Introduction
In 2014, the industrial sector accounted for about 34% of U.S. total delivered energy consumption. The manufacturing sector dominates total industrial energy consumption. In 2014, the manufacturing sector accounted for about 82% of the energy consumption in the industrial sector and 28% of the U.S. total delivered energy consumption (EIA 2016). Energy efficiency improvement is widely recognized as an important tool for reducing energy consumption. To this end, the historical trends of energy consumption and energy intensity are also of interest. This study reviews energy consumption trends in manufacturing over the 1998 to 2014 period, and examines the influence of key factors driving changes in energy use to help decision makers to better understand these changes. It utilizes a decomposition methodology to analyze the overall change in manufacturing energy consumption.

Data
Energy consumption data in this report come from the U.S. Energy Information Administration’s (EIA) Manufacturing Energy Consumption Survey (MECS). The MECS is a nationally representative sample survey that collects consumption data of various energy sources by U.S. manufacturers. It also provides data on the number of U.S. manufacturing establishments, their energy-related building characteristics, and their energy expenditures.

period, MECS was conducted every four years, and analyzing the sequence of surveys leads to four sub-intervals for more detailed analysis. MECS provides energy data for fuel use and non-fuel use (feedstock or raw material input) for 21 industrial subsectors (3-digit NAICS codes). Energy for manufacturing is mostly used as a fuel. In 2014, energy used as a fuel accounted for about 74% of manufacturing energy consumption. The analysis in this report focuses on first use of energy for fuel purposes.

Measure of industrial gross output is obtained from the Department of Commerce, Bureau of Economic Analysis (BEA) website. The grouping of the manufacturing industries in the decomposition analysis is based on BEA’s classification of industries for gross output.

Methodology
Aggregate energy intensity, defined as energy consumption per unit of an overall activity level is often used inaccurately as a proxy for energy efficiency.\(^1\) Although energy efficiency affects energy intensity, various non-efficiency (structural) factors such as shifts in activity among sectors, or changes in the mix of activities within sectors also contribute to changes in energy intensity.\(^2\)

To better understand changes in manufacturing energy consumption, the analysis identified three main components affecting manufacturing energy consumption:

- **Activity** refers to the value of manufacturing gross output
- **Structure** is represented by the mix of the industry types
- **Intensity** is defined as energy per unit of manufacturing output

\(^1\) Energy efficiency is defined as the ratio of services provided per unit of energy input.
\(^2\) Energy intensity is also affected by changes in fuel prices and energy conservation, but these factors are not separately considered in the decomposition analysis.
Over the years different methods have been described to decompose the structural and energy intensity effects. This study used the logarithmic mean Divisia method proposed by Ang and Choi (1997) that gives exact decomposition with no unexplained residual effect.³

To separate the effects of the three factors, energy use for \( m \) types of industry at year \( t \) was expressed as the product of real value of output, structure, and intensity:

\[
E_t = \sum_{i=1}^{m} E_{it} = \sum_{i=1}^{m} GO_{it} * \frac{E_{it}}{GO_{it}} = GO_t * \sum_{i=1}^{m} \frac{GO_{it}}{GO_t} * \frac{E_{it}}{GO_{it}} = GO_t * \sum_{i=1}^{m} S_{it} * I_{it},
\]

(1)

where

- \( E_t \) = total energy consumption at year \( t \);
- \( GO_t \) = total value of manufacturing output at year \( t \);
- \( GO_{it} \) = total value of manufacturing in \( i \)th industry at year \( t \);
- \( E_{it} \) = energy use in industry \( i \) at year \( t \);
- \( S_{it} \) = output share of industry \( i \) at year \( t \); and
- \( I_{it} \) = energy intensity in industry \( i \) at year \( t \).

By taking the derivative of equation (1) with respect to time, and further manipulation (Hojjati and Wade, 2012), the following expression was obtained:

\[
\frac{dlnE_t}{dt} = \sum_{i=1}^{m} w_{it} \left( \frac{dln \ GO_{it}}{dt} + \frac{dln \ S_{it}}{dt} + \frac{dln \ I_{it}}{dt} \right).
\]

(2)

where

- \( w_{it} \) = the share of energy in the \( i \)th industry at year \( t \).

After integrating both sides of expression (2) from year 0 to year \( t \), substituting for terms, and applying the log mean Divisia index (LMDI) method, the change in manufacturing energy consumption between two time periods was expressed as follows:

³Ang and Zhang (2000) and An Ang, Liu and Chew (2003) provide reviews of decomposition methods and various studies on this subject.
\[
\ln \left( \frac{E_t}{E_0} \right) = \sum_{i=1}^{m} w_i \ln \left( \frac{GO_t}{GO_0} \right) + \sum_{i=1}^{m} w_i \ln \left( \frac{S_{it}}{S_{i0}} \right) + \sum_{i=1}^{m} w_i \ln \left( \frac{I_{it}}{I_{i0}} \right),
\]

= output effect + industry type effect + energy intensity effect.

where

\[ E_t = \text{total energy consumption at year } t; \]
\[ E_0 = \text{total energy consumption at the base year}; \text{ and} \]
\[ w_i = \text{the log mean of energy share of industry } i. \]

The weights \((w_i)\) were normalized \((w^*_i)\) to sum to one:

\[
w^*_i = \frac{w_i}{\sum_i w_i} = \frac{L(w_{i0}, w_{it})}{\sum_{i=1}^{m} L(w_{i0}, w_{it})},
\]

and

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

**Energy use**

A wide variety of activities are performed in the manufacturing sector including producing food, textiles, apparel, wood products, paper, primary metals, petroleum, chemicals, computers, and machinery. Therefore, energy consumption varies across NAICS subsectors, as some industries require more energy than others. Between 1998 and 2014 U.S. manufacturing energy consumption as a fuel decreased by 17.2% or 1.1% per year, from 17,695 trillion Btu to 14,903 trillion Btu.\(^5\) According to MECS, chemicals, petroleum and coal, paper, and primary metals accounted for 10,814 trillion Btu, or more than two-thirds of manufacturing energy consumption in 2014 (Table 1).

\(^4\) Throughout the paper “energy use” refers to use of energy as a fuel.
\(^5\) For consistency with the decomposition of energy consumption changes into component effects, all reported percentage changes are logarithmic.
Table 1. Manufacturing consumption of energy as a fuel, 1998 and 2014 (trillion Btu)

<table>
<thead>
<tr>
<th>NAICS Code</th>
<th>Industry</th>
<th>1998</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>311&amp;312</td>
<td>Food, Beverages, &amp; Tobacco</td>
<td>1,152</td>
<td>1,209</td>
</tr>
<tr>
<td>313&amp;314</td>
<td>Textile Mills and Products</td>
<td>303</td>
<td>124</td>
</tr>
<tr>
<td>315&amp;316</td>
<td>Apparel &amp; Leather</td>
<td>56</td>
<td>8</td>
</tr>
<tr>
<td>321</td>
<td>Wood Products</td>
<td>504</td>
<td>384</td>
</tr>
<tr>
<td>322</td>
<td>Paper</td>
<td>2,744</td>
<td>2,090</td>
</tr>
<tr>
<td>323</td>
<td>Printing &amp; Related Support</td>
<td>98</td>
<td>89</td>
</tr>
<tr>
<td>324</td>
<td>Petroleum &amp; Coal Products</td>
<td>3,622</td>
<td>3,513</td>
</tr>
<tr>
<td>325</td>
<td>Chemicals</td>
<td>3,704</td>
<td>3,527</td>
</tr>
<tr>
<td>326</td>
<td>Plastics &amp; Rubber Products</td>
<td>327</td>
<td>294</td>
</tr>
<tr>
<td>327</td>
<td>Nonmetallic Mineral Products</td>
<td>969</td>
<td>827</td>
</tr>
<tr>
<td>331</td>
<td>Primary Metals</td>
<td>2,576</td>
<td>1,684</td>
</tr>
<tr>
<td>332</td>
<td>Fabricated Metal Products</td>
<td>441</td>
<td>344</td>
</tr>
<tr>
<td>333</td>
<td>Machinery</td>
<td>213</td>
<td>164</td>
</tr>
<tr>
<td>334</td>
<td>Computer &amp; Electronic Products</td>
<td>205</td>
<td>162</td>
</tr>
<tr>
<td>335</td>
<td>Electrical Equip. &amp; Appliances</td>
<td>116</td>
<td>71</td>
</tr>
<tr>
<td>336</td>
<td>Transportation Equipment</td>
<td>488</td>
<td>318</td>
</tr>
<tr>
<td>337</td>
<td>Furniture &amp; Related Products</td>
<td>88</td>
<td>37</td>
</tr>
<tr>
<td>339</td>
<td>Miscellaneous</td>
<td>88</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>17,695</td>
<td>14,903</td>
</tr>
</tbody>
</table>


The decline in energy consumption between 1998 and 2014 was mostly associated with the decline in energy use in the primary metals and paper subsectors, 892 trillion Btu (42.5%) and 654 trillion Btu (27.2%), respectively (Figure 1). Over this period, energy consumption increased only in food and tobacco processing as output for this category increased by more than 50% and also required more consumption of electricity.6

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6 Throughout the paper electricity represents “net electricity.” MECS defines "net electricity" as the sum of purchases, transfers in, and generation from noncombustible renewable resources (solar, wind, and hydropower), minus quantities sold and transferred out. Also, electricity from onsite cogeneration or generation from combustible fuels such as coal is not included as that energy is accounted for in generation fuel consumption.
Among the top four energy consuming subsectors (paper, petroleum and coal products, chemicals, and primary metals), shares of total manufacturing energy consumption decreased in primary metal and paper, but increased in petroleum and coal products and chemicals (Figure 2). The decline in primary metal energy consumption was mostly attributed to the decline in energy intensity, whereas the decline of energy consumption in the paper industry was associated with the decrease in this industry's production.

Figure 2. Energy shares by industry, 1998 and 2014


Figure 3. Manufacturing energy consumption by fuel source, 1998 and 2014

Note: “Other” includes net steam (the sum of purchases, generation from renewables, and net transfers), and other energy that respondents indicated was used to produce heat and power.
Fuel source
Consumption of all energy sources in manufacturing decreased between 1998 and 2014 (Figure 3). As energy consumption for fuel use decreased, the mix of manufacturing energy sources changed over this time period. Despite the decline in natural gas consumption, its share increased slightly and remained the main manufacturing energy source (Figure 4). Net electricity’s contribution to total fuel consumption in manufacturing remained at about 17% between 1998 and 2014, while its consumption decreased mostly as electricity consumption declined in the chemical and primary metal industries. The shares of coal (coal and coke products) and liquid fuels (fuel oil and liquefied petroleum gases) declined in favor of other energy sources. In 1998 coal accounted for 10.2% of total fuel used for energy consumption and liquid fuel accounted for 3.5%. By 2014, the share of coal decreased to 7.4% and the liquid fuel share decreased to 1.4%.

Figure 4. Distribution of fuel use of energy consumption in manufacturing, 1998 and 2014

As would be expected there were also notable differences across industries. For example, natural gas accounted for a major share (59%) of energy consumption in the textile product mills industry, while

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7 “Other” includes net steam (the sum of purchases, generation from renewables, and net transfers), and other energy that respondents indicated was used to produce heat and power.
electricity was the main source (69%) of energy consumption in computer and electronic products manufacturing.

In 2014, the chemical and petroleum and coal products sectors accounted for more than 50% of manufacturing natural gas consumption. The chemical industry continued to be the main user of natural gas as a fuel in 2014, at 34.% of manufacturing total natural gas consumption.

Natural gas was mostly used for process heating and boiler fuel, while electricity was mostly used for machine drive (MECS data).

**Gross output**

Manufacturing output is represented by BEA’s gross output in chained 2009 dollars (real gross output).

Between 1998 and 2014 the overall manufacturing sector and its subsectors showed varying amounts and directions of change with regard to the value of manufacturing real gross output (Figure 5). Overall, total real gross output in the manufacturing sector increased by about 6% from 1998 to 2014. However, among the most energy intensive subsectors, only the petroleum and coal products and chemicals showed an increase in gross output. Transportation equipment, and computer and electronic products, industries that are not among the highest users of energy, are responsible for most of the increase in gross output between 1998 and 2014.

Real manufacturing gross output fell by about 11% between 2006 and 2010, as a result of the U.S. economic recession from December 2007 through June 2009. But it grew by 10% from 2010 to 2014.

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8 According to BEA, “Gross output of an industry is the market value of the goods and services produced by an industry, including commodity taxes. The components of gross output include sales or receipts and other operating income, commodity taxes, plus inventory change.”

9 Energy intensive industries are paper, primary metals, nonmetallic mineral products, petroleum & coal products, and chemicals.
**Figure 5. Change in manufacturing real gross output, 1998-2014**

![Bar chart showing change in manufacturing real gross output from 1998 to 2014](chart.png)


BEA gross output data are available for 18 manufacturing subsectors. To be consistent with the BEA’s disaggregation of gross output data, MECS 21 subsectors are classified into 18 categories (Table 1) for the analysis by grouping the following NAICS codes:

**Table 2. Aggregation of selected industries**

<table>
<thead>
<tr>
<th>NAICS Code</th>
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</tr>
</thead>
<tbody>
<tr>
<td>311 and 312</td>
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<td>Textile Mills and Products</td>
</tr>
<tr>
<td>315 and 316</td>
<td>Apparel &amp; Leather</td>
</tr>
</tbody>
</table>

**Energy Intensity**

The aggregate energy intensity was defined as fuel use of energy consumption per dollar value of real gross output. Overall, this intensity declined by 23.6%, as the decline in energy consumption was faster than the growth in real gross output between 1998 and 2014. Overall the decline in manufacturing
energy intensity was affected by various factors such as changes in industry mix, investment in more energy-efficient technology, and retirements of older plants and equipment (DOE 2015).

Energy intensity varied widely across the subsectors (Figure 6). The paper industry, the most energy-intensive industry during the 1998-2014 period, experienced a 7% decrease in energy intensity over this time period (Figure 7). Among the top five energy-intensive industries, primary metals experienced the largest decrease in energy intensity (40%), mainly as a result of a decrease in energy consumption in the iron and steel mills and ferroalloys as well as smelting and alloying of aluminum between 1998 and 2014. Energy intensity only increased in the printing and related products subsector (Figure 7). However, this industry was not a large consumer of energy. Over the same time period, energy intensity in the petroleum and coal products, and bulk chemicals decreased by 17% and 13%, respectively. These two energy-intensive industries each contributed about 24% of manufacturing energy consumption in 2014.

**Figure 6. Energy intensity for selected industries, 1998 and 2014**

![Bar chart showing energy intensity for selected industries, 1998 and 2014](image)

Figure 7. Change in manufacturing energy intensity 1998-2014


Results
In the following section, the report presents several decompositions of changes in U.S. manufacturing energy consumption. The changes for the full period between 1998 and 2014 are analyzed first before presenting similar results for four sub-periods.

Total energy
Figure 8 presents the decomposition results for the 1998 to 2014 period during which U.S. manufacturing energy consumption decreased by 17.2%. The decomposed intensity effect had a
negative impact on total energy consumption, and if other factors had remained at the 1998 level, energy intensity would have decreased consumption by 16.8%. This was less than the decline in aggregate energy intensity noted earlier (23.6%). This difference was due to the -6.8% decomposed structural effect which accounted for 29% of the decline in aggregate energy intensity between 1998 and 2014.

Figure 9 quantifies the amount of avoided energy consumption in 2014. Representing the reduction in consumption as the amount of energy that would have been consumed if factors had remained at their 1998 levels, intensity and structural effects contributed to reductions of 2,734 trillion Btu and 1,097 trillion Btu, respectively.

The U. S. manufacturing sector consumed 14,903 trillion Btu of energy for fuel use in 2014. Without changes in the mix of industry types toward less energy intensive types and improvement in energy intensity, manufacturing would have used 18,734 trillion Btu, or an additional 26%.

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10 The negative growth in energy intensity could have been affected by energy price changes as the average real total energy price increased by more than one-third from 1998 and 2014. However, improvements in technology and manufacturing processes, more efficient motors, significant growth in application of combined heat and power systems (CHP), and wider use of energy control systems were likely to account for a major portion of the intensity decline (Nadel 2002 and 2015) during this period.

11 The avoided energy consumption would have been larger if the decomposition analysis was based on primary energy (includes losses in generation and transmission).
Figure 8. Decomposition of percent change in fuel use of energy consumption, 1998-2014


Figure 9. Decomposition of changes in fuel use of energy consumption 1998-2014

Note: Totals may not equal sum of components due to independent rounding.
Total natural gas
Figure 10 shows the decomposition results for natural gas consumption. Between 1998 and 2014 energy demand for natural gas consumption declined more slowly than total energy consumption. Natural gas consumption decreased by 12.6% while total energy decreased by 17.2%. Natural gas contributed 28% of the decline in total energy consumption over the study period.

In this decomposition, the activity effect is the same as for total energy consumption, since activity is represented by total gross output and is not fuel-specific. The impacts of energy intensity and structural change are lower than in the case of total energy. Similar to the previous case, the negative impact of the decomposed intensity effect was significantly higher than that of the structural effect. Over this period, aggregate natural gas energy intensity decreased by 19.0%, compared with a decline of 13.6% in the decomposed intensity. The difference between these intensities (-5.4%) represents the contribution of the structural effect to the change in aggregate natural gas intensity.

Figure 10. Decomposition of percent change in fuel use of natural gas consumption, 1998-2014

Electricity\(^\text{12}\)
Similar to the previous cases, both the structural and intensity effects acted to decrease electricity consumption. As was the case for natural gas, electricity consumption decreased slower than total energy (Figure 11), by 15.5% compared with a total site energy decrease of 17.2%. Electricity consumption increased in a few industries, mostly in food (food, beverages, and tobacco), and in the petroleum and coal products. The decomposed energy intensity declined by 15.1%, which is 31% less than the calculated change in the aggregate intensity (21.9%). Like the other cases, energy intensity change was the main driver of the decline in manufacturing total electricity consumption between 1998 and 2014.

**Figure 11. Decomposition of percent change in net electricity consumption, 1998-2014**

![Bar chart showing percent change in net electricity consumption]


\(^{12}\) As stated earlier, the analyses in this paper are based on net electricity consumption, which includes net self-generation associated with solar, wind, and hydropower. A separate decomposition for purchased electricity is presented in Appendix A.
Analysis of sub-periods
The decomposition results were sensitive to the period of analysis. To better understand the drivers behind the changes in manufacturing energy consumption, the following section presents decomposition results for the four MECS sub-periods: 1998 to 2002, 2002 to 2006, 2006 to 2010, and 2010 to 2014.

Total energy
From 1998 to 2014, total delivered energy consumption for fuel use declined by 17.2%. Most of this decline occurred during the first and the third sub-periods (Figure 12). Despite a slight decline in the activity effect (0.4%), energy consumption declined by 8.4% during the first period. This was mostly affected by the decline in energy intensity effect (7.6%). In the period from 2006 to 2010, the activity effect declined more rapidly (11.2%) and was the only driver of the decrease in energy consumption. As mentioned earlier, this period was affected by the severe December 2007-June 2009 U.S. economic recession. Following the decline in the third sub-period, the activity effect had the largest growth (10.5%) during the last sub-period and acted to increase energy consumption.

The analysis also showed significant differences across the sub-periods with respect to the structural and intensity effects. Except for the period between 2006 and 2010, these two effects acted to decrease energy consumption. The second sub-period had the largest decline in the intensity effect followed by the first sub-period, 9.5% and 7.6%, respectively. Contrary to the other sub-periods, the energy intensity effect increased by 1.7% between 2006 and 2010. This is similar to the calculated energy intensity as there were no changes in the structural effect. As will be noted later, the increased intensity during this period was influenced by the growth in natural gas consumption. The growth in manufacturing output offset the combined negative impacts of energy intensity and structural changes in the last sub-period. The structural effect was the main driver of the decline in energy consumption in this sub-period,
whereas the energy intensity effect was the main driver of the decline in energy consumption during the first and the second sub-periods.

As mentioned earlier, the difference between the aggregate intensity and the decomposed intensity is explained by the structural effect in this analysis. Except for the period between 2006 and 2010, the aggregate energy intensity overestimated the energy intensity effect, particularly in the last sub-period. Between 2010 and 2014, the calculated aggregate energy intensity exhibited a decline of 5.9%; this is about four times higher than the decomposition analysis estimate of -1.4%.

**Figure 12. Decomposition of percent change in total fuel use of energy consumption**

Note: Totals may not equal sum of components due to independent rounding.

**Natural gas**
Natural gas consumption declined more rapidly in the first sub-period, as a result of a decrease in the energy intensity effect (Figure 13). The intensity effect was more pronounced in the case of natural gas consumption than it was in total energy consumption decomposition, but varied across the sub-periods.

This effect contributed most of the decrease in natural gas consumption in the first two sub-periods,
while acting to increase natural gas consumption after 2006. Unlike the previous sub-periods, the structural effect (shift from more intensive to less intensive industries) was the only driver of the decline in natural gas consumption during the 2010-2014 period and reduced 2014 natural gas consumption relative to 2010 by 4.6%. However, the combined effects of increased manufacturing output (activity effect) and energy intensity (16.3%) more than offset the impact of the structural effect. As a result total natural gas consumption during this period grew by 11.7%. Without the structural shift, natural gas consumption would have increased by 16.3% between 2010 and 2014.

The calculated aggregate natural gas intensity exhibited an increase of 1.3% between 2010 and 2014 versus 5.9% growth in the decomposed intensity, almost five times higher than the aggregate.

**Figure 13. Decomposition of percent change in fuel use of natural gas consumption**

[Figure showing the percent change in fuel use of natural gas consumption from 1998 to 2014, with categories for activity effect, structural effect, and intensity effect, and the total effect.]


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13 In addition to energy efficiency improvements, a portion of intensity decline during the first and second sub-periods, possibly was affected by natural gas price changes. During these periods natural gas prices increased faster than electricity prices. Real natural gas prices increased by 35% and 70% during the first two sub-periods, respectively, versus 9% and 20% for electricity prices. Unlike the previous sub-periods, average natural gas prices decreased by 38% and 2% during the last two sub-periods, respectively; while electricity prices increased by 10% and 8% (MECS data).
**Net Electricity**

Figure 14 summarizes the decomposition results for electricity consumption for each sub-period. For all four periods, the structural and intensity effects had a negative effect on changes in electricity consumption. Similar to the previous case, the first and second sub-periods experienced the most decline in energy intensity. The combined impacts of energy intensity and structural effect almost offset the increase in electricity consumption associated with the activity effect during the 2002-2006 sub-period. As a result electricity consumption increased by less than 1%. If the structural and intensity effects had remained at the 2002 level, electricity consumption during this sub-period would have increased by 7.6% instead of 0.7%. Except for the last sub-period, the negative impacts of the intensity effect were more than twice the impacts of the structural effect.

**Figure 14. Decomposition of percent change in net electricity consumption**


**Summary**

This study applied the log mean Divisia index (LMDI) to separate out and quantify the relative contribution of three main components—activity (output), structural changes, and energy intensity—to
changes in U.S. manufacturing delivered energy consumption from 1998 to 2014. The results showed that there was a significant difference between the aggregate energy intensity and the decomposed intensity. This difference was affected by structural changes in the composition of manufacturing activity over the period of analysis that were embedded in the aggregate energy intensity, but factored out of the decomposed intensity.

Decomposition of the entire period revealed that the intensity effect had the most significant impact in reducing manufacturing delivered energy consumption from 1998 to 2014, followed by the structural effect. But, the combined negative effects of these factors was reduced by the positive effect of manufacturing production. The analysis of sub-periods 1998-2002, 2002-2006, 2006-2010, and 2010-2014 revealed that in all three decompositions, the first and second sub-periods showed greater intensity declines. This was likely affected by faster growth in energy efficiency improvements of motor systems, manufacturing processes, and manufacturing management in 2002 and 2006 relative to the base years of 1998 and 2002, respectively.
Appendix A. Decomposition of offsite-produced electricity\textsuperscript{14}

Figure A1. Decomposition of percent change in offsite-produced electricity consumption, 1998-2014


Figure A2. Decomposition of percent change in offsite-produced electricity consumption


\textsuperscript{14} Offsite-produced electricity refers to quantities of electricity that were purchased or transferred in, and is equivalent to “purchased electricity” as defined in the Annual Survey of Manufactures.
References


U.S. Energy Information Administration, Annual Energy Outlook, DOE/EIA-0383 (2016), Table A2 Washington, DC.


