchmark Number | Benchmark Building Type | 10% or less | 11% to 25% | 26% to 50% | 51% to 75% | 76% to 100% | Average WWR |
|---|---|---|---|---|---|---|---|
| 1 | Large Office | 0% | 13% | 26% | **47%** | 13% | 54% |
| 3 | Small Office | **43%** | 34% | 16% | 6% | 1% | 19% |
| 4 | Warehouse | **92%** | 6% | 1% | 0% | 0% | 6% |
| 5 | Stand-Alone Retail | **66%** | 27% | 6% | 1% | 0% | 11% |
| 10 | Fast Food | 18% | 21% | **37%** | 25% | 0% | 34% |

* Window area fractions developed consider only those buildings where WWR was reported. For all buildings but office, the fraction not reporting is small (less than 12% of wall area not reporting and less than 10.5% of buildings by buildings represented). For Large Office, however, the fraction not reporting added up to 27% of total wall area and 15.4% buildings represented.

## Distribution of Glazing

CBECS 2003 also reports whether or not the glass in a building is distributed equally on all sides or not in the equal glass (EQGLS) statistic. The CBECS 2003 data for post-1980 buildings is shown in Table 10, based on buildings represented in the population. If it was clear that a building sample was heavily weighted (60% or greater) toward equal or unequal dispersion, this is noted in the last two columns.[4] Where the weighting was more or less equivalent, we have not suggested an approach, although it may make more sense from a modeling perspective to presume equal orientation.

Fast food restaurants appear, to us, an anomaly, as personal experience suggests that few, if any, have equal glazing on all sides. Rather, the glass is likely equally distributed in the dining area, but kitchen areas are seldom glazed. Our suggestion would be that these also be modeled as unequally distributed glazing (this conclusion was strongly borne out in examining the CBECS pre-1980 data).

**Table 10. Distribution of Glazing for Post 1980 Buildings**

| Benchmark Number | Benchmark Building Type | Fraction of Buildings with Equal Glazing Distribution | Fraction of Buildings with Unequal Glazing Distribution | More Equally Dispersed | Less Equally Dispersed |
|---|---|---|---|---|---|
| 1 | Large Office | 94% | 6% | X | |
| 3 | Small Office | 42% | 58% | | X |
| 4 | Warehouse | 66% | 34% | X | |
| 5 | Stand-Alone Retail | 19% | 81% | | X |
| 10 | Fast Food | 42% | 58% | | X |

## Mechanical Systems

Several pieces of information are available in CBECS regarding heating and cooling equipment. The most obvious source data are the Main Cooling Equipment and Main Heating Equipment data fields. For each building in the CBECS survey, the responder is asked what the "main cooling" and "main heating" equipment is. The categories for response are shown in Table 11.

**Table 11. CBECS Response Categories for Main Cooling and Heating Equipment**

| Main Cooling | Main Heating |
|---|---|
| Central chillers inside the building | Boilers inside the building |
| District chilled water | District steam or hot water |
| Heat pumps for cooling (HP) | Furnaces that heat air directly |
| Individual room air conditioners (IRAC) | Heat pumps for heating (HP) |
| Packaged air conditioning units (PACU) | Individual space heaters (ISH) |
| Residential type central air conditioners | Packaged heating units (PHU) |
| Swamp coolers or evaporative coolers | Some other heating equipment |
| Some other cooling equipment | |

[4] There were three building types that were heavily weighted one way or the other, but not quite at 60%. These include motel at 59% equally distributed and small office and fast food at 58% unequal distribution. These are marked as though they were heavily weighted as the 60% cutoff is fairly arbitrary.

CBECS also presents data on the percent of the building heated and cooled by the above equipment types based on the survey responses. Where heat pumps are utilized, the survey asks further questions of the type of heat pumps (e.g., water source, ground source, air source, packaged, split system, individual room) used for heating and cooling in the building. CBECS also presents data on whether a Variable Air Volume (VAV) system is used in the building as well as the main and secondary heating or cooling fuels (e.g., gas, electric) used.

Unfortunately, due to terminology, not all the CBECS responses regarding equipment use are mutually exclusive. Particular equipment categories that can create problems in interpreting the data are packaged heating units and furnaces. *Packaged Units* are defined by CBECS as: "A type of heating and/or cooling equipment that is assembled at a factory and installed as a self-contained unit." Packaged units are in contrast to engineer-specified units built up from individual components for use in a given building. Some types of electric packaged units are also called "Direct Expansion" or DX units." While this definition exists in the CBECS2003 glossary, the responses captured in the survey are for "Packaged Cooling Units" or "Packaged Heating Units." "Packaged heating units" may easily be interpreted as "boxes that provide heating" to many occupants; identifying whether it is a furnace, unit heater, packaged boiler, or a even a heat pump may be difficult for those responding to the survey, and so "packaged heating unit" could mean any of these other three categories. The most common "packaged heating unit" is expected to be a gas or electric warm-air furnace installed as part of packaged rooftop cooling unit. However, hydronic coils within a packaged heating unit served by a boiler could be considered a packaged heating unit.

A *Furnace* is defined by CBECS as**: "**A type of space-heating equipment with an enclosed chamber where fuel is burned or electrical resistance is used to heat air directly, without using steam or hot water. The heated air is then distributed throughout the building, typically by air ducts." A "Furnace" reply could refer to a gas or electric furnace in a packaged rooftop unit, a standalone gas or electric furnace, or a gas or electric furnace with a direct expansion coil as with a residential split-system furnace/air handler. Based on these two definitions, it is clear that a large potential overlap exists between the categories of Packaged Heating unit and furnaces, an overlap that cannot be easily disaggregated through other survey responses. Our expectation is that for the purpose of modeling a system either a furnace or packaged heating unit is synonymous with a gas or electric warm-air furnace.

To examine HVAC system selection, PNNL extracted data for all post-1980 CBECS buildings as mapped to the 15 benchmark building types. The results of these extractions are shown in Table 12 for the sample of five Benchmark types discussed previously. CBECS extractions and overall conclusions for mechanical system selections for the entire set of 15 benchmarks can be found in Winiarski et al. (2006).

The CBECS data show the most common HVAC types by Benchmark building type[5], viewed both by fractions of buildings reporting this as main heating or cooling equipment and on the basis of total-floor area served by each class of equipment.

[5] Large, Medium, and Small Office in this analysis were broken out using the NREL approach of Small referring to 1 story, Medium referring to 2-4 stories, and large referring to >4 stories. Other methods of categorizing these would presumably influence the relative equipment usage statistics for these office Benchmarks.

**Table 12. Post-1980 Buildings in 2003 CBECS**

| Benchmark Number | Benchmark Building Type | By Number of Buildings | | By Floor Area | |
|---|---|---|---|---|---|
| | | Heating | Cooling | Heating | Cooling |
| 1 | Large Office | Boiler 40%<br>PHU 20%<br>District 7% | PACU 43%<br>Chiller 39%<br>District 5% | Boiler 29%<br>PHU 18%<br>District 16% | Chiller 50%<br>PACU 27%<br>District 12% |
| 3 | Small Office | PHU 39%<br>Furnace 33%<br>HP 20% | PACU 43%<br>Res AC 33%<br>HP 20% | PHU 38%<br>Furnace 32%<br>HP 19% | PACU 49%<br>Res AC 26%<br>HP 18% |
| 4 | Warehouse | None 57%<br>Furnace 19%<br>PHU 10% | None 61%<br>PACU 17%<br>Res AC 13% | Furnace 29%<br>PHU 27%<br>None 27% | PACU 45%<br>None 26% |
| 5 | Stand-alone Retail | Furnace 43%<br>PHU 31% | PACU 42%<br>Res AC 28% | PHU 42%<br>Furnace 30% | PACU 73% |
| 10 | Fast Food | PHU 60%<br>Furnace 24% | PACU 73%<br>Res AC. 22% | PHU 63%<br>Furnace 20% | PACU 74%<br>Res AC 24% |

PACU – Packaged Air Conditioning Unit    Res AC – Residential Air Conditioner
PHU – Packaged Heating Unit    HP – Heat Pump

We also did an extraction of heating and cooling equipment with the cooling equipment choices further disaggregated depending on whether or not the building has a VAV system. CBECS does not state which cooling systems this response applies to within a building or what fraction of the building floor area might be served by the VAV system. Further, there is no information in CBECS to directly indicate the fraction of floor space that is covered by air-distribution systems that are multi-zone or single zone. We assumed that a VAV = "yes" response implies a multi-zone system somewhere in the building (although there may be exceptions, as when VAV is used for building pressurization control in hospitals or laboratories).

When a given system is specified, the relative fraction of systems reporting the use of VAV is expected to be different than what is shown in Table 12 (e.g., for a small office where the main cooling equipment was defined to be a packaged air conditioner, we might expect fewer reports of the use of VAV systems, than for small offices as a whole). To account for this, a second check was made by examining only buildings that actually reported as the main cooling equipment, those equipment determined as the most representative based on floor space served as reported in Table 13 and checking to see if building types that reported the majority using VAV for all buildings in the Benchmark subgroup still reported this when examining only that subset actually using the most representative equipment type as the main cooling equipment (with the presumption that district cooling implied hydronic cooling, which in the Benchmark implementation would be mapped as a chiller system). Upon review, whether or not the majority of the building floor space indicated use of a VAV did not appear to change whether we examined all buildings or only the subset identified above.

**Table 13. Total Floorspace in Buildings Reporting Use of VAV Systems**

| Number | Type | Post-1980 Fraction of Floor space reported with VAV* |
|---|---|---|
| 1 | Large Office | 84% |
| 3 | Small Office | 24% |
| 4 | Warehouse | 22% |
| 5 | Stand-alone Retail | 12% |
| 10 | Fast Food | 12% |

* Fraction of those responding to question    NA – Not Available

What follows (Table 14) is the set of recommendations for equipment and system type for the five Benchmark buildings discussed in this paper. These are based on the review of the CBECS data shown above, our interpretation of the most likely meaning of packaged heating units, the desire to lump hydronic systems (chiller/district cooling and boiler/district heating) together for purposes of modeling energy impacts with the Benchmark models, and the desire to capture the most floor space served within benchmark categories.

**Table 14. PNNL Recommendations for Post-1980 Buildings – HVAC Equipment and Air Distribution**

| | | PNNL Recommendation | | |
|---|---|---|---|---|
| **Number** | **Type** | **Heating** | **Cooling** | **Air Distribution** |
| 1 | Large Office | Boiler | Chiller | MZ VAV |
| 3 | Small Office | Furnace | PACU | SZ CAV |
| 4 | Warehouse | Furnace | PACU | SZ CAV |
| 5 | Stand-alone Retail | Furnace | PACU | SZ CAV |
| 10 | Fast Food | Furnace | PACU | SZ CAV |

PACU – Packaged Air Conditioning Unit
SZ - Single Zone    MZ - Multi-Zone
CAV - Constant Volume    VAV – Variable Air Volume

## Conclusion

Our conclusion is that the Commercial Building Energy Consumption Survey can provide useful estimates of roof and wall construction, window-to-wall ratio, and heating and cooling equipment if sufficiently analyzed, and that this data can help provide information useful for developing prototypical buildings similar to DOE's Benchmarks. This paper outlines how CBECS data was used to identify "most typical" values of several key envelope construction and HVAC equipment selection. However, in the case of the envelope in particular, the data provided by CBECS are still limited and do not fully describe the underlying construction of the opaque surfaces, so other assumptions must be used in combination with the CBECS data to arrive at recommendations for the Benchmark buildings. Details on this process for other Benchmark models can be found in the reference literature.

## References


Deru M and B Griffith. 2006. *DOE Commercial Building Research Benchmarks For New Commercial Buildings*. Third Draft. National Renewable Energy Laboratory. Golden, Colorado.

Deru M, P Torcellini, B Griffith, M Halverson, D Winiarski, D Crawley. 2008. *DOE Commercial Building Benchmark Models*. In 2004 ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy-Efficient Economy, Washington, D.C.

EIA – Energy Information Administration. 1994. *1992 Commercial Building Energy Consumption Survey (CBECS)*. U.S. Department of Energy. Washington, D.C. Available at http://www.eia.doe.gov/emeu/cbecs/.

EIA – Energy Information Administration. 2006. *2003 Commercial Building Energy Consumption Survey (CBECS)*. U.S. Department of Energy. Washington, D.C. Available at http://www.eia.doe.gov/emeu/cbecs/.

Richman EE, JR Williams, RK Biyani, and SC Gaines. 2004. *Energy-Related Commercial Building Construction Characteristics: An Assessment of National Current Practice and Energy Code Compliance*. In 2004 ACEEE Summer Study on Energy Efficiency in Buildings, p. 12. American Council for an Energy-Efficient Economy, Washington, DC.

Skyscraper Source Media. 2007. The Tall Buildings Database. www.skyscraperpage.com. Skyscraper Source Media, Victoria, British Columbia, Canada.

Winiarski DW, MA Halverson, and W Jiang. 2007. "Analysis of Building Envelope Construction in 2003 CBECS Pre-1980 Buildings." PNNL-SA-55594, Pacific Northwest National Laboratory, Richland, Washington.

Winiarski DW, W Jiang, and MA Halverson. 2007. "Analysis of Building Envelope Construction in 2003 CBECS Post-1980 Buildings ." PNNL-SA-55888, Pacific Northwest National Laboratory, Richland, Washington.

Winarski, DW, W. Jiang, and MA Halverson. 2006. Review of Pre- and Post-1980 Buildings in CBECS – HVAC Equipment. In clearance. Pacific Northwest National Laboratory, Richland, Washington.