APPENDIX D

Final

EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Advanced Case

Presented to:

U.S. Energy Information Administration

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August 10, 2016

DISCLAIMER

August 2016

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The objective of this study is to develop baseline and projected performance/cost characteristics for residential and commercial end-use equipment in an "Advanced Case" that assumes accelerated adoption of energy-saving technologies due to increased R&D funding and market incentives.

- 2003/2012 (commercial) and 2009 (residential) baselines, as well as today's (2015)
  - Review of literature, standards, installed base, contractor, and manufacturer information.
  - Provide a relative comparison and characterization of the cost/efficiency of a generic product.
- Forecast of technology improvements that are projected to be available through 2040
  - Review of trends in standards, product enhancements, and Research and Development (R&D).
  - Projected impact of product improvements and enhancement to technology.

The performance/cost characterization of end-use equipment developed in this study will assist EIA in projecting national primary energy consumption.

Input from industry, including government, R&D organizations, and manufacturers, was used to project product enhancements concerning equipment performance and cost attributes.

- Technology forecasting involves many uncertainties.
- Technology developments impact performance and cost forecasts.
- Varied sources ensure a balanced view of technology progress and the probable timing of commercial availability.

- The following tables represent the current and projected efficiencies for residential and commercial building equipment ranging from the installed base in 2003 and 2012 (for commercial products) and 2009 (for residential) to the highest efficiency equipment that is expected to be commercially available by 2040, assuming incremental adoption. Below are definitions for the terms used in characterizing the status of each technology.
  - Installed Base: the installed and "in use" equipment for that year. Represents the installed stock of equipment, but does NOT represent sales.
  - Current Standard: the minimum efficiency (or maximum energy use) required (allowed) by current DOE standards, when applicable.
  - ENERGY STAR: the minimum efficiency required (or maximum energy use allowed) to meet the ENERGY STAR criteria, when applicable. Presented performance data represents certified products just meeting current ENERGY STAR specifications.
  - Low: The minimum available efficiency product or product mix available on the market. This typically reflects minimal compliance with DOE standards.
  - Typical: the average, or "typical," product being sold in the particular timeframe.
  - High: the product with the highest efficiency available in the particular timeframe.
  - Lumens: All reported lumens are initial lumens.
  - Correlated Color Temperature (CCT): a specification of the color appearance of the light emitted by a lamp.
  - Color Rendering Index (CRI): a scale from 0 to 100 percent indicating how accurate a "given" light source is at rendering color when compared to a "reference" light source. The higher the CRI, the better the color rendering ability.

- The following metrics are commonly referred to throughout the tables to follow. Below are the calculations for each metric
  - **Lighting**
    - **System Wattage** = (Lamp Wattage * Ballast Factor) / Ballast Efficiency
    - **System Lumens** = Lamp Lumens * Ballast Factor
    - **Lamp Efficacy** = Lamp Lumens / Lamp Wattage
    - **System Efficacy** = System Lumens / System Wattage
    - **Lamp Cost ($/klm)** = Lamp Cost / (Lamp Lumens / 1000)
    - **Total Equipment Cost** = Lamp Cost + Fixture (including ballast) Cost
    - **System Cost ($/klm)** = Total Equipment Cost / (System Lumens / 1000)
    - **Total Installed Cost** = Total Equipment Cost + Labor Installation Cost
    - **BLE** = A/(1+B*Avg Total Lamp Arc Power^(-C))
  - **Commercial Refrigeration**
    - **Nominal Capacity over Average Input (Btu in / Btu out)** = (Cooling or Heat Rejection Capacity)*24*365/(Annual Energy Consumption * 3412)
    - **Total Installed Cost** = Retail Equipment Cost + Labor Installation Cost
    - **Total Installed Cost ($/kBtu/hr)** = Total Installed Cost*1000 / (Cooling or Heat Rejection Capacity)
    - **Annual Maintenance Cost ($/kBtu/hr)** = Annual Maintenance Cost * 1000 / (Cooling or Heat Rejection Capacity)
  - **Ventilation**
    - **CFM out / Btu in / hr** = System Airflow / (System Fan Power * 3412)
    - **Total Installed Cost ($/1000 CFM)** = Total Installed Cost * 1000 / System Airflow
    - **Annual Maintenance Cost ($/1000 CFM)** = Annual Maintenance Cost * 1000 / System Fan Power

The market for the reviewed products has changed since the analysis was performed in 2012. These changes are noted and reflected in the efficiency and cost characteristics.

- DOE issued Federal minimum efficiency standards that have or will soon go into effect for General Service Fluorescent Lamps (effective 2012), Incandescent Reflector Lamps (July 2012), Fluorescent Lamp Ballasts (2014), Refrigerated Beverage Vending Machines (2012), Automatic Commercial Ice Makers (2018), Walk-In Coolers and Freezers (2017) and Commercial Refrigeration Equipment (2017). DOE published a Final Rule updating energy conservation standards for Refrigerated Beverage Vending Machines at the end of 2015, effective in 2018.

Residential Lighting

Note: More aggressive R&D investment and effort in the lighting industry will only change future projections of LED technologies as it is unlikely that additional funding/effort will be applied to traditional technologies that have been exceeded in performance by their LED counterparts. Therefore, the inputs for all non-LED technologies remain unchanged from the Reference Case and are therefore not included in this report.

The residential general service lamps characterized in this report are a 60 watt and a 75 watt medium screw based A-type incandescent lamp and their halogen, CFL, and LED equivalents. A standard 60 watt incandescent lamp produces approximately 800 lumens. A standard 75 watt incandescent lamp produces approximately 1100 lumens (ENERGY STAR Program).

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Fixture prices and installation costs are not included for the residential sector. Labor costs are assumed to be negligible as the homeowner likely replaces lamps themselves as they burn out. Therefore total installed cost is the price of a lamp, and annual maintenance costs are the cost of replacing the lamps, which is a function of lamp life, lamp price, and the <u>annual operating hours of 652 hours/year</u> for residential general service lamps (DOE SSL Program, 2012a).

Legislation:

- The Energy Independence and Security Act of 2007 (EISA 2007) established standards for 60 watt general service lamps effective in 2014 and 75 watt lamps effective in 2013. These standards cannot be achieved by incandescent bulbs, but can by halogen, CFL, and LED technologies. As a result, 2015 data is not provided for incandescent general service lamps.
- EISA 2007 also established a requirement that DOE establish standards for general service lamps that are equal to or greater than 45 lm/W by 2020. California's Appliance Efficiency Regulations will require 45 lm/W for general service lamps with certain bases beginning in 2018. These standards can not be achieved by traditional incandescent or halogen technologies currently on the market and given current and projected trends in industry it is not likely they will be met. It is currently assumed that industry will increase their investment in LED technology at the expense of incandescent, halogen, and CFL technologies.
- EPACT 2005 sets performance for medium based compact fluorescent lamps. It adopts ENERGY STAR performance requirements (August 6, 2001 version) for efficacy, lumen maintenance, lamp life, rapid cycle stress test, CRI, etc. The standard is effective for lamps manufactured on or after January 1, 2006. Note that EPACT 2005 standards do not apply to CFL lamps with screw bases other than medium (e.g., pin based). The Secretary may revise these requirements by rule or establish other requirements at a later date. An updated DOE standard is expected in 2017 with a potential effective date of 2020.
- Beginning in 2017, California's Title 24 will require all light sources to be high efficacy. All general service lamps with medium screw bases must meet the following requirements: initial efficacy ≥45 lm/W, power factor ≥0.90, CCT ≤3000K, CRI ≥90, rated life ≥15,000 hours.
- For ENERGY STAR qualification, general service, omnidirectional lamps must have a minimum lamp efficacy of 55 lm/W and 65 lm/W for lamps with rated wattage of <15W and ≥ 15 W, respectively. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2700, 3000, 3500, 4000/4100, 5000, or 6000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR, 2014). The ENERGY STAR Lamps Version 2.0 specification, currently under revision and will take effect January 2, 2017, will require 70 lm/W for omnidirectional lamps with CRI ≥ 90 and 80 lm/W for omnidirectional lamps with CRI < 90 (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	0%	0%	-0.5%	Limited as the technology is mature and the technology cannot meet legislative requirements.
Halogen	+0.5%	+0.5%	-0.5%	Limited as the technology is mature.
CFL	+0.5%	+0.5%	-0.5%	Improvements in efficacy can be made by using more rare-earth phosphors in compact fluorescent lamps. Lifetime improvements can be made by improving the compact fluorescent lamp electrodes.

Performance/Cost Characteristics » Residential General Service LED Lamps (60 Watt Equivalent)

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star[4]	Typical	High	Typical	High	Typical	High
Lamp Wattage	18	13	9	8	14	7	4	5	4	4	4
Lamp Lumens	800	850	837	865	800	840	840	840	840	840	840
Lamp Efficacy (lm/W)	44	64	93	104	59	123	197	171	230	219	230
CRI	80	83	84	81	92	84	84	84	84	84	84
Correlated Color Temperature (CCT)	3000	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700
Average Lamp Life (1000 hrs)	20	25	25	25	25	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	652	652	652	652	652	652	652	652	652	652	652
Lamp Price ($)	$68.00	$24.00	$7.53	$4.99	$11.98	$4.07	$4.07	$1.33	$1.33	$1.00	$1.00
Lamp Cost ($/klm)	$85.00	$28.22	$9.00	$5.77	$14.98	$4.84	$4.84	$1.58	$1.58	$1.19	$1.19
Labor Cost ($/hr)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost ($)	$68.00	$24.00	$7.53	$4.99	$11.98	$4.07	$4.07	$1.33	$1.33	$1.00	$1.00
Annual Maintenance Cost ($)	$2.22	$0.63	$0.20	$0.13	$0.31	$0.05	$0.05	$0.02	$0.02	$0.01	$0.01
Total Installed Cost ($/klm)	$85.00	$28.22	$9.00	$5.77	$14.98	$4.84	$4.84	$1.58	$1.58	$1.19	$1.19
Annual Maintenance Cost ($/klm)	$2.77	$0.74	$0.23	$0.15	$0.39	$0.06	$0.06	$0.02	$0.02	$0.02	$0.02

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. Represents the lowest efficacy product in the Energy Star Database (as downloaded on 11/4/15) for which all of the information in the table is available.

The residential reflector lamps characterized in this report are directional lamps that emit between approximately 550-750 lumens. Multiple baseline reflector lamps were analyzed, including: 65W Incandescent BR30, Halogen PAR30, Halogen Infrared Reflector (HIR) PAR30, CFL BR30, LED BR30, LED PAR38.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Fixture prices and installation costs are not included for the residential sector. Labor costs are assumed to be negligible as the homeowner likely replaces lamps themselves as they burn out. Therefore total installed cost is the price of a lamp, and annual maintenance costs are the cost of replacing the lamps, which is a function of lamp life, lamp price, and the annual operating hours of 642 hours/year for residential reflector lamps(DOE SSL Program, 2012a).

Legislation:

- EPACT92 established minimum performance standards for some reflector lamps and provided exemptions for certain specialty applications (e.g., ER/BR, vibration service, more than 5% neodymium oxide, impact resistant, infrared heat, colored). EPACT92 effectively phased-out R-shaped tungsten filament incandescent reflector lamps at certain wattages and bulb diameters, replacing them with more efficient and cost effective tungsten-halogen parabolic aluminized reflector (PAR) lamps. EISA 2007 took away certain exemptions from EPACT 1992, requiring certain previously exempted lamps to meet EPACT92 minimum performance standards by January 1, 2008. The 65W BR30, a large majority of the incandescent reflector lamp market is still exempted. In 2015, DOE issued a final rule which determined that amending the standards for incandescent reflector lamps could not be economically justified.
- For ENERGY STAR qualification, directional, reflector lamps must have a minimum lamp efficacy of 40 lm/W and 50 lm/W for lamps with rated wattage of <20W and ≥ 20 W, respectively. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2700, 3000, 3500, 4000/4100, 5000, or 6000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR, 2014). The ENERGY STAR Lamps Version 2.0 specification, currently under revision and will take effect January 2, 2017, will require 61 lm/W for omnidirectional lamps with CRI ≥ 90 and 70 lm/W for omnidirectional lamps with CRI < 90 (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	+0.2%	+0.5%	-0.5%	Improvements can be made by improved filament design and placement, higher pressure capsules, or higher efficiency reflector coatings.
Halogen	+0.5%	+0.5%	-0.5%	Improvements can be made by improved filament design and placement, higher pressure capsules, or higher efficiency reflector coatings.
CFL	+0.5%	+0.5%	-0.5%	In addition to benefiting from higher efficiency reflector coatings, improvements in efficacy can be made by using more rare-earth phosphors in compact fluorescent lamps. Lifetime improvements can be made by improving the compact fluorescent lamp electrodes.

Performance/Cost Characteristics » Residential Reflector LED BR30

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low[1]	Typical[2]	Best[3]	Energy Star[4]	Typical	Best	Typical	Best	Typical	Best
Lamp Wattage	18	11	10	8	12	6	4	5	3	4	3
Lamp Lumens	600	670	794	699	605	700	700	700	700	700	700
Lamp Efficacy (lm/W)	33	59	78	89	50	109	197	153	230	196	230
CRI	80	95	84	82	93	84	84	84	84	84	84
Correlated Color Temperature (CCT)	3000	2700	3000	5000	2700	3000	3000	3000	3000	3000	3000
Average Lamp Life (1000 hrs)	20	25	28	25	25	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	642	642	642	642	642	642	642	642	642	642	642
Lamp Price ($)	$98.40	$12.99	$16.67	$20.97	$74.57	$3.39	$3.39	$1.11	$1.11	$1.00	$1.00
Lamp Cost ($/klm)	$164.00	$19.39	$21.00	$30.01	$123.26	$4.84	$4.84	$1.58	$1.58	$1.43	$1.43
Labor Cost ($/hr)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost ($)	$98.40	$12.99	$16.67	$20.97	$74.57	$3.39	$3.39	$1.11	$1.11	$1.00	$1.00
Annual Maintenance Cost ($)	$3.16	$0.33	$0.38	$0.54	$1.91	$0.04	$0.04	$0.01	$0.01	$0.01	$0.01
Total Installed Cost ($/klm)	$164.00	$19.39	$21.00	$30.01	$123.26	$4.84	$4.84	$1.58	$1.58	$1.43	$1.43
Annual Maintenance Cost ($/klm)	$5.26	$0.50	$0.48	$0.77	$3.16	$0.06	$0.06	$0.02	$0.02	$0.02	$0.02

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. Represents the lowest efficacy product in the Energy Star Database (as downloaded on 11/4/15) for which all of the information in the table is available.

Performance/Cost Characteristics » Residential Reflector LED PAR38

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low[1]	Typical[2]	Best[3]	Energy Star[4]	Typical	Best	Typical	Best	Typical	Best
Lamp Wattage	28	18	16	17	20	13	7	9	6	7	6
Lamp Lumens	1000	1172	1328	1958	1050	1400	1400	1400	1400	1400	1400
Lamp Efficacy (lm/W)	36	64	83	116	53	109	197	153	230	196	230
CRI	80	91	84	81	93	84	84	84	84	84	84
Correlated Color Temperature (CCT)	3000	2700	3000	4000	3000	3000	3000	3000	3000	3000	3000
Average Lamp Life (1000 hrs)	20	25	28	25	25	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	642	642	642	642	642	642	642	642	642	642	642
Lamp Price ($)	$164.00	$25.68	$27.89	$36.59	$34.47	$6.78	$6.78	$2.21	$2.21	$1.67	$1.67
Lamp Cost ($/klm)	$164.00	$21.92	$21.00	$18.69	$32.83	$4.84	$4.84	$1.58	$1.58	$1.19	$1.19
Labor Cost ($/hr)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost ($)	$164.00	$25.68	$27.89	$36.59	$34.47	$6.78	$6.78	$2.21	$2.21	$1.67	$1.67
Annual Maintenance Cost ($)	$5.26	$0.66	$0.64	$0.94	$0.88	$0.09	$0.09	$0.03	$0.03	$0.02	$0.02
Total Installed Cost ($/klm)	$164.00	$21.92	$21.00	$18.69	$32.83	$4.84	$4.84	$1.58	$1.58	$1.19	$1.19
Annual Maintenance Cost ($/klm)	$5.26	$0.56	$0.48	$0.48	$0.84	$0.06	$0.06	$0.02	$0.02	$0.02	$0.02

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. Represents the lowest efficacy product in the Energy Star Database (as downloaded on 11/4/15) for which all of the information in the table is available.

This section characterizes commercial linear fixtures that house 2 4ft long linear lamps and their integrated luminaire equivalents. The technologies available for this system are linear fluorescent and LED.

- T5 lamps are approximately 40% narrower than T8 lamps and almost 60% narrower than T12 lamps. This allows T5 lamps to be coated with higher quality, more efficient phosphor blends than larger diameter lamps, resulting in a more efficacious lamp. The compact size of T5 lamps also permits greater flexibility in lighting design and construction.
- LED options for linear fixtures include replacement lamps that are able to fit directly into an existing fixture and fully integrated luminaire that can be used to replace existing fixtures. LED replacement lamps, also known as T lamps or TLEDs, do not require a ballast but can be installed in existing ballasted configurations with or without the removal of the linear fluorescent ballast. Replacement lamps are only sold to go into existing fixtures, if a new fixture is to be installed, a fully integrated LED luminaire is a more cost effective and efficient option. Because LED luminaires are fully integrated, they do not have lamp/fixture efficiency losses associated with ballasts and fixture optics.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- The total installed cost is the price of a lamp, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED replacement lamps which are sold only as a replacement for use in an existing fixture. The LED luminaire is more efficient and cost effective for new installations or fixture retrofits.
- Labor costs for lamp changes are assumed to be negligible as the homeowner likely replaces lamps themselves as they burn out. Therefore annual maintenance costs are the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 684 hours/year for residential linear systems(DOE SSL Program, 2012a).

Legislation:

- Beginning July 14, 2012 (or July 14, 2014 for T8 700-series phosphor lamps), DOE fluorescent lamp standards will require a minimum efficacy of 89 lm/W. While the amended performance-based standards do not explicitly prohibit T12 lamps, no T12 lamps met the standard at the time of its announcement. Since then, however, T12 lamps meeting the standard have entered the market.
- Beginning November 14, 2014, DOE standards will require that the characterized residential ballasts have a minimum BLE = 0.993 / (1 + 0.41 * Avg Total Lamp Arc power ^ (- 0.25)). Residential ballasts also must have a minimum power factor of 0.5.
- California's Title 24 mandates the use of electronic ballasts with high efficacy luminaires (including fluorescent) of 13 W or higher (CEC, 2005).
- ENERGY STAR residential fixtures require ≥ 65 lm/W per lamp-ballast platform before September 1, 2013 and ≥ 70 lm/W per lamp-ballast platform thereafter (ENERGY STAR, 2012).

Performance/Cost Characteristics » Residential 4-foot Linear 2-Lamp Lighting Systems

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
T12	0%	0%	-0.5%	Limited as the technology is mature.
T8	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
T5	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.

Performance/Cost Characteristics » Residential Linear LED Replacement Lamp 2 Lamp System

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	18	19	18	18	N/A	14	12	11	10	9	9
Lamp Lumens	1355	1743	2151	2309	N/A	2100	2100	2100	2100	2100	2100
Lamp Efficacy (lm/W)	75	92	116	132	N/A	151	173	199	203	230	230
System Wattage	36	38	37	35	N/A	28	24	21	21	18	18
System Lumens	2304	3103	3829	4110	N/A	3948	3948	4032	4032	4032	4032
System Efficacy (lm/W)	64	82	104	117	N/A	142	162	191	194	221	221
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	70	80	83	85	N/A	83	83	83	83	83	83
Correlated Color Temperature (CCT)	4000	4000	4100	5000	N/A	4100	4100	4100	4100	4100	4100
Average Lamp Life (1000 hrs)	35	50	45	50	N/A	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	684	684	684	684	684	684	684	684	684	684	684
Lamp Price ($)	$135.83	$22.19	$34.42	$38.30	N/A	$15.21	$15.21	$4.97	$4.97	$2.10	$2.10
Ballast Price ($)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)[3]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)	$100.25	$12.73	$16.00	$16.59	N/A	$7.24	$7.24	$2.36	$2.36	$1.00	$1.00
System (l/b/f) Cost ($/klm)[3]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Cost ($/hr)	$0.00	$0.00	$0.00	$0.00	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor System Installation (hr)[3]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Lamp Change (hr)	0	0	0	0	N/A	0	0	0	0	0	0
Total Installed Cost ($)	$271.67	$44.38	$68.84	$76.60	N/A	$30.43	$30.43	$9.93	$9.93	$4.20	$4.20
Annual Maintenance Cost ($)	$5.31	$0.61	$1.05	$1.05	N/A	$0.42	$0.42	$0.14	$0.14	$0.06	$0.06
Total Installed Cost ($/klm)	$200.49	$25.46	$32.00	$33.17	N/A	$14.49	$14.49	$4.73	$4.73	$2.00	$2.00
Annual Maintenance Cost ($/klm)	$3.92	$0.35	$0.49	$0.45	N/A	$0.20	$0.20	$0.06	$0.06	$0.03	$0.03

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. N/A because Linear LED Replacement Lamps are a retrofit option and sold only to be put in existing fixtures.
4. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.

Performance/Cost Characteristics » Residential Linear LED Luminaire

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low[1]	Typical[2]	Best[3]	Energy Star[4]	Typical	High	Typical	High	Typical	High
Lamp Wattage [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Efficacy (lm/W) [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	46	48	57	40	55	30	25	22	22	22	22
System Lumens	3395	4044	5697	4918	4000	5000	5000	5000	5000	5000	5000
System Efficacy (lm/W)	67	84	100	122	73	164	197	230	230	230	230
Ballast Efficiency (BLE) [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	87	83	83	83	82	83	83	83	83	83	83
Correlated Color Temperature (CCT)	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500	3500
Average Lamp Life (1000 hrs)	50	60	56	50	36	97	97	100	100	100	100
Annual Operating Hours (hrs/yr)	684	684	684	684	684	684	684	684	684	684	684
Lamp Price ($)	$731.04	$439.00	$176.61	$513.45	$139.00	$93.02	$93.02	$45.29	$45.29	$22.06	$22.06
Ballast Price ($) [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)[5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm) [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System (l/b/f) Cost ($/klm)[5]	$215.34	$108.56	$31.00	$104.41	$34.75	$18.60	$18.60	$9.06	$9.06	$4.41	$4.41
Labor Cost ($/hr)	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20
Labor System Installation (hr)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Labor Lamp Change (hr) [5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost ($)	$765.14	$473.10	$210.71	$547.55	$173.10	$127.12	$127.12	$79.39	$79.39	$56.16	$56.16
Annual Maintenance Cost ($)	$10.46	$5.39	$2.57	$7.49	$3.29	$0.90	$0.90	$0.54	$0.54	$0.38	$0.38
Total Installed Cost ($/klm)	$225.38	$116.99	$36.99	$111.35	$43.28	$25.42	$25.42	$15.88	$15.88	$11.23	$11.23
Annual Maintenance Cost ($/klm)	$3.08	$1.33	$0.45	$1.52	$0.82	$0.18	$0.18	$0.11	$0.11	$0.08	$0.08

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. Represents the lowest efficacy product in the Energy Star Database (as downloaded on 11/4/15) for which all of the information in the table is available.
5. N/A because Linear LED Luminaires are a fully integrated lighting solutions used to replace existing lamp/ballast/fixture systems and therefore does not have lamp, ballast, and fixture components.

Performance/Cost Characteristics » Residential Outdoor Lamps

- The residential outdoor lamps characterized in this report include reflector and general service lamps used for security and/or porch lighting that can be switched on from inside the home (i.e. parking lot/garage and outdoor common area lighting at multifamily buildings are excluded) with lumen outputs of approximately 1000 lumens. Multiple baseline lamps were analyzed according to estimates of installed base average lumens by lamp type, including:

Security (Reflector Lamps)	Porch (General Service Lamps)
Incandescent BR30	Incandescent A-Type
Halogen PAR38	Halogen A-Type
Halogen Infrared Reflector (HIR) PAR38	CFL Bare Spiral
CFL PAR38	LED A-Type Lamp
LED PAR38	

- In 2010, it was estimated that over 96% of residential outdoor lamps were incandescent, halogen, or CFL technologies. Approximately, 51% of residential outdoor lamps were general service and 24% were reflector lamps. The remaining share was made up of primarily decorative and miscellaneous lamp types (DOE, 2012(3)).

Performance:

- 65W BR30 is the only viable incandescent reflector lamp due to exemption from EISA 2007. The lumen output of this lamp type is well below other reflector lamp technologies characterized for residential outdoor spaces, thus its use is limited for this application.
- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Fixture prices and installation costs are not included for the residential sector. Labor costs are assumed to be negligible as the homeowner likely replaces lamps themselves as they burn out. Therefore total installed cost is the price of a lamp, and annual maintenance costs are the cost of replacing the lamps, which is a function of lamp life, lamp price, and the annual operating hours of 1059 hours/year for residential reflector lamps (DOE SSL Program, 2012b).

Legislation:

- For ENERGY STAR qualification, general service, omnidirectional lamps must have a minimum lamp efficacy of 55 lm/W and 65 lm/W for lamps with rated wattage of <15W and ≥ 15 W, respectively. The ENERGY STAR Lamps Version 2.0 specification, currently under revision and will take effect January 2, 2017, will require 70 lm/W for omnidirectional lamps with CRI ≥ 90 and 80 lm/W for omnidirectional lamps with CRI < 90 (ENERGY STAR).
- For ENERGY STAR qualification, directional, reflector lamps must have a minimum lamp efficacy of 40 lm/W and 50 lm/W for lamps with rated wattage of <20W and ≥ 20 W, respectively. Additionally, the lamps must have a CRI ≥ 80 Energy Star, nominal CCT of 2700, 3000, 3500, 4000/4100, 5000, or 6000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR, 2014).
- Additionally, the lamps must have a CRI ≥ 80 Energy Star, nominal CCT of 2700, 3000, 3500, 4000/4100, 5000, or 6000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR, 2014).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent Omnidirectional	0%	+0.5%	-0.5%	Limited as the technology is mature and the technology cannot meet legislative requirements.
Incandescent	+0.2%	+0.5%	-0.5%	Improvements can be made by improved filament design and placement, higher pressure capsules, or higher efficiency reflector coatings.
Halogen	+0.5%	+0.5%	-0.5%	Improvements can be made by improved filament design and placement, higher pressure capsules, or higher efficiency reflector coatings.
CFL	+0.5%	+0.5%	-0.5%	In addition to benefiting from higher efficiency reflector coatings, improvements in efficacy can be made by using more rare-earth phosphors in compact fluorescent lamps. Lifetime improvements can be made by improving the compact fluorescent lamp electrodes.

Performance/Cost Characteristics » Residential Outdoor Lamps (Security: LED Reflector)

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	28	18	16	17	20	13	7	9	6	7	6
Lamp Lumens	1000	1172	1328	1958	1050	1400	1400	1400	1400	1400	1400
Lamp Efficacy (lm/W)	36	64	83	116	53	109	197	153	230	196	230
CRI	80	91	84	81	93	84	84	84	84	84	84
Correlated Color Temperature (CCT)	3000	2700	3000	4000	3000	3000	3000	3000	3000	3000	3000
Average Lamp Life (1000 hrs)	20	25	28	25	25	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	1059	1059	1059	1059	1059	1059	1059	1059	1059	1059	1059
Lamp Price ($)	$164.00	$25.68	$27.89	$36.59	$34.47	$6.78	$6.78	$2.21	$2.21	$1.67	$1.67
Lamp Cost ($/klm)	$164.00	$21.92	$21.00	$18.69	$32.83	$4.84	$4.84	$1.58	$1.58	$1.19	$1.19
Labor Cost ($/hr)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Change (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost ($)	$164.00	$25.68	$27.89	$36.59	$34.47	$6.78	$6.78	$2.21	$2.21	$1.67	$1.67
Annual Maintenance Cost ($)	$8.68	$1.09	$1.05	$1.55	$1.46	$0.15	$0.15	$0.05	$0.05	$0.04	$0.04
Total Installed Cost ($/klm)	$164.00	$21.92	$21.00	$18.69	$32.83	$4.84	$4.84	$1.58	$1.58	$1.19	$1.19
Annual Maintenance Cost ($/klm)	$8.68	$0.93	$0.79	$0.79	$1.39	$0.10	$0.10	$0.03	$0.03	$0.03	$0.03

Data based on an indoor 100W Equivalent LED A-type lamp, scaled to lumen output reported for the building exterior low-output technologies in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)

Performance/Cost Characteristics » Residential Outdoor Lamps (Porch: LED A-Type)

DATA	2009	2015				2020		2030		2040	
	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	18	13	9	8	14	8	5	6	4	4	4
Lamp Lumens	964	964	964	964	964	964	964	964	964	964	964
Lamp Efficacy (lm/W)	44	64	93	104	71	123	197	171	230	219	230
CRI	80	83	84	81	92	84	84	84	84	84	84
Correlated Color Temperature (CCT)	3000	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700
Average Lamp Life (1000 hrs)	20	25	25	25	25	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	1059	1059	1059	1059	1059	1059	1059	1059	1059	1059	1059
Lamp Price ($)	$68.00	$24.00	$8.68	$4.99	$11.98	$5.02	$5.02	$1.64	$1.64	$1.04	$1.04
Lamp Cost ($/klm)	$85.00	$24.90	$9.00	$5.18	$12.43	$4.84	$4.84	$1.58	$1.58	$1.00	$1.00
Labor Cost ($/hr)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Change (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost ($)	$68.00	$24.00	$8.68	$4.99	$11.98	$5.02	$5.02	$1.64	$1.64	$1.04	$1.04
Annual Maintenance Cost ($)	$3.60	$1.02	$0.37	$0.21	$0.51	$0.11	$0.11	$0.03	$0.03	$0.02	$0.02
Total Installed Cost ($/klm)	$70.54	$24.90	$9.00	$5.18	$12.43	$5.21	$5.21	$1.70	$1.70	$1.08	$1.08
Annual Maintenance Cost ($/klm)	$3.73	$1.05	$0.38	$0.22	$0.53	$0.11	$0.11	$0.04	$0.04	$0.02	$0.02

Data based on an indoor 100W Equivalent LED A-type lamp, scaled to lumen output reported for the building exterior low-output technologies in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)

Commercial Lighting

Note: More aggressive R&D investment and effort in the lighting industry will only change future projections of LED technologies as it is unlikely that additional funding/effort will be applied to traditional technologies that have been exceeded in performance by their LED counterparts. Therefore, the inputs for all non-LED technologies remain unchanged from the Reference Case and are therefore not included in this report.

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Performance/Cost Characteristics » Commercial General Service Lamps in Recessed Can Fixtures

This section characterizes commercial omnidirectional incandescent, halogen, CFL, and LED screw based general service lamps emitting approximately 1600 lumens (equivalent to a 100W incandescent lamp) used in recessed can fixtures. A recessed can is a directional fixture set into the ceiling, in which all of the light is directed downwards from the opening. Therefore, an omnidirectional lamp is not well suited for use in such fixtures, as light that emits upwards and out of the sides must be reflected downwards and out of the fixture and some light is absorbed in the process. A fixture efficiency of 61% is used to characterize these lumen losses for all omnidirectional lamps. For all lamp technologies, an annual fixture renovation rate of 10% (i.e., 10-year fixture service life) is used to reflect the proportion of equipment that retires each year.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- The total installed cost is the price of a lamp, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED replacement lamps which are sold only as a replacement for use in an existing fixture. There are integrated LED luminaires that are more efficient and cost effective for new installations or fixture retrofits. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Annual maintenance costs are the cost of labor for replacing the lamps and the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 3868 hours/year for commercial general service lamps (DOE SSL Program, 2012a).

Legislation:

- The Energy Independence and Security Act of 2007 (EISA 2007) established standards for 100W lamps effective in 2012. These standards cannot be achieved by incandescent bulbs, but can by halogen, CFL, and LED technologies. As a result, 2015 data is not provided for incandescent general service lamps.
- EISA 2007 also established a requirement that DOE establish standards for general service lamps that are equal to or greater than 45 lm/W by 2020. California's Appliance Efficiency Regulations will require 45 lm/W for general service lamps with certain bases beginning in 2018. These standards can not be achieved by traditional incandescent or halogen technologies currently on the market and given current and projected trends in industry it is not likely they will be met. It is currently assumed that industry will increase their investment in LED technology at the expense of incandescent, halogen, and CFL technologies.
- EPACT 2005 sets performance for medium based compact fluorescent lamps. It adopts ENERGY STAR performance requirements (August 6, 2001 version) for efficacy, lumen maintenance, lamp life, rapid cycle stress test, CRI, etc. The standard is effective for lamps manufactured on or after January 1, 2006. Note that EPACT 2005 standards do not apply to CFL lamps with screw bases other than medium (e.g., pin based). The Secretary may revise these requirements by rule or establish other requirements at a later date. An updated DOE standard is expected in 2017 with a potential effective date of 2020.
- For ENERGY STAR qualification, general service, omnidirectional lamps, must have a minimum lamp efficacy of 55 lm/W and 65 lm/W for lamps with rated wattage of <15W and ≥ 15 W, respectively. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2700, 3000, 3500, 4000/4100, 5000, or 6000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR, 2014). The ENERGY STAR Lamps Version 2.0 specification, currently under revision and will take effect January 2, 2017, will require 70 lm/W for omnidirectional lamps with CRI ≥ 90 and 80 lm/W for omnidirectional lamps with CRI < 90 (ENERGY STAR).
- The ENERGY STAR Luminaires v1.2 specification took effect on December 21, 2012 and requires 42 lm/W for recessed downlights (ENERGY STAR, 2012). The ENERGY STAR Luminaires v2.0 specification will supersede v1.2 effective June 1, 2016 and will require 55 lm/W for recessed downlights (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	0%	0%	-0.5%	Limited as the technology is mature and the technology cannot meet legislative requirements.
Halogen	+0.5%	+0.5%	-0.5%	Limited as the technology is mature.
CFL	+0.5%	+0.5%	-0.5%	Improvements in efficacy can be made by using more rare-earth phosphors in compact fluorescent lamps. Lifetime improvements can be made by improving the compact fluorescent lamp electrodes.

Performance/Cost Characteristics » Commercial General Service 100W Equivalent LED Replacement Lamp in Recessed Can Fixture

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star[4]	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	27	17	15	16	23	11	10	8	7	7	7
Lamp Lumens	N/A	1600	1580	1646	1710	1600	1600	1600	1600	1600	1600	1600
Lamp Efficacy (lm/W)	N/A	60	92	108	110	71	150	161	209	220	230	230
System Wattage	N/A	27	17	15	16	23	11	10	8	7	7	7
System Lumens	N/A	976	964	1004	1043	976	976	976	976	976	976	976
System Efficacy (lm/W)	N/A	36.6	56.4	66.2	67.3	43.4	91.6	98.1	127.4	133.9	140.3	140.3
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	N/A	80	84	83	81	82	83	83	83	83	83	83
Correlated Color Temperature (CCT)	N/A	3000	3000	2700	2700	3000	2700	2700	2700	2700	2700	2700
Average Lamp Life (1000 hrs)	N/A	22	25	25	25	25	48	49	50	50	50	50
Annual Operating Hours (hrs/yr)	N/A	3868	3868	3868	3868	3868	3868	3868	3868	3868	3868	3868
Lamp Price ($)	N/A	$40.00	$14.71	$15.30	$15.99	$22.99	$7.74	$7.74	$2.53	$2.53	$1.60	$1.60
Ballast Price ($)[5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)[5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)	N/A	$25.00	$9.31	$9.30	$9.35	$14.37	$4.84	$4.84	$1.58	$1.58	$1.00	$1.00
System (l/b/f) Cost ($/klm)[5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Cost ($/hr)	N/A	$77.05	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95
Labor System Installation (hr)	N/A	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Labor Lamp Change (hr)	N/A	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Total Installed Cost ($)	N/A	$117.05	$96.66	$97.25	$97.94	$104.94	$89.69	$89.69	$84.48	$84.48	$83.55	$83.55
Annual Maintenance Cost ($)	N/A	$7.71	$2.91	$3.00	$3.11	$4.19	$0.95	$0.93	$0.51	$0.51	$0.44	$0.44
Total Installed Cost ($/klm)	N/A	$73.16	$61.18	$59.10	$57.27	$65.59	$56.06	$56.06	$52.80	$52.80	$52.22	$52.22
Annual Maintenance Cost ($/klm)	N/A	$4.82	$1.84	$1.82	$1.82	$2.62	$0.60	$0.58	$0.32	$0.32	$0.28	$0.28

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. Represents the lowest efficacy product in the Energy Star Database (as downloaded on 11/4/15) for which all of the information in the table is available.
5. N/A b/c this is an LED Replacement lamp that is for existing fixtures. For installations where a fixture must be purchased, an integrated LED Luminaire would be more efficient and cost effective.

This section characterizes commercial halogen, HIR, and LED screw based reflector lamps emitting approximately 1400 lumens used in recessed can fixtures.

- Halogen infrared reflector (HIR) lamps contain a tungsten halogen capsule with a film coating on the inside of the capsule. The coating reflects infrared radiation back into the lamp filament, which forces the filament to burn at a higher temperature. This increases the efficacy of the lamp, without reducing operating life.
- A recessed can is a directional fixture set into the ceiling, in which all of the light is directed downwards from the opening. Therefore, a reflector lamp, which employs reflective coating to direct light out in only one direction, is well suited for use in such fixtures. However, some light is not able to escape the fixture, and a fixture efficiency of 93% is used to characterize these minimal lumen losses. For all lamp technologies, an annual fixture renovation rate of 10% (i.e., 10-year fixture service life) is used to reflect the proportion of equipment that retires each year.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- The total installed cost is the price of a lamp, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED replacement lamps which are sold only as a replacement for use in an existing fixture. There are integrated LED luminaires that are more efficient and cost effective for new installations or fixture retrofits. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Annual maintenance costs are the cost of labor for replacing the lamps and the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 3860 hours/year for commercial reflector lamps (DOE SSL Program, 2012a).

Legislation:

- EPACT92 established minimum performance standards for some reflector lamps and provided exemptions for certain specialty applications (e.g., ER/BR, vibration service, more than 5% neodymium oxide, impact resistant, infrared heat, colored). EPACT92 effectively phased-out R-shaped tungsten filament incandescent reflector lamps at certain wattages and bulb diameters, replacing them with more efficient and cost effective tungsten-halogen parabolic aluminized reflector (PAR) lamps. EISA2007 took away certain exemptions from EPACT 1992, requiring certain previously exempted lamps to meet EPACT92 minimum performance standards by January 1, 2008. In 2015, DOE issued a final rule which determined that amending the standards for incandescent reflector lamps could not be economically justified.
- For ENERGY STAR qualification, directional, reflector lamps must have a minimum lamp efficacy of 40 lm/W and 50 lm/W for lamps with rated wattage of <20W and ≥ 20 W, respectively. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2700, 3000, 3500, 4000/4100, 5000, or 6000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR, 2014). The ENERGY STAR Lamps Version 2.0 specification, currently under revision and will take effect January 2, 2017, will require 61 lm/W for omnidirectional lamps with CRI ≥ 90 and 70 lm/W for omnidirectional lamps with CRI < 90 (ENERGY STAR).
- The ENERGY STAR Luminaires v1.2 specification took effect on December 21, 2012 and requires 42 lm/W for recessed downlights (ENERGY STAR, 2012). The ENERGY STAR Luminaires v2.0 specification will supersede v1.2 effective June 1, 2016 and will require 55 lm/W for recessed downlights (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

	Efficacy	Lifetime	Price	Potential for Improvements
Halogen	+0.5%	+0.5%	-0.5%	Improvements can be made by improved filament design and placement, higher pressure capsules, or higher efficiency reflector coatings.
HIR	+0.5%	+0.5%	-0.5%	Improvements can be made by improved filament design and placement, higher pressure capsules, or higher efficiency reflector coatings.
CFL	+0.5%	+0.5%	-0.5%	Improvements in efficacy can be made by using more rare-earth phosphors in compact fluorescent lamps. Lifetime improvements can be made by improving the compact fluorescent lamp electrodes.

Performance/Cost Characteristics » Commercial LED Reflector Lighting (PAR38)

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star[4]	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	17	18	16	17	20	12	11	9	8	7	6
Lamp Lumens	N/A	1045	1172	1328	1958	1050	1400	1400	1400	1400	1400	1400
Lamp Efficacy (lm/W)	N/A	61	64	83	116	53	116	124	162	170	209	216
System Wattage	N/A	17	18	16	17	20	12	11	9	8	7	6
System Lumens*	N/A	972	1090	1235	1821	977	1302	1302	1302	1302	1302	1302
System Efficacy (lm/W)	N/A	57	59	78	108	49	108	115	151	158	194	201
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	N/A	83	91	84	81	93	84	84	84	84	84	84
Correlated Color Temperature (CCT)	N/A	3000	2700	3000	4000	3000	3000	3000	3000	3000	3000	3000
Average Lamp Life (1000 hrs)	N/A	22	25	28	25	25	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	N/A	3860	3860	3860	3860	3860	3860	3860	3860	3860	3860	3860
Lamp Price ($)	N/A	$52.25	$25.68	$27.89	$36.59	$34.47	$6.78	$6.78	$2.21	$2.21	$1.40	$1.40
Ballast Price ($)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)	N/A	$50.00	$21.92	$21.00	$18.69	$32.83	$4.84	$4.84	$1.58	$1.58	$1.00	$1.00
System (l/b/f) Cost ($/klm)[5]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Cost ($/hr)	N/A	$77.05	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95	$81.95
Labor System Installation (hr)[5]	N/A	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Labor Lamp Change (hr)	N/A	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Total Installed Cost ($)	N/A	$56.99	$30.72	$32.93	$41.63	$39.51	$11.82	$11.82	$7.25	$7.25	$6.44	$6.44
Annual Maintenance Cost ($)	N/A	$10.00	$4.74	$4.54	$6.43	$6.10	$0.93	$0.93	$0.56	$0.56	$0.50	$0.50
Total Installed Cost ($/klm)	N/A	$54.53	$26.22	$24.79	$21.26	$37.63	$8.44	$8.44	$5.18	$5.18	$4.60	$4.60
Annual Maintenance Cost ($/klm)	N/A	$9.57	$4.05	$3.42	$3.28	$5.81	$0.66	$0.66	$0.40	$0.40	$0.36	$0.36

1. Based on lowest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. Represents the lowest efficacy product in the Energy Star Database (as downloaded on 11/4/15) for which all of the information in the table is available.
5. N/A b/c this is an LED Replacement lamp that is for existing fixtures. For installations where a fixture must be purchased, an integrated LED Luminaire would be more efficient and cost effective.

This section characterizes commercial linear fixtures that house 2 4ft long linear lamps and their integrated luminaire equivalents. The technologies available for this system are linear fluorescent and LED.

- Linear fluorescent options are T5, T8, and T12 lamps. T5 lamps are approximately 40% narrower than T8 lamps and almost 60% narrower than T12 lamps. This allows T5 lamps to be coated with higher quality, more efficient phosphor blends than larger diameter lamps, resulting in a more efficacious lamp. The compact size of T5 lamps also permits greater flexibility in lighting design and construction.
- LED options for linear fixtures include replacement lamps that are able to fit directly into an existing fixture and fully integrated luminaire that can be used to replace existing fixtures. LED replacement lamps, also known as T lamps or TLEDs, do not require a ballast but can be installed in existing ballasted configurations with or without the removal of the linear fluorescent ballast. Replacement lamps are only sold to go into existing fixtures, if a new fixture is to be installed, a fully integrated LED luminaire is a more cost effective and efficient option. Because LED luminaires are fully integrated, they do not have lamp/fixture efficiency losses associated with ballasts and fixture optics. For all lamp technologies, an annual fixture renovation rate of 10% (i.e., 10-year fixture service life) is used to reflect the proportion of equipment that retires each year.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- The total installed cost is the price of 2 lamps, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED replacement lamps which are sold only as a replacement for use in an existing fixture. There are integrated LED luminaires that are more efficient and cost effective for new installations or fixture retrofits. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Annual maintenance costs are the cost of labor for replacing the lamps and the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 4055 hours/year for commercial 4ft linear systems (DOE SSL Program, 2012a).

Legislation:

- Beginning July 14, 2012 (or July 14, 2014 for T8 700-series phosphor lamps), DOE fluorescent lamp standards will require a minimum efficacy of 89 lm/W. While the amended performance-based standards do not explicitly prohibit T12 lamps, no T12 lamps met the standard at the time of its announcement. Since then, however, T12 lamps meeting the standard have entered the market.
- California's Title 24 mandates the use of electronic ballasts with high efficacy luminaires (including fluorescent) of 13 W or higher (CEC, 2005).
- ENERGY STAR does not cover commercial linear luminaires (ENERGY STAR, 2012).

Performance/Cost Characteristics » Commercial 4-foot Linear 2-Lamp Lighting Systems

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
T8 F32 Commodity	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
T8 F32 High Efficiency/High Output	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
T5 F28	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.

Performance/Cost Characteristics » Commercial 4-ft Linear LED Replacement Lamp in 2-Lamp System

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	21	19	18	18	N/A	14	12	11	10	9	9
Lamp Lumens	N/A	2091	1743	2151	2303	N/A	2100	2100	2100	2100	2100	2100
Lamp Efficacy (lm/W)	N/A	101	92	116	132	N/A	151	173	199	221	230	230
System Wattage	N/A	42	38	37	35	N/A	28	24	21	19	18	18
System Lumens	N/A	3555	3102	3829	4099	N/A	3948	3948	4032	4032	4032	4032
System Efficacy (lm/W)	N/A	85	82	104	117	N/A	142	162	191	212	221	221
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	N/A	86	80	83	85	N/A	83	83	83	83	83	83
Correlated Color Temperature (CCT)	N/A	4100	4000	4100	5000	N/A	4100	4100	4100	4100	4100	4100
Average Lifetime (1000 hrs)	N/A	50	50	45	50	N/A	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	N/A	4055	4055	4055	4055	N/A	4055	4055	4055	4055	4055	4055
Lamp/Luminaire Price ($)	N/A	$234.66	$22.19	$34.42	$38.30	N/A	$15.21	$15.21	$4.97	$4.97	$2.10	$2.10
Ballast Price ($)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)	N/A	$112.20	$12.73	$16.00	$16.63	N/A	$7.24	$7.24	$2.36	$2.36	$1.00	$1.00
System (l/b/f) Cost ($/klm)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Cost ($/hr)	N/A	$65.10	$68.20	$68.20	$68.20	N/A	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20
Labor System Installation (hr)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Lamp Change (hr)	N/A	0.40	0.40	0.40	0.40	N/A	0.40	0.40	0.40	0.40	0.40	0.40
Total Installed Cost ($)	N/A	$495.15	$71.43	$95.90	$103.65	N/A	$42.27	$42.27	$32.02	$32.02	$29.15	$29.15
Annual Maintenance Cost ($)	N/A	$40.16	$5.79	$8.64	$8.41	N/A	$3.50	$3.50	$2.60	$2.60	$2.36	$2.36
Total Installed Cost ($/klm)	N/A	$236.76	$40.98	$44.57	$45.01	N/A	$20.13	$20.13	$15.25	$15.25	$13.88	$13.88
Annual Maintenance Cost ($/klm)	N/A	$19.20	$3.32	$4.02	$3.65	N/A	$1.67	$1.67	$1.24	$1.24	$1.13	$1.13

1. Based on lowest efficacy product in the DLC Qualified Product Database (as downloaded on 11/18/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. N/A because Linear LED Replacement Lamps are a retrofit option and sold only to be put in existing fixtures.

Performance/Cost Characteristics » Commercial 4-ft Linear LED Luminaire to Replace 2-Lamp Systems

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Efficacy (lm/W)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	36.4	51	48	57	40	N/A	30	25	22	22	22	22
System Lumens	548	4818	4044	5697	4918	N/A	5000	5000	5000	5000	5000	5000
System Efficacy (lm/W)	15	94	84	100	122	N/A	164	197	230	230	230	230
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	92	84	83	83	83	N/A	83	83	83	83	83	83
Correlated Color Temperature (CCT)	3500	3500	3500	3500	3500	N/A	3500	3500	3500	3500	3500	3500
Average Lifetime (1000 hrs)	50	67	60	56	50	N/A	97	97	100	100	100	100
Annual Operating Hours (hrs/yr)	4055	4055	4055	4055	4055	N/A	4055	4055	4055	4055	4055	4055
Lamp/Luminaire Price ($)	$215.19	$610.32	$439.00	$176.61	$513.45	N/A	$93.02	$93.02	$45.29	$45.29	$22.06	$22.06
Ballast Price ($)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System (l/b/f) Cost ($/klm)	$392.68	$126.67	$108.56	$31.00	$104.41	N/A	$18.60	$18.60	$9.06	$9.06	$4.41	$4.41
Labor Cost ($/hr)	$110.50	$65.10	$68.20	$68.20	$68.20	N/A	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20
Labor System Installation (hr)	0.5	0.50	0.50	0.50	0.50	N/A	0.50	0.50	0.50	0.50	0.50	0.50
Labor Lamp Change (hr)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost ($)	$270.44	$642.87	$473.10	$210.71	$547.55	N/A	$127.12	$127.12	$79.39	$79.39	$56.16	$56.16
Annual Maintenance Cost ($)	$0.07	$38.91	$31.98	$15.26	$44.41	N/A	$5.31	$5.31	$3.22	$3.22	$2.28	$2.28
Total Installed Cost ($/klm)	$493.50	$133.43	$116.99	$36.99	$111.35	N/A	$25.42	$25.42	$15.88	$15.88	$11.23	$11.23
Annual Maintenance Cost ($/klm)	$0.13	$8.08	$7.91	$2.68	$9.03	N/A	$1.06	$1.06	$0.64	$0.64	$0.46	$0.46

1. Based on lowest efficacy product in the DLC Qualified Product Database (as downloaded on 11/18/15) for which all of the information in the table is available.
2. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
3. Based on highest efficacy product in the DLC Qualified Product Database (as downloaded on 11/18/15) for which all of the information in the table is available.
4. N/A because Linear LED Luminaires are a fully integrated lighting solutions used to replace existing lamp/ballast/fixture systems and therefore does not have lamp, ballast, and fixture components

Performance/Cost Characteristics » Commercial 8-foot Linear 2-Lamp Lighting Systems

This section characterizes commercial linear fixtures that house 2 8ft long linear lamps and their integrated luminaire equivalents. The technologies available for this system are linear fluorescent and LED.

- Linear fluorescent options are T5, T8, and T12 lamps. T5 lamps are approximately 40% narrower than T8 lamps and almost 60% narrower than T12 lamps. This allows T5 lamps to be coated with higher quality, more efficient phosphor blends than larger diameter lamps, resulting in a more efficacious lamp. The compact size of T5 lamps also permits greater flexibility in lighting design and construction.
- LED options for linear fixtures include replacement lamps that are able to fit directly into an existing fixture and fully integrated luminaire that can be used to replace existing fixtures. LED replacement lamps, also known as T lamps or TLEDs, do not require a ballast but can be installed in existing ballasted configurations with or without the removal of the linear fluorescent ballast. Replacement lamps are only sold to go into existing fixtures, if a new fixture is to be installed, a fully integrated LED luminaire is a more cost effective and efficient option. Because LED luminaires are fully integrated, they do not have lamp/fixture efficiency losses associated with ballasts and fixture optics. For all lamp technologies, an annual fixture renovation rate of 10% (i.e., 10-year fixture service life) is used to reflect the proportion of equipment that retires each year.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- The total installed cost is the price of 2 lamps, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED replacement lamps which are sold only as a replacement for use in an existing fixture. There are integrated LED luminaires that are more efficient and cost effective for new installations or fixture retrofits. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Annual maintenance costs are the cost of labor for replacing the lamps and the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 4147 hours/year for commercial 8ft linear systems (DOE SSL Program, 2012a).

Legislation:

- Beginning July 14, 2012 (or July 14, 2014 for T8 700-series phosphor lamps), DOE fluorescent lamp standards will require a minimum efficacy of 89 lm/W. While the amended performance-based standards do not explicitly prohibit T12 lamps, no T12 lamps met the standard at the time of its announcement. Since then, however, T12 lamps meeting the standard have entered the market.
- California's Title 24 mandates the use of electronic ballasts with high efficacy luminaires (including fluorescent) of 13 W or higher (CEC, 2005).
- ENERGY STAR does not cover commercial linear luminaires (ENERGY STAR, 2012).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
T8 F59 Typical Efficiency	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
T8 F59 High Efficiency	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
T8 F96 High Output	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.

Performance/Cost Characteristics » Commercial 8-ft Linear LED Replacement Lamp for a 2 Lamp System

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical[1]	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	N/A	N/A	36	N/A	N/A	39	34	30	27	25	25
Lamp Lumens	N/A	N/A	N/A	3975	N/A	N/A	5650	5650	5650	5650	5650	5650
Lamp Efficacy (lm/W)	N/A	N/A	N/A	111	N/A	N/A	144	165	190	211	230	230
System Wattage	N/A	N/A	N/A	71	N/A	N/A	79	69	59	54	49	49
System Lumens	N/A	N/A	N/A	7076	N/A	N/A	10622	10622	10848	10848	10848	10848
System Efficacy (lm/W)	N/A	N/A	N/A	99	N/A	N/A	135	155	182	203	221	221
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	N/A	N/A	N/A	80	N/A	N/A	80	80	80	80	80	80
Correlated Color Temperature (CCT)	N/A	N/A	N/A	5000	N/A	N/A	5000	5000	5000	5000	5000	5000
Average Lifetime (1000 hrs)	N/A	N/A	N/A	50	N/A	N/A	49	49	50	50	50	50
Annual Operating Hours (hrs/yr)	N/A	N/A	N/A	4147	N/A	N/A	4147	4147	4147	4147	4147	4147
Lamp/Luminaire Price ($)	N/A	N/A	N/A	$75.53	N/A	N/A	$48.60	$48.60	$15.87	$15.87	$5.65	$5.65
Ballast Price ($)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)	N/A	N/A	N/A	$19.00	N/A	N/A	$8.60	$8.60	$2.81	$2.81	$1.00	$1.00
System (l/b/f) Cost ($/klm)[2]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Cost ($/hr)	N/A	N/A	N/A	$68.20	N/A	N/A	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20
Labor System Installation (hr)[2]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Lamp Change (hr)	N/A	N/A	N/A	0.4	N/A	N/A	0.4	0.4	0.4	0.4	0.4	0.4
Total Installed Cost ($)	N/A	N/A	N/A	$176.63	N/A	N/A	$74.18	$74.18	$41.44	$41.44	$32.70	$32.70
Annual Maintenance Cost ($)	N/A	N/A	N/A	$14.65	N/A	N/A	$6.28	$6.28	$3.44	$3.44	$2.71	$2.71
Total Installed Cost ($/klm)	N/A	N/A	N/A	$44.43	N/A	N/A	$13.13	$13.13	$7.33	$7.33	$5.79	$5.79
Annual Maintenance Cost ($/klm)	N/A	N/A	N/A	$3.69	N/A	N/A	$1.11	$1.11	$0.61	$0.61	$0.48	$0.48

1. Based on the average of products in the LED Lighting Facts Database (as downloaded on 10/30/15).
2. N/A because Linear LED Replacement Lamps are a retrofit option and sold only to be put in existing fixtures.

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical[1]	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Efficacy (lm/W)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	N/A	N/A	N/A	73	N/A	N/A	46	41	35	35	35	35
System Lumens	N/A	N/A	N/A	8000	N/A	N/A	8000	8000	8000	8000	8000	8000
System Efficacy (lm/W)	N/A	N/A	N/A	110	N/A	N/A	173	197	230	230	230	230
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	N/A	N/A	N/A	90	N/A	N/A	90	90	90	90	90	90
Correlated Color Temperature (CCT)	N/A	N/A	N/A	4000	N/A	N/A	4000	4000	4000	4000	4000	4000
Average Lifetime (1000 hrs)	N/A	N/A	N/A	75	N/A	N/A	97	97	100	100	100	100
Annual Operating Hours (hrs/yr)	N/A	N/A	N/A	4147	N/A	N/A	4147	4147	4147	4147	4147	4147
Lamp/Luminaire Price ($)	N/A	N/A	N/A	$640.00	N/A	N/A	$384.08	$384.08	$187.02	$187.02	$91.07	$91.07
Ballast Price ($)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)[2]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System (l/b/f) Cost ($/klm)	N/A	N/A	N/A	$80.00	N/A	N/A	$48.01	$48.01	$23.38	$23.38	$11.38	$11.38
Labor Cost ($/hr)	N/A	N/A	N/A	$68.20	N/A	N/A	$68.20	$68.20	$68.20	$68.20	$68.20	$68.20
Labor System Installation (hr)	N/A	N/A	N/A	1.0	N/A	N/A	1.0	1.0	1.0	1.0	1.0	1.0
Labor Lamp Change (hr)[2]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost ($)	N/A	N/A	N/A	$708.20	N/A	N/A	$452.28	$452.28	$255.22	$255.22	$159.27	$159.27
Annual Maintenance Cost ($)	N/A	N/A	N/A	$39.16	N/A	N/A	$19.34	$19.34	$10.58	$10.58	$6.60	$6.60
Total Installed Cost ($/klm)	N/A	N/A	N/A	$88.53	N/A	N/A	$56.53	$56.53	$31.90	$31.90	$19.91	$19.91
Annual Maintenance Cost ($/klm)	N/A	N/A	N/A	$4.89	N/A	N/A	$2.42	$2.42	$1.32	$1.32	$0.83	$0.83

1. Based on the CREE CS18-80LHE found on Grainger online of 11/20/15
2. N/A because Linear LED Luminaires are a fully integrated lighting solutions used to replace existing lamp/ballast/fixture systems and therefore does not have lamp, ballast, and fixture components.

The commercial low bay lighting characterized in this report is a one-lamp and one-ballast system in a low/high bay fixture that emits between 6,000 and 10,000 system lumens. Low bay lighting is defined as "interior lighting where the roof trusses or ceiling height is less than 25ft. above the floor"(IESNA, 2000). For all lamp technologies, an annual fixture renovation rate of 10% (i.e., 10-year fixture service life) is used to reflect the proportion of equipment that retires each year.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- The total installed cost is the price of a lamp, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED luminaires which are sold as one integrated system. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Annual maintenance costs are the cost of labor for replacing the lamps and the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 4042 hours/year for commercial low-bay systems (DOE SSL Program, 2012a).

Legislation:

- ENERGY STAR does not cover low/high bay luminaires (ENERGY STAR, 2012).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Mercury Vapor	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
Metal Halide	+0.5%	+0.5%	-0.5%	Limited as the technology is mature.
Sodium Vapor	+0.5%	+0.5%	-0.5%	Limited as the technology is mature.
T5 4xF54 HO Linear System	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.

Performance/Cost Characteristics » Commercial LED Low-bay Luminaire

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Efficacy (lm/W)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	36	68	104	71	46	N/A	47	36	34	30	30	30
System Lumens	548	4877	8410	7042	6294	N/A	7000	7000	7000	7000	7000	7000
System Efficacy (lm/W)	15	72	81	100	136	N/A	150	197	207	230	230	230
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	92	85	75	81	84	N/A	81	81	81	81	81	81
Correlated Color Temperature (CCT)	4000	4000	5000	4000	4000	N/A	4000	4000	4000	4000	4000	4000
Average Lifetime (1000 hrs)	50	50	100	60	100	N/A	97	97	100	100	100	100
Annual Operating Hours (hrs/yr)	4042	4042	4042	4042	4042	N/A	4042	4042	4042	4042	4042	4042
Lamp/Luminaire Price ($)	$215.19	$761.95	$447.31	$267.59	$332.80	N/A	$159.63	$159.63	$77.73	$77.73	$37.85	$37.85
Ballast Price ($)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System (l/b/f) Cost ($/klm)	$392.68	$156.23	$53.19	$38.00	$52.88	N/A	$22.80	$22.80	$11.10	$11.10	$5.41	$5.41
Labor Cost ($/hr)	$36.83	$68.99	$68.99	$68.99	$68.99	N/A	$68.99	$68.99	$68.99	$68.99	$68.20	$68.20
Labor System Installation (hr)	1.5	1.5	1.5	1.5	1.5	N/A	1.5	1.5	1.5	1.5	1.5	1.5
Labor Lamp Change (hr)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost ($)	$270.44	$865.44	$550.80	$371.08	$436.29	N/A	$263.12	$263.12	$181.22	$181.22	$140.15	$140.15
Annual Maintenance Cost ($)	$0.07	$69.95	$22.26	$25.00	$17.63	N/A	$10.96	$10.96	$7.32	$7.32	$5.66	$5.66
Total Installed Cost ($/klm)	$493.50	$177.44	$65.49	$52.70	$69.32	N/A	$37.59	$37.59	$25.89	$25.89	$20.02	$20.02
Annual Maintenance Cost ($/klm)	$0.13	$14.34	$2.65	$3.55	$2.80	N/A	$1.57	$1.57	$1.05	$1.05	$0.81	$0.81

1. Based on lowest efficacy product in the DLC Qualified Product Database (as downloaded on 11/18/15) for which all of the information in the table is available.
2. Based on the average of products in the DLC Qualified Product Database (as downloaded on 11/18//15).
3. Based on highest efficacy product in the LED Lighting Facts Database (as downloaded on 10/30/15) for which all of the information in the table is available.
4. LED Low-Bay Luminaires are a fully integrated lighting solutions used to replace existing lamp/ballast/fixture systems and therefore does not have lamp, ballast, and fixture components.

The commercial high-bay lighting characterized in this report is a one-lamp and one-ballast system in a low/high bay fixture that emits greater than 10,000 system lumens. High-bay lighting is defined as “interior lighting where the roof trusses or ceiling height is greater than 25ft. above the floor” (IESNA, 2000). For all lamp technologies, an annual fixture renovation rate of 10% (i.e., 10-year fixture service life) is used to reflect the proportion of equipment that retires each year.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2700K and give off a warm, yellowish white color, but products with CCTs of 3000K, 3500K, 4100K (neutral white), 5000K (daylight) and 6500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2700K. When replacing a light bulb, it is advised to chose a product with a similar CCT value in order to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but for CFL and LEDs products commonly fall between 70 and 90 CRI, with an average around 80. CRI values of 80 are considered suitable for general illumination, with high CRI products being preferable for retail and display applications where improved color quality is of real value. Higher CRI is not expected to be a focus for future LED products except for these very specific retail and display applications.

Cost:

- The total installed cost is the price of a lamp, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED luminaires which are sold as one integrated system. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy. Therefore typical lamp prices in 2015 reflecting a mix of lamp characteristics and features were used as the basis for projections for both typical and high efficacy products in the future.
- Annual maintenance costs are the cost of labor for replacing the lamps and the cost of the replacement lamp itself. The frequency at which lamps are replaced is a function of lamp life and the annual operating hours of 4042 hours/year for commercial low-bay systems (DOE SSL Program, 2012a).

Legislation:

- ENERGY STAR does not cover low/high bay luminaires (ENERGY STAR, 2012).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2020, 2030, and 2040. Assumptions were made that the focus would be on improving efficacy, lifetime and price for products at constant CRI and CCT values.
- *Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors* (Navigant, 2014).
- For LED Technology, efficacy, lifetime, and price improvements were based on the model described in the Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014). For traditional technologies, the following future improvements were assumed to occur year over year through 2040:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Mercury Vapor	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.
Metal Halide	+0.5%	+0.5%	-0.5%	Limited as the technology is mature.
Sodium Vapor	+0.5%	+0.5%	-0.5%	Limited as the technology is mature.
T5 4xF54 HO Linear System	+0.2%	+0.5%	-0.5%	Limited as the technology is mature.

Performance/Cost Characteristics » Commercial LED High-bay Luminaire

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low[1]	Typical[2]	High[3]	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Efficacy (lm/W)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	36	212	189	183	101	N/A	100	76	72	65	65	65
System Lumens	548	18915	15070	18722	13640	N/A	15000	15000	15000	15000	15000	15000
System Efficacy (lm/W)	15	89	80	102	135	N/A	150	197	207	230	230	230
Ballast Efficiency (BLE)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	92	74	73	80	83	N/A	80	80	80	80	80	80
Correlated Color Temperature (CCT)	5000	5000	5000	4000	4100	N/A	4000	4000	4000	4000	4000	4000
Average Lifetime (1000 hrs)	50	70	50	60	50	N/A	97	97	100	100	100	100
Annual Operating Hours (hrs/yr)	4042	4042	4042	4042	4042	N/A	4042	4042	4042	4042	4042	4042
Lamp/Luminaire Price ($)	$215.19	$2,395.94	$398.34	$711.42	$297.76	N/A	$342.07	$342.07	$166.57	$166.57	$81.11	$81.11
Ballast Price ($)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price ($)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost ($/klm)[4]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System (l/b/f) Cost ($/klm)	$392.68	$126.67	$26.43	$38.00	$21.83	N/A	$22.80	$22.80	$11.10	$11.10	$5.41	$5.41
Labor Cost ($/hr)	$36.83	$72.71	$68.99	$68.99	$68.99	N/A	$68.99	$68.99	$68.99	$68.99	$68.99	$68.99
Labor System Installation (hr)	2	2	2	1.5	1.5	N/A	1.5	1.5	1.5	1.5	1.5	1.5
Labor Lamp Change (hr)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost ($)	$270.44	$2,505.00	$501.83	$814.90	$401.25	N/A	$445.55	$445.55	$270.05	$270.05	$184.59	$184.59
Annual Maintenance Cost ($)	$0.07	$144.63	$40.56	$54.89	$32.43	N/A	$18.56	$18.56	$10.91	$10.91	$7.46	$7.46
Total Installed Cost ($/klm)	$493.50	$132.44	$33.30	$43.53	$29.42	N/A	$29.70	$29.70	$18.00	$18.00	$12.31	$12.31
Annual Maintenance Cost ($/klm)	$0.13	$7.65	$2.69	$2.93	$2.38	N/A	$1.24	$1.24	$0.73	$0.73	$0.50	$0.50

1. Based on lowest efficacy product in the DLC Qualified Product Database (as downloaded on 11/18/15) for which all of the information in the table is available.
2. Based on the average of products in the DLC Qualified Product Database (as downloaded on 11/18/15).
3. Based on highest efficacy product in the DLC Qualified Product Database (as downloaded on 11/18/15) for which all of the information in the table is available.
4. LED High-Bay Luminaires are a fully integrated lighting solutions used to replace existing lamp/ballast/fixture systems and therefore does not have lamp, ballast, and fixture components.

Additional Technologies of Interest: Lighting

- Tables were not provided for technologies of interest utilizing occupancy sensors and other controls due to lack of available data and currently small market presence.
  - Lighting controls can save energy by either reducing input wattage or limiting hours of operation.
  - The following table indicates prevalence of various lighting controls in 2010 (DOE SSL Program, 2012a).
  - Leading experts claim that controls penetration remains low, particularly for integrated/advanced controls (DOE Connected Lighting Systems Meeting, November 2015).
  - As a result, there is not enough information to determine the price and performance impacts of controls on current lighting technologies or to project improvements going forward.

Prevalence of Lighting Controls by Sector and Lamp Type

		None	Dimmer	Light Sensor	Motion Detector	Timer	EMS	Total
Residential	Incandescent	76%	5%	0%	0%	2%	16%	100%
	Halogen	73%	5%	0%	1%	3%	18%	100%
	CFL	77%	0%	0%	3%	2%	18%	100%
	Linear Fluorescent	68%	3%	1%	7%	4%	17%	100%
	HID	71%	0%	2%	1%	6%	20%	100%
	Other	85%	0%	0%	0%	0%	15%	100%
Commercial	Incandescent	76%	5%	0%	0%	2%	16%	100%
	Halogen	73%	5%	0%	1%	3%	18%	100%
	CFL	77%	0%	0%	3%	2%	18%	100%
	Linear Fluorescent	68%	3%	1%	7%	4%	17%	100%
	HID	71%	0%	2%	1%	6%	20%	100%
	Other	85%	0%	0%	0%	0%	15%	100%

EMS: Energy Management System
HID: High Intensity Discharge:
CFL: Compact Fluorescent Lamp

Refrigeration
Advanced Case

Commercial Compressor Rack Systems

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Total Capacity (kBtu/hr) [1]	1,050	1,200	1,200	1,190	930	N/A	830	775	777	679	777	679
Median Store Size (ft^2)	44,000	46,500	46,500	46,500	46,500	N/A	46,500	46,500	46,500	46,500	46,500	46,500
Power Input (kW)	180	162	162	160	125	N/A	104	102	85	74	74	70
Energy Use (MWh/yr) [2]	1,618	1,497	1,497	1,484	1,160	N/A	1033	914	841	735	841	735
Indexed Annual Efficiency[3]	1.00	1.08	1.08	1.09	1.40	N/A	1.57	1.77	1.92	2.20	1.92	2.20
Average Life (yrs)	15	15	15	15	15	N/A	15	15	15	15	15	15
Total Installed Cost ($1000) [4]	$630	$630	$630	$625	$488	N/A	$452	$422	$408	$356	$408	$356
Total Installed Cost ($/kBtu/hr)	$600	$525	$525	$525	$525	N/A	$545	$545	$524	$524	$524	$524
Annual Maintenance Cost ($1000)[5]	$33	$34	$34	$34	$34	N/A	$34	$34	$34	$34	$34	$34
Annual Maintenance Cost ($/kBtu/hr)	$31.14	$28	$28	$29	$37	N/A	$41	$44	$44	$50	$44	$50

[1] The total capacity represents the nominal compressor capacity required for the entire refrigeration system of a typical supermarket. This usually includes two low temperature racks and two medium temperature racks. For 2012 a 1,200 MBtu/hr total cooling capacity is based on a 100 ton estimate for total capacity – 80 tons for the medium temperature racks and 20 tons for the low temperature racks. Beyond 2012, estimates are based on data provided by a supermarket refrigeration efficiency consultant.

[2] Capacity and Annual energy consumption for 2012 and beyond are based on interviews with supermarket refrigeration consultants

[3] Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use).

[4] The total installed cost for 2003 is based on the entire supermarket compressor rack system (two medium temperature racks and two low temperature racks). The equipment purchase price for an entire supermarket compressor rack system is approximately $130,000, the installation cost (including piping, electrical, startup and commissioning) is approximately $400,000, and the rack defrost and lighting controls are approximately $100,000. Therefore the total installed cost for a typical supermarket compressor rack system is approximately $630,000. Total installed cost for 2012 and beyond is based on updated Navigant estimates. Note the decrease in cost over time as required capacity is decreased.

[5] Maintenance cost includes oil changes, bearing lubrication, filter replacement, and system functionality checks.

Commercial Compressor Rack Systems

- Commercial compressor rack systems that serve commercial supermarket display cases and walk-ins consist of a number of parallel-connected compressors located in a separate machine room. By modulating compressor capacity, these integrated systems provide higher efficiency and mechanical longevity.
- Rack integrators generally supply a packaged compressor rack for which much of the necessary piping, insulation, components, and controls are pre-assembled.
- A typical supermarket will have 10 to 20 compressors mounted in racks in the 3-hp to 15-hp size range. Usually there are 3 to 5 compressors per rack serving a series of loads with nearly identical evaporator temperature.
- The duty cycle for compressors is usually in the range 60% to 70%.
- Approximately 34 percent of the total annual electricity consumption for a typical supermarket is attributable to compressors. (NCI, 2009)
- There are an estimated 140,000 compressor rack systems installed in supermarkets across the U.S. as of 2008. (NCI, 2009)
- Installed cost, power draw, and capacity are all expected to decrease in the future due to the reduced load of supermarket display cases
- **For this advanced case, a 10% reduction in energy consumption and a 5% reduction in required capacity is assumed to occur over the reference case for 2020 and beyond due to VIP adoption by display cases and a relaxation in charge size limits for more efficient, low GWP, but toxic/flammable refrigerants such as ammonia and propane due to improved safety technology such as leak detection**.

Commercial Condensers

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Total Capacity (kBtu/hr) [1]	1,680	1,680	1,680	1,666	1,302	N/A	1,121	1,065	904	833	904	833
Median Store Size (ft^2)	44,000	46,500	46,500	46,500	46,500	N/A	46,500	46,500	46,500	46,500	46,500	46,500
Power Input (kW)	25	25	24	22	18	N/A	14	13	11	9	11	9
Energy Use (MWh/yr)	138	120	115	106	86	N/A	67	64	52	46	52	43
Indexed Annual Efficiency [2]	1.00	1.15	1.20	1.30	1.60	N/A	2.06	2.17	2.64	3.03	2.64	3.18
Average Life (yrs)	10	10	10	10	10	N/A	10	10	10	10	10	10
Total Installed Cost ($1000)	$47	$54	$54	$53	$51	N/A	$51	$50	$50	$50	$50	$50
Total Installed Cost ($/kBtu/hr)	$27.87	$32	$32	$32	$39	N/A	$45	$47	$55	$60	$55	$60
Annual Maintenance Cost [3]	$817	$954	$954	$954	$954	N/A	$956	$956	$956	$956	$956	$956
Annual Maintenance Cost ($/kBtu/hr)	$0.49	$0.57	$0.57	$0.57	$0.73	N/A	$0.85	$0.90	$1.06	$1.15	$1.06	$1.15

[1] Total capacity is the total heat rejected (THR) of condensers comprised of two low temperature condensers (THRL = 240 MBtu/hr each, suction temperature = -25°F, condensing temperature 110°F) and two medium temperature (THRM = 520 MBtu/hr each, suction temperature = 15°F, condensing temperature = 115°F) condensers; ambient temperature = 95°F. (NCI, 2009). For 2012 and beyond, capacity was estimated based on consultation with a supermarket refrigeration expert.

[2] Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use).

[3] Maintenance cost includes coil cleaning, leak checking, belt replacement as necessary, and system functionality checks. Note a slight expected increase in maintenance costs due to the expected implementation of hybrid condenser systems.

Commercial Condensers

- Condensers are designed with multiple methods of cooling: air-cooled, water-cooled, and evaporative. These units can be single-circuit or a multiple circuit.
- Commercial condensers are remotely located, typically installed on the roof of a supermarket.
- For use with parallel compressors in supermarkets, air-cooled units are the most commonly used condensers. This analysis is based on multiple air-cooled condensers connected to a supermarket refrigeration system comprised of two low temperature condensers and two medium temperature condensers, using R-404A refrigerant.
- Each compressor rack has a dedicated condenser or a separate circuit of a single common condenser. Condenser temperatures of multiple racks are often different.
- The duty cycle for condensers is usually in the range 50 - 70%.
- Approximately 5 percent of the total annual electricity consumption for a typical supermarket is attributable to condensers. (NCI, 2009)
- There are an estimated 140,000 condensers installed in supermarkets across the U.S. as of 2008. (NCI, 2009)
- Total installed cost is expected to decrease over time due to an expected reduction in required capacity due to more efficient display cases
- **For this advanced case, a 10% reduction in energy consumption and a 5% reduction in required capacity is assumed to occur over the reference case for 2020 and beyond due to VIP adoption by display cases and a relaxation in charge size limits for more efficient, low GWP, but toxic/flammable refrigerants such as ammonia and propane due to improved safety technology such as leak detection**.

Commercial Supermarket Display Cases

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	20,000	17623	17623	17623	17623	N/A	17623	17623	17623	17623	17623	17623
Median Store Size (ft^2)	44,000	46,500	46,500	46,500	46,500	N/A	46,500	46,500	46,500	46,500	46,500	46,500
Case Length (ft)	12	12	10	10	10	N/A	10	10	10	10	10	10
Energy Use (kWh/yr) [1,2]	21,000	13,497	13,497	12,565	11,746	N/A	11,787	10,467	9,420	8,938	7,823	7,667
Energy Use (kWh/ft)	1,750	1,125	1,350	1,257	1,175	N/A	1,179	1,047	942	894	782	767
Indexed Annual Efficiency [3]	1.00	1.56	1.56	1.67	1.79	N/A	1.78	2.01	2.23	2.35	2.68	2.74
Average Life (yrs)	10	10	10	10	10	N/A	10	10	10	10	10	10
Retail Equipment Cost	$4,371	$8,510	$8,510	$8,940	$9,601	N/A	$9,356	$9,454	$9,926	$10,868	$10,096	$10,302
Total Installed Cost	$6,452	$10,811	$10,811	$11,241	$11,902	N/A	$11,657	$11,755	$12,227	$13,169	$12,397	$12,603
Total Installed Cost ($/kBtu/hr)	323	613	613	638	675	N/A	661	667	694	747	703	715
Annual Maintenance Cost [4]	$657	$940	$940	$940	$940	N/A	$940	$940	$940	$940	$940	$940
Annual Maintenance Cost ($/kBtu/hr)	$32.85	$53.34	$53.34	$53.34	$53.34	N/A	$53.34	$53.34	$53.34	$53.34	$53.34	$53.34

[1] DOE's Federal energy conservation standards for Commercial Refrigeration Equipment (CRE) went into effect on January 1, 2012. The 2012 typical and 2015 low efficiency values are based on minimal compliance with this standard. For 2015 and beyond, energy consumption and cost values were estimated using shipments-weighted averages reported in DOE's 2014 CRE Final Rule TSD for equipment commonly used as display cases. DOE's updated conservation standard goes into effect in 2017, so units sold in 2020 are assumed to comply with this standard.

[2] **For consistency with DOE rulemaking practices, Supermarket Display Case Energy Use reported above includes energy use of the compressor racks and condensers. To avoid double counting, do not add Energy Use from the Compressor Rack or Condenser Systems tabs if calculating total energy consumption.**

[3] **Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use).**

[4] Maintenance cost includes preventative maintenance costs such as cleaning evaporator coils, drain pans, fans, and intake screens as well as lamp replacements and other lighting maintenance activities. After 2012, these values are based on a reported maintenance and repair cost of $220 per unit for preventative maintenance plus approximately $60 per linear foot for additional repair and maintenance

Commercial Supermarket Display Cases

- DOE set Federal energy efficiency standards for Commercial Refrigeration Equipment (CRE) in 2009. These standards set maximum daily energy consumption levels, in kWh/day, for display cases manufactured and/or sold in the United States on or after January 1, 2012.
- DOE updated its Energy Conservation Standards for Commercial Refrigeration Equipment in 2014, for equipment sold on or after March 27, 2017.
- The table below lists equipment used as supermarket display cases and their corresponding Energy Conservation Standard levels. The maximum allowable daily energy consumption for each equipment class is a linear function of Total Display Area (TDA)

Equipment Description	DOE Designation	Standards Equation (2012)	Standards Equation (2017)
Vertical Open Cooler	VOP.RC.M	0.82xTDA+4.07	0.64xTDA+4.07
Semi vertical Open Cooler	SVO.RC.M	0.83xTDA+3.18	0.66xTDA+3.18
Horizontal Open Cooler	HZO.RC.M	0.35xTDA+2.88	0.35xTDA+2.88
Transparent-Doored Cooler	VCT.RC.M	0.22xTDA+1.95	0.15xTDA+1.95
Deli Display Cooler	SOC.RC.M	0.51xTDA+0.11	0.44xTDA+0.11
Transparent-Doored Freezer	VCT.RC.L	0.56xTDA+2.61	0.49xTDA+2.61
Horizontal Open Freezer	HZO.RC.L	0.57xTDA+6.88	0.55xTDA+6.88

Commercial Supermarket Display Cases

- The Food Marketing Institute reported the median total supermarket size in 2003 was 44,000 sq. ft., and in 2013, the last year reported in the study, it was listed as 46,500 sq. ft.
- Unit energy consumption for 2012 and beyond is estimated using a shipments weighted average by efficiency level and equipment class, using data in DOE's 2014 CRE Final Rule TSD and Engineering Spreadsheet. The equipment classes analyzed are listed in the table on the previous slide.
- Supermarket refrigeration systems consist of refrigerated display cases, condensing units, and centralized compressor racks
- A typical supermarket display case contains lighting, evaporators, evaporator fans, piping, insulation, valves, and controls.
- Approximately 20% of total annual electricity consumption for a typical supermarket is directly attributable to display cases (this does not include the energy consumed by compressors and condensers necessary to cool the display cases). (NCI, 2009)
- The efficiency of supermarket display cases can be increased through the use of improved evaporator coils, larger evaporators, higher efficiency evaporator fan blades, high efficiency doors, LED lighting, and improved insulation.
- Unit energy consumption for supermarket display cases is expected to decrease over time as a result of DOE's updated energy conservation standards
- In addition, a transition from open to transparent-doored display cases is expected to occur as supermarkets increase focus on energy efficiency.
- **For this advanced scenario, the typical display case in 2020 is assumed to minimally comply DOE's updated ECS.**
- **For 2020 and beyond, accelerated adoption of energy savings technologies is assumed to take place over the reference case, including accelerated shipments migration to doored over open units, where applicable, as well as vacuum insulated panels.**
- **The incremental cost of VIPs is assumed to decrease from its present value due to increased R&D funding**
- **Projected installed costs for this advanced scenario are higher than the reference case, even assuming increased R&D funding. Advanced energy-saving technologies are assumed to be made financially viable for operators by increased market incentives such as utility efficiency rebate programs and/or carbon pricing.**
- **This advanced case assumes a transition from HFC to more efficient propane and ammonia refrigerants by 2040**

Commercial Reach-In Refrigerators

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	3,000	2,929	2,929	2,929	2,929	2,929	2,929	2,929	2,929	2,929	2,929	2,929
Size (ft^3)	49	49	49	49	49	49	49	49	49	49	49	49
Energy Use (kWh/yr)	3,800	2,340	2,665	2,033	1,394	1,394	1,448	1,303	1,099	1,047	1,047	1,026
Energy Use (kWh/yr/ft^3) [1]	79	48	54	41	28	28	30	27	22	21	21	21
Indexed Annual Efficiency[3]	1.00	1.62	1.43	1.87	2.73	2.73	2.62	2.92	3.46	3.63	3.63	3.70
Average Life (yrs)	10	10	10	10	10	10	10	10	10	10	10	10
Retail Equipment Cost	$2,810	$2,624	$2,728	$2,780	$3,021	$3,021	$2,947	$3,242	$3,632	$3,335	$3,115	$3,271
Total Installed Cost[4]	$2,966	$3,454	$3,591	$3,643	$3,884	$3,884	$3,810	$4,105	$4,495	$4,198	$3,978	$4,134
Total Installed Cost ($/kBtu/hr)	$989	$1,227	$1,226	$1,244	$1,326	$1,326	$1,301	$1,402	$1,535	$1,434	$1,358	$1,411
Annual Maintenance Cost[5]	$143	$185	$185	$185	$185	$185	$185	$185	$185	$185	$185	$185
Annual Maintenance Cost ($/kBtu/hr)	$48	$63	$63	$63	$63	$63	$63	$63	$63	$63	$63	$63

[1] EPACT 2005 energy standards went into effect in 2010. 2015 low efficiency cost and energy consumption values are based on minimum compliance with this standard. Unless otherwise noted, all other cases are based on shipments-weighted averages of solid and transparent doored units reported in the 2014 CRE TSD. DOE's updated Energy Conservation standards go into effect in 2017; therefore, compliance with this standard is assumed for 2020 and beyond.

[2] The Energy Star category is based on a shipments weighted average of solid and transparent-doored units that are minimally compliant with Energy Star v3, effective October 1, 2014. Units compliant with Energy Star are found to be the most efficient reach-in refrigeration equipment on the market in 2015

[3] Annual efficiency normalized to the typical efficiency of the 2003 installed base. Normalized Annual Efficiency = (Typical 2003 Energy Use) / (Energy Use)[4] Installation cost for 2003 is based on ADL, 1996 & NCI, 2009 reports which assumes a cost of $156. Installation cost for 2012 and beyond is based DOE's CRE Final Rule, which assumes a installation cost of $863 for self-contained equipment.

[4] Maintenance costs after 2003 are based on DOE's CRE Final Rule TSD, which reports $35 annual preventative maintenance, per unit, per year, plus approximately $40 per linear foot, per year of additional repair and maintenance costs for the units characterized

Commercial Reach-In Refrigerators

- The Energy Policy Act of 2005 (EPACT 2005) set maximum daily energy consumption levels, in kWh/day, for commercial reach-in refrigerators that went into effect on January 1, 2010. The daily energy consumption is based on the volume of the unit (V).
- In 2014, DOE updated its energy conservation standards for Reach-in refrigerators, effective March 27, 2017. Both standards are reported in the table below.

Equipment Class	EPCA Standard Level (2010)	DOE Standard Level (2017)
Solid Door (VCS.SC.M)	0.10xV+2.04	0.05xV + 1.36
Glass Door (VCT.SC.M)	0.12xV+3.34	0.1xV+0.86

- In 2013, EPA updated its Energy Star® for Reach-in refrigerators, effective October 1, 2014. These standards are also based on the refrigerated volume of the unit.

Reach-In Refrigerator Size	$0 < V < 15$	$15 \le V < 30$	$30 \le V < 50$	$50 \le V$
Solid Door (VCS.SC.M)	0.02xV+1.60	0.09xV+0.55	0.01xV+2.95	0.06xV+0.45
Glass Door (VCT.SC.M)	0.10xV+1.07	0.15xV+0.32	0.06xV+3.02	0.08xV+2.02

Commercial Reach-In Refrigerators

- Unit energy consumption for 2012 and beyond was estimated based on shipment-weighted averages by efficiency level and equipment class for 49 ft^3 VCS.SC.M and VCT.SC.M units reported in DOE's 2014 CRE Final Rule TSD. These units were estimated to comprise approximately 85% and 15% of total reach-in refrigerator shipments, respectively.
- The efficiency of commercial reach-in refrigerators can be increased through the use of efficient compressors, efficient evaporator fans, efficient condenser fans, electric defrost, and more efficient lighting.
- Unit energy consumption is expected to decrease as a result of DOE's updated energy conservation standards, as well as a transition to more efficient propane refrigerant due to compliance with EPA SNAP
- **For this advanced scenario, the typical unit in 2020 is assumed to comply with DOE's updated energy conservation standards for commercial refrigeration**
- **A shipments migration from transparent to solid-doored units is assumed for the advanced case**
- **By 2040, the adoption of vacuum insulated panels is assumed to occur, with the aid of decreased incremental costs due to increased R&D funding**
- **Projected installed costs for this advanced scenario are higher than the reference case, even assuming increased R&D funding. Advanced energy-saving technologies are assumed to be made financially viable for operators by increased market incentives such as utility efficiency rebate programs and/or carbon pricing.**
- **This analysis finds that with increased R&D and market incentives for energy efficiency technologies, a limit of possible efficiency improvements for self-contained, vapor compression refrigeration systems will be reached by 2040.**

Commercial Reach-In Freezers

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star[3]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	4,341	4,341	4,341	4,341	4,341	4,341	4,341	4,341	4,341	4,341	4,341	4,341
Size (ft^3)	49	49	49	49	49	49	49	49	49	49	49	49
Energy Use (kWh/yr) [1]	9,392	6,023	7,658	5,592	4,563	4,763	4,453	4,008	3,656	3,473	3,473	3,369
Energy Use (kWh/yr/ft^3)	192	123	156	114	93	97	93	93	93	93	93	93
Indexed Annual Efficiency[4]	1.00	1.56	1.23	1.68	2.06	1.97	2.11	2.34	2.57	2.70	2.70	2.79
Average Life (yrs)	8	10	10	10	10	10	10	10	10	10	10	10
Retail Equipment Cost	$2,498	$2,886	$3,002	$3,033	$3,186	$3,118	$3,395	$3,490	$4,099	$4,304	$3,674	$3,777
Total Installed Cost[5]	$2,654	$3,749	$3,865	$3,896	$4,049	$3,981	$4,258	$4,353	$4,962	$5,167	$4,537	$4,640
Total Installed Cost ($/kBtu/hr)	$611	$864	$890	$897	$933	$917	$981	$1,003	$1,143	$1,190	$1,045	$1,069
Annual Maintenance Cost[6]	$140	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181
Annual Maintenance Cost ($/kBtu/hr)	$32.25	$41.70	$41.70	$41.70	$41.70	$41.70	$41.70	$41.70	$41.70	$41.70	$41.70	$41.70

[1] EPACT 2005 energy standards went into effect in 2010. The 2015 low energy consumption and cost values are based on minimal compliance with this standard.

[2] A 49 ft^3 unit was characterized, as this was the representative size selected for DOE's rulemaking analysis.

[3] The Energy Star category was based on a solid doored unit that is minimally compliant with Energy Star v3, effective October 1, 2014

[4] **Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use).**

[5] Installation cost for 2003 is based on ADL, 1996 & NCI, 2009 reports which assumes a cost of $156. Installation cost for 2012 and beyond is based on DOE's on-going CRE rulemaking which assumes a cost of $863 for self-contained equipment.

[6] Maintenance costs are calculated based on a $35 per unit annual preventative maintenance cost, plus an additional $45 per linear foot repair and maintenance cost estimated based on values reported in the in the CRE TSD

Commercial Reach-In Freezers

- EPACT 2005 set maximum daily energy consumption levels, in kWh/day, for commercial reach-in freezers that went into effect on January 1, 2010. The daily energy consumption is based on the volume of the unit (V).
- In December of 2014, DOE updated its energy conservation standards for commercial refrigeration equipment, including reach-in freezers. Both the EPCA and DOE standards are reported in the table below.

Equipment Class	EPCA (2010)	DOE Standard Level (2017)
Solid Door (VCS.SC.L)	0.4xV+1.38	0.22xV+1.38
Transparent Door (VCT.SC.L)	0.75xV+4.10	0.29xV+2.95

- In 2013, EPA updated its Energy Star standards for reach-in freezers, effective October 1, 2014. These standards are also based on the refrigerated volume of the unit

Reach-In Freezer Size	0 < V < 15	15 ≤ V < 30	30 ≤ V < 50	50 ≤ V
Solid Door (VCS.SC.L)	0.25xV+1.55	0.20xV+2.30	0.25xV+0.80	0.14xV+6.30
Glass Door (VCT.SC.L)	0.56xV+1.61	0.30xV+5.50	0.55xV+2.00	0.32xV+9.49

Commercial Reach-In Freezers

- The commercial reach-in freezer characterized in this report, which is the typical unit according to DOE's 2014 CRE rulemaking, is a 49 cubic ft. solid two-door unit with a nominal compressor size 4,341 Btu/hr.
- The efficiency of commercial reach-in freezers can be increased through the use of efficient compressors, efficient evaporator fans, efficient condenser fans, electric defrost, and more efficient lighting.
- Unit energy consumption for reach-in freezers is expected to decrease as a result of DOE's updated energy conservation standards, as well as a transition to more efficient propane refrigerant due to EPA SNAP compliance.
- **For this advanced scenario, the typical unit in 2020 is assumed to comply with DOE's updated energy conservation standards for commercial refrigeration**
- **By 2040, the adoption of vacuum insulated panels is assumed to occur, with the aid of decreased incremental costs due to increased R&D funding**
- **Projected installed costs for this advanced scenario are higher than the reference case, even assuming increased R&D funding. Advanced energy-saving technologies are assumed to be made financially viable for operators by increased market incentives such as utility efficiency rebate programs.**
- **This analysis finds that with increased R&D and market incentives for energy efficiency technologies, a limit of possible efficiency improvements for self-contained, vapor compression refrigeration systems will be reached by 2040.**

Commercial Walk-In Refrigerators

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	37,820	37,820	37,820	37,820	37,820	N/A	37,820	37,820	37,820	37,820	37,820	37,820
Size (ft2)[1]	305	305	305	305	305	N/A	305	305	305	305	305	305
Energy Use (kWh/yr)[2]	53,756	30,689	31,892	30,689	27,571	N/A	16,014	14,413	14,453	14,310	14,019	13,880
Energy Use (kWh/ft2/yr)	176	101	105	101	90	N/A	53	47	47	47	46	46
Indexed Annual Efficiency[3]	1.00	1.38	1.69	1.75	1.95	N/A	3.36	3.73	3.72	3.76	3.83	3.87
Insulated Box Average Life (yrs)	12	12	12	12	12	N/A	12	12	12	12	12	12
Compressor Average Life (yrs)	10	10	10	10	10	N/A	10	10	10	10	10	10
Retail Equipment Cost	$19,607	$23,598	$23,583	$23,598	$23,644	N/A	$24,290	$25,696	$25,504	$25,696	$25,504	$25,696
Total Installed Cost[4]	$23,846	$27,012	$26,997	$27,012	$27,057	N/A	$27,703	$29,280	$29,088	$29,280	$29,088	$29,280
Total Installed Cost($/kBtu/hr)	$631	$714	$714	$714	$715	N/A	$733	$774	$769	$774	$769	$774
Annual Maintenance Cost[5]	$573	$716	$741	$741	$741	N/A	$741	$741	$741	$741	$741	$741
Annual Maintenance Cost ($/kBtu/hr)	$15.15	$18.93	$19.59	$19.59	$19.59	N/A	$19.59	$19.59	$19.59	$19.59	$19.59	$19.59

[1] Size is estimated based on analysis from the 2014 WICF TSD, which lists the average size of a walk in cooler as 305 ft^2

[2] EISA 2007 includes prescriptive standards for walk-in refrigerators that went into effect in 2009. All units for 2012 and beyond include these prescriptive standards. In 2014, DOE updated energy conservation standards for walk-ins. All units 2015 and beyond use data from this rulemaking, and all units 2020 and beyond are assumed to comply with DOE's updated standards.

[3] Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use)

[4] Installation cost for 2003 is based on ADL, 1996 & NCI, 2009 reports which assume a cost of $4,163 and $4,891 respectively. Installation cost for 2012 and beyond is based on DOE's Walk-In TSD

[5] Maintenance cost includes checking and maintaining refrigerant charge levels, checking settings, and cleaning heat exchanger coils.

Commercial Walk-In Refrigerators

- The unit characterized in this report is a walk-in storage cooler with an area of 305 ft^2, the average floor area reported by DOE's 2014 Final Rule TSD for this equipment type.
- A typical walk-in refrigerator includes:
  - insulated floor and wall panels
  - merchandising doors, shelving, and lighting (not included in cost estimate)
  - semi-hermetic reciprocating compressor
  - refrigerant (R404A)
  - condenser
  - evaporator
- Energy consumption is assumed to scale with AWEF (Annual Walk-in Energy Factor), defined as the ratio of total heat removed from the refrigerated volume per year to the total electrical energy input of refrigeration systems over the same time period.
- The installation cost consists of freight and delivery costs in addition to on-site assembly.
- **This advanced scenario assumes a projected 10% decrease in energy consumption over the reference case due to adoption of more efficient refrigerants.**

Commercial Walk-In Refrigerators

- The Energy Independence and Security Act (EISA) of 2007 included prescriptive standards for walk-in refrigerators (coolers) that went into effect in 2009. These prescriptive standards, which are included in the analysis for all units for 2012 and beyond, state that all walk-in refrigerators manufactured after January 1, 2009 must:
  - have automatic door closers
  - have strip doors, spring hinged doors, or other method of minimizing infiltration when doors are open
  - contain wall, ceiling, and door insulation of at least R–25, except for glazed portions of doors and structural members
  - use electronically commutated motors or 3-phase motors (for evaporator fan motors of under 1 horsepower and less than 460 volts)
  - use electronically commutated motors, permanent split capacitor-type motors, or 3-phase motors (for condenser fan motors of under 1 horsepower)
  - use light sources with an efficacy of 40 lumens per watt or more, including ballast losses (if any), except that light sources with an efficacy of 40 lumens per watt or less, including ballast losses (if any), may be used in conjunction with a timer or device that turns off the lights within 15 minutes of when the walk-in refrigerator is not occupied by people.

Commercial Walk-In Refrigerators

- In 2014, DOE updated its energy conservation standards for walk-in coolers and freezers. Minimum AWEFs (Annual Walk-in Energy Factor) was set for refrigeration systems, as well as upper limits on energy consumption attributable to passage, freight, and display doors. DOE elected not to set new standards for the R-value of Walk-in Panels.

ENERGY CONSERVATION STANDARDS FOR WALK-IN COOLERS AND WALK-IN FREEZERS

Class descriptor	Class	Standard level
Refrigeration Systems Minimum AWEF (Btu/W-h)		
Dedicated Condensing, Medium Temperature, Indoor System, <9,000 Btu/h Capacity	DC.M.I, <9,000	5.61
Dedicated Condensing, Medium Temperature, Indoor System, ≥ 9,000 Btu/h Capacity	DC.M.I, ≥ 9,000	5.61
Dedicated Condensing, Medium Temperature, Outdoor System, <9,000 Btu/h Capacity	DC.M.O, <9,000	7.60
Dedicated Condensing, Medium Temperature, Outdoor System, ≥ 9,000 Btu/h Capacity	DC.M.O,≥9,000	7.60
Dedicated Condensing, Low Temperature, Indoor System, <9,000 Btu/h Capacity	DC.L.I, <9,000	$5.93 \cdot 10^{-5} \cdot Q + 2.33$
Dedicated Condensing, Low Temperature, Indoor System, ≥ 9,000 Btu/h Capacity	DC.L.I, ≥9,000	3.10
Dedicated Condensing, Low Temperature, Outdoor System, <9,000 Btu/h Capacity	DC.L.O, <9,000	$2.30 \cdot 10^{-4} \cdot Q + 2.73$
Dedicated Condensing, Low Temperature, Outdoor System, ≥ 9,000 Btu/h Capacity	DC.L.O, ≥9,000	4.79
Multiplex Condensing, Medium Temperature	MC.M	10.89
Multiplex Condensing, Low Temperature	MC.L	6.57
Panels Minimum R-value (h-ft2-°F/Btu)		
Structural Panel, Medium Temperature	SP.M	25
Structural Panel, Low Temperature	SP.L	32
Floor Panel, Low Temperature	FP.L	28
Non-Display Doors Maximum energy consumption (kWh/day) **		
Passage Door, Medium Temperature	PD.M	$0.05 \cdot A_{nd} + 1.7$
Passage Door, Low Temperature	PD.L	$0.14 \cdot A_{nd} + 4.8$
Freight Door, Medium Temperature	FD.M	$0.04 \cdot A_{nd} + 1.9$
Freight Door, Low Temperature	FD.L	$0.12 \cdot A_{nd} + 5.6$
Display Doors Maximum Energy Consumption (kWh/day) †		
Display Door, Medium Temperature	DD.M	$0.04 \cdot A_{dd} + 0.41$
Display Door, Low Temperature	DD.L	$0.15 \cdot A_{dd} + 0.29$

Commercial Walk-In Freezers

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	22,114	22,114	22,114	22,114	22,114	N/A	22,114	22,114	22,114	22,114	22,114	22,114
Size (ft^2) [1]	172	172	172	172	172	N/A	172	172	172	172	172	172
Energy Use (kWh/yr) [2]	33,540	22,862	23,610	22,862	20,878	N/A	13,421	12,079	12,113	12,006	11,749	11,645
Energy Use (kWh/ft^2/yr)	195	133	137	133	121	N/A	78	70	70	70	68	68
Indexed Annual Efficiency[3]	1.00	1.47	1.42	1.47	1.61	N/A	2.50	2.78	2.77	2.79	2.85	2.88
Insulated Box Average Life (yrs)	12	12	12	12	12	N/A	12	12	12	12	12	12
Compressor Average Life (yrs)	10	10	10	10	10	N/A	10	10	10	10	10	10
Retail Equipment Cost	$16,333	$22,008	$21,993	$22,008	$22,054	N/A	$22,793	$25,856	$25,130	$25,856	$25,130	$25,856
Total Installed Cost[4]	$18,570	$24,058	$24,043	$24,058	$24,103	N/A	$24,843	$28,115	$27,389	$28,115	$27,389	$28,115
Total Installed Cost ($/kBtu/hr)	$840	$1,088	$1,087	$1,088	$1,090	N/A	$1,123	$1,271	$1,239	$1,271	$1,239	$1,271
Annual Maintenance Cost[5]	$573	$741	$741	$741	$741	N/A	$741	$741	$741	$741	$741	$741
Annual Maintenance Cost ($/kBtu/hr)	$25.91	$33.51	$33.51	$33.51	$33.51	N/A	$33.51	$33.51	$33.51	$33.51	$33.51	$33.51

[1] Based on DOE's 2014 WICF Final Rule TSD which states the average floor area for a walk-in storage freezer as 172 ft^2

[2] EISA 2007 includes prescriptive standards for walk-in freezers that went into effect in 2009. All units for 2012 and beyond include these prescriptive standards. Units for 2015 and beyond are characterized using data from DOE's 2014 WICF rulemaking. All units 2020 and beyond are assumed to comply with this standard

[3] Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use)

[4] Installation cost for 2003 is based on ADL, 1996 & NCI, 2009 reports which assume a cost of $1,040. Installation cost for 2012 and beyond is based on DOE's WICF TSD.

[5] Maintenance cost includes checking and maintaining refrigerant charge levels, checking settings, and cleaning heat exchanger coils

Commercial Walk-In Freezers

- The commercial walk-in freezer characterized in this report is a walk-in storage freezer with an area of 172 ft^2 , the average size reported by DOE's WICF TSD
- A typical walk-in freezer includes:
  - insulated floor, door, and wall panels
  - semi-hermetic reciprocating compressor
  - refrigerant (R404A)
  - condenser
  - evaporator
- Energy consumption is assumed to scale with AWEF (Annual Walk-in Energy Factor), defined as the ratio of total heat removed from the refrigerated volume per year to the total electrical energy input of refrigeration systems over the same time period.
- The installation cost consists of freight and delivery costs in addition to on-site assembly.
- **This advanced scenario assumes a projected 10% decrease in energy consumption over the reference case due to adoption of more efficient refrigerants.**

Commercial Walk-In Freezers: EISA 2007

- EISA 2007 included prescriptive standards for walk-in freezers that went into effect in 2009. These prescriptive standards, which are included in all units for 2011 and beyond, state that all walk-in freezers manufactured after January 1, 2009 must:
  - have automatic door closers
  - have strip doors, spring hinged doors, or other method of minimizing infiltration when doors are open
  - contain wall, ceiling, and door insulation of at least R–32, except for glazed portions of doors and structural members
  - contain floor insulation of at least R–28
  - use electronically commutated motors or 3-phase motors (for evaporator fan motors of under 1 horsepower and less than 460 volts)
  - use electronically commutated motors, permanent split capacitor-type motors, or 3-phase motors (for condenser fan motors of under 1 horsepower)
  - use light sources with an efficacy of 40 lumens per watt or more, including ballast losses (if any), except that light sources with an efficacy of 40 lumens per watt or less, including ballast losses (if any), may be used in conjunction with a timer or device that turns off the lights within 15 minutes of when the walk-in freezer is not occupied by people.

Commercial Walk-In Freezers: DOE 2014 Standards

- In 2014, DOE updated its energy conservation standards for walk-in coolers and freezers. Minimum AWEFs (Annual Walk-in Energy Factor) was set for refrigeration systems, as well as upper limits on energy consumption attributable to passage, freight, and display doors. DOE elected not to set new standards for the R-value of Walk-in Panels.

ENERGY CONSERVATION STANDARDS FOR WALK-IN COOLERS AND WALK-IN FREEZERS

Class descriptor	Class	Standard level
Refrigeration Systems Minimum AWEF (Btu/W-h)		
Dedicated Condensing, Medium Temperature, Indoor System, <9,000 Btu/h Capacity	DC.M.I, <9,000	5.61
Dedicated Condensing, Medium Temperature, Indoor System, ≥ 9,000 Btu/h Capacity	DC.M.I, ≥ 9,000	5.61
Dedicated Condensing, Medium Temperature, Outdoor System, <9,000 Btu/h Capacity	DC.M.O, <9,000	7.60
Dedicated Condensing, Medium Temperature, Outdoor System, ≥ 9,000 Btu/h Capacity	DC.M.O,≥9,000	7.60
Dedicated Condensing, Low Temperature, Indoor System, <9,000 Btu/h Capacity	DC.L.I, <9,000	5.93 · 10¥5 · *Q* + 2.33
Dedicated Condensing, Low Temperature, Indoor System, ≥ 9,000 Btu/h Capacity	DC.L.I, ≥9,000	3.10
Dedicated Condensing, Low Temperature, Outdoor System, <9,000 Btu/h Capacity	DC.L.O, <9,000	2.30 · 10¥4 · *Q* + 2.73
Dedicated Condensing, Low Temperature, Outdoor System, ≥ 9,000 Btu/h Capacity	DC.L.O, ≥9,000	4.79
Multiplex Condensing, Medium Temperature	MC.M	10.89
Multiplex Condensing, Low Temperature	MC.L	6.57
Panels Minimum R-value (h-ft2-°F/Btu)		
Structural Panel, Medium Temperature	SP.M	25
Structural Panel, Low Temperature	SP.L	32
Floor Panel, Low Temperature	FP.L	28
Non-Display Doors Maximum energy consumption (kWh/day) **		
Passage Door, Medium Temperature	PD.M	$0.05 \cdot A_{nd} + 1.7$
Passage Door, Low Temperature	PD.L	$0.14 \cdot A_{nd} + 4.8$
Freight Door, Medium Temperature	FD.M	$0.04 \cdot A_{nd} + 1.9$
Freight Door, Low Temperature	FD.L	$0.12 \cdot A_{nd} + 5.6$
Display Doors Maximum Energy Consumption (kWh/day) †		
Display Door, Medium Temperature	DD.M	$0.04 \cdot A_{dd} + 0.41$
Display Door, Low Temperature	DD.L	$0.15 \cdot A_{dd} + 0.29$

Commercial Ice Machines

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star[5]	Typical	High	Typical	High	Typical	High
Output (lbs/day)[1]	300	300	300	300	300	300	300	300	300	300	300	300
Cooling Capacity (Btu/hr)[2]	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963
Water Use (gal/100 lbs)	20	20	20	20	20	20	20	20	20	20	20	20
Energy Use (kWh/100 lbs)	8.4	7.7	7.7	6.7	6.1	6.7	6.1	5.4	5.7	5.4	5.4	5.4
Energy Use (kWh/yr)[3]	3,833	3,185	3,185	3,078	3,009	3,078	2901.0	2,611	2,525	2,508	2,399	2,383
Normalized Annual Efficiency[4]	1.00	1.20	1.20	1.25	1.27	1.25	1.32	1.47	1.52	1.53	1.60	1.61
Average Life (yrs)	8.0	8	8	8	8	8	8	8	8	8	8	8
Retail Equipment Cost	$1,374	$2,146	$2,189	$2,284	$2,392	$2,284	$2,392	$2,548	$2,548	$2,925	$2,925	$2,925
Total Installed Cost (with Bin)	$1,499	$2,484	$2,484	$2,579	$2,687	$2,579	$2,699	$2,855	$2,855	$3,232	$3,232	$3,232
Total Installed Cost ($/kBtu/hr)	$763	$1,265	$1,265	$1,314	$1,369	$1,314	$1,375	$1,455	$1,455	$1,647	$1,647	$1,647
Annual Maintenance Cost[6]	$639	$826	$826	$826	$826	$826	$826	$826	$826	$826	$826	$826
Annual Maintenance Cost ($/kBtu/hr)	$326	$421	$421	$421	$421	$421	$421	$421	$421	$421	$421	$421

1 Based on the Final Rule shipment data from DOE's Automatic Ice Maker rulemaking which states the most common equipment type is a small air cooled unit with an integrated ice making head with a representative capacity of 300 lbs/day.

2 Defined as the average heat load to remove the latent and sensible heat required to freeze the daily output capacity of ice

3 EPACT 2005 energy standards went into effect in 2010. The 2015 Low values are based on this standard. In 2014, DOE set new standards for commercial ice machines, with compliance required by 2018. The unit characterized for 2012 and beyond use data from this rulemaking. All units 2020 and beyond are assumed to comply with the updated standard.

4 Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use)

5 The Energy Star category is based on minimum compliance with the Energy Star v2.0 standard, which went into effect on February 1, 2013. According to this analysis, Energy Star certification is typical for the small air-cooled IMH unit characterized.

6 Maintenance cost includes cleaning and maintaining refrigerant levels, replacing filters, checking water distribution lines for leaks, cleaning, sanitizing, and descaling the bin and water system. Maintenance cost decreases as the size of the ice machine (i.e. output) decreases.

Commercial Ice Machines

- **For this advanced case, a 10% reduction in energy consumption is projected over the reference case due to the adoption of more efficient refrigerants such as propane, which, while not currently required by EPA SNAP, are a source of possible efficiency improvements**
- The commercial ice machine characterized in this report is an air-cooled, ice maker head unit with an approximate output of 300 lbs/day. Commercial ice machines are typically integrated with an insulated ice storage bin or mounted on top of a separate storage bin. The retail equipment cost includes the ice making head and the integrated storage bin. Commercial ice machine condensers are either air-cooled or water-cooled. Approximately 90% of all units are the air-cooled type.
- Commercial ice machine maintenance includes periodic cleaning (every 2 to 6 weeks) to remove lime and scale, and sanitizing to kill bacteria. Some ice machines are self-cleaning/sanitizing.
- ENERGY STAR® updated its maximum energy consumption levels, in KWh/100 lbs ice, for air cooled ice machines that went into effect on February 1, 2013. These efficiency levels are based on the harvest rate, in lbs/24 hrs. (H). Water cooled ice machines are not eligible for Energy Star certification.

ENERGY STAR Requirements for Air-Cooled Batch-Type Ice Makers			
Equipment Type	Applicable Ice Harvest Rate Range (lbs of ice/24 hrs)	Energy Consumption Rate (kWh/100 lbs ice)	Potable Water Use (gal/100 lbs ice)
IMH	$200 \le H \le 1600$	$\le 37.72 * H^{-0.298}$	≤ 20.0
RCU	$400 \le H \le 1600$	$\le 22.95 * H^{-0.258} + 1.00$	≤ 20.0
	$1600 \le H \le 4000$	$\le -0.00011 * H + 4.60$	≤ 20.0
SCU	$50 \le H \le 450$	$\le 48.66 * H^{-0.326} + 0.08$	≤ 25.0

ENERGY STAR Requirements for Air-Cooled Continuous-Type Ice Makers		
Equipment Type	Energy Consumption Rate (kWh/100 lbs ice)	Potable Water Use (gal/100 lbs ice)
IMH	$\le 9.18 * H^{-0.057}$	≤ 15.0
RCU	$\le 6.00 * H^{-0.162} + 3.50$	≤ 15.0
SCU	$\le 59.45 * H^{-0.349} + 0.08$	≤ 15.0

Commercial Ice Machines: EPACT 2005

- EPACT 2005 issued standard levels for commercial ice machines with capacities between 50 and 2500 pounds per 24-hour period that are manufactured and/or sold in the United States on or after January 1, 2010. The energy consumption is based on the harvest rate in pounds per 24 hours (H).

Equipment Type	Type of Cooling	Harvest Rate (lbs ice/24 hrs)	Maximum Energy Use (kWh/100 lbs ice)	Maximum Condenser Water Use (gal/100 lbs ice)
Ice Making Head	Water	<500	7.80-0.0055 H	200-0.022 H
		≥500 and <1436	5.58-0.0011 H	200-0.022 H
		≥1436	4.0	200-0.022 H
	Air	<450	10.26-0.0086 H	Not Applicable
		≥450	6.89-0.0011 H	Not Applicable
Remote Condensing (but not remote compressor)	Air	<1000	8.85-0.0038 H	Not Applicable
		≥1000	5.10	Not Applicable
Remote Condensing and Remote Compressor	Air	<934	8.85-0.0038 H	Not Applicable
		≥934	5.3	Not Applicable
Self Contained	Water	<200	11.40-0.019 H	191-0.0315 H
		≥200	7.60	191-0.0315 H
	Air	<175	18.0-0.0469 H	Not Applicable
		≥175	9.80	Not Applicable

Commercial Ice Machines: 2014 DOE Standards

Energy Conservation Standards for Batch Type Automatic Commercial Ice Makers Effective January 2018

Equipment Type	Type of Cooling	Harvest Rate lb ice/24 hours	Maximum Energy Use kWh/100 lb ice*	Maximum Condenser Water Use gal/100 lb ice**
Ice-Making Head	Water	<300	6.88 - 0.0055H	200 - 0.022H
		300 and <850	5.80 - 0.00191H	200 - 0.022H
		850 and <1,500	4.42 - 0.00028H	200 - 0.022H
		1500 and <2,500	4.0	200 - 0.022H
		2500 and <4,000	4.0	145
Ice-Making Head	Air	<300	10 - 0.01233H	Not Applicable
		300 and <800	7.05 - 0.0025H	Not Applicable
		800 and <1500	5.55 - 0.00063H	Not Applicable
		1500 and <4,000	4.61	Not Applicable
Remote Condensing (but not remote compressor)	Air	50 and <1,000	7.97 - 0.00342H	Not Applicable
		1,000 and <4,000	4.55	Not Applicable
Remote Condensing and Remote Compressor	Air	<942	7.97 - 0.00342H	Not Applicable
		942 and <4,000	4.75	Not Applicable
Self-Contained	Water	<200	9.5 - 0.019H	191 - 0.0315H
		200 and <2,500	5.7	191 - 0.0315H
		2500 and <4,000	5.7	112
Self-Contained	Air	<110	14.79 - 0.0469H	Not Applicable
		110 and <200	12.42 - 0.02533H	Not Applicable
		200 and <4,000	7.35	Not Applicable

Energy Conservation Standards for Continuous Type Automatic Commercial Ice Makers Effective January 2018

Equipment Type	Type of Cooling	Harvest Rate lb ice/24 hours	Maximum Energy Use kWh/100 lb ice*	Maximum Condenser Water Use gal/100 lb ice**
Ice-Making Head	Water	<801	6.48 - 0.00267H	180 - 0.0198H
		801 and <2,500	4.34	180 - 0.0198H
		2,500 and <4,000	4.34	130.5
Ice-Making Head	Air	<310	9.19 - 0.00629H	Not Applicable
		310 and <820	8.23 - 0.0032H	Not Applicable
		820 and <4,000	5.61	Not Applicable
Remote Condensing (but not remote compressor)	Air	<800	9.7 - 0.0058H	Not Applicable
		800 and <4,000	5.06	Not Applicable
Remote Condensing and Remote Compressor	Air	<800	9.9 - 0.0058H	Not Applicable
		800 and <4,000	5.26	Not Applicable
Self-Contained	Water	<900	7.6 - 0.00302H	153 - 0.0252H
		900 and <2,500	4.88	153 - 0.0252H
		2500 and <4,000	4.88	90
Self-Contained	Air	<200	14.22 - 0.03H	Not Applicable
		200 and <700	9.47 - 0.00624H	Not Applicable
		700 and <4,000	5.1	Not Applicable

Commercial Beverage Merchandisers

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	4,689	4,689	4,689	4,689	4,689	4,689	4,689	4,689	4,689	4,689	4,689	4,689
Size (ft^3)	27	27	27	27	27	27	27	27	27	27	27	27
Energy Use (kWh/yr)	3,900	1,829	2,523	1,781	1,694	1,694	1,380	1,242	1,119	1,063	1,063	1,041
Energy Use (kWh/ft^3/yr) [1]	144	68	93	66	63	63	51	46	41	39	39	39
Indexed Annual Efficiency[3]	1.00	2.13	1.55	2.19	2.30	2.30	2.83	3.14	3.49	3.67	3.67	3.75
Average Life (yrs)	8.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Retail Equipment Cost	$1,457	$2,382	$2,326	$2,602	$2,628	$2,628	$2,811	$2,839	$3,398	$3,432	$3,034	$3,064
Total Installed Cost[4]	$1,457	$2,382	$2,326	$2,602	$2,628	$2,628	$2,811	$2,839	$3,398	$3,432	$3,034	$3,064
Total Installed Cost ($/kBtu/hr)	$311	$508	$496	$555	$560	$560	$599	$605	$725	$732	$647	$654
Annual Maintenance Cost[5]	$84	$108	$108	$98	$95	$95	$95	$95	$95	$95	$95	$95
Annual Maintenance Cost ($/kBtu/hr)	$17.91	$23.03	$23.03	$20.79	$20.15	$20.15	$20.15	$20.15	$20.15	$20.15	$20.15	$20.15

[1] EPACT 2005 energy conservation standards went into effect in 2010. The 2015 Low values are based on this standard. In 2015, DOE updated its energy conservation standards for commercial refrigeration equipment, including transparent-doored refrigerators with pull-down capability. Compliance with this standard is required by 2017. Units characterized for 2012 and beyond use data reported in this rulemaking's TSD. Units 2020 and beyond are assumed to comply with this updated standard.

[2] The Energy Star category characterizes a unit that is compliant with Energy Star v3, effective October 1, 2014. This standard does not separately define units with pull-down capability

[3] Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use)

[4] Beverage merchandisers are shipped ready to be plugged in, so installation costs are assumed to be negligible

[5] Maintenance costs are estimated based on CRE Final Rule TSD data. Note that maintenance costs decrease slightly for more efficient units, which are assumed to include LED lighting with lower associated maintenance costs

Commercial Beverage Merchandisers

- EPACT 2005 sets maximum daily energy consumption levels, in kWh/day, for commercial refrigerators with a self-contained condensing unit designed for pull-down temperature applications and transparent doors (i.e., beverage merchandisers) that went into effect on January 1, 2010.
- In 2014, DOE updated its energy consumption standards for commercial refrigeration equipment, including beverage merchandisers, effective March 27, 2015. Both the DOE and EPCA standards are reported below.

Equipment Type	EPCA (2010)	DOE Standards (2017)
Beverage Merchandisers (PD.SC.M)	0.126xV + 3.51	0.11xV+0.81

- In 2013, EPA updated its Energy Star standards for glass doored commercial refrigerators, which can be used as beverage merchandisers, effective October 1, 2014. These standards are also based on the volume of the unit (V). Note that Energy Star does not have a separate equipment class for units with pull-down capability.

Beverage Merchandiser Size	0 < V < 15	15 ≤ V < 30	30 ≤ V < 50	50 ≤ V
Glass Door	0.118*V + 1.382	≤ 0.140*V + 1.050	≤ 0.088*V + 2.625	≤ 0.110*V + 1.500

Commercial Beverage Merchandisers

- The beverage merchandiser characterized in this report, which is the typical unit according to DOE's 2014 CRE rulemaking, is a 27 cubic foot cooler with a single hinged, transparent door, bright lighting, and shelving with a nominal compressor size of 4,689 Btu/hr..
- The efficiency of beverage merchandisers can be increased through the use of more efficient compressors, fluorescent lighting with electronic ballasts, and improved insulation.
- Beverage merchandisers have an estimated installed base of 920,000 units in 2008. Of those beverage merchandisers 460,000 are one-door units, which represents the most common type of beverage merchandiser.
- Unit energy consumption of beverage merchandisers is expected to decrease as a result of DOE's updated Energy Conservation Standards, as well as a transition from R-134a to more efficient propane refrigerant due to EPA SNAP compliance
- **For this advanced scenario, the typical unit in 2020 is assumed to comply with DOE's updated energy conservation standards for commercial refrigeration**
- **By 2040, the adoption of vacuum insulated panels is assumed to occur, with the aid of decreased incremental costs due to increased R&D funding**
- **Projected installed costs for this advanced scenario are higher than the reference case, even assuming increased R&D funding. Advanced energy-saving technologies are assumed to be made financially viable for operators by increased market incentives such as utility efficiency rebate programs and/or carbon pricing.**
- **This analysis finds that with increased R&D and market incentives for energy efficiency technologies, a limit of possible efficiency improvements for self-contained, vapor compression refrigeration systems will be reached by 2040.**

Commercial Refrigerated Vending Machines

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810
Can Capacity	500	470	470	470	470	470	470	470	470	470	470	470
Size (ft^3)	26	26	26	26	26	26	26	26	26	26	26	26
Energy Use (kWh/yr) [1]	3,000	1,632	1,718	1,632	1,504	1,504	1,360	1,224	803	701	701	687
Energy Use (kWh/ft^3/yr)	115	63	66	63	58	58	52	47	31	27	27	26
Indexed Annual Efficiency[3]	1.00	1.84	1.75	1.84	1.99	1.99	2.21	2.45	3.74	4.28	4.28	4.37
Average Life (yrs)	14	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Retail Equipment Cost	$1,769	$3,209	$3,187	$3,209	$3,276	$3,276	$3,551	$3,626	$4,479	$4,612	$4,343	$4,434
Total Installed Cost	$1,844	$3,320	$3,298	$3,320	$3,387	$3,387	$3,662	$3,737	$4,590	$4,723	$4,454	$4,545
Total Installed Cost ($/kBtu/hr)	$1,019	$1,834	$1,822	$1,834	$1,872	$1,872	$2,023	$2,065	$2,536	$2,609	$2,461	$2,511
Annual Maintenance Cost[4]	$209	$270	$270	$270	$250	$250	$250	$250	$250	$250	$250	$250
Annual Maintenance Cost ($/kBtu/hr)	$115	$149.17	$149.17	$149.17	$138.12	$138.12	$138.12	$138.12	$138.12	$138.12	$138.12	$138.12

[1] Energy use for 2012 and beyond is estimated based on DOE’s 2015 BVM Final Rule

[2] The Energy Star category assumes units that are compliant with the Energy Star v3 standard, since combination units are currently not separately defined by Energy Star. This standard went into effect on March 1, 2013. Our analysis finds Energy Star certified equipment to be the most efficient currently available on the market

[3] Annual efficiency normalized to the efficiency of the 2003 installed base. Indexed Annual Efficiency = (2003 Energy Use) / (Energy Use)

[4] Maintenance cost includes preventative maintenance costs such as checking and maintaining refrigerant charge levels, cleaning heat exchanger coils and also includes an annualized cost for refurbishments/remanufacturing.

Commercial Refrigerated Vending Machines

- DOE set Federal energy efficiency standards for refrigerated vending machines in 2009. These standards set maximum daily energy consumption levels, in kWh/day, for commercial refrigerated vending machines manufactured and/or sold in the United States on or after August 31, 2012. The daily energy consumption is based on the volume of the unit (V).
  - Refrigerated Vending Machines that are fully-cooled (Type A) ≤ 0.055*V + 2.56
  - Refrigerated Vending Machines that are zone-cooled (Type B) ≤ 0.073*V + 3.16
- Energy Star® updated its maximum daily energy consumption efficiency levels, also in KWh/day, for refrigerated vending machines, which went into effect on March 1, 2013. These efficiency levels are based on refrigerated volume.

Equipment Type	Maximum Daily Energy Consumption	Low Power Mode Requirement
Class A (Transparent-Front)	MDEC= 0.0523 x V + 2.432	Hard-wired controls and/or software capable of placing the machine into a low power mode during periods of extended inactivity while still connected to its power source
Class B (Solid-Front)	MDEC = 0.0657 x V + 2.844	

- **Currently, stakeholders such as Coca Cola have indicated a preference for CO_2 refrigerant, which is less efficient. However, this advanced case scenario assumes a shift to more efficient propane for cost and energy consumption projections due to the superior efficiency of propane refrigerant.**
- **By 2040, the adoption of vacuum insulated panels is assumed to occur, with the aid of decreased incremental costs due to increased R&D funding**
- **Projected installed costs for this advanced scenario are higher than the reference case, even assuming increased R&D funding. Advanced energy-saving technologies are assumed to be made financially viable for operators by increased market incentives such as utility efficiency rebate programs and/or carbon pricing.**
- **This analysis finds that with increased R&D and market incentives for energy efficiency technologies, a limit of possible efficiency improvements for self-contained, vapor compression refrigeration systems will be reached by 2040.**

Commercial Refrigerated Vending Machines

- In December 2015, DOE updated its energy conservation standards for beverage vending machines, and defined two new product classes for combination vending machines Compliance with these standards is required by 2019. For this analysis, compliance with these updated standards is assumed for equipment sold in 2020 and beyond. The updated standards and DOE equipment definitions are listed in the table below.

Equipment Class	Maximum daily energy consumption (kilowatt hours per day)
Class A – a refrigerated bottled or canned beverage vending machine that is not a combination vending machine and in which 25 percent or more of the surface area on the front side of the beverage vending machine is transparent	MDEC = 0.052 x V + 2.43
Class B – any refrigerated bottled or canned beverage vending machine that is not considered to be Class A and is not a combination vending machine	MDEC = 0.052 x V + 2.20
Combination A – a combination vending machine where 25 percent or more of the surface area on the front side of the beverage vending machine is transparent	MDEC = 0.086 x V + 2.66
Combination B – a combination vending machine that is not considered to be Combination A	MDEC = 0.111 x V + 2.04

Commercial Ventilation Advanced Case

Commercial Constant Air Volume

Assumes increased rate of technology advancement (lower energy use)

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average[3]	Low[4,5]	Typical[4,6]	Best[4,7]	Energy Star	Typical[4,7]	Best[4,8]	Typical[4,8,9]	Best[4,8,9]	Typical[4,8,9]	Best[4,8,9]
System Airflow (CFM)	15,000	15,000	15,000	15,000	15,000	N/A	15,000	15,000	15,000	15,000	15,000	15,000
System Fan Power (kW)	11.80	11.56	11.56	11.56	11.56	N/A	11.56	11.56	11.56	11.56	11.56	11.56
Specific Fan Power (W/CFM)	0.787	0.771	0.771	0.771	0.771	N/A	0.771	0.771	0.771	0.771	0.771	0.771
Annual Fan Energy Use (kWh/yr)[1]	44,858	43,924	23,038	20,018	15,226	N/A	15,226	11,155	10,597	9,482	9,482	8,366
Average Life (yrs)	20	20	20	20	20	N/A	20	20	20	20	20	20
Total Installed Cost ($)[2]	$68,539	$68,539	$68,979	$68,979	$74,178	N/A	$74,178	$74,778	$75,378	$75,978	$75,978	$76,578
Annual Maintenance Cost ($)	$900	$900	$900	$900	$900	N/A	$900	$900	$900	$900	$900	$900
Total Installed Cost ($/1000 CFM)	$4,569	$4,569	$4,599	$4,599	$4,945	N/A	$4,945	$4,985	$5,025	$5,065	$5,065	$5,105
Annual Maintenance Cost ($/1000 CFM)	$60	$60	$60	$60	$60	N/A	$60	$60	$60	$60	$60	$60

1 Based on 3800 operating hours per year (ADL, 1999) and typical zone air flow requirement profile (ASHRAE S45.11-2012).

2 Total installed cost of 15,000 CFM CAV AHU and hypothetical supply ductwork layout.

3 Based on ASHRAE 90.1-2007 fan power limit (Table 6.5.3.1.1A) with no pressure drop adjustment. Assumed 80% motor load and 91% motor efficiency.

4 ASHRAE 90.1-2010 & 2013 Section 6.5.3.2 require minimum 2-speed fan control (no longer always constant volume).

5 Two-speed motor.

6 Two-speed VFD.

7 Modulating VFD (66-100%).

8 Modulating VFD (50-100%).

9 High aerodynamic efficiency fan.

Commercial Constant Air Volume

- Constant air volume (CAV) ventilation systems are common, inexpensive, air-side HVAC systems that operate in response to a single control zone. Historically, these systems provide a constant flow rate of air (typically a mix of recirculated and outside air) and adjust the supply temperature of that air in order to maintain space temperature setpoint. Recent energy efficiency standard changes (ASHRAE 90.1-2013) now mandate at least two fan speed settings with the requirement of a maximum 40% power at 66% flow. This analysis examines only the fan energy of the CAV system.
- There is movement in the industry and in energy codes to reduce fan power. ASHRAE 90.1 includes fan power limits for CAV systems. Fan power can be minimized through good design practice (efficient duct layout, low pressure drop ductwork, filters, coils), proper fan selection, and high efficiency type fans. ASHRAE 90.1-2013 now requires a minimum fan efficiency grade (FEG, based on AMCA 205-12: Energy Efficiency Classification for Fans) of 67 and a design operating fan efficiency within 15% of the maximum fan total efficiency. There are exceptions to this requirement, including packaged systems such as the CAV system type considered here. Still the fan power limits are expected to become more stringent, and fan efficiency will become more important throughout the industry.
- The unit characterized in this report is a 15,000 CFM CAV system. The average commercial building is approximately 15,000 square feet (CBECS 2003 and BED 2007). Assuming 1 CFM is needed per square foot of floor area results in a 15,000 CFM air handling unit.
- A 15,000 CFM CAV packaged indoor air handling unit with cooling and heating coils can be installed for approximately $60,722 (RS Means 2016). Ductwork would cost approximately $7,817 additional ($68,539 total). A 2-speed motor (estimated $440 incremental cost) and variable frequency drive (estimated $5,639) add cost.
- ASHRAE Standard 90.1, which is used as a basis for most state energy codes, limits the fan power (brake HP or nameplate HP) for CAV systems. The 2007 version of Standard 90.1 was used to represent the 2012 minimum efficiency level (state energy codes typically refer to older versions of Standard 90.1 due to code revision cycles).
- Fan energy is affected by several factors, including: fan type (e.g., centrifugal, axial), fan blade shape (e.g., forward-curved, backward-curved, backward-inclined, airfoil), drive type (belt or direct), configuration (plenum or housed centrifugal), system effects, duct design, filter and coil pressure drops, motor efficiency, and speed/flow control.

Commercial Variable Air Volume

Assumes increased rate of technology advancement (lower energy use)

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average[3]	Low[4]	Typical[5]	Best[6]	Energy Star	Typical[8]	Best[6,7]	Typical[6,7]	Best[6,7]	Typical[6,7]	Best[6,7]
System Airflow (CFM)	15,000	15,000	15,000	15,000	15,000	N/A	15,000	15,000	15,000	15,000	15,000	15,000
System Fan Power (kW)	16.72	15.99	15.99	15.99	15.99	N/A	15.99	15.99	15.99	15.99	15.99	15.99
Specific Fan Power (W/CFM)	1.115	1.066	1.066	1.066	1.066	N/A	1.066	1.066	1.066	1.066	1.066	1.066
Annual Fan Energy Use (kWh/yr)[1]	25,839	24,699	24,699	18,181	16,425	N/A	15,604	15,604	14,783	14,783	13,961	13,140
Average Life (yrs)	20	20	20	20	20	N/A	20	20	20	20	20	20
Total Installed Cost ($)[2]	$88,207	$88,207	$88,207	$93,846	$94,346	N/A	$94,446	$94,946	$94,446	$94,946	$94,446	$94,946
Annual Maintenance Cost ($)	$900	$900	$900	$900	$900	N/A	$900	$900	$900	$900	$900	$900
Total Installed Cost ($/1000 CFM)	$5,880	$5,880	$5,880	$6,256	$6,290	N/A	$6,296	$6,330	$6,296	$6,330	$6,296	$6,330
Annual Maintenance Cost ($/1000 CFM)	$60	$60	$60	$60	$60	N/A	$60	$60	$60	$60	$60	$60

[1] Based on 3800 operating hours per year (ADL, 1999) and typical zone air flow requirement profile (ASHRAE S45.11-2012).

[2] Total installed cost of 15,000 CFM VAV AHU, VFD, (10) VAV boxes, and hypothetical supply ductwork layout.

[3] Based on ASHRAE 90.1-2007 fan power limit (Table 6.5.3.1.1A) with no pressure drop adjustment. Assumed 80% motor load and 91% motor efficiency.

[4] ASHRAE 90.1-2010 Section 6.5.3.2 minimum power-flow requirement.

[5] ASHRAE 90.1-2013 fan power limit and typical VAV power-flow relationship for 50%-100% flow.

[6] ASHRAE 90.1-2013 fan power limit and typical VAV power-flow relationship for 30%-100% flow.

[7] High aerodynamic efficiency fan.

Commercial Variable Air Volume

- Variable air volume (VAV) ventilation systems are the most common multi-zone system type specified today for conditioning commercial buildings. These systems provide conditioned air to multiple zone terminal units (VAV boxes) that use dampers to modulate the amount of cool air to each zone. An individual zone thermostat controls the VAV box damper to allow more or less cooling. If a zone requires heating then the VAV box provides the minimum flow rate and typically includes a reheat coil to meet space temperature setpoint. As VAV box dampers close in the system, a variable frequency drive reduces fan speed and flow continuously to meet current requirements.
- This analysis examines only the fan energy of the VAV system. VAV systems vary fan speed/flow to meet space conditioning requirements; minimum flow settings apply for DX cooling stages and gas furnace heating stages. Most hours of operation are much lower than full speed, and fan power varies with the cube of fan speed according to fan affinity laws. The 2012 ASHRAE Handbook: HVAC Systems and Equipment (p. 45.11) provided the typical flow profile used for this analysis. The unit characterized in this report is a 15,000 CFM VAV system.
- There is movement in the industry and in energy codes to reduce fan power. ASHRAE 90.1 includes fan power limits for VAV systems. Fan power can be minimized through good design practice (efficient duct layout, low pressure drop ductwork, filters, coils), proper fan selection, and high efficiency type fans. ASHRAE 90.1-2013 now requires a minimum fan efficiency grade (FEG, based on AMCA 205-12: Energy Efficiency Classification for Fans) of 67 and a design operating fan efficiency within 15% of the maximum fan total efficiency. There are exceptions to this requirement, including packaged systems such as the VAV system type considered here. Still the fan power limits are expected to become more stringent, and fan efficiency will become more important throughout the industry.
- A 15,000 CFM VAV packaged indoor air handling unit with cooling and heating coils can be installed for approximately $69,100 (RS Means 2016). Ductwork and (10) VAV boxes with reheat would cost approximately $19,107 additional ($88,207 total). A 20 hp variable frequency drive (estimated $5,639) is an additional cost.
- ASHRAE Standard 90.1, which is used as a basis for most state energy codes, limits the fan power for VAV systems (brake HP or nameplate HP). The 2007 version of Standard 90.1 was used to represent the 2012 minimum efficiency level (state energy codes typically refer to older versions of Standard 90.1 due to code revision cycles).
- Fan energy is affected by several factors, including: fan type (e.g., centrifugal, axial), fan blade shape (e.g., forward-curved, backward-curved, backward-inclined, airfoil), drive type (belt or direct), configuration (plenum or housed centrifugal), system effects, duct design, filter and coil pressure drops, and motor VFD efficiency.

Commercial Fan Coil Units

Assumes increased rate of technology advancement (lower energy use)

DATA	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average[5]	Low[3]	Typical[6]	Best[6]	Energy Star	Typical[4,7]	Best[4,8]	Typical[4,8]	Best[4,8,9]	Typical[4,8,9]	Best[4,8,9]
System Airflow (CFM)	800	800	800	800	800	N/A	800	800	800	800	800	800
System Fan Power (kW)	0.315	0.241	0.748	0.241	0.148	N/A	0.148	0.148	0.148	0.141	0.141	0.133
Specific Fan Power (W/CFM)	0.394	0.302	0.935	0.301	0.185	N/A	0.185	0.185	0.185	0.176	0.176	0.166
Annual Fan Energy Use (kWh/yr)[1]	709	543	1,683	543	333	N/A	152	94	94	89	89	84
Average Life (yrs)	20	20	20	20	20	N/A	20	20	20	20	20	20
Total Installed Cost ($)[2]	$2,429	$2,429	$2,429	$2,429	$2,753	N/A	$2,753	$2,995	$2,753	$2,995	$2,995	$3,044
Annual Maintenance Cost ($)	$100	$100	$100	$100	$100	N/A	$100	$100	$100	$100	$100	$100
Total Installed Cost ($/1000 CFM)	$3,036	$3,036	$3,036	$3,036	$3,441	N/A	$3,441	$3,744	$3,441	$3,744	$3,744	$3,805
Annual Maintenance Cost ($/1000 CFM)	$125	$125	$125	$125	$125	N/A	$125	$125	$125	$125	$125	$125

[1] Based on 2250 operating hours per year (ADL, 1999) and typical zone air flow requirement profile (ASHRAE S45.11-2012).

[2] Total installed cost of 2-ton horizontal 2-pipe fan coil unit, housing and controls.

[3] Based on ASHRAE 90.1-2010 fan power limit (Table 6.5.3.1.1A) with no pressure drop adjustment. Assumed 80% motor load and 60% motor efficiency.

[4] Based on ASHRAE 90.1-2013 Section 6.5.3.5 requirement of electronically commutated or 70+% efficient fan motor.

[5] Permanent split capacitor fan motor.

[6] Electronically commutated fan motor (single speed).

[7] Electronically commutated fan motor (two-speed).

[8] Electronically commutated fan motor (variable speed).

[9] High aerodynamic efficiency fan.

Commercial Fan Coil Units

- Commercial fan coil units (FCUs) are self-contained, mass-produced assemblies that provide cooling, heating, or cooling and heating, but do not include the source of cooling or heating. The unit characterized in this report is a cooling only (2-pipe), horizontal unit with housing and controls. Fan coil units are typically installed in or adjacent to the space being served and have no (or very limited) ductwork.
- According to manufacturer literature, the cooling capacity for a nominal 800 CFM fan coil unit is about 2 tons. This analysis examines only the fan energy of FCUs.
- Fan coil unit fan motors can be shaded pole, a single phase AC motor with offset start winding and no capacitor; PSC, a single phase AC motor with offset start winding with capacitor; or ECM, an AC electronically commutated permanent magnet DC motor. PSC motors are currently the most common motor type in FCUs, but most manufacturers offer ECM as an option. ASHRAE 90.1-2013 requires an electronically commutated fan motor (or minimum motor efficiency of 70%) for this system.
- There is movement in the industry and in energy codes to reduce fan power. ASHRAE 90.1 includes fan power limits for FCUs. Fan power can be minimized through good design practice and high efficiency type fans. ASHRAE 90.1-2013 now requires a minimum fan efficiency grade (FEG, based on AMCA 205-12: Energy Efficiency Classification for Fans) of 67 and a design operating fan efficiency within 15% of the maximum fan total efficiency. There are exceptions to this requirement, including small systems such as the FCU considered here. Still the fan power limits are expected to become more stringent, and fan efficiency will become more important throughout the industry.
- Fan coil units have higher maintenance costs than central air systems due to the distributed nature of the system. For each unit the filters must be changed and drain systems must be flushed periodically.
- ASHRAE Standard 90.1, which is used as a basis for most state energy codes, limits the fan power (brake HP or nameplate HP). The 2007 version of Standard 90.1 was used to represent the 2012 minimum efficiency level (state energy codes typically refer to older versions of Standard 90.1 due to code revision cycles).
- Fan energy is affected by several factors, including: fan type configuration, filter and coil pressure drops, motor efficiency, and fan speed control.

Appendix A
Data Sources

Navigant Consulting, Inc.
1200 19th Street, NW, Suite 700
Washington, D.C. 20036

And

Leidos
8301 Greensboro Drive
McLean, VA 22102

Residential Lighting

Final

Data Sources » Residential General Service LED Lamps (60 Watt Equivalent)

<table>
<tr><th rowspan="2">DATA SOURCES</th><th>2009</th><th colspan="4">2015</th><th colspan="2">2020</th><th colspan="2">2030</th><th colspan="2">2040</th></tr>
<tr><th>Installed Stock Average</th><th>Low</th><th>Typical</th><th>High</th><th>Energy Star</th><th>Typical</th><th>High</th><th>Typical</th><th>High</th><th>Typical</th><th>High</th></tr>
<tr><td>Lamp Wattage</td><td>Calculated</td><td colspan="3" rowspan="4">LED Lighting Facts Database (downloaded 10/31/15)</td><td rowspan="2">Energy Star Light Bulb product database (downloaded 11/4/15)</td><td colspan="6">Calculated</td></tr>
<tr><td>Lamp Lumens</td><td>Product Catalogs</td><td colspan="6">Calculated from 2015 Values</td></tr>
<tr><td>Lamp Efficacy (lm/W)</td><td>2012 SSL MYPP</td><td>Calculated</td><td colspan="4">U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)</td><td colspan="2">Calculated</td></tr>
<tr><td>CRI</td><td rowspan="3">Product Catalogs</td><td rowspan="2">Energy Star Light Bulb product database (downloaded 11/4/15)</td><td colspan="6" rowspan="2">Assume Unchanged From 2015 Typical</td></tr>
<tr><td>Correlated Color Temperature (CCT)</td><td>LED Lighting Facts Database (downloaded 10/31/15)</td><td rowspan="2">SSL R&D Plan Table 2.1 (DOE SSL Program, 2015)</td><td>LED Lighting Facts Database (downloaded 10/31/15)</td></tr>
<tr><td>Average Lamp Life (1000 hrs)</td><td>Retailer Websites</td><td colspan="2">Retailer Websites</td><td colspan="4">U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)</td><td colspan="2">Assume Unchanged</td></tr>
<tr><td>Annual Operating Hours (hrs/yr)</td><td colspan="11">U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.</td></tr>
<tr><td>Lamp Price ($)</td><td>Calculated</td><td>Retailer Websites</td><td>Calculated</td><td colspan="2">Retailer Websites</td><td colspan="6">Calculated</td></tr>
<tr><td>Lamp Cost ($/klm)</td><td>2012 SSL MYPP</td><td>Calculated</td><td>SSL R&D Plan Table 2.1 +adjustment (DOE SSL Program, 2015)</td><td colspan="2">Calculated</td><td colspan="4">U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)</td><td colspan="2">Calculated</td></tr>
<tr><td>Labor Cost ($/hr)</td><td colspan="11" rowspan="2">N/A</td></tr>
<tr><td>Labor Lamp Installation (hr)</td></tr>
<tr><td>Total Installed Cost ($)</td><td colspan="11" rowspan="4">Calculated</td></tr>
<tr><td>Annual Maintenance Cost ($)</td></tr>
<tr><td>Total Installed Cost ($/klm)</td></tr>
<tr><td>Annual Maintenance Cost ($/klm)</td></tr>
</table>

Data Sources » Residential Reflector LED BR30

DATA SOURCES	2009 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage	Calculated				Energy Star Light Bulb product database (downloaded 11/4/15)	Calculated					
Lamp Lumens	Adjusted based on PAR38 values	LED Lighting Facts Database (downloaded 10/31/15)				Nominal lumen output based on historical values					
Lamp Efficacy (lm/W)					Calculated	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
CRI					Energy Star Light Bulb product database (downloaded 11/4/15)						
Correlated Color Temperature (CCT)	Adjusted based on PAR38 values	LED Lighting Facts Database (downloaded 10/31/15)	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	LED Lighting Facts Database (downloaded 10/31/15)		Assume Unchanged					
Average Lamp Life (1000 hrs)		Retailer Websites		Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.										
Lamp Price ($)	Calculated	Retailer Websites	Calculated	Retailer Websites		Calculated					
Lamp Cost ($/klm)	Adjusted based on PAR38 values	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Labor Cost ($/hr)	N/A										
Labor Lamp Installation (hr)											
Total Installed Cost ($)	Calculated										
Annual Maintenance Cost ($)											
Total Installed Cost ($/klm)											
Annual Maintenance Cost ($/klm)											

Data Sources » Residential Reflector LED PAR38

DATA SOURCES	2009	2015				2020		2030		2040	
	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	Calculated	LED Lighting Facts Database (downloaded 10/31/15)			Energy Star Light Bulb product database (downloaded 11/4/15)	Calculated					
Lamp Lumens	Product Catalogs					Nominal lumen output based on historical values					
Lamp Efficacy (lm/W)	2012 SSL MYPP				Calculated	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
CRI	Product Catalogs				Energy Star Light Bulb product database (downloaded 11/4/15)	Assume Unchanged					
Correlated Color Temperature (CCT)		LED Lighting Facts Database (downloaded 10/31/15)	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	LED Lighting Facts Database (downloaded 10/31/15)							
Average Lamp Life (1000 hrs)		Retailer Websites		Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.										
Lamp Price ($)	Calculated	Retailer Websites	Calculated	Retailer Websites		Calculated				Calculated	
Lamp Cost ($/klm)	2012 SSL MYPP	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Labor Cost ($/hr)	N/A										
Labor Lamp Installation (hr)											
Total Installed Cost ($)	Calculated										
Annual Maintenance Cost ($)											
Total Installed Cost ($/klm)											
Annual Maintenance Cost ($/klm)											

Data Sources » Residential Linear LED Replacement Lamp 2 Lamp System*

DATA SOURCES	2009 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage	DOE SSL Program: LED Application Series, Linear Fluorescent Replacement Lamps (DOE SSL Program, 2011)	LED Lighting Facts Qualified Product List (Downloaded 11/17/15)			N/A	Calculated					
Lamp Lumens						Adjusted for 2015 Typical Lumen Output					
Lamp Efficacy (lm/W)	Calculated					U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
System Wattage	Calculated					Calculated					
System Lumens	DOE SSL Program R&D Plan (DOE SSL Program, 2015)					DOE SSL Program R&D Plan (DOE SSL Program, 2015)					
System Efficacy (lm/W)	Calculated					Calculated					
Ballast Efficiency (BLE)	N/A					N/A					
CRI	DOE SSL Program: LED Application Series, Linear Fluorescent Replacement Lamps (DOE SSL Program, 2011)	LED Lighting Facts Qualified Product List (Downloaded 11/17/15)	LED Lighting Facts Qualified Product List Downloaded 11/17/15	LED Lighting Facts Qualified Product List (Downloaded 11/17/15)		Assume Unchanged					
Correlated Color Temperature (CCT)			DOE SSL Program R&D Plan (DOE SSL Program, 2015)								
Average Lamp Life (1000 hrs)		Retailer Websites		Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp Price ($)	DOE SSL Program: LED Application Series, Linear Fluorescent Replacement Lamps (DOE SSL Program, 2011)	Retailer Websites	Calculated	Retailer Websites		Calculated					
Ballast Price ($)	N/A					N/A					
Fixture Price ($)*											
Lamp Cost ($/klm)	Calculated	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
System (l/b/f) Cost ($/klm)*	N/A					N/A					
Labor Cost ($/hr)	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Labor System Installation (hr)*											
Labor Lamp Change (hr)											
Total Installed Cost ($)	Calculated					Calculated					
Annual Maintenance Cost ($)											
Total Installed Cost ($/klm)											
Annual Maintenance Cost ($/klm)											

DATA SOURCES	2009	2015				2020		2030		2040	
	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A										
Lamp Lumens											
Lamp Efficacy (lm/W)											
System Wattage	Calculated	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 10/31/15)	DLC Qualified Product List (Downloaded 11/18/15)	Energy Star Light Bulb product database (downloaded 11/4/15)	Calculated					
System Lumens		Calculated		Calculated		Adjusted for 2015 Typical Lumen Output					
System Efficacy (lm/W)		DLC Qualified Product List (Downloaded 11/18/15)		DLC Qualified Product List (Downloaded 11/18/15)	Calculated	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Ballast Efficiency (BLE)	N/A										
CRI	Calculated	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 10/31/15)	DLC Qualified Product List (Downloaded 11/18/15)	Energy Star Light Bulb product database (downloaded 11/4/15)	Assume Unchanged					
Correlated Color Temperature (CCT)											
Average Lifetime (1000 hrs)			DOE SSL Program R&D Plan (DOE SSL Program, 2015)			U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.										
Lamp/Luminaire Price ($)	Calculated	Retailer Websites	Calculated	Retailer Websites	Retailer Websites	Calculated					
Ballast Price ($)	N/A										
Fixture Price ($)											
Lamp Cost ($/klm)											
System (l/b/f) Cost ($/klm)	Calculated	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated	Calculated	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Labor Cost ($/hr)	Assume Same as T5										
Labor System Installation (hr)											
Labor Lamp Change (hr)	N/A										
Total Installed Cost ($)	Calculated										
Annual Maintenance Cost ($)											
Total Installed Cost ($/klm)											
Annual Maintenance Cost ($/klm)											

Data Sources » Residential Outdoor Lamps (Security: LED PAR38)

DATA SOURCES	2009	2015				2020		2030		2040	
	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	Calculated	LED Lighting Facts Database (downloaded 10/31/15)			Energy Star Light Bulb product database (downloaded 11/4/15)	Calculated					
Lamp Lumens	Product Catalogs					Nominal lumen output based on historical values					
Lamp Efficacy (lm/W)	2012 SSL MYPP				Calculated	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
CRI	Product Catalogs				Energy Star Light Bulb product database (downloaded 11/4/15)	Assume Unchanged					
Correlated Color Temperature (CCT)		LED Lighting Facts Database (downloaded 10/31/15)	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	LED Lighting Facts Database (downloaded 10/31/15)							
Average Lamp Life (1000 hrs)		Retailer Websites		Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.										
Lamp Price ($)	Calculated	Retailer Websites	Calculated	Retailer Websites		Calculated				Calculated	
Lamp Cost ($/klm)	2012 SSL MYPP	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Labor Cost ($/hr)	N/A										
Labor Lamp Installation (hr)											
Total Installed Cost ($)	Calculated										
Annual Maintenance Cost ($)											
Total Installed Cost ($/klm)											
Annual Maintenance Cost ($/klm)											

Data Sources » Residential Outdoor Lamps (Porch: LED A-Type*)

DATA SOURCES	2009	2015				2020		2030		2040	
	Installed Stock Average	Low	Typical	High	Energy Star*	Typical	High	Typical	High	Typical	High
Lamp Wattage	Calculated										
Lamp Lumens	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)										
Lamp Efficacy (lm/W)	Scaled based on 60W Residential A-type Lamp										
CRI											
Correlated Color Temperature (CCT)											
Average Lamp Life (1000 hrs)											
Annual Operating Hours (hrs/yr)	DOE SSL Program, Residential Lighting End-Use Consumption Study: Estimation Framework and Initial Estimates (DOE SSL Program, 2012)										
Lamp Price ($)	Calculated										
Lamp Cost ($/klm)	Scaled based on 60W Residential A-type Lamp										
Labor Cost ($/hr)	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)										
Labor Lamp Installation (hr)											
Total Installed Cost ($)	Calculated										
Annual Maintenance Cost ($)											
Total Installed Cost ($/klm)											
Annual Maintenance Cost ($/klm)											

Commercial Lighting

Final

DATA SOURCES	2003 Installed Stock Average	2012 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage		DOE SSL Program, 2013 Multi-Year Program Plan (DOE SSL Program, 2013)	LED Lighting Facts Database (downloaded 10/31/15)			Energy Star Light Bulb product database (downloaded 11/4/15)	Calculated					
Lamp Lumens							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Lamp Efficacy (lm/W)						Calculated					Calculated	
System Wattage		Calculated										
System Lumens*												
System Efficacy (lm/W)												
Ballast Efficiency (BLE)												
CRI		DOE SSL Program, 2013 Multi-Year Program Plan (DOE SSL Program, 2013)	LED Lighting Facts Database (downloaded 10/31/15)			Energy Star Light Bulb product database (downloaded 11/4/15)	Assume Unchanged					
Correlated Color Temperature (CCT)			Retailer Websites	Assume Same as A19 60W equiv	Retailer Websites							
Average Lamp Life (1000 hrs)		Calculated					U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Annual Operating Hours (hrs/yr)	N/A	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.										
Lamp Price ($)		Calculated	Retailer Websites	Calculated	Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Ballast Price ($)		N/A										
Fixture Price ($)**												
Lamp Cost ($/klm)		DOE SSL Program, 2013 Multi-Year Program Plan (DOE SSL Program, 2013)	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated	Calculated	Calculated				Calculated	
System (l/b/f) Cost ($/klm)		N/A										
Labor Cost ($/hr)		Same as for CFL										
Labor System Installation (hr)**												
Labor Lamp Change (hr)												
Total Installed Cost ($)		Calculated										
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)												
Annual Maintenance Cost ($/klm)												

Data Sources » Commercial LED Reflector Lighting (PAR38)

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DATA SOURCES	2003 Installed Stock Average	2012 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage		LED Lighting Facts Qualified Product List (Downloaded 11/17/15)				Energy Star Light Bulb product database (downloaded 11/4/15)	Calculated					
Lamp Lumens							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Lamp Efficacy (lm/W)						Calculated					Calculated	
System Wattage		Calculated										
System Lumens*												
System Efficacy (lm/W)												
Ballast Efficiency (BLE)		N/A										
CRI		LED Lighting Facts Qualified Product List (Downloaded 11/17/15)		LED Lighting Facts Qualified Product List (Downloaded 11/17/15)	LED Lighting Facts Qualified Product List (Downloaded 11/17/15)	Energy Star Light Bulb product database (downloaded 11/4/15)	Assume Unchanged					
Correlated Color Temperature (CCT)				DOE SSL Program R&D Plan (DOE SSL Program, 2015)								
Average Lamp Life (1000 hrs)	N/A	Calculated	Retailer Websites		Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)		U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.										
Lamp Price ($)		Calculated	Retailer Websites	Calculated	Retailer Websites		Calculated				Calculated	
Ballast Price ($)		N/A										
Fixture Price ($)**												
Lamp Cost ($/klm)		DOE SSL Program, 2013 Multi-Year Program Plan (DOE SSL Program, 2013)	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
System (l/b/f) Cost ($/klm)**		N/A										
Labor Cost ($/hr)		Same as for Halogen										
Labor System Installation (hr)**												
Labor Lamp Change (hr)												
Total Installed Cost ($)		Calculated										
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)												
Annual Maintenance Cost ($/klm)												

Data Sources » Commercial 4-ft Linear LED Replacement Lamp in 2-Lamp System

Final

DATA SOURCES	2003 Installed Stock Average	2012 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage	N/A	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)			N/A	Calculated					
Lamp Lumens							Adjusted for 2015 Typical Lumen Output					
Lamp Efficacy (lm/W)							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
System Wattage		Calculated					Calculated					
System Lumens												
System Efficacy (lm/W)												
Ballast Efficiency (BLE)												
CRI		DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)				Assume Unchanged					
Correlated Color Temperature (CCT)												
Average Lamp Life (1000 hrs)			Retailer Websites	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)		U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp Price ($)		Calculated	Retailer Websites	Calculated	Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Ballast Price ($)		N/A					N/A					
Fixture Price ($)*												
Lamp Cost ($/klm)		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
System (l/b/f) Cost ($/klm)*		N/A					N/A					
Labor Cost ($/hr)		Calculated	Assume Same as Analgous Conventional Tech				Assume Unchanged					
Labor System Installation (hr)*		N/A										
Labor Lamp Change (hr)		Calculated										
Total Installed Cost ($)		Calculated					Calculated					
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)												
Annual Maintenance Cost ($/klm)												

Data Sources » Commercial 4-ft Linear LED Luminaire to Replace 2-Lamp Systems*

Final

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage												
Lamp Lumens												
Lamp Efficacy (lm/W)	N/A						N/A					
System Wattage							Calculated					
System Lumens							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
System Efficacy (lm/W)	2008 EIA Reference Case	DLC Qualified Product List (Downloaded 11/18/15)		LED Lighting Facts Qualified Product List (Downloaded 11/17/15)	DLC Qualified Product List (Downloaded 11/18/15)						Calculated	
Ballast Efficiency (BLE)	N/A						N/A					
CRI												
Correlated Color Temperature (CCT)	2008 EIA Reference Case						Assume Unchanged from 2015					
Average Lifetime (1000 hrs)	Calculated	DLC Qualified Product List (Downloaded 11/18/15)		LED Lighting Facts Qualified Product List (Downloaded 11/17/15)	DLC Qualified Product List (Downloaded 11/18/15)		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.						U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp/Luminaire Price ($)	2008 EIA Reference Case	Calculated	Retailer Website	Calculated	Retailer Website		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Ballast Price ($)						N/A						
Fixture Price ($)	N/A						N/A					
Lamp Cost ($/klm)												
System (l/b/f) Cost ($/klm)	Calculated	U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Labor Cost ($/hr)	2008 EIA Reference Case											
Labor System Installation (hr)	2008 EIA Reference Case	Calculated									Assume Unchanged	
Labor Lamp Change (hr)	N/A						N/A					
Total Installed Cost ($)												
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)	Calculated						Calculated					
Annual Maintenance Cost ($/klm)												

Data Sources » Commercial 8-ft Linear LED Replacement Lamp for a 2 Lamp System*

DATA SOURCES	2003 Installed Stock Average	2012 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage							Calculated					
Lamp Lumens				LED Lighting Facts Qualified Product List (Downloaded 11/17/15)			Nominal Lumen output based on 2015 values					
Lamp Efficacy (lm/W)							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
System Wattage												
System Lumens							Calculated					
System Efficacy (lm/W)				Calculated								
Ballast Efficiency (BLE)				N/A								
CRI				Calculated from LED Lighting Facts Qualified Product List Downloaded 11/17/15			Assume Unchanged from 2015					
Correlated Color Temperature (CCT)				DOE SSL Program R&D Plan (DOE SSL Program, 2015)								
Average Lamp Life (1000 hrs)							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Annual Operating Hours (hrs/yr)	N/A			U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.	N/A		U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp Price ($)				Calculated			U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Ballast Price ($)							N/A					
Fixture Price ($)*				N/A								
Lamp Cost ($/klm)				Navigant Price Analysis			U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
System (l/b/f) Cost ($/klm)*				N/A			N/A					
Labor Cost ($/hr)				Assume Same as Analgous Conventional Tech								
Labor System Installation (hr)*							Assume Unchanged from 2015					
Labor Lamp Change (hr)												
Total Installed Cost ($)												
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)				Calculated			Calculated					
Annual Maintenance Cost ($/klm)												

Data Sources » Commercial 8-ft Linear LED Luminaire Replacement for a 2-Lamp System*

DATA SOURCES	2003 Installed Stock Average	2012 Installed Stock Average	2015 Low	2015 Typical	2015 High	2015 Energy Star	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Lamp Wattage		N/A		Calculated	N/A				N/A			
Lamp Lumens												
Lamp Efficacy (lm/W)												
System Wattage				Retailer Websites					Calculated			
System Lumens							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
System Efficacy (lm/W)											Calculated	
Ballast Efficiency (BLE)				N/A					N/A			
CRI				Retailer Websites					Assume Unchanged from 2015			
Correlated Color Temperature (CCT)												
Average Lifetime (1000 hrs)							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Annual Operating Hours (hrs/yr)				U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.			U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp/Luminaire Price ($)				Calculated					Calculated			
Ballast Price ($)				N/A					N/A			
Fixture Price ($)												
Lamp Cost ($/klm)												
System (l/b/f) Cost ($/klm)				Navigant Price analysis			U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Labor Cost ($/hr)				Assume Same as Analgous Conventional Tech							Assume Unchanged	
Labor System Installation (hr)												
Labor Lamp Change (hr)				N/A					N/A			
Total Installed Cost ($)				Calculated					Calculated			
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)												
Annual Maintenance Cost ($/klm)												

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A					N/A	N/A					
Lamp Lumens												
Lamp Efficacy (lm/W)												
System Wattage	2008 EIA Reference Case	Calculated	DLC Qualified Product List (Downloaded 11/18/15)	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)		Calculated					
System Lumens							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
System Efficacy (lm/W)											Calculated	
Ballast Efficiency (BLE)	N/A						N/A					
CRI	2008 EIA Reference Case	Calculated	DLC Qualified Product List (Downloaded 11/18/15)	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)		Assume Unchanged from 2015					
Correlated Color Temperature (CCT)				DOE SSL Program R&D Plan (DOE SSL Program, 2015)								
Average Lifetime (1000 hrs)	Calculated			DLC Qualified Product List (Downloaded 11/18/15)	Retailer Websites		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.						U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp/Luminaire Price ($)	2008 EIA Reference Case	Calculated	Retailer Websites	Calculated	Retailer Websites		Calculated					
Ballast Price ($)	N/A						N/A					
Fixture Price ($)												
Lamp Cost ($/klm)												
System (l/b/f) Cost ($/klm)	Calculated	Calculated	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Labor Cost ($/hr)	2008 EIA Reference Case		Assume Same as Analgous Conventional Tech								Assume Unchanged	
Labor System Installation (hr)												
Labor Lamp Change (hr)	N/A						N/A					
Total Installed Cost ($)	Calculated						Calculated					
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)												
Annual Maintenance Cost ($/klm)												

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Energy Star	Typical	High	Typical	High	Typical	High
Lamp Wattage												
Lamp Lumens	N/A						N/A					
Lamp Efficacy (lm/W)												
System Wattage		DLC Qualified Product List (Downloaded 11/18/15)	DLC Qualified Product List (Downloaded 11/18/15)	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)		Calculated					
System Lumens							U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Assume Unchanged	
System Efficacy (lm/W)	2008 EIA Reference Case										Calculated	
Ballast Efficiency (BLE)	N/A						N/A					
CRI		DLC Qualified Product List (Downloaded 11/18/15)	DLC Qualified Product List (Downloaded 11/18/15)	DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)							
Correlated Color Temperature (CCT)	2008 EIA Reference Case			DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Retailer Websites		Assume Unchanged from 2015					
Average Lifetime (1000 hrs)	Calculated			DLC Qualified Product List (Downloaded 11/18/15)	LED Lighting Facts Database (downloaded 11/17/15)		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)					
Annual Operating Hours (hrs/yr)	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					N/A	U.S. DOE SSL Program, 2010 Lighting Market Characterization, Prepared by Navigant Consulting Inc., January 2012.					
Lamp/Luminaire Price ($)	2008 EIA Reference Case	Calculated	Retailer Websites	Calculated	Retailer Websites		Calculated					
Ballast Price ($)												
Fixture Price ($)							N/A					
Lamp Cost ($/klm)	N/A											
System (l/b/f) Cost ($/klm)	Calculated	Calculated	Calculated	DOE SSL Program R&D Plan (DOE SSL Program, 2015)	Calculated		U.S. DOE SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2014)				Calculated	
Labor Cost ($/hr)	2008 EIA Reference Case	Assume Same as Analgous Conventional Tech										
Labor System Installation (hr)	Assume Same as Analgous Conventional Tech										Assume Unchanged	
Labor Lamp Change (hr)	N/A						N/A					
Total Installed Cost ($)												
Annual Maintenance Cost ($)												
Total Installed Cost ($/klm)	Calculated						Calculated					
Annual Maintenance Cost ($/klm)												

Refrigeration

Data Sources » Commercial Compressor Rack Systems

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Total Capacity (MBtu/hr)	ADL, 1996	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Median Store Size	Food Marketing Institute (FMI), 2012	Food Marketing Institute, 2015 / Navigant Analysis, 2015										
Power Input (kW)	Copeland, 2008	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Energy Use (MWh/yr)	ADL, 1996 / NCI Analysis, 2015	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Normalized Annual Efficiency	Calculated											
Nominal Capacity Over Average Input (Btu out / Btu in)	Calculated											
Average Life (yrs)	Kysor-Warren, 2008	EIA, 2012										
Total Installed Cost ($1000)	NCI, 2009 / NCI Analysis, 2012	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost ($1000)	ADL, 1996 / NCI Analysis, 2008	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Data Sources » Commercial Condensers

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Total Capacity (MBtu/hr)	NCI Analysis, 2008 / Heatcraft, 2008 / ADL, 1996	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Median Store Size	Food Marketing Institute (FMI), 2012	Food Marketing Institute, 2015 / Navigant Analysis, 2015										
Power Input (kW)	NCI Analysis, 2008 / Heatcraft, 2008 / ADL, 1996	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Energy Use (MWh/yr)	NCI Analysis, 2008 / ADL, 1996	Interview with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Indexed Annual Efficiency	#REF!											
Average Life (yrs)	ADL, 1996 / NCI Analysis, 2008	EIA, 2012										
Total Installed Cost ($1000)	NCI Analysis, 2008 / Heatcraft, 2008 / RS Means, 2007	Interviews with supermarket refrigeration efficiency consultant / Navigant Analysis, 2015										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	NCI Analysis, 2008	EIA, 2012										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	DOE, 2007 / NCI Analysis, 2008	Navigant Analysis, 2015										
Median Store Size (ft^2)	Food Marketing Institute (FMI), 2012	Food Marketing Institute, 2015 / Navigant Analysis										
Case Length	DOE, 2014: CRE TSD											
Energy Use (kWh/yr)	DOE, 2007 / NCI Analysis, 2008	DOE 2014: CRE Engineering Spreadsheet / Navigant Analysis										
Energy Use (kWh/ft)	Calculated											
Indexed Annual Efficiency	Calculated											
Average Life (yrs)	DOE, 2007 / NCI Analysis, 2008	DOE 2014: CRE TSD										
Retail Equipment Cost	DOE, 2007 / NCI Analysis, 2008	DOE 2014: CRE Engineering Spreadsheet / Navigant Analysis										
Total Installed Cost	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis										
Total Installed Cst ($/kBtu/hr)	Navigant Analysis, 2015											
Annual Maintenance Cost	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Data Sources » Commercial Reach-In Refrigerators

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE Engineering Spreadsheet										
Size (ft^3)	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE TSD										
Energy Use (kWh/yr)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis										
Energy Use (kWh/yr/ft^3)	NCI Analysis, 2012	Calculated										
Indexed Annual Efficiency	Calculated											
Average Life (yrs)	ACEEE, 2002	DOE, 2014: CRE TSD										
Retail Equipment Cost	ADL, 1996/ Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis										
Total Installed Cost	Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Data Sources » Commercial Reach-In Freezers

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE TSD										
Size (ft^3)	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE TSD										
Energy Use (kWh/yr)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis, 2015										
Energy Use (kWh/yr/ft^3)	NCI Analysis, 2012	Calculated										
Normalized Annual Efficiency	Calculated											
Nominal Capacity Over Average Input (Btu out / Btu in)	Calculated											
Average Life (yrs)	ACEEE, 2002	DOE, 2014: CRE TSD										
Retail Equipment Cost	ADL, 1996/ Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis, 2015										
Total Installed Cost	Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis, 2015										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	NCI Analysis, 2008	DOE, 2014: CRE TSD										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Data Sources » Commercial Walk-In Refrigerators

<table>
<tr><th rowspan="2">DATA SOURCES</th><th>2003</th><th>2012</th><th colspan="4">2015</th><th colspan="2">2020</th><th colspan="2">2030</th><th colspan="2">2040</th></tr>
<tr><th>Installed Stock Average</th><th>Installed Stock Average</th><th>Low</th><th>Typical</th><th>Energy Star</th><th>High</th><th>Typical</th><th>High</th><th>Typical</th><th>High</th><th>Typical</th><th>High</th></tr>
<tr><td>Cooling Capacity (Btu/hr)</td><td>ADL, 1996 / NCI Analysis, 2008</td><td colspan="11">DOE, 2014: WICF TSD</td></tr>
<tr><td>Size (ft^2)</td><td>ADL, 1996 / NCI Analysis, 2008</td><td colspan="11">DOE, 2014: WICF TSD</td></tr>
<tr><td>Energy Use (kWh/yr)</td><td>ADL, 1996 / PG&E, 2004 / NCI Analysis, 2008</td><td colspan="11">DOE, 2014: WICF TSD / Navigant Analysis, 2015</td></tr>
<tr><td>Energy Use (kWh/ft^2/yr)</td><td colspan="12">Calculated</td></tr>
<tr><td>Indexed Annual Efficiency</td><td colspan="12">Calculated</td></tr>
<tr><td>Insulated Box Average Life (yrs)</td><td>ADL, 1996 / PG&E, 2004</td><td colspan="11">DOE, 2014: WICF TSD</td></tr>
<tr><td>Compressor Average Life (yrs)</td><td>ADL, 1996 / PG&E, 2004</td><td colspan="11">DOE, 2014: WICF TSD</td></tr>
<tr><td>Retail Equipment Cost</td><td>ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008</td><td colspan="11">DOE, 2014: WICF TSD / Navigant Analysis, 2015</td></tr>
<tr><td>Total Installed Cost</td><td>ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008</td><td colspan="11">DOE, 2014: WICF TSD / Navigant Analysis, 2015</td></tr>
<tr><td>Total Installed Cost ($/kBtu/hr)</td><td colspan="12">Calculated</td></tr>
<tr><td>Annual Maintenance Cost</td><td>ADL, 1996 / FMI, 2005 / NCI Analysis, 2008</td><td colspan="11">DOE, 2014: WICF TSD / Navigant Analysis, 2015</td></tr>
<tr><td>Annual Maintenance Cost ($/kBtu/hr)</td><td colspan="12">Calculated</td></tr>
</table>

Data Sources » Commercial Walk-In Freezers

DATA SOURCES	2003 Installed Stock Average	2012 Installed Stock Average	2015 Low	2015 Typical	2015 Energy Star	2015 High	2020 Typical	2020 High	2030 Typical	2030 High	2040 Typical	2040 High
Cooling Capacity (Btu/hr)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: WICF TSD										
Size (ft^2)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: WICF TSD										
Energy Use (kWh/yr)	ADL, 1996 / PG&E, 2004 / NCI Analysis, 2008	DOE, 2014: WICF TSD / Navigant Analysis, 2015										
Energy Use (kWh/ft²/yr)	Calculated											
Indexed Annual Efficiency	Calculated											
Insulated Box Average Life (yrs)	ADL, 1996 / PG&E, 2004	DOE, 2014: WICF TSD										
Compressor Average Life (yrs)	ADL, 1996 / PG&E, 2004	DOE, 2014: WICF TSD										
Retail Equipment Cost	ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: WICF TSD / Navigant Analysis, 2015										
Total Installed Cost	ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: WICF TSD / Navigant Analysis, 2015										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	DOE, 2014: WICF TSD / Navigant Analysis, 2014											
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Output (lbs/day)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Water Use (gal/100 lbs)	ADL, 1996 / Distributor Web Sites	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Energy Use (kWh/100 lbs)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Energy Use (kWh/yr)	ACEEE, 2002 / NCI Analysis, 2012	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Average Life (yrs)	ADL, 1996/ Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Retail Equipment Cost	Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Total Installed Cost (with Bin)	NCI Analysis, 2008	DOE, 2014: ACIM TSD / Distributor Websites / Navigant Analysis, 2015										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: ACIM TSD / Navigant Analysis, 2015										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Data Sources » Commercial Beverage Merchandisers

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	DOE, 2014: CRE TSD											
Size (ft^3)	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE TSD										
Energy Use (kWh/yr)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE TSD / Navigant Analysis, 2015										
Energy Use (kWh/ft^3/yr)	Calculated											
Normalized Annual Efficiency	Calculated											
Nominal Capacity Over Average Input (Btu out / Btu in)	Calculated											
Average Life (yrs)	ACEEE, 2002	DOE, 2015: CRE TSD										
Retail Equipment Cost	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE TSD / Navigant Analysis, 2015										
Total Installed Cost	DOE, 2014: CRE TSD, Navigant Analysis											
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	DOE, 2014: CRE TSD, Navigant Analysis, 2015											
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Data Sources » Commercial Refrigerated Vending Machines

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Energy Star	High	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)	DOE, 2008 / NCI Analysis, 2008	DOE, 2015: BVM Engineering Spreadsheet										
Can Capacity	CEC, 2005 / NREL, 2003 / FEMP, 2004	DOE, 2015: BVM FR TSD / Navigant Analysis, 2015										
Size (ft^3)	DOE, 2015: BVM Engineering Spreadsheet											
Energy Use (kWh/yr)	ADL, 1996 / CEC, 2008 / NREL, 2003	DOE, 2015: BVM Engineering Spreadsheet										
Energy Use (kWh/ft^3/yr)	Calculated											
Normalized Annual Efficiency	Calculated											
Nominal Capacity Over Average Input (Btu out / Btu in)	Calculated											
Average Life (yrs)	ADL,1996	DOE, 2015: BVM FR TSD										
Retail Equipment Cost	Distributor Web Sites / NCI Analysis, 2008 / DOE, 2008	DOE, 2015: BVM Engineering Spreadsheet										
Total Installed Cost	Distributor Web Sites / NCI Analysis, 2008 / DOE, 2008	DOE, 2015: BVM FR TSD										
Total Installed Cost ($/kBtu/hr)	Calculated											
Annual Maintenance Cost	DOE, 2008	DOE, 2014: BVM FR TSD / Navigant Analysis, 2015										
Annual Maintenance Cost ($/kBtu/hr)	Calculated											

Commercial Ventilation

Commercial Constant Air Volume

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Best	Energy Star	Typical	Best	Typical	Best	Typical	Best
System Airflow (CFM)	CBECS 2003 & BED 2007											
System Fan Power (kW)	ASHRAE 90.1-2004	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Leidos								
Specific Fan Power (W/CFM)	ASHRAE 90.1-2004	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Leidos								
Annual Fan Energy Use (kWh/yr)[1]	ASHRAE 90.1-2004	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Leidos								
Average Life (yrs)	ASHRAE A37.3-2015											
Total Installed Cost ($)[2]	2016 RS Means Online											
Annual Maintenance Cost ($)	2016 RS Means Online											
Total Installed Cost ($/1000 CFM)	Calculated											
Annual Maintenance Cost ($/1000 CFM)	Calculated											

Commercial Variable Air Volume

<table>
<tr><th rowspan="2">DATA SOURCES</th><th>2003</th><th>2012</th><th colspan="4">2015</th><th colspan="2">2020</th><th colspan="2">2030</th><th colspan="2">2040</th></tr>
<tr><th>Installed Stock Average</th><th>Installed Stock Average</th><th>Low</th><th>Typical</th><th>Best</th><th>Energy Star</th><th>Typical</th><th>Best</th><th>Typical</th><th>Best</th><th>Typical</th><th>Best</th></tr>
<tr><td>System Airflow (CFM)</td><td colspan="12">CBECS 2003 & BED 2007</td></tr>
<tr><td>System Fan Power (kW)</td><td rowspan="3">ASHRAE 90.1-2004</td><td rowspan="3">ASHRAE 90.1-2007</td><td rowspan="3">ASHRAE 90.1-2010</td><td rowspan="3" colspan="9">Leidos</td></tr>
<tr><td>Specific Fan Power (W/CFM)</td></tr>
<tr><td>Annual Fan Energy Use (kWh/yr)[1]</td></tr>
<tr><td>Average Life (yrs)</td><td colspan="12">ASHRAE A37.3-2015</td></tr>
<tr><td>Total Installed Cost ($)[2]</td><td colspan="12">2016 RS Means Online</td></tr>
<tr><td>Annual Maintenance Cost ($)</td><td colspan="12">2016 RS Means Online</td></tr>
<tr><td>Total Installed Cost ($/1000 CFM)</td><td rowspan="2" colspan="12">Calculated</td></tr>
<tr><td>Annual Maintenance Cost ($/1000 CFM)</td></tr>
</table>

Commercial Fan Coil Units

DATA SOURCES	2003	2012	2015				2020		2030		2040	
	Installed Stock Average	Installed Stock Average	Low	Typical	Best	Energy Star	Typical	Best	Typical	Best	Typical	Best
System Airflow (CFM)	Product Literature											
System Fan Power (kW)	Product Literature	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Leidos								
Specific Fan Power (W/CFM)												
Annual Fan Energy Use (kWh/yr)[1]												
Average Life (yrs)	ASHRAE A37.3-2015											
Total Installed Cost ($)[2]	2016 RS Means Online											
Annual Maintenance Cost ($)	2016 RS Means Online											
Total Installed Cost ($/1000 CFM)	Calculated											
Annual Maintenance Cost ($/1000 CFM)												

Appendix B
References

Navigant Consulting, Inc.
1200 19th Street, NW, Suite 700
Washington, D.C. 20036

And

Leidos
11951 Freedom Drive
Reston, VA 20190

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