Introduction

The commercial sector is one of the four major end-use sectors in the United States, accounting for 17.7 percent of total primary energy consumption in 2003 (EIA 2011). Between 1989 and 2003, U.S. commercial sector primary energy consumption grew by 31.4 percent compared with 20.1 percent in transportation, 18.7 percent in residential, and 3.9 percent in industrial sectors (EIA 2011). Consequently, carbon dioxide emissions by the commercial sector also grew faster than any other sector during this period. Most energy consumption in the commercial sector occurs within buildings, for example, in 2003, buildings accounted for about 97 percent of the total. Because of the importance of commercial buildings energy use to the environment and the economy, this study is undertaken to help provide a better understanding of the factors affecting energy consumption and intensity within energy using buildings in this sector.

Data

The U.S. Energy Information Administration, Commercial Buildings Energy Consumption Survey (CBECS), is the most detailed energy-related data available for commercial buildings and is the main source of data for this report.1 Currently conducted quadrennially, CBECS is a national-level sample survey of buildings greater than 1,000 square feet in size that devote more than 50 percent of their floorspace to commercial activity.2 CBECS data are developed from a multistage area probability statistical sample designed to provide estimates of national and regional data. CBECS is supported by an extensive questionnaire that includes a wealth of information covering building characteristics. CBECS also provides estimated energy consumption for several key end uses developed based on regression

1 A CBECS survey was conducted in 1979, after which surveys were done triennially from 1983 to 1995 and quadrennially since 1995. This study focuses on 1989 through 2003 since previous surveys did not provide data on a consistent basis. Furthermore, the estimation results reported are all based on all buildings using energy, and may differ from the figures reported on the CBECS website.
2 The commercial sector consists of business establishments and other organizations that provide services. The sector includes service businesses (e.g., retail and wholesale stores, hotels, restaurants), public and private schools, correctional institutions, and religious and fraternal organizations. Excluded from the sector are the goods-producing industries (e.g., manufacturing, agriculture, mining, forestry and fisheries, and construction).
models relating energy consumption to relevant building characteristics. CBECS is most recently available for the year 2003.\(^3\) A time-series analysis of national CBECS data from 1989 to 2003 is the main focus of this report.

### Overview of Energy Consumption

In 2003, CBECS estimates that U.S. commercial buildings consumed more than 6.5 quadrillion Btu (quads) of site energy, the sum of electricity, natural gas, fuel oil and district heat.\(^4\) Commercial buildings energy consumption grew faster than the stock of buildings and floorspace, which increased the aggregate energy intensity over the 14-year period. Between 1989 and 2003 commercial buildings site energy increased by 1.2 quads or 20.1 percent.\(^5\) Over this same interval, the number of buildings grew by 11.4 percent and total floorspace by 18.3 percent. Thus, aggregate energy intensity increased by 8.7 percent on a per building basis and 1.9 percent on a per square foot basis.

### Methodology

Aggregate energy intensity as used here is defined as total commercial site energy consumption per square foot of total floorspace. Changes in aggregate energy intensity include the effects of three major structural factors: changes in the mix of commercial activities (e.g., health care, retail sales, and food service), the regional distribution of buildings, and the average size of buildings within types and regions. Decomposed intensity isolates changes in energy conservation and energy efficiency from aggregate energy intensity by separately quantifying the impacts of the aforementioned structural effects. This study applies a decomposition technique to isolate the impact of the three main components affecting commercial buildings energy consumption: activity, structural changes, and intensity:

- activity is defined as the number of buildings,
- three structural factors are analyzed: shifts in the composition of building types, the regional distribution of buildings across U.S. Census regions, and the average floorspace per building within regions and types, and

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\(^3\) The 2007 CBECS did not yield valid statistical estimates of building counts, energy characteristics, consumption, and expenditures for the U.S. commercial building population. Because the data do not meet EIA standards for quality, credible energy information, neither data tables nor a public use file were released.

\(^4\) The Btu value of energy at the point it enters the home, building, or establishment, is referred to as delivered or site energy. It does not include losses that occur in the generation, transmission, and distribution of energy.

\(^5\) For consistency with the decomposition of energy consumption changes into component effects, all reported percentage changes related to decomposition are logarithmic.
• decomposed intensity is defined as the ratio of site energy consumption to floorspace area after accounting for the impacts of structural factors.

Since 1920, numerous methods have been used for decomposing the effects of changes in underlying factors as they contribute to changes in an aggregate concept. The logarithmic mean Divisia (LMDI) method introduced by Ang and Choi (1997) was the first method to provide a “perfect” decomposition which does not leave a residual term. In the present context, the impacts of changes in the underlying factors exactly partition the change in total energy consumption. Ang, Liu and Chew (2003) present a review of extant methods and use the nomenclature Log Mean Divisia Index method II (LMDI-II) to describe their 1997 methodology. 6

The results which follow are based on the LMDI-II method due to its wide use in the literature, relative ease of computation and perfect partitioning of factor impacts. Construction of the decomposition methodology with notation for the present context of commercial building energy intensity is described in Appendix B.

Factors Affecting Energy Consumption

Building Type

Most energy consumption in the commercial sector occurs within commercial buildings. 7 Unlike residential buildings, a wide variety of heterogeneous activities are performed in commercial buildings. In 2003, CBECS characterized 100 specific activities and 14 principal building activities. To provide a more manageable analysis and also to be consistent with the National Energy Modeling System (NEMS), a higher-level classification into 11 categories is used. 8 The type of commercial activity in the building influences the mix of end use services provided in a building (e.g., water heating, cooking, lighting, elevator and escalator transport, medical imaging, etc.) and ultimately how much energy a building consumes. In 2003, mercantile and service accounted for the most energy consumption while food sales

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6 Boyd and Roop (2004) demonstrate another perfect decomposition methodology based on the Fischer index; however, it is computationally burdensome with the required calculations expanding factorially with the number of factors analyzed.
7 Non-building energy consumption includes outdoor/street lighting and municipal uses (e.g., municipal water supply and treatment).
8 The eleven activities are: assembly, education, food service, food sales, health care (inpatient), lodging, large offices (>50,000 square feet), small offices (<=50,000 square feet), mercantile and service, warehouse, and other. CBECS aggregates activities into 14 principal building activities: education, food sales, food service, health care, lodging, mercantile, office, public assembly, public order and safety, religious worship, service, warehouse and storage, other, and vacant. To test the sensitivity of intensity estimates to the building category choice we performed additional analysis (Appendix A) by aggregating to just 5 types based on grouping similar intensities and trying to get more even numbers of buildings in each category. We also summarize analysis with and without regions in the appendix table.
grew faster from 1989 than other building types with respect to energy consumption. Mercantile and service buildings, which are relatively less energy intensive, accounted for 27.2 percent of buildings, 21.6 percent of floorspace, and 20.4 percent of total commercial buildings energy consumption in 2003 (Figures 1 and 2). On the other hand, health care buildings, which are the second most energy intensive, accounted for 0.2 percent of buildings, 2.7 percent of floorspace, and 7.3 percent of energy consumption.

Figure 1. Distribution of commercial buildings energy consumption, number of buildings, and floorspace by building type, 2003

Figure 2. Energy intensity per square foot by building type, 2003

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9 For consistency with the decomposition of energy consumption the shares are computed based on all buildings using energy.
Because energy intensity across the building types varies by more than a factor of 5 (Figure 2), changes in the composition of building types have the potential to greatly impact the aggregate commercial intensity.

Size Effects

Over the 14-year period, aggregate average floorspace per building grew by 6.8 percent with substantial variation in growth rates across building types and Census regions (Figures 3 and 4). The average size of health care buildings grew by over 240 percent\(^\text{10}\), while three building types experienced reductions in average size. Wide variation across Census regions also occurred: the average size of buildings in the South grew fastest, by over 20 percent, while the average size of buildings in the Midwest decreased by more than 5 percent.

Figure 3. Percent change in average floorspace per building by type category, 1989-2003

\(^{10}\) Our health care category is for inpatient facilities only (versus combined inpatient and outpatient in all the published CBECS tables, except CBECS 2003, which split into subcategories). Inpatient health care is one of the most intensive energy users, but represents the smallest number of buildings and thus has relatively large standard errors compared with other building categories with larger building populations. However, this increase in floorspace was highly significant; by pre-aggregating further, the unique intensity features of these types of buildings would be lost.
Fuel Source Changes

Over the study period, electricity consumption in commercial buildings has grown at a faster rate than other energy sources with the mix shifting away from natural gas and fuel oil (Figure 5). In 1989 electricity accounted for 47.6 percent of site energy consumption, natural gas 36.8 percent, and fuel oil 6.1 percent. Electricity continued to be the main energy source in commercial buildings throughout the period. In 2003, the share of electricity increased to 54.6 percent, the natural gas share declined to 32.2 percent, and the share of fuel oil declined to 3.5 percent. The share of district heat in 2003 was similar to that of 1989.
While the fuel mix by building is not a separate decomposition element, intensity effects are expected to vary on a fuel-by-fuel basis. To show the fuel-specific features, separate decompositions are presented for total site energy, electricity, and natural gas consumption.

Regional Distributions

Between 1989 and 2003, the regional distribution of buildings shifted slightly towards the Midwest Census region of the U.S. (Figure 6). The share of buildings in the Midwest increased by 15 percent, whereas the shares in the Northeast and South regions declined by 8 percent and 5 percent, respectively. This shift has implications for aggregate energy intensity since energy consumption per square foot varies by region (Figure 7). However, as will be shown later we do not expect the impact of regional distribution to be significant.11

Figure 6. Distribution of commercial buildings by Census region, 1989, 1995, and 2003

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11 In Appendix A we present the decomposition results both with and without a regional effect.
Results

Decompositions of U.S. commercial buildings energy consumption are presented for total site energy, electricity and natural gas for both the entire period and specifically for 1995 split into two sub-periods. The 1995 survey is close to the midpoint of the interval and its choice was further motivated by its usefulness as a demarcation point for the increasing prevalence and effectiveness of energy efficiency
standards. To focus the discussion, results for the two sub-periods are provided in a separate section following the discussion for the entire time period.

**Decomposition of National Effects for 1989-2003**

**Total Energy**

Figure 8 summarizes the decomposition results at the national level for the 1989 to 2003 period during which commercial buildings energy consumption increased by 20.1 percent. The increase in the average size of buildings was the main driver of this increase in energy consumption followed by growth in the number of buildings. Under LMDI-II, there is no difference between the aggregate and the decomposed effect for the activity variable, thus growth in the number of buildings *ceteris paribus* increased energy consumption by 11.4 percent. The decomposed impact of floorspace per building was 18.9 percent, compared with the previously noted 6.8 percent growth in aggregate average size of buildings. This disparity indicates that building sizes were increasing most in the more energy intensive building types and/or regions. The combined effects of the number of buildings and average size together would have increased energy consumption in commercial buildings by 30.3 percent.

These two factors forcing toward higher demand for energy were partially offset by the estimated 9.8 percent reduction in consumption associated with changes in composition of building types as well as a decline of 1.1 percent in decomposed intensity per square foot. The decomposition results in a reversal of the direction of intensity effect versus the aggregate intensity presented in the overview section. The decomposition analysis estimates an intensity decline of 1.1 percent versus the aggregate intensity growth of 1.9 percent.

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13 To streamline the ensuing discussion, whenever individual effects are described they will refer to *ceteris paribus* conditions, meaning all other factors remain unchanged unless otherwise stated.
14 Energy consumption over the period of study has also been impacted by Federal equipment standards, state and local building energy codes, Federal and state tax credits, as well as other voluntary programs such as Energy Star buildings.
15 To test the sensitivity of decomposition results to the choice of categories we aggregated building types in 5 sub-categories based on grouping similar intensities and trying to get an even number of buildings in each. The five types are: warehouse and assembly, small offices and education, mercantile and services, other and lodging, and food sales and food services. The results of decomposition using these 5 categories (with and without regional effects) are reported in Appendix A. The building type attributions are indeed sensitive to the choice of categories, but the intensity results are much more stable and different from the aggregate intensity (Tables A1 and A2).
Defining the reduction in consumption as the amount of energy that would have been consumed if factors had remained at their 1989 levels, the building type mix and intensity effect had large impacts on energy consumption, reductions of 0.6 and 0.1 quads, respectively. Since U.S. commercial buildings consumed 6.5 quads of energy in 2003, without changes in the building type mix and energy intensity reduction they would have instead used 7.2 quads, about 11 percent more.

Figure 8. Decomposition of percent change in total energy consumption, 1989-2003
Total Electricity

There were significant differences in the energy history as well as the decomposition results for electricity use versus total site energy. Between 1989 and 2003 electricity consumption increased faster than total energy (Figure 9), by 33.8 percent compared with a total site energy increase of 20.1 percent. One of the key reasons for the more rapid growth in electricity consumption is the increasing number of new miscellaneous electric end uses as well as increasing penetration of these and more traditional end uses.\(^{16}\) Aggregate electricity intensity increased by 15.4 percent between 1989 and 2003 versus only 1.9 percent for total site energy.

Figure 9. Decomposition of total electricity, 1989-2003

The decomposed electricity intensity effect acted to increase energy consumption, but the effect was about 36 percent lower than the calculated aggregate intensity change. This represents a substantial difference, with intensity increasing energy consumption by 11.3 percent, nearly as great as the impact of the growth in the number of commercial buildings. This result is a consequence of the growth and penetration of miscellaneous electric end uses. At the same time, the effect of change in building type composition was toward less intensive types, -6.3 percent, less pronounced than for total site energy.

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\(^{16}\) Miscellaneous equipment includes computers and printers, other office equipment, medical imaging and diagnostic equipment, etc. For example, in the 1989 CBECS, the use of desktop computers was rare enough that questions concerning their use were not asked.
Natural gas

Figure 10 summarizes the decomposition results for natural gas consumption. An estimated 35.7 percent of natural gas consumption in 2003 was in the Midwest. Mercantile and service, education, lodging, and health care buildings consumed more than 50 percent of natural gas in 2003. Between 1989 and 2003 natural gas consumption grew more slowly than total site energy or electricity consumption, by 6.8 percent (Figure 10) compared to 20.1 percent and 33.8 percent, respectively. In this decomposition the building effect is different from the first two decompositions, since only a subset of buildings use natural gas. The impact of the growth in the number of buildings using natural gas is only 7.6 percent versus 11.4 percent for total site. Over this period, aggregate energy intensity per square foot of floorspace decreased by 12.6 percent.

The decomposition results are also quite different than for the other cases. Perhaps most notable is that the decomposed intensity exhibits an 18.7 percent decline; this is almost 50 percent greater than the calculated aggregate intensity decline – and underscores the importance of quantifying structural effects instead of relying on aggregate statistics. The natural gas intensity decline contrasts dramatically with the intensity increase of 11.3 percent for total electricity consumption – over this period the use of energy per square foot in buildings shifted dramatically toward electricity, with a 1.1 percent decline in decomposed

Figure 10. Decomposition of natural gas, 1989-2003

<table>
<thead>
<tr>
<th>Number of Buildings</th>
<th>Region</th>
<th>Building Type</th>
<th>Average Size</th>
<th>Energy Intensity</th>
<th>Total Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>7.6</td>
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<td></td>
<td></td>
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<tr>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The regional shift effect was more significant than was found in either the total site energy or the electricity analyses, accounting for a 2.0 percent increase in natural gas consumption.

17 For the decomposition of natural gas only buildings using natural gas as a fuel were included.
This is consistent with the shift in location of commercial buildings using natural gas towards the Midwest and Northeast with increasing heating requirements. Converted to energy terms, the natural gas intensity decline translates into an estimated reduction in consumption of 0.4 quads.

Natural gas is mostly used for space heating, which was also influenced by other factors such as improvements in energy efficiency of buildings, weather, and fuel prices, not considered in our analysis. Using heating degree-days as a measure of winter weather,\textsuperscript{18} there were 5.6 percent fewer heating degree days in 2003 than 1989 which would also imply lower intensity in 2003.\textsuperscript{19} Real natural gas prices were 26.9 percent higher in 2003 than in 1989, while electricity prices declined by 14.8 percent over the same period. As a possible response to the higher prices, the purchased efficiency of new and replacement natural gas space heating equipment could increase, further reducing the heating component of intensity. However, since heating equipment can last 30 years or more, a lagged response to the rise in natural gas prices could impact the replacement of furnaces with the more efficient units. As will be shown later, the impact of change in intensity is sensitive to the time period of analysis.


\textbf{Total Energy}

In this section, the 1989-1995 and 1995-2003 sub-periods are considered separately to help in understanding the changes in energy consumption. The change in energy consumption was significantly different between the two periods (Figure 11). Energy consumption decreased by 0.2 percent between 1989 and 1995 but grew by 20.4 percent between 1995 and 2003. Growth in the first sub-period from increases in the number of buildings, regional distribution and energy intensity (6.7 percent) was offset by the negative impacts of building size and building type mix (-7.0 percent). From 1995 to 2003, even though the percentage change in building type declined more than six times faster than in the earlier sub-period, the number of buildings grew somewhat faster and the average size of buildings grew by about 24.6 percent. Energy intensity declined, contrary to the increase during the 1989-1995 period. The net of all these effects was an increase of 20.4 percent in total energy consumption during the latter sub-period.

\textsuperscript{18} Heating degree days is a measure of how cold a location was over a period of time, relative to a base temperature. In this paper it is the number of days temperature was below 65 degrees Fahrenheit in one year.

\textsuperscript{19} In Hojjati and Wade (2012), weather was included as a structural factor in the decomposition of residential energy consumption. For commercial buildings, which tend to be less weather sensitive, the statistical analysis supporting weather decomposed consumption is less definitive and not incorporated as a quantified effect here.
The change in electricity consumption for 1995-2003 was 31.1 percent, compared with 2.7 percent for 1989-1995 (Figure 12). As mentioned before, the higher growth in intensity during 1995-2003 is likely partially driven by new and expanding electric end uses which offset the impact of energy efficiency improvements. The most significant change in the latter sub-period was the 22.9 percent growth in the average size of buildings which was much larger than the negative impacts of type, and region effects. The positive intensity effect of electricity was larger in the second sub-period.
Natural Gas

Despite the decline in energy intensity in the post-1995 sub-period, total natural gas consumption increased by 7.6 percent during this time period (Figure 13). This increase was mainly due to the 28.0 percent increase in the average size of buildings, which more than offset any other factors that effected decreases in natural gas consumption. Contrary to the latter period, natural gas consumption declined slightly during 1989-1995. This decline in the first sub-period stems from declines in the region, type, and average size effects, which more than offset the positive impact of the building effect. The region effect in the post-1995 sub-period was more significant than for the other two decompositions. Also the increase in the number of buildings using natural gas in the second sub-period was smaller than in the first period.

Figure 13. Decomposition of natural gas consumption, 1989-1995 and 1995-2003

Conclusion

The results show that change in the mix of the 11 building types was the dominant reducing effect for total energy consumption and total electricity consumption, *ceteris paribus*. Contrasting with the other two energy consumption concepts, building mix was still an important reducing effect for total natural gas, but intensity reduction was the dominant effect, roughly three times larger than building mix. Potential reasons for this reduction were noted – more efficient heating equipment potentially resulting from standards as well as rising natural gas prices, and lower heating requirements based on generally warmer weather in 2003.
When analyzing two sub-periods split in 1995, we found that an increase in the average size of buildings in the post-1995 sub-period had the largest increasing effect on energy consumption. Except for total electricity consumption, energy intensity per square foot declined faster in the second sub-period, which could be a reflection of the increasing prevalence and effectiveness of energy efficiency standards. The positive intensity effect of electricity was larger in the second sub-period. This increasing intensity has implications for any policy aimed at sustainability and reducing carbon dioxide.

To test the sensitivity of decomposition results to the choice of categories we aggregated building types in 5 sub-categories. We found that the building type attributions are indeed sensitive to the choice of categories, but the intensity results are much more stable as well as significantly different from the calculated aggregate intensities.

References


## Appendix A. Additional Decomposition Results and Data

Table A1. Decomposition results by different building type categories with and without regions

<table>
<thead>
<tr>
<th></th>
<th>No Regions, 11 Types</th>
<th>No Regions, 5 Types</th>
<th>Regions, 5 Types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>2003</td>
<td>2003</td>
</tr>
<tr>
<td>Total Energy</td>
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<td></td>
<td></td>
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<tr>
<td>Number of Buildings</td>
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<td>NA</td>
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<tr>
<td>Building Type</td>
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<td>-9.5</td>
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<td>Energy Intensity</td>
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<td>-1.4</td>
<td>-0.2</td>
</tr>
<tr>
<td>Total Change</td>
<td>-0.2</td>
<td>20.4</td>
<td>20.1</td>
</tr>
<tr>
<td>Total Electricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Buildings</td>
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<td>6.4</td>
<td>11.5</td>
</tr>
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<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Building Type</td>
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<td>-5.9</td>
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<td>Average Size</td>
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<td>14.9</td>
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<td>13.3</td>
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<tr>
<td>Total Change</td>
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<td>Total Natural Gas</td>
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<td>Building Type</td>
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<td>-8.0</td>
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<td>-17.7</td>
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<tr>
<td>Total Change</td>
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<td>6.8</td>
</tr>
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</table>


Note: NA=Not applicable.
Table A2. Comparison of aggregate and decomposed energy intensity by building types

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<th>Site Energy</th>
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<td>1995</td>
<td>2003</td>
<td>1995</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate (no decomposition)</td>
</tr>
<tr>
<td>11 Building Types</td>
</tr>
<tr>
<td>5 Building Types</td>
</tr>
<tr>
<td>No Regions, 11 Types</td>
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<td>No Regions, 5 Types</td>
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<table>
<thead>
<tr>
<th></th>
<th>1989</th>
<th>1995</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Energy Consumption (trillion Btu)</td>
<td>5,333</td>
<td>5,321</td>
<td>6,523</td>
</tr>
<tr>
<td>Total Floorspace (million square feet)</td>
<td>58,489</td>
<td>57,214</td>
<td>70,203</td>
</tr>
<tr>
<td>Number of Buildings (thousand)</td>
<td>4,121</td>
<td>4,351</td>
<td>4,620</td>
</tr>
<tr>
<td>Average Floorspace (thousand square feet)</td>
<td>14.2</td>
<td>13.1</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Appendix B. Development of LMDI-II Methodology

As mentioned in the report, we distinguished among three main components affecting commercial buildings energy use within a Census region: activity, structure, and energy intensity. The decomposition methodology was applied first to each of the four Census regions to isolate the effects of these components.

We applied equations below to each Census region; U.S. national results are developed in a “second stage” using an LMDI-II analysis that combines Census regions. The total energy consumption for a decomposition including 11 building types for each region can be expressed as:

\[
E = BD \sum_{i=1}^{11} \left( \frac{BD_i}{BD} \cdot \frac{SQFT_i}{BD_i} \cdot E_i \right) = BD \sum_{i=1}^{11} \frac{E_i}{BD} = \sum_{i=1}^{11} E_i
\]

where

\( E \) = total energy consumption\(^{20} \),  
\( i \) = represents the 11 types of buildings,  
\( BD \) = total number of buildings,  
\( BD_i \) = number of building type \( i \),  
\( SQFT_i \) = total floorspace of building type \( i \),  
\( E_i \) = energy consumption in building type \( i \),

Let

\[
\frac{BD_i}{BD} = S_i \quad \text{share of building type } i
\]

\[
\frac{SQFT_i}{BD_i} = F_i \quad \text{average floorspace of building type } i
\]

\[
\frac{E_i}{SQFT_i} = I_i \quad \text{average energy intensity of building type } i
\]

\(^{20}\) All of the variables in the following equations also pertain to particular time periods and have an implicit time dimension, \( t \), omitted for ease of notation until required for the decomposition equations beginning at expression (8) below.
Then expression (1) can be written as

\[ E = BD \sum_{i=1}^{11} S_i F_i^* I_i \]  

(2)

The derivative of Equation (2) with respect to time (applying the product rule) is

\[ \frac{dE}{dt} = \sum_{i=1}^{11} S_i F_i^* I_i \frac{dBD}{dt} + \sum_{i=1}^{11} BD S_i F_i^* I_i \frac{dS_i}{dt} + \sum_{i=1}^{11} BD S_i F_i^* I_i \frac{dF_i}{dt} + \sum_{i=1}^{11} BD S_i F_i^* I_i \frac{dI_i}{dt} \]  

(3)

By dividing both sides of equation (3) by \( E \) and replacing \( \frac{1}{E} \frac{dE}{dt} \) with \( \frac{d \ln E}{dt} \) we obtain the following expression:

\[ \frac{d \ln E}{dt} = \frac{1}{E} \frac{dE}{dt} = \frac{1}{E} \left( \sum_{i=1}^{11} BD S_i F_i^* I_i \frac{d \ln BD}{dt} + \sum_{i=1}^{11} BD S_i F_i^* I_i \frac{d \ln S_i}{dt} \right) + \sum_{i=1}^{11} BD S_i F_i^* I_i \left( \frac{d \ln F_i}{dt} + \frac{d \ln I_i}{dt} \right) \]  

(4)

Since the share of energy in the \( i \)th building type is

\[ \frac{BD S_i F_i^* I_i}{E} = \frac{E_i}{E} = e_i , \]  

(5)

The growth rate of energy in continuous time can be expressed as the weighted average growth rates of the components

\[ \frac{d \ln E}{dt} = \sum_{i=1}^{11} e_i \left( \frac{d \ln BD}{dt} + \frac{d \ln S_i}{dt} + \frac{d \ln F_i}{dt} + \frac{d \ln I_i}{dt} \right) \]  

(6)

The discrete approximation to expression (6) between year 0 and \( t \) is obtained by integrating both sides of expression (6) from year 0 to \( t \), so the percentage change in total energy consumption between year 0 and \( t \) for each Census region can be written as

\[ \ln \left( \frac{E_t}{E_0} \right) = \sum_{i=1}^{11} \left( \int_0^t e_i \frac{d \ln BD}{dt} \, dt + \int_0^t e_i \frac{d \ln S_i}{dt} \, dt + \int_0^t e_i \frac{d \ln F_i}{dt} \, dt + \int_0^t e_i \frac{d \ln I_i}{dt} \, dt \right) \]  

(7)
By applying the LMDI II method and integration rules to expression (7) we obtain the following expression:

\[
\ln \left( \frac{E_t}{E_0} \right) = \sum_{i=1}^{11} w_{it} \ln \left( \frac{BD_i}{BD_0} \right)
\]

number of buildings effect\(^{21}\)

\[
+ \sum_{i=1}^{11} w_{it} \ln \left( \frac{S_{it}}{S_{i0}} \right)
\]

building type effect

\[
+ \sum_{i=1}^{11} w_{it} \ln \left( \frac{F_{it}}{F_{i0}} \right)
\]

average size effect

\[
+ \sum_{i=1}^{11} w_{it} \ln \left( \frac{I_{it}}{I_{i0}} \right)
\]

energy intensity effect

\[
(8)
\]

where \(w_{it}\) is the log-mean weight specified as

\[
w_{it} = L(e_{i0}, e_{it}) = \frac{(e_{it} - e_{i0})}{\ln \left( \frac{e_{it}}{e_{i0}} \right)}
\]

(9)

and

\[e_{it} = \text{represents the share of energy in the } i^{th} \text{ building type at year } t\]

\[L(e_{i0}, e_{it}) = \text{the log-mean weight function}\]

The final weights \((w_{it}^*)\) are normalized to sum to one:

\[
w_{it}^* = \frac{L(e_{i0}, e_{it})}{\sum_{i=1}^{11} L(e_{i0}, e_{it})}
\]

(10)

\(^{21}\) At the U.S. level, the region effect is calculated as the difference between the simple growth in the aggregate number of buildings and the decomposed number of buildings effect from the 2-stage LMDI-II analysis for combined regions.