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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October 14, 2022

DISCLAIMER

October 2022

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Objective

The objective of this study is to develop baseline and projected performance and 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.

- Examine 2012 and 2018 (commercial) and 2015 and 2020 (residential) baselines, as well as this year's baseline (2022).
  - Review literature, standards, installed base, contractor, and manufacturer information.
  - Provide a relative comparison and characterization of the cost and efficiency of a generic product.
- Forecast technology improvements that are projected to be available through 2050.
  - Review trends in standards, product enhancements, and research and development (R&D).
  - Project impact of product improvements and technology enhancement.

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

Methodology

Input from industry stakeholders, 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 affect performance and cost forecasts.
- Varied sources ensure a balanced view of technology progress and the probable timing of commercial availability.

Definitions

The following tables represent the current and projected efficiencies for residential and commercial building equipment ranging from the installed base in 2012 and 2018 (for commercial products) and 2015 and 2020 (for residential) to the highest efficiency equipment that is expected to be commercially available by 2050, assuming incremental adoption. Below are definitions for the terms used in characterizing the status of each technology.

- **Installed Stock Average**: 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 U.S. Department of Energy (DOE) standards, when applicable. For lighting, if no product exists at the standard efficiency level, a hypothetical wattage and lumen output is given for the standard's efficiency level.
- **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. For lighting, if no products exist at the ENERGY STAR efficiency level, a hypothetical wattage and lumen output is given for the ENERGY STAR efficiency level.
- **Low**: The minimum efficiency product or product mix available on the market. This rating 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 (lm):** the unit for luminous flux used in the SI unit system. This unit is used to indicate a light source's light output. All reported lumens are initial lumens. 1 kilolumen (klm) = 1,000 lumens.
- **Correlated Color Temperature (CCT)**: a specification of the color appearance of the light emitted by a lamp. Note: CCT is not a performance metric.
- **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.
- **British thermal unit (Btu)**: a measure of the heat content of fuels or energy sources. It is the quantity of heat required to raise the temperature of one pound of liquid water by 1°F at the temperature that water has its greatest density (approximately 39 °F). 1 kBtu = 1,000 Btu.
- **Cubic Feet per Minute (CFM)**: a measure of airflow volume equal to the number of cubic feet of air flowing through a two-dimensional plane in one minute.
- **Not Available (N/A)**: data is not available where indicated.

Calculations

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 ($/klm)** = Lamp Cost / (Lamp Lumens / 1,000)
  - **Total Equipment Cost** = Lamp Cost + Fixture (including ballast) Cost
  - **System Cost ($/klm)** = Total Equipment Cost/ (System Lumens / 1,000). l/b/f denotes that the cost includes the luminaire, the ballast, and the fixture.
  - **Total Installed Cost** = Total Equipment Cost+ Labor Installation Cost
  - **Ballast Luminous Efficiency (BLE)** = A/(1+B*Avg Total Lamp Arc Power^(-C)) where A, B, and C are pre-defined constants by DOE Energy Conservation Standards for Fluorescent Lamp Ballasts.
- **Commercial Refrigeration**
  - **Nominal Capacity over Average Input (Btu in / Btu out)** = (Cooling or Heat Rejection Capacity)*24*365/(Annual Energy Consumption * 3,412)
  - **Total Installed Cost** = Retail Equipment Cost+ Labor Installation Cost
  - **Total Installed Cost ($/kBtu/hour)** = Total Installed Cost*1,000 / (Cooling or Heat Rejection Capacity). h used as an abbreviation for hour throughout
  - **Annual Maintenance Cost ($/kBtu/h)** = Annual Maintenance Cost* 1,000 / (Cooling or Heat Rejection Capacity)
- **Ventilation**
  - **CFM out / Btu in / h** = System Airflow / (System Fan Power* 3,412)
  - **Total Installed Cost ($/1,000 CFM)** = Total Installed Cost* 1,000 / System Airflow
  - **Annual Maintenance Cost ($/1,000 CFM)** = Annual Maintenance Cost* 1,000 / System Fan Power

Market Transformation

The market for the reviewed products has changed since this analysis was performed in 2015. These changes are noted and reflected in the efficiency and cost characteristics.

- DOE issued federal minimum efficiency standards that have gone into effect for General Service Fluorescent Lamps (2012), Incandescent Reflector Lamps (2012), and Fluorescent Lamp Ballasts (2019).

- In April 2022, DOE codified into the Code of Federal Regulations the 45 lumens per watt (lm/W) backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act (10 CFR 430, 87 FR 27439). This action also amended the definition of general service lamps to include previously exempted product classes, such as reflector lamps. The rule will go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023.

- DOE published a Final Rule updating energy conservation standards for Refrigerated Beverage Vending Machines at the end of 2015, effective in 2018. DOE also issued federal minimum efficiency standards that have or will soon go into effect for Refrigerated Beverage Vending Machines (2012), Automatic Commercial Ice Makers (2018), Walk-In Coolers and Freezers (2017), and Commercial Refrigeration Equipment (2017).

Residential Lighting

Note: More R&D investment and effort in the lighting industry only changes projections of LED technologies because additional funding and effort will likely not 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 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 (E26) A-type incandescent lamp and their halogen, CFL, and LED equivalents. A standard 60-watt incandescent lamp produces approximately 800 – 850 lumens. A standard 75-watt incandescent lamp produces approximately 1,100 lumens.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2,700K and give off a warm, yellowish white color, but products with CCTs of 3,000K, 3,500K, 4,100K (neutral white), 5,000K (daylight), and 6,500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2,700K. 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. However, 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. High CRI products are 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 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 2022 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 because homeowners 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.
- Disposal costs are not characterized for residential lighting in this analysis. In residential cases, disposal is done by the occupant. Lamp and product burnout are assumed to result in no "added" cost aside from the work performed to install the replacement.

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 be by halogen, CFL, and LED technologies.
- In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. This action also amended the definition of general service lamps to include previously exempted product classes, such as reflector lamps. These standards can not be achieved by traditional incandescent or halogen technologies currently on the market, and given current and projected trends in industry, they will likely not be met. It is currently assumed that industry will increase its investment in LED technology at the expense of incandescent, halogen, and CFL technologies. The rule will go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023.

ENERGY STAR:

- For ENERGY STAR qualification, general service omnidirectional lamps must have a minimum lamp efficacy of 70 lm/W for products with CRI ≥ 90 and 80 lm/W for lamps with CRI < 90. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2,700, 3,000, 3,500, 4,000/4,100, 5,000, or 6,000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume manufacturers will focus 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, halogen, and fluorescent) and established market competitors (Navigant, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
Halogen	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements as of 2022.
CFL	+0.5%	0%	-0.5%	Improvements in efficacy can be made by using more rare-earth phosphors in compact fluorescent lamps.

Performance and Cost Characteristics » Residential General Service LED Lamps (60 W Incandescent Equivalent)

Higher efficacy compared with Reference Case

DATA	2015	2020	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[1]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	8.7	9.2	10.0	8.9	8.0	13.8	17.8	5.7	5.1	4.4	4.0	3.8	3.4
Lamp Lumens	656	803	800	800	800	800	800	800	800	800	800	800	800
Lamp Efficacy (lm/W)	75.5	87.1	80.0	90.0	100.0	80.0	45.0	141.5	157.2	180.2	200.2	209.0	232.1
CRI	81	85	80	81	90	80	N/A	81	90	81	90	81	90
Correlated Color Temperature (CCT)	2,700	2,700	2,700	2,700	2,700	2,700	N/A	2,700	2,700	2,700	2,700	2,700	2,700
Average Lamp Life (thousand hours)	25	21	15	14	18	15	N/A	14	18	14	18	14	18
Annual Operating Hours (h/y)	657	657	657	657	657	657	N/A	657	657	657	657	657	657
Lamp Price (2022$)	$13.53	$4.56	$6.20	$3.92	$5.32	$6.20	N/A	$3.23	$4.39	$2.84	$3.86	$2.46	$3.33
Lamp Cost (2022$/klm)	$20.63	$5.68	$7.75	$4.90	$6.65	$7.75	N/A	$7.02	$7.02	$3.57	$3.57	$2.38	$2.38
Labor Cost (2022$/h)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hours)	0.0	0.0	0.0	0.0	0.0	0.0	N/A	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$13.53	$4.56	$6.20	$3.92	$5.32	$6.20	N/A	$3.23	$4.39	$2.84	$3.86	$2.46	$3.33
Annual Maintenance Cost (2022$)	$0.35	$0.15	$0.27	$0.18	$0.19	$0.27	N/A	$0.15	$0.16	$0.13	$0.14	$0.11	$0.12
Total Installed Cost (2022$/klm)	$20.63	$5.68	$7.75	$4.90	$6.65	$7.75	N/A	$4.04	$5.49	$3.56	$4.83	$3.07	$4.17
Annual Maintenance Cost (2022$/klm)	$0.54	$0.18	$0.34	$0.22	$0.24	$0.34	N/A	$0.18	$0.20	$0.16	$0.17	$0.14	$0.15

1. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.

Performance and Cost Characteristics » Residential General Service Filament- LED Lamps (60 W Incandescent Equivalent)

Higher efficacy compared with Reference Case

DATA	2015	2020	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[1]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	9.7	7.1	5.5	6.9	8.0	13.8	17.8	5.4	5.1	4.2	4.0	3.6	3.4
Lamp Lumens	457	650	450	650	800	800	800	800	800	800	800	800	800
Lamp Efficacy (lm/W)	47.1	91.7	81.8	94.8	100.0	80.0	45.0	149.0	157.2	189.8	200.2	220.0	232.1
CRI	82	84	90	84	80	80	N/A	81	90	81	90	81	90
Correlated Color Temperature (CCT)	2,700	2,700	2,700	2,700	2,700	2,700	N/A	2,700	2,700	2,700	2,700	2,700	2,700
Average Lamp Life (thousand hours)	23	21	15	15	15	15	N/A	15	15	15	15	15	15
Annual Operating Hours (h/y)	657	657	657	657	657	N/A	N/A	657	657	657	657	657	657
Lamp Price (2022$)	$15.17	$6.88	$6.25	$5.91	$7.75	N/A	N/A	$4.87	$6.39	$4.29	$5.62	$3.70	$4.86
Lamp Cost (2022$/klm)	$33.20	$10.58	$13.89	$9.09	$9.69	N/A	N/A	$7.02	$7.02	$3.57	$3.57	$2.38	$2.38
Labor Cost (2022$/h)	$0.00	$0.00	$0.00	$0.00	$0.00	N/A	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hours)	0.0	0.0	0.0	0.0	0.0	N/A	N/A	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$15.17	$6.88	$6.25	$5.91	$7.75	N/A	N/A	$4.87	$6.39	$4.29	$5.62	$3.70	$4.86
Annual Maintenance Cost (2022$)	$0.43	$0.21	$0.27	$0.26	$0.34	N/A	N/A	$0.21	$0.28	$0.19	$0.25	$0.16	$0.21
Total Installed Cost (2022$/klm)	$33.20	$10.58	$13.89	$9.09	$9.69	N/A	N/A	$6.09	$7.99	$5.36	$7.03	$4.63	$6.07
Annual Maintenance Cost (2022$/klm)	$0.93	$0.33	$0.61	$0.40	$0.42	N/A	N/A	$0.27	$0.35	$0.23	$0.31	$0.20	$0.27

1. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.

Performance and Cost Characteristics » Residential Reflector Lamps

The residential reflector lamps characterized in this report are directional lamps that emit approximately 550 – 850 lumens (except for LED PAR38s which have outputs up to 1,700 lumens). Multiple baseline reflector lamps were analyzed, including 65W Incandescent BR30, Halogen PAR30, Halogen Infrared Reflector (HIR) PAR30, CFL BR30, LED BR30, and LED PAR38.

Performance:

- A majority of residential lamps have a nominal CCT rating of 2,700K and give off a warm, yellowish white color, but products with CCTs of 3,000K, 3,500K, 4,100K (neutral white), 5,000K (daylight), and 6,500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2,700K. 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.
- Fixture prices and installation costs are not included for the residential sector. Labor costs are assumed to be negligible because homeowners 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.
- Disposal costs are not characterized for residential lighting in this analysis. In residential cases, disposal is done by the occupant. Lamp and product burnout are assumed to result in no "added" cost aside from the work performed to install the replacement.

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, was still exempted until 2022.
- In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. **This action also amended the definition of general service lamps to include previously exempted product classes, such as reflector lamps.** These standards can not be achieved by traditional incandescent or halogen technologies currently on the market, and given current and projected trends in industry, they will likely not be met. It is currently assumed that industry will increase its investment in LED technology at the expense of incandescent, halogen, and CFL technologies. The rule will go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023.

ENERGY STAR:

- For ENERGY STAR qualification, general service, reflector lamps must have a minimum lamp efficacy of 61 lm/W for products with CRI ≥ 90 and 70 lm/W for lamps with CRI < 90, respectively. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2,700, 3,000, 3,500, 4,000/4,100, 5,000, or 6,000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume manufacturers will focus 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
Halogen	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements as of 2022.
CFL	+0.5%	0%	-0.5%	In addition to 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 and Cost Characteristics » Residential Reflector LED BR30

Higher efficacy compared with Reference Case

DATA	2015	2020	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[1]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	14.2	10.9	11.0	8.8	7.2	10.7	14.4	5.5	4.7	4.8	4.1	4.2	3.7
Lamp Lumens	706	781	800	683	650	650	650	650	650	650	650	650	650
Lamp Efficacy (lm/W)	49.8	71.5	72.7	78.6	90.3	61.0	45.0	119.2	137.0	136.3	156.7	153.4	176.3
CRI	82	85	92	87	90	80	N/A	87	90	87	90	87	90
Correlated Color Temperature (CCT)	2,700	2,700	2,700	2,700	2,700	2,700	N/A	2,700	2,700	2,700	2,700	2,700	2,700
Average Lamp Life (thousand hours)	25	25	25	19	18	15	N/A	19	18	19	18	19	18
Annual Operating Hours (h/y)	730	730	730	730	730	N/A	N/A	730	730	730	730	730	730
Lamp Price (2022$)	$21.40	$15.36	$4.09	$5.01	$5.96	N/A	N/A	$4.11	$4.89	$3.62	$4.31	$3.14	$3.74
Lamp Cost (2022$/klm)	$30.31	$19.66	$5.11	$7.33	$9.17	N/A	N/A	$6.32	$7.53	$5.57	$6.64	$4.83	$5.75
Labor Cost (2022$/h)	$0.00	$0.00	$0.00	$0.00	$0.00	N/A	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hours)	0.0	0.0	0.0	0.0	0.0	N/A	N/A	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$21.40	$15.36	$4.09	$5.01	$5.96	N/A	N/A	$4.11	$4.89	$3.62	$4.31	$3.14	$3.74
Annual Maintenance Cost (2022$)	$0.63	$0.45	$0.12	$0.20	$0.24	N/A	N/A	$0.16	$0.19	$0.14	$0.17	$0.12	$0.15
Total Installed Cost (2022$/klm)	$30.31	$19.66	$5.11	$7.33	$9.17	N/A	N/A	$6.32	$7.53	$5.57	$6.64	$4.83	$5.75
Annual Maintenance Cost (2022$/klm)	$0.89	$0.57	$0.15	$0.29	$0.37	N/A	N/A	$0.25	$0.30	$0.22	$0.26	$0.19	$0.23

1. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.

Higher efficacy compared with Reference Case

DATA	2015	2020	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[1]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	19.2	15.5	17.0	16.4	17.0	10.7	29.9	10.8	11.2	9.4	9.8	8.4	8.7
Lamp Lumens	1,202	1,211	1,200	1,344	1,700	650	1,344	1,344	1,700	1,344	1,700	1,344	1,700
Lamp Efficacy (lm/W)	62.7	77.9	70.6	82.0	100.0	61.0	45.0	124.5	151.7	142.4	173.6	160.2	195.3
CRI	83	86	82	86	82	80	N/A	86	86	86	86	86	86
Correlated Color Temperature (CCT)	3,000	3,000	2,700	3,000	3,000	2,700	N/A	3,000	3,000	3,000	3,000	3,000	3,000
Average Lamp Life (thousand hours)	24	27	25	27	25	15	N/A	27	25	27	25	27	25
Annual Operating Hours (h/y)	730	730	730	730	730	N/A	N/A	730	730	730	730	730	730
Lamp Price (2022$)	$35.23	$22.44	$23.71	$23.09	$15.69	N/A	N/A	$19.40	$13.18	$17.36	$11.79	$15.37	$10.45
Lamp Cost (2022$/klm)	$29.31	$18.54	$19.76	$17.18	$9.23	N/A	N/A	$14.43	$7.75	$12.91	$6.94	$11.44	$6.14
Labor Cost (2022$/h)	$0.00	$0.00	$0.00	$0.00	$0.00	N/A	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hours)	0.0	0.0	0.0	0.0	0.0	N/A	N/A	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$35.23	$22.44	$23.71	$23.09	$15.69	N/A	N/A	$19.40	$13.18	$17.36	$11.79	$15.37	$10.45
Annual Maintenance Cost (2022$)	$1.07	$0.60	$0.69	$0.62	$0.46	N/A	N/A	$0.52	$0.38	$0.46	$0.34	$0.41	$0.31
Total Installed Cost (2022$/klm)	$29.31	$18.54	$19.76	$17.18	$9.23	N/A	N/A	$14.43	$7.75	$12.91	$6.94	$11.44	$6.14
Annual Maintenance Cost (2022$/klm)	$0.89	$0.49	$0.58	$0.46	$0.27	N/A	N/A	$0.39	$0.23	$0.35	$0.20	$0.31	$0.18

1. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress presed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023, and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.

This section characterizes commercial linear fixtures that house two 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 narrowness 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 can fit directly into an existing fixture and fully integrated luminaires that can be used to replace existing fixtures. LED replacement lamps are also known as TLEDs. Type A TLEDs can be installed with existing ballasts and Type B and C TLEDs require the ballast to be disconnected. 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 and fixture efficiency losses associated with ballasts and fixture optics.

Performance:

- Residential linear lamps often have a nominal CCT rating of 3500K, but products with CCTs of 3000K, 4000K, and 4100K (neutral white) are also common. 5000K (daylight) lamps are available as well. When replacing a light bulb, it is important to choose a product with a similar CCT value to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but 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 2022 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 because homeowners likely replace 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 for residential linear systems.
- Disposal costs are not characterized for residential lighting in this analysis. In residential cases, disposal is done by the occupant. Lamp and product burnout are assumed to result in no "added" cost aside from the work performed to install the replacement.

Legislation:

- Beginning July 14, 2012 (or July 14, 2014, for T8 700-series phosphor lamps), DOE fluorescent lamp standards required a minimum efficacy of 89 lm/W. Although 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 required that the characterized residential ballasts have a minimum BLE= 0.993 / (1 + 0.41 * Avg Total Lamp Arcpower ^ (- 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:

- ENERGY STAR does not cover linear lamps. (ENERGY STAR, 2020)

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume that manufacturers will focus 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050:

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

Higher efficacy compared with Reference Case

DATA	2015	2020	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	18.5	16.3	16.0	13.7	11.0	8.9	7.2	7.7	7.2	7.7	7.2
Lamp Lumens	2,013	2,130	1,800	1,920	1,800	1,920	1,800	1,920	1,800	1,920	1,800
Lamp Efficacy (lm/W)	111.0	130.7	112.5	140.1	163.6	216.1	250.0	250.0	250.0	250.0	250.0
System Wattage	36.9	32.6	32.0	27.4	22.0	17.8	14.4	15.4	14.4	15.4	14.4
System Lumens	3,583	4,004	3,456	3,686	3,456	3,686	3,456	3,686	3,456	3,686	3,456
System Efficacy (lm/W)	97.0	122.8	108.0	134.5	157.1	207.4	240.0	240.0	240.0	240.0	240.0
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	83	81	82	81	80	81	80	81	80	81	80
Correlated Color Temperature (CCT)	4,100	3,500	4,100	4,100	5,000	4,100	5,000	4,100	5,000	4,100	5,000
Average Lamp Life (thousand hours)	55	50	50	54	50	54	50	54	50	54	50
Annual Operating Hours (h/y)	584	584	584	584	584	584	584	584	584	584	584
Lamp Price (2022$)	$27.00	$12.89	$14.63	$11.11	$4.28	$9.97	$3.84	$9.87	$3.80	$9.77	$3.77
Ballast Price (2022$)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)	$13.41	$6.05	$8.13	$5.79	$2.38	$5.19	$2.13	$5.14	$2.11	$5.09	$2.09
System (l/b/f) Cost (2022$/klm)	$15.07	$6.44	$8.47	$6.03	$2.48	$5.41	$2.22	$5.35	$2.20	$5.30	$2.18
Labor Cost (2022$/h)[2]	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor System Installation (hours)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Lamp Change (hours)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$54.00	$25.78	$29.26	$22.22	$8.56	$19.95	$7.68	$19.74	$7.60	$19.55	$7.53
Annual Maintenance Cost (2022$)	$0.57	$0.30	$0.34	$0.24	$0.10	$0.22	$0.09	$0.21	$0.09	$0.21	$0.09
Total Installed Cost (2022$/klm)	$15.07	$6.44	$8.47	$6.03	$2.48	$5.41	$2.22	$5.35	$2.20	$5.30	$2.18
Annual Maintenance Cost (2022$/klm)	$0.16	$0.08	$0.10	$0.07	$0.03	$0.06	$0.03	$0.06	$0.03	$0.06	$0.03

1. N/A because a fixture and an LED replacement lamp would not be purchased separately for a new installation or retrofit when there are integrated LED luminaires that are more efficient and cost effective. These lamps are sold only as replacements to go into existing fixtures.

Assume no labor is associated with lamp replacement in the residential sector because residents likely replace the lamps themselves.

Performance and Cost Characteristics » Residential Linear LED Luminaire

Higher efficacy compared with Reference Case

DATA	2015	2020	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	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
Lamp Lumens	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
System Wattage	50.0	43.1	49.0	44.0	35.0	27.4	21.8	23.0	19.2	21.2	19.2
System Lumens	4,615	4,945	5,024	5,302	4,800	5,302	4,800	5,302	4,800	5,302	4,800
System Efficacy (lm/W)	92.3	114.7	102.5	120.5	137.1	193.4	220.1	230.4	250.0	250.0	250.0
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	83	82	80	79	80	79	80	79	80	79	80
Correlated Color Temperature (CCT)	3,838	3,000	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Average Lamp Life (thousand hours)	56	58	54	53	50	53	50	53	50	53	50
Annual Operating Hours (h/y)	730	730	730	730	730	730	730	730	730	730	730
Lamp or Luminaire Price (2022$)	$181.60	$158.60	$144.85	$152.54	$207.80	$121.11	$164.98	$105.34	$143.50	$90.11	$122.76
Ballast Price (2022$)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)[1]	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 (2022$/klm)	$78.70	$64.15	$57.66	$57.54	$86.58	$45.68	$68.74	$39.74	$59.79	$33.99	$51.15
Labor Cost (2022$/h)	$80.90	$80.90	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Labor Lamp Change (hours)*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost (2022$)	$403.65	$357.65	$322.70	$338.08	$448.60	$275.22	$362.97	$243.68	$320.01	$213.23	$278.52
Annual Maintenance Cost (2022$)	$2.89	$2.49	$2.40	$2.56	$3.52	$2.12	$2.89	$1.91	$2.58	$1.70	$2.27
Total Installed Cost (2022$/klm)	$87.46	$72.33	$64.23	$63.76	$93.46	$51.91	$75.62	$45.96	$66.67	$40.22	$58.03
Annual Maintenance Cost (2022$/klm)	$0.63	$0.50	$0.48	$0.48	$0.73	$0.40	$0.60	$0.36	$0.54	$0.32	$0.47

1. N/A because the lamp and fixture are both included in the luminaire.

- 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 1,000 – 1,400 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	

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. This product is, as of 2022, expected to be eliminated by DOE’s 45 lm/W backstop requirement.
- A majority of residential lamps have a nominal CCT rating of 2,700K and give off a warm, yellowish white color, but products with CCTs of 3,000K, 3,500K, 4,100K (neutral white), 5,000K (daylight), and 6,500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2,700K. 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. However, 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. High CRI products are 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 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 because homeowners 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 for residential reflector lamps.
- Disposal costs are not characterized for residential lighting in this analysis. In residential cases, disposal is done by the occupant. Lamp and product burnout are assumed to result in no "added" cost aside from the work performed to install the replacement.

Legislation:

- In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. **This action also amended the definition of general service lamps to include previously exempted product classes, such as reflector lamps.** These standards can not be achieved by traditional incandescent or halogen technologies currently on the market, and given current and projected trends in industry, they will likely not be met. It is currently assumed that industry will increase its investment in LED technology at the expense of incandescent, halogen, and CFL technologies. The rule will go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023.

ENERGY STAR:

- For ENERGY STAR qualification, general service omnidirectional lamps must have a minimum lamp efficacy of 70 lm/W for products with CRI ≥ 90 and 80 lm/W for lamps with CRI < 90.
- For ENERGY STAR qualification, general service reflector lamps must have a minimum lamp efficacy of 61 lm/W for products with CRI ≥ 90 and 70 lm/W for lamps with CRI < 90.
- Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2,700, 3,000, 3,500, 4,000/4,100, 5,000, or 6,000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume manufacturers will focus 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent Omnidirectional	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
Incandescent Directional	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
Halogen	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
CFL	+0.5%	0%	-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 and Cost Characteristics » Residential Outdoor Lamps (Security: LED Reflector)

Higher efficacy compared with Reference Case

DATA	2015	2020	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[1]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	19.2	15.5	17.0	16.4	17.0	10.7	29.9	10.8	11.2	9.4	9.8	8.4	8.7
Lamp Lumens	1,202	1,211	1,200	1,344	1,700	650	1,344	1,344	1,700	1,344	1,700	1,344	1,700
Lamp Efficacy (lm/W)	62.7	77.9	70.6	82.0	100.0	61.0	45.0	124.5	151.7	142.4	173.6	160.2	195.3
CRI	83	86	82	86	82	80	N/A	86	86	86	86	86	86
Correlated Color Temperature (CCT)	3,000	3,000	2,700	3,000	3,000	2,700	N/A	3,000	3,000	3,000	3,000	3,000	3,000
Average Lamp Life (thousand hours)	24	27	25	27	25	15	N/A	27	25	27	25	27	25
Annual Operating Hours (h/y)	730	730	730	730	730	N/A	N/A	730	730	730	730	730	730
Lamp Price (2022$)	$35.23	$22.44	$23.71	$23.09	$15.69	N/A	N/A	$19.40	$13.18	$17.36	$11.79	$15.37	$10.45
Lamp Cost (2022$/klm)	$29.31	$18.54	$19.76	$17.18	$9.23	N/A	N/A	$14.43	$7.75	$12.91	$6.94	$11.44	$6.14
Labor Cost (2022$/h)	$0.00	$0.00	$0.00	$0.00	$0.00	N/A	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hours)	0.0	0.0	0.0	0.0	0.0	N/A	N/A	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$35.23	$22.44	$23.71	$23.09	$15.69	N/A	N/A	$19.40	$13.18	$17.36	$11.79	$15.37	$10.45
Annual Maintenance Cost (2022$)	$1.07	$0.60	$0.69	$0.62	$0.46	N/A	N/A	$0.52	$0.38	$0.46	$0.34	$0.41	$0.31
Total Installed Cost (2022$/klm)	$29.31	$18.54	$19.76	$17.18	$9.23	N/A	N/A	$14.43	$7.75	$12.91	$6.94	$11.44	$6.14
Annual Maintenance Cost (2022$/klm)	$0.89	$0.49	$0.58	$0.46	$0.27	N/A	N/A	$0.39	$0.23	$0.35	$0.20	$0.31	$0.18

1. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress presed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.

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

Higher efficacy compared with Reference Case

DATA	2015	2020	2022				2023[1]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	12.9	11.8	13.5	11.9	11.0	13.6	24.4	7.6	7.0	6.0	5.5	5.1	4.7
Lamp Lumens	1,073	1,102	1,100	1,089	1,100	1,089	1,100	1,100	1,100	1,100	1,100	1,100	1,100
Lamp Efficacy (lm/W)	83.1	93.5	81.5	92.2	100.0	80	45.0	144.9	157.2	184.6	200.2	214.0	232.1
CRI	81	85	80	86	80	80	N/A	86	80	86	80	86	80
Correlated Color Temperature (CCT)	2,700	2,700	3,000	2,700	2,700	2,700	N/A	2,700	2,700	2,700	2,700	2,700	2,700
Average Lamp Life (thousand hours)	25	21	25	18	25	N/A	N/A	18	25	18	25	18	25
Annual Operating Hours (h/y)	657	657	657	657	657	N/A	N/A	657	657	657	657	657	657
Lamp Price (2022$)	$18.13	$8.48	$4.39	$3.92	$5.29	N/A	N/A	$3.23	$4.36	$2.84	$3.84	$2.46	$3.31
Lamp Cost (2022$/klm)	$16.90	$7.70	$3.99	$3.60	$4.81	N/A	N/A	$7.02	$7.02	$3.57	$3.57	$2.38	$2.38
Labor Cost (2022$/h)	$0.00	$0.00	$0.00	$0.00	$0.00	N/A	N/A	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor Lamp Installation (hours)	0.0	0.0	0.0	0.0	0.0	N/A	N/A	0.0	0.0	0.0	0.0	0.0	0.0
Total Installed Cost (2022$)	$18.13	$8.48	$4.39	$3.92	$5.29	N/A	N/A	$3.23	$4.36	$2.84	$3.84	$2.46	$3.31
Annual Maintenance Cost (2022$)	$0.49	$0.27	$0.12	$0.14	$0.14	N/A	N/A	$0.12	$0.11	$0.10	$0.10	$0.09	$0.09
Total Installed Cost (2022$/klm)	$16.90	$7.70	$3.99	$3.60	$4.81	N/A	N/A	$2.94	$3.97	$2.59	$3.49	$2.23	$3.01
Annual Maintenance Cost (2022$/klm)	$0.45	$0.24	$0.10	$0.13	$0.13	N/A	N/A	$0.11	$0.10	$0.09	$0.09	$0.08	$0.08

1. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress presed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.

Commercial Lighting

Note: More R&D investment and effort in the lighting industry will only change future projections of LED technologies because additional funding and effort will likely not 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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This section characterizes commercial omnidirectional incandescent, halogen, CFL, and LED screw-based general service lamps emitting approximately 1,600 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 because 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 general service lamps have a nominal CCT rating of 2,700K and give off a warm, yellowish white color, but products with CCTs of 3,000K, 3,500K, 4,100K (neutral white), 5,000K (daylight), and 6,500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2,700K. 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. However, 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. High CRI products are 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 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 for commercial general service lamps (DOE SSL Program, 2012a).
- Commercial lighting disposal costs are estimated to be $0.12 per linear foot of fluorescent lamps, $1.50 per lamp for high intensity discharge (HID) lamps, and $0.50 for CFLs (EPA, 2022).

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 they can be met by halogen, CFL, and LED technologies from 2012 to 2023.
- In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. This action also amended the definition of general service lamps to include previously exempted product classes, such as reflector lamps. These standards can not be achieved by traditional incandescent or halogen technologies currently on the market, and given current and projected trends in industry, they will likely not be met. It is currently assumed that industry will increase its investment in LED technology at the expense of incandescent, halogen, and CFL technologies. The rule will go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023.

ENERGY STAR:

- For ENERGY STAR qualification, general service omnidirectional lamps must have a minimum lamp efficacy of 70 lm/W for products with CRI ≥ 90 and 80 lm/W for lamps with CRI < 90. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2,700, 3,000, 3,500, 4,000/4,100, 5,000, or 6,000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume manufacturers will 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
Halogen	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements as of 2022
CFL	+0.5%	0%	-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 and Cost Characteristics » Commercial General Service 100W Equivalent LED Replacement Lamp in Recessed Can Fixture

Higher efficacy compared with Reference Case

DATA	2012	2018	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[1]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	26.7	14.5	16.0	14.8	13.0	20.0	34.8	9.4	8.3	7.4	6.5	6.4	6.4
Lamp Lumens	1,600	1,528	1,600	1,567	1,600	1,600	1,567	1,567	1,600	1,567	1,600	1,567	1,600
Lamp Efficacy (lm/W)	60.0	105.1	100.0	106.0	123.1	80.0	45.0	166.7	193.5	212.2	246.4	246.1	250.0
System Wattage	26.7	14.5	16.0	14.8	13.0	20.0	34.8	9.4	8.3	7.4	6.5	6.4	6.4
System Lumens[3]	976	932	976	956	976	976	956	956	976	956	976	956	976
System Efficacy (lm/W)	36.6	64.1	61.0	64.7	75.1	48.8	27.5	101.7	118.0	129.5	150.3	150.1	152.5
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	N/A
CRI	80	80	90	84.8	84	80	N/A	84.8	84.8	84.8	84.8	84.8	84.8
Correlated Color Temperature (CCT)	3,000	3,000	2,700	2,700	5,000	N/A	N/A	2,700	2,700	2,700	2,700	2,700	2,700
Average Lamp Life (thousand hours)	22.0	17.9	25.0	16.9	25.0	15.0	N/A	16.9	25.0	16.9	25.0	16.9	25.0
Annual Operating Hours (h/y)	4,928	4,928	4,928	4,928	4,928	N/A	N/A	4,928	4,928	4,928	4,928	4,928	4,928
Lamp Price (2022$)	$47.45	$11.28	$5.62	$7.04	$3.39	N/A	N/A	$5.81	$2.80	$5.11	$2.46	$4.41	$2.12
Ballast Price (2022$)	N/A	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 (2022$)	$23.72	$26.38	$22.07	$22.07	$22.07	N/A	N/A	$21.20	$21.20	$20.17	$20.17	$19.18	$19.18
Lamp Cost (2022$/klm)	$25.00	$7.38	$3.51	$4.49	$2.12	N/A	N/A	$3.71	$1.75	$3.26	$1.54	$2.82	$1.33
System (l/b/f) Cost (2022$/klm)	$72.92	$40.40	$28.37	$30.46	$26.09	N/A	N/A	$28.26	$24.59	$26.45	$23.18	$24.68	$21.83
Labor Cost (2022$/h)	$77.22	$77.22	$66.00	$66.00	$66.00	N/A	N/A	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	1.0	1.0	1.0	1.0	1.0	N/A	N/A	1.0	1.0	1.0	1.0	1.0	1.0
Labor Lamp Change (hours)	0.05	0.05	0.05	0.05	0.05	N/A	N/A	0.05	0.05	0.05	0.05	0.05	0.05
Total Installed Cost (2022$)	$148.39	$114.88	$93.69	$95.11	$91.46	N/A	N/A	$93.01	$90.00	$91.27	$88.63	$89.59	$87.30
Annual Maintenance Cost (2022$)	$11.49	$4.16	$1.76	$3.02	$1.32	N/A	N/A	$2.66	$1.20	$2.45	$1.14	$2.25	$1.07
Total Installed Cost (2022$/klm)	$152.04	$123.25	$95.99	$99.52	$93.71	N/A	N/A	$97.32	$92.21	$95.51	$90.81	$93.75	$89.45
Annual Maintenance Cost (2022$/klm)	$11.77	$4.46	$1.80	$3.16	$1.35	N/A	N/A	$2.78	$1.23	$2.57	$1.16	$2.35	$1.10

1. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress presed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. All LED lighting products exceed the new minimum efficacy standards.
3. Based on a fixture efficiency of 61% for an omnidirectional lamp installed in a recessed can fixture.

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

- 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 design 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 reflector lamps have a nominal CCT rating of 2,700K and give off a warm, yellowish white color, but products with CCTs of 3,000K, 3,500K, 4,100K (neutral white), 5,000K (daylight), and 6,500K (blueish white) are also available. Traditional incandescent light bulbs have a nominal CCT of about 2,700K. 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. However, 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. High CRI products are 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 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. Many factors influence the price of LED lamps including CRI, lifetime, dimming capabilities, and efficacy.
- 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 for commercial reflector lamps (DOE SSL Program, 2012a).
- Commercial lighting disposal costs are estimated to be $0.12 per linear foot of fluorescent lamps, $1.50 per lamp for HID lamps, and $0.50 for CFLs (EPA, 2022).

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 that determined that amending the standards for incandescent reflector lamps could not be economically justified.
- In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress prescribed in the Energy Policy and Conservation Act. **This action also amended the definition of general service lamps to include previously exempted product classes, such as reflector lamps.** These standards can not be achieved by traditional incandescent or halogen technologies currently on the market, and given current and projected trends in industry, they will likely not be met. It is currently assumed that industry will increase its investment in LED technology at the expense of incandescent, halogen, and CFL technologies. The rule will go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023.

ENERGY STAR:

- For ENERGY STAR qualification, general service reflector lamps must have a minimum lamp efficacy of 61 lm/W for products with CRI ≥ 90 and 70 lm/W for lamps with CRI < 90. Additionally, the lamps must have a CRI ≥ 80, nominal CCT of 2,700, 3,000, 3,500, 4,000/4,100, 5,000, or 6,000 K, and rated lifetime ≥ 10,000 hours (ENERGY STAR).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume manufacturers will 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

Technology	Efficacy	Lifetime	Price	Potential for Improvements
Incandescent	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements.
Halogen	0%	0%	-0.5%	Limited because the technology is mature and the technology cannot meet legislative requirements as of 2022
CFL	+0.5%	0%	-0.5%	In addition to 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.

Higher efficacy compared with Reference Case

DATA	2012	2018	2022				2023[2]	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[3]	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	17.2	16.6	17.0	16.4	17.0	22.0	29.9	14.0	11.2	9.4	9.8	8.4	8.7
Lamp Lumens	1,045	1,210	1,200	1,344	1,700	1,344	1,344	1,344	1,700	1,344	1,700	1,344	1,700
Lamp Efficacy (lm/W)	60.9	73.0	70.6	82.0	100.0	61.0	45.0	95.7	151.7	142.4	173.6	160.2	195.3
System Wattage	17.2	16.6	17.0	16.4	17.0	22.0	29.9	14.0	11.2	9.4	9.8	8.4	8.7
System Lumens[1]	972	1,125	1,116	1,250	1,581	1,250	1,250	1,250	1,581	1,250	1,581	1,250	1,581
System Efficacy (lm/W)	56.6	67.9	65.6	76.1	93.0	56.7	41.9	89.0	141.1	132.4	161.4	149.0	181.6
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	N/A
CRI	83	83	82	86	82	80	N/A	86	82	86	82	86	82
Correlated Color Temperature (CCT)	3,000	3,000	2,700	3,000	3,000	3,000	N/A	3,000	3,000	3,000	3,000	3,000	3,000
Average Lamp Life (thousand hours)	22	15	25	28	25	25	N/A	28	25	28	25	28	25
Annual Operating Hours (h/y)	4,928	4,928	4,928	4,928	4,928	N/A	N/A	4,928	4,928	4,928	4,928	4,928	4,928
Lamp Price (2022$)	$61.98	$28.10	$23.71	$23.09	$15.69	N/A	N/A	$19.40	$13.18	$17.36	$11.79	$15.37	$10.45
Ballast Price (2022$)	N/A	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 (2022$)	$23.72	$26.38	$22.07	$22.07	$22.07	N/A	N/A	$21.20	$21.20	$20.17	$20.17	$19.18	$19.18
Lamp Cost (2022$/klm)	$59.31	$23.23	$19.76	$17.18	$9.23	N/A	N/A	$14.43	$7.75	$12.91	$6.94	$11.44	$6.14
System (l/b/f) Cost (2022$/klm)	$88.18	$48.42	$41.02	$36.13	$23.88	N/A	N/A	$32.48	$21.75	$30.02	$20.22	$27.64	$18.74
Labor Cost (2022$/h)	$77.22	$77.22	$66.00	$66.00	$66.00	N/A	N/A	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	1.0	1.0	1.0	1.0	1.0	N/A	N/A	1.0	1.0	1.0	1.0	1.0	1.0
Labor Lamp Change (hours)	0.05	0.05	0.05	0.05	0.05	N/A	N/A	0.05	0.05	0.05	0.05	0.05	0.05
Total Installed Cost (2022$)	$162.93	$131.71	$111.78	$111.16	$103.76	N/A	N/A	$106.60	$100.38	$103.52	$97.96	$100.55	$95.63
Annual Maintenance Cost (2022$)	$14.75	$10.50	$5.32	$4.64	$3.74	N/A	N/A	$3.99	$3.25	$3.64	$2.98	$3.29	$2.71
Total Installed Cost (2022$/klm)	$167.64	$117.04	$100.16	$88.92	$65.63	N/A	N/A	$85.28	$63.49	$82.81	$61.96	$80.44	$60.48
Annual Maintenance Cost (2022$/klm)	$15.17	$9.33	$4.77	$3.72	$2.37	N/A	N/A	$3.20	$2.05	$2.91	$1.88	$2.63	$1.71

1. Based on a fixture efficiency of 93% for an omnidirectional lamp installed in a recessed can fixture.
2. In April 2022, DOE codified into the Code of Federal Regulations the 45 lm/W backstop requirement for general service lamps that Congress presed in the Energy Policy and Conservation Act. The new minimum efficacy requirements go into effect for manufacture and import in January 2023 and for retail and distribution in July 2023. This Final Rule also amended the definition of GSLs to include previously exempted product classes, including reflector lamps. All LED lighting products exceed the new minimum efficacy standards.
3. Criteria outlined in ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs): Eligibility Criteria Version 2.1 (Published June, 2017, Revised June 2020)

This section characterizes commercial linear fixtures that house two 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 narrowness 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 can fit directly into an existing fixture and fully integrated luminaires that can be used to replace existing fixtures. LED replacement lamps are also known as TLEDs. Type A TLEDs can be installed with existing ballasts and Type B and C TLEDs require the ballast to be disconnected. 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 and 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:

- Linear lamps often have a nominal CCT rating of 3,500K, but products with CCTs of 3,000K, 4,000K, and 4,100K (neutral white) are also common. 5,000K (daylight) lamps are available as well. When replacing a light bulb, it is important to choose a product with a similar CCT value to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but 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 two lamps, ballast (if applicable), and fixture plus the cost for labor associated with the installation, except for in the case of LED replacement lamp, 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 2022, 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 per year for commercial 4ft linear systems (DOE SSL Program, 2012a).
- Commercial lighting disposal costs are estimated to be $0.12 per linear foot of fluorescent lamps, $1.50 per lamp for HID lamps, and $0.50 for CFLs (EPA, 2022).

Legislation:

- Beginning July 14, 2012 (or July 14, 2014, for T8 700-series phosphor lamps), DOE fluorescent lamp standards required a minimum efficacy of 89 lm/W. Although 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:

- ENERGY STAR does not cover commercial linear luminaires (ENERGY STAR, 2020).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume that manufacturers will focus 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

Technology	Efficacy	Lifetime	Price	Potential for Improvements
T8 F32 Commodity	0%	0%	-0.5%	Limited because the technology is mature.
T8 F32 High Efficiency/High Output	0%	0%	-0.5%	Limited because the technology is mature.
T5 F28	0%	0%	-0.5%	Limited because the technology is mature.

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

Higher efficacy compared with Reference Case

DATA	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	20.8	17.0	16.0	13.7	11.0	8.9	7.2	7.7	7.2	7.7	7.2
Lamp Lumens	2,091	2,003	1,800	1,920	1,800	1,920	1,800	1,920	1,800	1,920	1,800
Lamp Efficacy (lm/W)	100.5	117.8	112.5	140.1	163.6	216.1	250.0	250.0	250.0	250.0	250.0
System Wattage	41.6	34.0	32.0	27.4	22.0	17.8	14.4	15.4	14.4	15.4	14.4
System Lumens	3,555	3,565	3,456	3,686	3,456	3,686	3,456	3,686	3,456	3,686	3,456
System Efficacy (lm/W)	85.4	104.9	108.0	134.5	157.1	207.4	240.0	240.0	240.0	240.0	240.0
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	86	81	82	81	80	81	80	81	80	81	80
Correlated Color Temperature (CCT)	4,100	4,020	4,100	3,500	5,000	3,500	5,000	3,500	5,000	3,500	5,000
Average Lamp Life (thousand hours)	50	54	50	54	50	54	50	54	50	54	50
Annual Operating Hours (h/y)	4,055	3,541	3,541	3,541	3,541	3,541	3,541	3,541	3,541	3,541	3,541
Lamp Price (2022$)	$278.36	$35.06	$14.63	$11.11	$4.28	$9.88	$3.81	$9.66	$3.72	$9.44	$3.64
Ballast Price (2022$)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)	$133.10	$17.50	$8.13	$5.79	$2.38	$5.15	$2.11	$5.03	$2.07	$4.92	$2.02
System (l/b/f) Cost (2022$/klm)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Cost (2022$/h)	$77.22	$77.22	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Lamp Change (hours)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total Installed Cost (2022$)	$587.35	$70.12	$29.26	$22.22	$8.56	$19.76	$7.61	$19.31	$7.44	$18.89	$7.28
Annual Maintenance Cost (2022$)	$47.63	$6.61	$3.93	$3.17	$2.46	$3.01	$2.39	$2.98	$2.38	$2.95	$2.37
Total Installed Cost (2022$/klm)	$165.20	$19.67	$8.47	$6.03	$2.48	$5.36	$2.20	$5.24	$2.15	$5.12	$2.11
Annual Maintenance Cost (2022$/klm)	$13.40	$1.85	$1.14	$0.86	$0.71	$0.82	$0.69	$0.81	$0.69	$0.80	$0.69

1. N/A because a fixture and an LED replacement lamp would not be purchased separately for a new installation or retrofit when there are integrated LED luminaires that are more efficient and cost effective. These lamps are sold only as replacements to go into existing fixtures.

Higher efficacy compared with Reference Case

DATA	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens [1]	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) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	51.5	50.0	49.0	44.0	35.0	27.4	21.8	23.0	19.2	21.2	19.2
System Lumens	4,818	4,673	5,024	5,302	4,800	5,302	4,800	5,302	4,800	5,302	4,800
System Efficacy (lm/W)	93.6	93.5	102.5	120.5	137.1	193.4	220.1	230.4	250.0	250.0	250.0
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	84	79	80	79	80	79	80	79	80	79	80
Correlated Color Temperature (CCT)	3,500	3,650	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Average Lifetime (thousand hours)	67	53	54	53	50	53	50	53	50	53	50
Annual Operating Hours (h/y)	4,055	3,431	3,431	3,431	3,431	3,431	3,431	3,431	3,431	3,431	3,431
Lamp or Luminaire Price (2022$)	$723.96	$188.00	$144.85	$152.54	$207.80	$127.58	$173.80	$118.37	$161.25	$109.57	$149.27
Ballast Price (2022$) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm) [1]	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 (2022$/klm)	$150.25	$40.23	$57.66	$57.54	$86.58	$24.06	$36.21	$22.33	$33.59	$20.67	$31.10
Labor Cost (2022$/h)	$77.22	$77.22	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Labor Lamp Change (hours)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost (2022$)	$762.57	$226.61	$322.70	$338.08	$448.60	$160.58	$206.80	$151.37	$194.25	$142.57	$182.27
Annual Maintenance Cost (2022$)	$46.16	$14.67	$11.30	$12.01	$16.52	$10.40	$14.19	$9.80	$13.33	$9.23	$12.51
Total Installed Cost (2022$/klm)	$158.27	$48.49	$64.23	$63.76	$93.46	$30.29	$43.08	$28.55	$40.47	$26.89	$37.97
Annual Maintenance Cost (2022$/klm)	$9.58	$3.14	$2.25	$2.27	$3.44	$1.96	$2.96	$1.85	$2.78	$1.74	$2.61

1. N/A because the lamp and fixture are both included in the luminaire.

This section characterizes commercial linear fixtures that house two 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 narrowness 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 can fit directly into an existing fixture and fully integrated luminaires that can be used to replace existing fixtures. LED replacement lamps are also known as TLEDs. Type A TLEDs can be installed with existing ballasts and Type B and C TLEDs require the ballast to be disconnected. 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 and 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:

- Linear lamps often have a nominal CCT rating of 3,500K, but products with CCTs of 3,000K, 4,000K, and 4,100K (neutral white) are also common. 5,000K (daylight) lamps are available as well. When replacing a light bulb, it is important to choose a product with a similar CCT value to achieve the same look.
- Incandescent and halogen lamps have perfect color rendering with a CRI value of 100, but 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 two 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 2022 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 per year for commercial 8ft linear systems (DOE SSL Program, 2012a).
- Commercial lighting disposal costs are estimated to be $0.12 per linear foot of fluorescent lamps, $1.50 per lamp for HID lamps, and $0.50 for CFLs (EPA, 2022).

Legislation:

- Beginning July 14, 2012 (or July 14, 2014, for T8 700-series phosphor lamps), DOE fluorescent lamp standards required a minimum efficacy of 89 lm/W. Although 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:

- ENERGY STAR does not cover commercial linear luminaires (ENERGY STAR, 2020).

Future Performance Improvements:

- Projections were provided for both typical and high performing products for 2030, 2040, and 2050. We assume that manufacturers will focus 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050:

Technology	Efficacy	Lifetime	Price	Potential for Improvements
T8 F59 Typical Efficiency	0%	0%	-0.5%	Limited because the technology is mature.
T8 F59 High Efficiency	0%	0%	-0.5%	Limited because the technology is mature.
T8 F96 High Output	0%	0%	-0.5%	Limited because the technology is mature.

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

Higher efficacy compared with Reference Case

DATA	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	35.7	34.0	39.0	40.0	25.3	25.9	21.9	22.4	19.8	22.0
Lamp Lumens	N/A	3,975	4,200	4,960	5,500	4,960	5,500	4,960	5,500	4,960	5,500
Lamp Efficacy (lm/W)	N/A	111.2	123.5	127.2	137.5	196.1	212.0	226.7	245.1	250.0	250.0
System Wattage	N/A	71.5	68.0	78.0	80.0	50.6	51.9	43.8	44.9	39.7	44.0
System Lumens	N/A	7,473	8,064	9,523	10,560	9,523	10,560	9,523	10,560	9,523	10,560
System Efficacy (lm/W)	N/A	104.5	118.6	122.1	132.0	188.2	203.5	217.7	235.3	240.0	240.0
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	N/A	80	82	81	82	81	82	81	82	81	82
Correlated Color Temperature (CCT)	N/A	5,000	4,000	4,000	5,000	4,000	5,000	4,000	5,000	4,000	5,000
Average Lamp Life (thousand hours)	N/A	50	50	50	50	50	50	50	50	50	50
Annual Operating Hours (h/y)	N/A	4,147	4,147	4,147	4,147	4,147	4,147	4,147	4,147	4,147	4,147
Lamp Price (2022$)	N/A	$89.59	$33.11	$37.22	$41.44	$32.35	$36.02	$31.71	$35.30	$31.11	$34.64
Ballast Price (2022$)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)	N/A	$19.00	$7.88	$7.50	$7.53	$6.52	$6.55	$6.39	$6.42	$6.27	$6.30
System (l/b/f) Cost (2022$/klm)[1]	N/A	$23.98	$8.21	$7.82	$7.85	$6.79	$6.82	$6.66	$6.69	$6.53	$6.56
Labor Cost (2022$/h)	N/A	$77.22	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Labor Lamp Change (hours)	N/A	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total Installed Cost (2022$)	N/A	$200.80	$84.70	$92.92	$101.36	$83.18	$90.52	$81.90	$89.09	$80.70	$87.76
Annual Maintenance Cost (2022$)	N/A	$16.65	$7.02	$7.71	$8.41	$6.90	$7.51	$6.79	$7.39	$6.69	$7.28
Total Installed Cost (2022$/klm)	N/A	$50.51	$10.50	$9.76	$9.60	$8.73	$8.57	$8.60	$8.44	$8.47	$8.31
Annual Maintenance Cost (2022$/klm)	N/A	$4.19	$0.87	$0.81	$0.80	$0.72	$0.71	$0.71	$0.70	$0.70	$0.69

1. N/A because a fixture and an LED replacement lamp would not be purchased separately for a new installation or retrofit when there are integrated LED luminaires that are more efficient and cost effective. These lamps are sold only as replacements to go into existing fixtures.

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

Higher efficacy compared with Reference Case

DATA	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	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
Lamp Lumens	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
System Wattage	N/A	73.0	90.0	78.0	72.0	49.7	45.9	42.4	41.6	37.9	41.6
System Lumens	N/A	8,000	8,200	9,465	10,400	9,465	10,400	9,465	10,400	9,465	10,400
System Efficacy (lm/W)	N/A	109.6	91.1	121.3	144.4	190.4	226.7	223.1	250.0	250.0	250.0
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	N/A	90	80	81	80	81	80	81	80	81	80
Correlated Color Temperature (CCT)	N/A	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Average Lifetime (thousand hours)	N/A	75	50	73	100	73	100	73	100	73	100
Annual Operating Hours (h/y)	N/A	3,431	3,431	3,431	3,431	3,431	3,431	3,431	3,431	3,431	3,431
Lamp or Luminaire Price (2022$)	N/A	$759.16	$119.99	$142.48	$153.91	$109.90	$118.71	$96.00	$103.70	$82.68	$89.31
Ballast Price (2022$)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)	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 (2022$/klm)	N/A	$80.00	$14.63	$15.05	$14.80	$11.61	$11.41	$10.14	$9.97	$8.73	$8.59
Labor Cost (2022$/h)	N/A	$77.22	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	N/A	1.0	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Labor Lamp Change (hours)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost (2022$)	N/A	$708.20	$206.52	$229.01	$240.44	$196.42	$205.24	$182.53	$190.23	$169.20	$175.83
Annual Maintenance Cost (2022$)	N/A	$39.16	$22.40	$17.46	$13.53	$14.40	$11.11	$13.09	$10.08	$11.84	$9.10
Total Installed Cost (2022$/klm)	N/A	$88.53	$25.18	$24.20	$23.12	$20.75	$19.73	$19.28	$18.29	$17.88	$16.91
Annual Maintenance Cost (2022$/klm)	N/A	$4.89	$2.73	$1.84	$1.30	$1.52	$1.07	$1.38	$0.97	$1.25	$0.87

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:

- Low bay conventional lighting technologies, such as metal halide and sodium vapor lamps, provide higher efficacy ranging from 80 lm/W to 100 lm/W. Older, mercury vapor lamps have much lower efficacy at approximately 40 lm/W.
- CCT and CRI values range broadly based on technology type for low bay products.

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 luminaires, including CRI, lifetime, dimming capabilities, and efficacy. Therefore, typical luminaire prices in 2022 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 for commercial low-bay systems (DOE SSL Program, 2012a).
- Commercial lighting disposal costs are estimated to be $0.12 per linear foot of fluorescent lamps, $1.50 per lamp for HID lamps, and $0.50 for CFLs (EPA, 2022).

ENERGY STAR:

- 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 2030, 2040, and 2050. We assume manufacturers will 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

	Efficacy	Lifetime	Price	Potential for Improvements
Mercury Vapor	0%	0%	-0.5%	Limited because the technology is mature.
Metal Halide	0%	0%	-0.5%	Limited because the technology is mature.
Sodium Vapor	0%	0%	-0.5%	Limited because the technology is mature.

Performance and Cost Characteristics » Commercial LED Low-Bay Luminaire

Higher efficacy compared with Reference Case

DATA	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens[1]	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) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	68.1	84.0	40.0	73.0	76.0	47.1	49.0	40.5	48.0	40.0	48.0
System Lumens	4,877	10,000	5,000	10,000	12,000	10,000	12,000	10,000	12,000	10,000	12,000
System Efficacy (lm/W)	71.6	119.0	125.0	137.0	157.9	212.5	244.9	246.7	250.0	250.0	250.0
Ballast Efficiency	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	85	78	84	81	80	81	84	81	84	81	81
Correlated Color Temperature (CCT)	4,000	4,806	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	4,000
Average Lifetime (thousand hours)	50	74	75	65	60	65	60	65	60	65	60
Annual Operating Hours (h/y)	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042
Lamp or Luminaire Price (2022$)	$903.82	$281.00	$63.99	$145.46	$285.89	$123.82	$243.37	$111.24	$218.63	$99.09	$194.75
Ballast Price (2022$) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)[1]	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 (2022$/klm)	$185.31	$28.10	$12.80	$14.55	$23.82	$12.38	$20.28	$11.12	$18.22	$9.91	$16.23
Labor Cost (2022$/h)	$77.22	$77.22	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Labor Lamp Change (hours)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost (2022$)	$865.44	$396.83	$162.99	$244.46	$384.89	$222.82	$342.37	$210.24	$317.63	$198.09	$293.75
Annual Maintenance Cost (2022$)	$69.95	$37.02	$12.23	$24.24	$45.18	$21.55	$39.45	$19.99	$36.12	$18.48	$32.90
Total Installed Cost (2022$/klm)	$177.44	$39.68	$32.60	$24.45	$32.07	$22.28	$28.53	$21.02	$26.47	$19.81	$24.48
Annual Maintenance Cost (2022$/klm)	$14.34	$3.70	$2.45	$2.42	$3.77	$2.16	$3.29	$2.00	$3.01	$1.85	$2.74

1. N/A because the lamp and fixture are both included in the luminaire.

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:

- High bay conventional lighting technologies, such as metal halide and sodium vapor lamps, provide higher efficacy ranging from 80 lm/W to 100 lm/W. Older, mercury vapor lamps have much lower efficacy at approximately 40 lm/W.
- CCT and CRI values range broadly based on technology type for high bay products.

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 luminaires including, CRI, lifetime, dimming capabilities, and efficacy. Therefore, typical luminaire prices in 2022 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 for commercial high bay systems (DOE SSL Program, 2012a).
- Commercial lighting disposal costs are estimated to be $0.12 per linear foot of fluorescent lamps, $1.50 per lamp for HID lamps, and $0.50 for CFLs (EPA, 2022).

ENERGY STAR:

- 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 2030, 2040, and 2050. We assume manufacturers will 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, 2019).
- 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, 2019). For traditional technologies, the following future improvements were assumed to occur year over year through 2050.

	Efficacy	Lifetime	Price	Potential for Improvements
Mercury Vapor	0%	0%	-0.5%	Limited because the technology is mature.
Metal Halide	0%	0%	-0.5%	Limited because the technology is mature.
Sodium Vapor	0%	0%	-0.5%	Limited because the technology is mature.

Higher efficacy compared with Reference Case

DATA	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Lumens[1]	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) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
System Wattage	212	167	150	138	130	89	84	76	76	74	76
System Lumens	18,915	18,797	18,500	18,500	18,900	18,500	18,900	18,500	18,900	18,500	18,900
System Efficacy (lm/W)	89	113	123	134	145	208	225	242	250	250	250
Ballast Efficiency	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CRI	74	78	80	80	80	80	80	80	80	80	80
Correlated Color Temperature (CCT)	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Average Lifetime (thousand hours)	70	67	100	100	100	100	100	100	100	100	100
Annual Operating Hours (h/y)	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042	4,042
Lamp or Luminaire Price (2022$)	$2,842.05	$448.43	$177.54	$195.81	$234.20	$162.12	$193.90	$148.87	$178.06	$136.20	$162.90
Ballast Price (2022$) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fixture Price (2022$) [1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lamp Cost (2022$/klm)[1]	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 (2022$/klm)	$150.25	$23.86	$9.60	$10.58	$12.39	$8.76	$10.26	$8.05	$9.42	$7.36	$8.62
Labor Cost (2022$/h)	$77.22	$77.22	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00	$66.00
Labor System Installation (hours)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Labor Lamp Change (hours)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Installed Cost (2022$)	$2,957.88	$564.26	$276.54	$294.81	$333.20	$261.12	$292.90	$247.87	$277.06	$235.20	$261.90
Annual Maintenance Cost (2022$)	$170.78	$34.07	$11.18	$11.91	$13.47	$10.55	$11.84	$10.02	$11.20	$9.51	$10.58
Total Installed Cost (2022$/klm)	$156.38	$30.02	$14.95	$15.94	$17.63	$14.11	$15.50	$13.40	$14.66	$12.71	$13.86
Annual Maintenance Cost (2022$/klm)	$9.03	$1.81	$0.60	$0.64	$0.71	$0.57	$0.63	$0.54	$0.59	$0.51	$0.56

1. N/A because the lamp and fixture are both included in the luminaire.

Refrigeration

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Total Capacity (kBtu/h)[1]	1,200	1,200	1,200	1,190	930	N/A	1,190	930	1,190	930	1,190	930
Median Store Size (ft^2)	46,500	31,997	35,197	35,197	35,197	N/A	35,197	35,197	35,197	35,197	35,197	35,197
Power Input (kW)	162	155	162	160	125	N/A	160	125	160	125	160	125
Annual Energy Use (MMWh/y)[2]	1,497	1,497	1,305	1,232	1,160	N/A	1,109	1,044	998	939	898	845
Indexed Annual Efficiency[3]	1.00	1.00	1.15	1.21	1.29	N/A	1.35	1.43	1.50	1.59	1.67	1.77
Average Life (years)	15	15	15	15	15	N/A	15	15	15	15	15	15
Total Installed Cost (2022$)	$630,000	$630,000	$488,000	$625,000	$630,000	N/A	$625,000	$630,000	$625,000	$630,000	$625,000	$630,000
Total Installed Cost (2022$/kBtu/h)	$525,000	$525,000	$406,667	$525,210	$677,419	N/A	$525,210	$677,419	$525,210	$677,419	$525,210	$677,419
Annual Maintenance Cost (2022$)[4]	$3,400	$3,400	$3,400	$3,400	$3,400	N/A	$3,400	$3,400	$3,400	$3,400	$3,400	$3,400
Annual Maintenance Cost (2022$/kBtu/h)	$2,833	$2,833	$2,833	$2,857	$3,656	N/A	$2,857	$3,656	$2,857	$3,656	$2,857	$3,656

1. The total capacity represents the nominal compressor capacity required for the entire refrigeration system of a typical supermarket. This refrigeration system usually includes two low temperature racks and two medium temperature racks. For 2018, a 1,200 MBtu/h total cooling capacity is based on a 200-ton estimate for total capacity–80 tons for the medium temperature racks and 20 tons for the low temperature racks.
2. Capacity and annual energy consumption for 2022 and beyond are based on market research and Guidehouse estimates.
3. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Maintenance cost includes oil changes, bearing lubrication, filter replacement, and system functionality checks-approximately half a day per rack of labor for technician is assumed.

- 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-horsepower (hp) to 15-hp size range. Usually, each rack has three to five compressors serve a series of loads with nearly identical evaporator temperature.
- The duty cycle for compressors is usually in the range of 60% to 70%.
- Energy use and capacity for the Reference Case are projected to remain static over the coming decades because commercial compressor racks systems are a mature technology. The Reference Case assumes low R&D efforts because it is an established technology.
- **For this Advanced Case, a 10% reduction in energy consumption is assumed to occur over the Reference Case for 2022 and beyond due to vacuum insulated panel (VIP) adoption by display cases and a relaxation in charge size limits for more efficient, low global warming potential (GWP) refrigerants. Also, increased adoption of toxic/flammable refrigerants such as ammonia and propane due to improved safety technology such as leak detection**.

Lower annual energy use compared with Reference Case

DATA	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2022 ENERGY STAR	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Total Capacity (kBtu/h)[1]	1,680	1,520	1,440	1,440	1,440	N/A	1,440	1,368	1,300	1,300	1,235	1,235
Median Store Size (ft^2)	46,500	31,997	35,197	35,197	35,197	N/A	35,197	35,197	35,197	35,197	35,197	35,197
Power Input (kW)	25	25	18	18	18	N/A	18	18	18	18	18	18
Annual Energy Use (MMWh/y)	120	120	115	106	86	N/A	95	77	86	70	77	63
Indexed Annual Efficiency[2]	1.00	1.00	1.04	1.13	1.40	N/A	1.26	1.55	1.40	1.72	1.55	1.91
Average Life (years)	10	10	10	10	10	N/A	10	10	10	10	10	10
Total Installed Cost (2022$)	$54,000	$60,000	$54,000	$60,000	$80,000	N/A	$60,000	$80,000	$60,000	$80,000	$60,000	$80,000
Total Installed Cost (2022$/kBtu/h)	$32,143	$39,474	$37,500	$41,667	$55,556	N/A	$41,667	$58,480	$46,168	$61,538	$48,598	$64,777
Annual Maintenance Cost (2022$)[3]	$954	$954	$954	$954	$954	N/A	$954	$954	$954	$954	$954	$954
Annual Maintenance Cost (2022$/kBtu/h)	$0.57	$0.63	$0.66	$0.66	$0.66	N/A	$0.66	$0.70	$0.73	$0.73	$0.77	$0.77

1. Total capacity is the total heat rejected (THR) by condensers comprised of two low temperature condensers (THRL = 240 MBtu/h each, suction temperature = -25°F, condensing temperature-110°F) and two medium temperature condensers (THRM = 520 MBtu/h each, suction temperature = 15°F, condensing temperature = 115°F); ambient temperature = 95°F. (NCI, 2009). For 2022 and beyond, capacity was estimated by Guidehouse.
2. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
3. Maintenance cost includes coil cleaning, leak checking, belt replacement as necessary, and system functionality checks.

- 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.
- 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%.
- **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. Also, increased adoption of toxic/flammable refrigerants such as ammonia and propane due to improved safety technology such as leak detection**.

Lower annual energy use, increased installed cost compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	17,623	11,850	11,850	11,850	11,850	N/A	11,850	11,850	11,850	11,850	11,850	11,850
Median Store Size (ft^2)	46,500	31,997	35,197	35,197	35,197	N/A	35,197	35,197	35,197	35,197	35,197	35,197
Case Length (ft)	12	12	12	12	12	N/A	12	12	12	12	12	12
Annual Energy Use (kWh/y)[1,2]	13,497	10,506	10,506	9,771	9,087	N/A	9,282	8,632	8,818	8,201	8,377	7,791
Annual Energy Use / Case Length (kWh/ft)	1,125	876	876	814	757	N/A	774	719	735	683	698	649
Indexed Annual Efficiency[3]	1.00	1.28	1.28	1.38	1.49	N/A	1.45	1.56	1.53	1.65	1.61	1.73
Average Life (years)	10	10	10	10	10	N/A	10	10	10	10	10	10
Retail Equipment Cost (2022$)	$8,510	$10,650	$7,265	$9,500	$10,680	N/A	$9,500	$10,680	$9,500	$10,680	$9,500	$10,680
Total Installed Cost (2022$)	$10,811	$12,650	$9,265	$11,500	$12,680	N/A	$11,500	$12,680	$11,500	$12,680	$11,500	$12,680
Total Installed Cost (2022$/kBtu/h)	613	1,068	782	970	1,070	N/A	970	1,070	970	1,070	970	1,070
Annual Maintenance Cost (2022$)[4]	$940	$940	$940	$940	$940	N/A	$940	$940	$940	$940	$940	$940
Annual Maintenance Cost (2022$/kBtu/h)	$53.34	$79.32	$79.32	$79.32	$79.32	N/A	$79.32	$79.32	$79.32	$79.32	$79.32	$79.32

1. For 2022 and beyond, energy consumption and cost values were estimated using shipment-weighted averages reported in DOE's 2014 CRE Final Rule Technical Support Document (TSD) for equipment commonly used as display cases. DOE's updated conservation standard went into effect in 2017, so units sold in 2018 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 2012 installed base. Indexed Annual Efficiency = (2012 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.

- DOE set federal energy efficiency standards for Commercial Refrigeration Equipment (CRE) in 2009. These standards set maximum daily energy consumption levels, in kilowatt-hours per day, for display cases manufactured 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	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

- According to CBECS 2018 microdata, the average building size for food sale building type is 31,997.
- Unit energy consumption for 2022 and beyond is estimated using a shipment-weighted average by efficiency level and equipment class, using data in DOE's 2014 CRE Final Rule TSD with updated analysis from Guidehouse in 2016. 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.
- 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.
- **For 2020 and beyond, accelerated adoption of energy savings technologies is assumed to take place more than in 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 Case 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 Hydrofluorocarbons (HFC) to more efficient propane and ammonia refrigerants by 2040.**
- **Advanced Case assumes a 5% reduction in energy use per decade based on technology and efficiency improvements.**

Lower annual energy use, increased installed cost compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	2,929	2,400	2,349	2,349	2,349	2,349	2,349	2,349	2,349	2,349	2,349	2,349
Size (ft^3)	49	49	46	46	46	47	46	46	46	46	46	46
Annual Energy Use (kWh/y)	2,340	2,222	1,935	1,351	810	810	1,283	770	1,283	770	1,283	770
Annual Energy Use / Volume ($kWh/y/ft^3$)[1]	48	45	42	29	18	17	28	17	28	17	28	17
Indexed Annual Efficiency[3]	1.00	1.05	1.21	1.73	2.89	2.89	1.82	3.04	1.82	3.04	1.82	3.04
Average Life (years)	10	10	10	10	10	10	10	10	10	10	10	10
Retail Equipment Cost (2022$)	$2,624	$2,403	$2,728	$2,780	$3,021	$3,021	$3,058	$3,323	$3,323	$3,364	$3,655	$3,655
Total Installed Cost (2022$)[4]	$3,454	$3,282	$3,591	$3,643	$3,884	$3,884	$3,932	$4,197	$4,197	$4,238	$4,529	$4,529
Total Installed Cost (2022$/kBtu/h)	$1,179	$1,368	$1,529	$1,551	$1,654	$1,654	$1,885	$2,568	$1,885	$2,568	$1,885	$2,568
Annual Maintenance Cost (2022$)[5]	$185	$185	$185	$185	$185	$185	$185	$185	$185	$185	$185	$185
Annual Maintenance Cost (2022$/kBtu/h)	$63	$77	$79	$79	$79	$79	$79	$79	$79	$79	$79	$79

1. EPACT 2005 energy standards went into effect in 2010. 2022 low efficiency cost and energy consumption values are based on minimum compliance with this standard. Unless otherwise noted, all other cases are based on shipment-weighted averages solid- and transparent-doored units reported in the 2014 CRE TSD. DOE's updated Energy Conservation standards went into effect in 2017; therefore, compliance with this standard is assumed for 2022 and beyond.
2. The ENERGY STAR category is based on a shipment 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 2022.
3. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Installation cost for 2012 is based on NCI 2009 report that assumes a cost of $863. Installation cost for 2022 and beyond is based DOE's 2014 CRE Final Rule and additional analysis by Guidehouse, which assumes an installation cost of $878 for self-contained equipment.
5. Maintenance costs after 2012 are based on DOE's CRE 2014 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.

- The Energy Policy Act of 2005 (EPACT 2005) set maximum daily energy consumption levels, in kilowatt-hours per 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 ft^3.
- 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 specifications for reach-in refrigerators, effective March 27, 2017. These standards are also based on the refrigerated volume of the unit.

Reach-In Refrigerator Size	0 < V < 15	15 ≤ V < 30	30 ≤ V < 50	50 ≤ V
Solid Door (VCS.SC.M)	0.022xV+0.97	0.066xV+0.31	0.04xV+1.09	0.024xV+1.89
Glass Door (VCT.SC.M)	0.095xV+0.445	0.05xV+1.12	0.076xV+0.034	0.105xV-1.111

- 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 with updated analysis from Guidehouse in 2016. 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.
- After 2022, the high efficiency cases are based on solid-doored units rather than shipment-weighted averages due to the assumption that stakeholders will increasingly value energy conservation.
- **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 Significant New Alternatives Policy (SNAP).**
- **For this Advanced Case, 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 Case 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-efficient technologies, a limit of possible efficiency improvements for self-contained, vapor compression refrigeration systems will be reached by 2040.**

Lower annual energy use, increased installed cost compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	4,341	4,340	4,340	4,340	4,340	4,340	4,340	4,340	4,340	4,340	4,340	4,340
Size (ft^3)	49	49	49	49	49	49	49	49	49	49	49	49
Annual Energy Use (kWh/y)[1]	6,023	5,585	5,585	4,847	4,110	4,110	4,362	3,699	3,926	3,329	3,533	2,996
Annual Energy Use / Volume (kWh/y/ft^3)	123	114	114	99	84	84	89	75	80	68	72	61
Indexed Annual Efficiency[3]	1.00	1.08	1.08	1.24	1.47	1.47	1.38	1.63	1.53	1.81	1.70	2.01
Average Life (years)	10	10	10	10	10	10	10	10	10	10	10	10
Retail Equipment Cost (2022$)	$2,886	$2,886	$2,886	$3,175	$3,493	$3,493	$3,493	$3,842	$3,842	$4,226	$4,226	$4,649
Total Installed Cost (2022$)[4]	$3,749	$3,749	$3,749	$4,125	$4,443	$4,443	$4,443	$4,792	$4,792	$5,176	$5,176	$5,599
Total Installed Cost (2022$/kBtu/h)	$864	$864	$864	$950	$1,024	$1,024	$1,024	$1,104	$1,104	$1,193	$1,193	$1,290
Annual Maintenance Cost (2022$)[5]	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181
Annual Maintenance Cost (2022$/kBtu/h)	$41.70	$41.71	$41.71	$41.71	$41.71	$41.71	$41.71	$41.71	$41.71	$41.71	$41.71	$41.71

1. A 49 ft^3 unit was characterized, because it was the representative size selected for DOE's rulemaking analysis.
2. The ENERGY STAR category was based on a solid-doored unit that is minimally compliant with ENERGY STAR v3, effective October 1, 2014.
3. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Installation cost for 2012 and 2018 is based on DOE's on-going CRE rulemaking, which assumes a cost of $863 for self-contained equipment and $950 for 2022 and beyond based on analysis from Guidehouse.
5. 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 CRE TSD.

- EPACT 2005 set maximum daily energy consumption levels, in kilowatt-hours per 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 ft^3.
- In March of 2017, 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 specifications for reach-in freezers, effective March 27, 2017. These standards are also based on the refrigerated volume of the unit.

Reach-In Freezer Size	$0 < V < 15$	$15 \le V < 30$	$30 \le V < 50$	$50 \le V$
Solid Door (VCS.SC.L)	0.21xV+0.9	0.12xV+2.248	0.285xV-2.703	0.142xV+4.445
Glass Door (VCT.SC.L)	0.232xV+2.36	0.232xV+2.36	0.232xV+2.36	0.232xV+2.36

- 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 of 4,341 Btu/h.
- 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.**
- **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 Case 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-efficient technologies, a limit of possible efficiency improvements for self-contained, vapor compression refrigeration systems will be reached by 2040.**

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/hr)[1]	37,820	39,422	41,024	41,024	41,024	N/A	41,024	41,024	41,024	41,024	41,024	41,024
Size (ft^2)	305	240	240	240	240	N/A	240	240	240	240	240	240
Annual Energy Use (kWh/yr)[2]	30,689	20,040	17,600	16,200	14,800	N/A	14,580	13,320	13,122	11,988	11,810	10,789
Annual Energy Use / Area ($kWh/ft^2/yr$)	101	84	73	68	62	N/A	61	56	55	50	49	45
Indexed Annual Efficiency[3]	1.00	1.53	1.74	1.89	2.07	N/A	2.10	2.30	2.34	2.56	2.60	2.84
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 (2022$)	$23,598	$19,847	$16,050	$19,847	$23,644	N/A	$16,050	$23,644	$16,050	$23,644	$16,050	$23,644
Total Installed Cost (2022$)[4]	$27,012	$23,897	$20,100	$23,897	$27,694	N/A	$20,100	$27,694	$20,100	$27,694	$20,100	$27,694
Total Installed Cost (2022$/kBtu/hr)	$714	$606	$490	$583	$675	N/A	$490	$675	$490	$675	$490	$675
Annual Maintenance Cost (2022$)[5]	$716	$740	$740	$740	$740	N/A	$740	$740	$740	$740	$740	$740
Annual Maintenance Cost (2022$/kBtu/hr)	$18.93	$18.77	$18.04	$18.04	$18.04	N/A	$18.04	$18.04	$18.04	$18.04	$18.04	$18.04

1. Assumes medium temperature units are refrigerators.
2. Average unit energy consumption was adapted from the DOE CRE 2016 report by assuming electronically commutated motor (ECM) evaporator fan motors are required for Energy Policy & Conservation Act (EPCA) compliance, as well as ECM condenser fan motors.
3. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Installation cost for 2012 and beyond is based on DOE's Walk-In Technical Support Document (TSD).
5. Maintenance cost includes checking and maintaining refrigerant charge levels, checking settings, and cleaning heat exchanger coils.

- For 2012 and beyond, the unit characterized was a walk-in storage cooler, based on DOE's WICF TSD.
- 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 the 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 Case assumes a projected 10% decrease in energy consumption over the Reference Case due to adoption of more efficient refrigerants.**

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:

- For 2012 and beyond
- 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 three-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 three-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.

In 2014, DOE updated its energy conservation standards for walk-in coolers and freezers. Minimum AWEF (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	$0.15 \cdot A_{dd} + 0.29$

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	22,114	23,500	23,500	23,500	23,500	N/A	23,500	23,500	23,500	23,500	23,500	23,500
Size (ft^2)[1]	172	161	161	161	161	N/A	161	161	161	161	161	161
Annual Energy Use (kWh/y)[2]	22,862	17,600	21,400	21,400	21,400	N/A	19,260	19,260	17,334	17,334	15,601	15,601
Annual Energy Use / Area (kWh/ft^2/y)	133	109	133	133	133	N/A	120	120	108	108	97	97
Indexed Annual Efficiency[3]	1.00	1.30	1.07	1.07	1.07	N/A	1.19	1.19	1.32	1.32	1.47	1.47
Insulated Box Average Life (years)	12	12	12	12	12	N/A	12	12	12	12	12	12
Compressor Average Life (years)	10	10	10	10	10	N/A	10	10	10	10	10	10
Retail Equipment Cost (2022$)	$22,008	$21,950	$21,950	$22,850	$23,750	N/A	$22,850	$23,750	$22,850	$23,750	$22,850	$23,750
Total Installed Cost (2022$)[4]	$24,058	$23,950	$23,950	$24,850	$25,750	N/A	$24,850	$25,750	$24,850	$25,750	$24,850	$25,750
Total Installed Cost (2022$/kBtu/h)	$1,088	$1,019	$1,019	$1,057	$1,096	N/A	$1,057	$1,096	$1,057	$1,096	$1,057	$1,096
Annual Maintenance Cost (2022$)[5]	$741	$741	$741	$740	$741	N/A	$740	$741	$740	$741	$740	$741
Annual Maintenance Cost (2022$/kBtu/h)	$33.51	$31.53	$31.53	$31.49	$31.53	N/A	$31.49	$31.53	$31.49	$31.53	$31.49	$31.53

1. Based on DOE's 2014 WICF Final Rule TSD and additional analysis by Guidehouse, the average floor area for a walk-in storage freezer as 161 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 2022 and beyond are characterized using data from DOE's 2014 WICF rulemaking. All units for 2022 and beyond are assumed to comply with this standard.
3. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Installation cost for 2012 and beyond is based on DOE's WICF TSD and additional analysis by Guidehouse.
5. Maintenance cost includes checking and maintaining refrigerant charge levels, checking settings, and cleaning heat exchanger coils.

- The commercial walk-in freezer characterized in this report is a walk-in storage freezer with an area of 161 ft^2.
- 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 the 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 Case assumes a projected 10% decrease in energy consumption over the Reference Case due to adoption of more efficient refrigerants.**

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 three-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 three-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.

In 2014, DOE updated its energy conservation standards for walk-in coolers and freezers. Minimum AWEF (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	$0.15 \cdot A_{dd} + 0.29$

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[6]	Typical	High	Typical	High	Typical	High
Output (pounds [lbs] per day)[1]	300	641	700	700	700	700	700	700	700	700	700	700
Cooling Capacity (Btu/h)[2]	1963	4194	4580	4580	4580	4580	4580	4580	4580	4580	4580	4580
Water Use per Hundred Pounds (gal/hundred lbs)[3]	20	25	25	20	15	15	20	15	20	15	20	15
Energy Use per Hundred Pounds (kWh/hundred lbs)	7.7	7.5	7.1	5.8	4.8	4.8	5.8	4.8	5.8	4.8	5.8	4.8
Annual Energy Use (kWh/y)[4]	3,185	2,502	1,675	1,478	1,190	1,190	1,330	1,071	1,197	964	1,077	868
Indexed Annual Efficiency[5]	1.00	1.27	1.90	2.15	2.68	2.68	2.39	2.97	2.66	3.30	2.96	3.67
Average Life (years)	8.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Retail Equipment Cost (2022$)	$2,146	$2,616	$2,946	$3,020	$3,368	$3,368	$3,020	$3,368	$3,020	$3,368	$3,020	$3,368
Total Installed Cost (with Bin)	$2,441	$3,626	$3,276	$3,350	$3,737	$3,737	$3,350	$3,737	$3,350	$3,737	$3,350	$3,737
Total Installed Cost (2022$/kBtu/h)	$1,244	$865	$715	$732	$816	$816	$732	$816	$732	$816	$732	$816
Annual Maintenance Cost (2022$)[7]	$826	$826	$800	$800	$800	$800	$800	$800	$800	$800	$800	$800
Annual Maintenance Cost (2022$/kBtu/h)	$421	$197	$175	$175	$175	$175	$175	$175	$175	$175	$175	$175

1. Based on the average output from the Compliance Certification Database and values within 2022 Automatic Commercial Ice Maker (ACIM) TSD.
2. Defined as the average heat load to remove the latent and sensible heat required to freeze the daily output capacity of ice.
3. Water use refers to potable water.
4. 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 uses data from this rulemaking. All units for 2020 and beyond are assumed to comply with the updated standard.
5. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
6. The ENERGY STAR category is based on minimum compliance with the ENERGY STAR v3.0 standard, which went into effect on January 28, 2018. According to this analysis, ENERGY STAR certification is typical for the small air-cooled ice-making head (IMH) unit characterized.
7. Maintenance cost is based on the average cost of equipment within the 700 lb/day output range and 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 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 kilowatt-hours per 100 pounds of ice, for air-cooled ice machines that went into effect on January 28, 2018. These efficiency levels are based on the harvest rate, in pounds per 24 hours. (H). Water-cooled ice machines are not eligible for ENERGY STAR certification.
- **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.**

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/hundred 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/hundred lbs ice)	Potable Water Use (gal/hundred 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

EPACT 2005 issued standard levels for commercial ice machines with capacities between 50 pounds and 2500 pounds per 24-hour period that are manufactured 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). In 2015, DOE finalized new standards for ACIMs extending coverage to flake, nugget, and tube-type machines and to capacities up to 4,000 pounds per 24 hours.

Equipment Type	Type of Cooling	Harvest Rate (lbs ice/24 hrs)	Maximum Energy Use (kWh/hundred lbs ice)	Maximum Condenser Water Use (gal/hundred lbs ice)
Ice Making Head	Water	<500	7.80-0.0055 H	200-0.022 H
		≥500 and <1,436	5.58-0.0011 H	200-0.022 H
		≥1,436	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	<1,000	8.85-0.0038 H	Not Applicable
		≥1,000	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

Water use is for the condenser only and does not include potable water used to make ice.

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

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	4,689	4,700	4,700	4,700	4,700	4,700	4,700	4,700	4,700	4,700	4,700	4,700
Size (ft^3)	27	27	27	27	27	27	27	27	27	27	27	27
Annual Energy Use (kWh/y)	1,829	1,635	1,380	1,141	902	902	1,141	902	1,084	857	1,030	814
Annual Energy Use / Volume ($kWh/ft^3/y$)[1]	68	73	55	35	26	26	35	26	35	26	35	26
Indexed Annual Efficiency[3]	1.00	1.12	1.33	1.60	2.03	2.03	1.60	2.03	1.69	2.13	1.78	2.25
Average Life (years)	10.0	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 (2022$)	$2,382	$2,051	$1,710	$2,762	$3,332	$3,332	$2,762	$3,332	$2,762	$3,332	$2,762	$3,332
Total Installed Cost (2022$)[4]	$2,382	$2,051	$1,710	$2,762	$3,332	$3,332	$2,762	$3,332	$2,762	$3,332	$2,762	$3,332
Total Installed Cost (2022$/kBtu/h)	$508	$436	$364	$588	$709	$709	$588	$709	$588	$709	$588	$709
Annual Maintenance Cost (2022$)	$108	$108	$95	$95	$95	$95	$95	$95	$95	$95	$95	$95
Annual Maintenance Cost (2022$/kBtu/h)	$23.03	$22.98	$20.21	$20.21	$20.11	$20.11	$20.21	$20.11	$20.21	$20.11	$20.21	$20.11

1. EPACT 2005 energy conservation standards went into effect in 2010. 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 2018 and beyond use data reported in this rulemaking's TSD. Units sold in 2022 and beyond are assumed to comply with this updated standard.
2. The ENERGY STAR category characterizes a unit that is compliant with ENERGY STAR v4, effective March 2017. This standard does not separately define units with pull-down capability.
3. Annual efficiency normalized to the efficiency of the 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Beverage merchandisers are shipped ready to be plugged in, so installation costs are assumed to be negligible.

- EPACT 2005 sets maximum daily energy consumption levels, in kilowatt-hours per day, for commercial refrigerators with transparent doors and self-contained condensing unit designed for pull-down temperature applications (i.e., beverage merchandisers) and 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 specifications 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	$0 < V < 15$	$15 \leq V < 30$	$30 \leq V < 50$	$50 \leq V$
Glass Door	0.118*V + 1.382	≤ 0.140*V + 1.050	≤ 0.088*V + 2.625	≤ 0.110*V + 1.500

- The beverage merchandiser characterized in this report, which is the typical unit according to DOE's 2014 CRE rulemaking and additional analysis by Guidehouse, is a 27 cubic foot cooler with a single hinged, transparent door, bright lighting, and shelving with a nominal compressor size of 4,700 Btu/h.
- The efficiency of beverage merchandisers can be increased through the use of more efficient compressors, fluorescent lighting with electronic ballasts, LED lighting, and improved insulation.
- For the Reference Case, beverage merchandisers are assumed to be mature technologies with few technology advancements in the coming years that would dramatically improve the efficiency.
- **For this Advanced Case, the typical unit in 2030 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**
- **Beverage merchandisers may transition from HFC to more efficient propane.**
- **Projected installed costs for this Advanced Case are the same as the Reference Case, 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 and a 5% decrease in energy use from 2030 to 2040.**

Final

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR[2]	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	1,810	1,707	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810	1,810
Can Capacity	470	500	500	500	500	500	500	500	500	500	500	500
Size (ft^3)	26	35	35	35	35	35	35	35	35	35	35	35
Annual Energy Use (kWh/y)[1]	1,632	1,550	1,550	1,531	1,443	1,443	1,455	1,371	1,382	1,302	1,313	1,237
Annual Energy Use / Volume (kWh/ft^3/y)	63	44	44	44	41	41	42	39	39	37	38	35
Indexed Annual Efficiency[3]	1.00	1.05	1.05	1.07	1.13	1.13	1.12	1.19	1.18	1.25	1.24	1.32
Average Life (years)	13.5	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 (2022$)	$3,209	$2,553	$3,059	$3,272	$3,520	$3,520	$3,272	$3,520	$3,272	$3,520	$3,272	$3,520
Total Installed Cost (2022$)	$3,320	$2,705	$3,276	$3,489	$3,737	$3,737	$3,489	$3,737	$3,489	$3,737	$3,489	$3,737
Total Installed Cost (2022$/kBtu/h)	$1,834	$1,585	$1,810	$1,928	$2,065	$2,065	$1,928	$2,065	$1,928	$2,065	$1,928	$2,065
Annual Maintenance Cost (2022$)[4]	$270	$270	$333	$333	$333	$333	$333	$333	$333	$333	$333	$333
Annual Maintenance Cost (2022$/kBtu/h)	$149	$149	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184

1. Energy use for 2018 and beyond is estimated based on DOE's 2020 BVM Final Rule and the 2022 Compliance Certification Database.
2. The ENERGY STAR category assumes units are compliant with the ENERGY STAR v4 standard because combination units are currently not separately defined by ENERGY STAR. This standard went into effect on April 29, 2020. 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 2012 installed base. Indexed Annual Efficiency = (2012 Energy Use) / (Energy Use).
4. Maintenance cost includes preventative maintenance costs such as checking and maintaining refrigerant charge levels, cleaning heat exchanger coils, and an annualized cost for refurbishments/remanufacturing.

- DOE set federal energy efficiency standards for refrigerated vending machines. These standards set maximum daily energy consumption levels, in kilowatt-hours per day, for commercial refrigerated vending machines manufactured 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).
- In December 2015, DOE updated its energy conservation standards for beverage vending machines and defined two new product classes for combination vending machines. The energy conservation standard remains the same in the updated 2022 technical support document for vending machines. Compliance with these standards was required by 2019. For this analysis, compliance with these updated standards is assumed for equipment sold in 2022 and beyond. The updated standards and DOE equipment definitions are listed in the table below.

Equipment Type	Maximum Daily Energy Consumption
Class A (Transparent-Front)	MDEC= 0.052 × V + 2.43
Class B (Solid-Front)	MDEC = 0.052 × V + 2.20
Combination A	MDEC = 0.086 × V + 2.66
Combination B	MDEC = 0.111 × V + 2.04

ENERGY STAR® updated its maximum daily energy consumption efficiency levels, also in kilowatt-hours per day, for refrigerated vending machines that went into effect on April 29, 2020. These efficiency levels are based on refrigerated volume.

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% or more of the surface area on the front side of the beverage vending machine is transparent	MDEC = 0.04836 x V + 2.2599
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 = 0.04576 x V+1.936
Combination A – a combination vending machine where 25% or more of the surface area on the front side of the beverage vending machine is transparent	MDEC = 0.07998 x V + 2.4738
Combination B – a combination vending machine that is not considered to be Combination A	MDEC = 0.09768 x V + 1.7952

- 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) $\leq 0.055*V + 2.56$
  - Refrigerated Vending Machines that are zone-cooled (Type B) $\leq 0.073*V + 3.16$
- 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 Case 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.**

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

Final

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average[3]	Low[4,5]	Typical[4,6]	High[4,7]	ENERGY STAR	Typical[4,6]	High[4,7]	Typical[4,6]	High[4,7]	Typical[4,6]	High[4,7]
System Airflow (CFM)	15,000	16,300	16,300	16,300	16,300	N/A	16,300	16,300	16,300	16,300	16,300	16,300
System Fan Power (kW)	11.56	11.56	11.56	10.98	10.78	N/A	10.98	10.78	10.98	10.78	10.98	10.78
Specific Fan Power (W/CFM)	0.771	0.709	0.709	0.674	0.661	N/A	0.674	0.661	0.674	0.661	0.674	0.661
Annual Fan Energy Use (kWh/y)[1]	43,924	23,038	23,038	21,886	20,792	N/A	20,792	19,752	19,752	18,765	18,765	17,826
Average Life (years)	35	35	35	35	35	N/A	35	35	35	35	35	35
Total Installed Cost (2022$)[2]	$80,288	$83,083	$83,083	$86,901	$90,651	N/A	$86,901	$90,651	$86,901	$90,651	$86,901	$90,651
Annual Maintenance Cost (2022$)	$1,054	$1,054	$1,054	$1,054	$1,054	N/A	$1,054	$1,054	$1,054	$1,054	$1,054	$1,054
Total Installed Cost (2022$/thousand CFM)	$5,353	$5,097	$5,097	$5,331	$5,561	N/A	$5,331	$5,561	$5,331	$5,561	$5,331	$5,561
Annual Maintenance Cost (2022$/thousand CFM)	$70	$65	$65	$65	$65	N/A	$65	$65	$65	$65	$65	$65

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 16,300 CFM constant air volume (CAV) air handling unit (AHU) and hypothetical supply ductwork layout
3. Based on ASHRAE 90.1-2016 and 2019 fan power limit (Table 6.5.3.1.1-1) with no pressure drop adjustment. Assumed 80% motor load and 91% motor efficiency
4. ASHRAE 90.1-2016 and 2019 Section 6.5.3.2 require minimum two-speed fan control (no longer always constant volume).
5. Two-speed variable frequency drive (VFD)
6. Modulating VFD
7. Modulating custom engineered VFD

- 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 the space temperature setpoint. Beginning with ASHRAE 90.1-2013 and continued in ASHRAE 90.1-2019, new CAV ventilation systems were mandated to have at least two fan speed settings with the requirement of a maximum 40% power at 66% flow. Systems with variable speed fans are increasingly popular, making the term “constant air volume” somewhat of a misnomer for this system type. 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 90.1-2019 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 16,300 CFM CAV system. The average commercial building is approximately 16,300 square feet (CBECS 2018). Assuming 1 CFM is needed per square foot of floor area results in a 16,300 CFM air handling unit.
- A 16,300 CFM CAV packaged indoor air handling unit with cooling and heating coils can be installed for approximately $71,829 (RS Means 2022). Ductwork would cost approximately $9,272 additional ($81,101 total). A two-speed motor (estimated $500 incremental cost) and variable frequency drive (estimated $5,800) add cost. Custom engineered variable frequency drives (estimated $9,550) and premium efficiency motors (estimated additional $1,500) add an additional cost to the system.
- Annual maintenance cost assumes 8 hours worth of labor by a technician to perform the necessary tasks (e.g., filter replacement, draining condenser water, etc.)
- 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 2016 version of Standard 90.1 was used to represent the 2018 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 and flow control.
- **For this Advanced Case, the projections from 2030 to 2050 for system fan power and annual fan energy use assume a 5% improvement per decade based on the assumption that use of variable frequency drives and incremental improvements in technology will increase.**

Lower annual energy use compared with Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average[3]	Low[4]	Typical[5]	High[6]	ENERGY STAR	Typical[6]	High[6,7]	Typical[6,7]	High[6,7]	Typical[6,7]	High[6,7]
System Airflow (CFM)	15,000	16,300	16,300	16,300	16,300	N/A	16,300	16,300	16,300	16,300	16,300	16,300
System Fan Power (kW)	15.99	15.99	15.99	15.99	15.99	N/A	15.99	15.19	15.99	15.19	15.99	15.19
Specific Fan Power (W/CFM)	1.066	1.066	0.981	0.981	0.981	N/A	0.981	0.932	0.981	0.932	0.981	0.932
Annual Fan Energy Use (kWh/yr)[1]	24,699	24,082	24,082	22,878	21,734	N/A	21,734	20,647	20,647	19,615	19,615	18,634
Average Life (yrs)	28	28	28	28	28	N/A	28	28	28	28	28	28
Total Installed Cost (2022$)[2]	$103,327	$110,414	$118,814	$124,495	$124,995	N/A	$124,495	$124,995	$124,495	$124,995	$124,495	$124,995
Annual Maintenance Cost (2022$)	$1,054	$1,054	$1,054	$1,054	$1,054	N/A	$1,054	$1,054	$1,054	$1,054	$1,054	$1,054
Total Installed Cost (2022$/1000 CFM)	$6,888	$6,774	$7,289	$7,638	$7,668	N/A	$7,638	$7,668	$7,638	$7,668	$7,638	$7,668
Annual Maintenance Cost (2022$/1000 CFM)	$70	$65	$65	$65	$65	N/A	$65	$65	$65	$65	$65	$65

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 16,300 CFM VAV AHU, VFD, (10) VAV boxes, (10) VAV controllers with associated space temperature sensor, and hypothetical supply ductwork layout
3. Based on ASHRAE 90.1-2016 and 2019 fan power limit (Table 6.5.3.1.1-1) with no pressure drop adjustment. Assumed 80% motor load and 91% motor efficiency
4. ASHRAE 90.1-2016 and 2019 Section 6.5.3.2 minimum power-flow requirement
5. ASHRAE 90.1-2019 fan power limit and typical VAV power-flow relationship for 40%-100% flow
6. ASHRAE 90.1-2019 fan power limit and typical VAV power-flow relationship for 30%-100% flow
7. High aerodynamic efficiency fan

- 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 the 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 and 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 16,300 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 90.1-2019 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 16,300 CFM VAV packaged indoor air handling unit with cooling and heating coils can be installed for approximately $82,023 (RS Means 2022). Ductwork and (10) VAV boxes with reheat would cost approximately an additional $28,272. (10) VAV controllers and the associated space temperature sensor would cost approximately $8,400 ($118,695 total). A 15 hp variable frequency drive (estimated $5,800) 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 2016 version of Standard 90.1 was used to represent the 2018 minimum efficiency level (state energy codes typically refer to older versions of Standard 90.1 due to code revision cycles).
- Annual maintenance cost assumes 8 hours worth of labor by a technician to perform the necessary tasks (e.g., filter replacement, draining condenser water, etc.)
- 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.
- **For this Advanced Case, the projections from 2030 to 2050 for system fan power and annual fan energy use assume a 5% improvement per decade based on the assumption use of variable frequency drives and incremental improvements in technology will increase.**

Same as Reference Case

DATA	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average[5]	Low[3]	Typical[5]	High[6]	ENERGY STAR	Typical[4,6]	High[4,7]	Typical[4,7]	High[4,8]	Typical[4,8]	High[4,8,9]
System Airflow (CFM)	800	800	800	800	800	N/A	800	800	800	800	800	800
System Fan Power (kW)	0.241	0.241	0.241	0.148	0.148	N/A	0.141	0.134	0.134	0.136	0.136	0.129
Specific Fan Power (W/CFM)	0.302	0.302	0.301	0.185	0.185	N/A	0.176	0.167	0.167	0.170	0.170	0.162
Annual Fan Energy Use (kWh/y)[1]	543	542	542	333	333	N/A	316	301	301	306	306	291
Average Life (years)	37	37	37	37	37	N/A	37	37	37	37	37	37
Total Installed Cost (2022$)[2]	$2,845	$2,688	$3,038	$3,521	$3,961	N/A	$3,961	$4,161	$3,961	$4,161	$3,961	$4,161
Annual Maintenance Cost (2022$)	$117	$117	$117	$117	$117	N/A	$117	$117	$117	$117	$117	$117
Total Installed Cost (2022$/thousand CFM)	$3,557	$3,360	$3,798	$4,401	$4,951	N/A	$4,951	$5,201	$4,951	$5,201	$4,951	$5,201
Annual Maintenance Cost (2022$/thousand CFM)	$146	$146	$146	$146	$146	N/A	$146	$146	$146	$146	$146	$146

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 two-pipe fan coil unit, housing, and controls
3. Based on ASHRAE 90.1-2016 and 2019 fan power limit (Table 6.5.3.1.1-1) with no pressure drop adjustment. Assumed 80% motor load and 91% motor efficiency
4. Based on ASHRAE 90.1-2016 and 2019 Section 6.5.3.6 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 (FCUs) are self-contained, mass-produced assemblies that provide cooling, heating, or cooling and heating, but they do not include the source of cooling or heating. The unit characterized in this report is a cooling only (two-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 manufacturers also offer single speed, two speed, and ECM motors as an option. ASHRAE 90.1-2019 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 90.1-2019 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 2016 version of Standard 90.1 was used to represent the 2018 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

Guidehouse
1200 19th Street, NW, Suite 700
Washington, D.C. 20036

And

Leidos
8301 Greensboro Drive
McLean, VA 22102

Residential Lighting

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

<table>
<tr><th rowspan="2">DATA SOURCES</th><th>2015</th><th>2020</th><th colspan="4">2022</th><th>2023**</th><th colspan="2">2030</th><th colspan="2">2040</th><th colspan="2">2050</th></tr>
<tr><th>Installed Stock Average</th><th></th><th>Low</th><th>Typical</th><th>High</th><th>ENERGY STAR</th><th>Standard</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 rowspan="6">Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td><td rowspan="6">2020 DOE LED Pricing Analysis</td><td colspan="3" rowspan="2">Distributor Websites or Product Catalogs</td><td rowspan="6">ENERGY STAR, 2020</td><td rowspan="3">DOE, 2022</td><td colspan="6">Calculated</td></tr>
<tr><td>Lamp Lumens</td><td colspan="6">Assume Unchanged</td></tr>
<tr><td>Lamp Efficacy (lm/W)</td><td colspan="3">Calculated</td><td colspan="6">Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td></tr>
<tr><td>CRI</td><td colspan="3" rowspan="3">Distributor Websites or Product Catalogs</td><td rowspan="3">N/A</td><td colspan="6" rowspan="2">Assume Unchanged</td></tr>
<tr><td>Correlated Color Temperature (CCT)</td></tr>
<tr><td>Average Lamp Life (thousand hours)</td><td colspan="6">Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td></tr>
<tr><td>Annual Operating Hours (h/y)</td><td colspan="13">DOE, 2017</td></tr>
<tr><td>Lamp Price (2022$)</td><td>Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td><td>2020 DOE LED Pricing Analysis</td><td colspan="3">Distributor Websites or Product Catalogs</td><td>N/A</td><td></td><td colspan="6">Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td></tr>
<tr><td>Lamp Cost (2022$/klm)</td><td colspan="13">Calculated</td></tr>
<tr><td>Labor Cost (2022$/h)</td><td colspan="13" rowspan="2">N/A</td></tr>
<tr><td>Labor Lamp Installation (hours)</td></tr>
<tr><td>Total Installed Cost (2022$)</td><td colspan="6" rowspan="4">Calculated</td><td rowspan="4">N/A</td><td colspan="6" rowspan="4">Calculated</td></tr>
<tr><td>Annual Maintenance Cost (2022$)</td></tr>
<tr><td>Total Installed Cost (2022$/klm)</td></tr>
<tr><td>Annual Maintenance Cost (2022$/klm)</td></tr>
</table>

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

<table>
<tr><th rowspan="2">DATA SOURCES</th><th>2015</th><th>2020</th><th colspan="4">2022</th><th>2023**</th><th colspan="2">2030</th><th colspan="2">2040</th><th colspan="2">2050</th></tr>
<tr><th>Installed Stock Average</th><th></th><th>Low</th><th>Typical</th><th>High</th><th>ENERGY STAR</th><th>Standard</th><th>Typical</th><th>High</th><th>Typical</th><th>High</th><th>Typical</th><th>High</th></tr>
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<tr><td>Lamp Lumens</td><td colspan="6">Assume Unchanged</td></tr>
<tr><td>Lamp Efficacy (lm/W)</td><td colspan="3">Calculated</td><td colspan="6">Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td></tr>
<tr><td>CRI</td><td colspan="3" rowspan="3">Distributor Websites or Product Catalogs</td><td rowspan="3">N/A</td><td colspan="6" rowspan="2">Assume Unchanged</td></tr>
<tr><td>Correlated Color Temperature (CCT)</td></tr>
<tr><td>Average Lamp Life (thousand hours)</td><td colspan="6">Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td></tr>
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<tr><td>Lamp Price (2022$)</td><td>Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td><td>2020 DOE LED Pricing Analysis</td><td colspan="3">Distributor Websites or Product Catalogs</td><td>N/A</td><td></td><td colspan="6">Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)</td></tr>
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<tr><td>Labor Cost (2022$/h)</td><td colspan="13" rowspan="2">N/A</td></tr>
<tr><td>Labor Lamp Installation (hours)</td></tr>
<tr><td>Total Installed Cost (2022$)</td><td colspan="6" rowspan="4">Calculated</td><td rowspan="4">N/A</td><td colspan="6" rowspan="4">Calculated</td></tr>
<tr><td>Annual Maintenance Cost (2022$)</td></tr>
<tr><td>Total Installed Cost (2022$/klm)</td></tr>
<tr><td>Annual Maintenance Cost (2022$/klm)</td></tr>
</table>

Data Sources » Residential Reflector LED BR30

DATA SOURCES	2015 Installed Stock Average	2020	2022 Low	2022 Typical	2022 High	2022 ENERGY STAR	2023** Standard	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Lamp Wattage	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	2020 DOE LED Pricing Analysis	Distributor Websites or Product Catalogs			ENERGY STAR, 2020	DOE, 2022	Calculated					
Lamp Lumens								Assume Unchanged					
Lamp Efficacy (lm/W)			Calculated					Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
CRI			Distributor Websites or Product Catalogs				N/A	Assume Unchanged					
Correlated Color Temperature (CCT)													
Average Lamp Life (thousand hours)								Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Annual Operating Hours (h/y)	DOE, 2017												
Lamp Price (2022$)	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	2020 DOE LED Pricing Analysis	Distributor Websites or Product Catalogs			N/A		Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Lamp Cost (2022$/klm)	Calculated												
Labor Cost (2022$/h)	N/A												
Labor Lamp Installation (hours)													
Total Installed Cost (2022$)	Calculated						N/A	Calculated					
Annual Maintenance Cost (2022$)													
Total Installed Cost (2022$/klm)													
Annual Maintenance Cost (2022$/klm)													

Data Sources » Residential Reflector LED PAR38

DATA SOURCES	2015	2020	2022				2023**	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs			ENERGY STAR, 2020	DOE, 2022	Calculated					
Lamp Lumens								Assume Unchanged					
Lamp Efficacy (lm/W)			Calculated					Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
CRI			Distributor Websites or Product Catalogs				N/A	Assume Unchanged					
Correlated Color Temperature (CCT)													
Average Lamp Life (thousand hours)								Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Annual Operating Hours (h/y)	DOE, 2017												
Lamp Price (2022$)	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs			N/A		Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Lamp Cost (2022$/klm)	Calculated												
Labor Cost (2022$/h)	N/A												
Labor Lamp Installation (hours)													
Total Installed Cost (2022$)	Calculated						N/A	Calculated					
Annual Maintenance Cost (2022$)													
Total Installed Cost (2022$/klm)													
Annual Maintenance Cost (2022$/klm)													

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

DATA SOURCES	2015	2020	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	LED Webscrape Database	DOE Webscrape Database	Distributor Websites			Calculated					
Lamp Lumens						Assume Same as 2022 Typical and High					
Lamp Efficacy (lm/W)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
System Wattage	Calculated										
System Lumens											
System Efficacy (lm/W)											
Ballast Efficiency (BLE)	N/A										
CRI	2016 EIA Ref. Case	Distributor Websites	Distributor Websites								
Correlated Color Temperature (CCT)	2016 EIA Ref. Case										
Average Lamp Life (thousand hours)	LED Webscrape Database	DOE Web Scrape Database									
Annual Operating Hours (h/y)	DOE, 2017										
Lamp Price (2022$)	LED Webscrape Database	DOE Web Scrape Database	Distributor Websites			Calculated					
Ballast Price (2022$)		N/A									
Fixture Price (2022$)											
Lamp Cost (2022$/klm)	Calculated										
System (l/b/f) Cost (2022$/klm)											
Labor Cost (2022$/h)	N/A										
Labor System Installation (hours)											
Labor Lamp Change (hours)											
Total Installed Cost (2022$)	Calculated										
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

Data Sources » Residential Linear LED Luminaire

DATA SOURCES	2015	2020	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A										
Lamp Lumens											
Lamp Efficacy (lm/W)											
System Wattage	LED Webscrape Database	DOE Web Scrape Database	Distributor Websites			Calculated					
System Lumens						Assume Same as 2022 Typical and High					
System Efficacy (lm/W)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Efficiency (BLE)	N/A										
CRI	LED Webscrape Database	DOE Web Scrape Database	Distributor Websites			Distributor Websites					
Correlated Color Temperature (CCT)											
Average Lamp Life (thousand hours)											
Annual Operating Hours (h/y)	DOE, 2017										
Lamp or Luminaire Price (2022$)	LED Webscrape Database	DOE Web Scrape Database	Distributor Websites			Calculated					
Ballast Price (2022$)	N/A										
Fixture Price (2022$)											
Lamp Cost (2022$/klm)											
System (l/b/f) Cost (2022$/klm)											
Labor Cost (2022$/h)	2016 EIA Ref. Case		2022 RS Means Online								
Labor System Installation (hours)											
Labor Lamp Change (hours)			N/A								
Total Installed Cost (2022$)	Calculated										
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

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

DATA SOURCES	2015	2020	2022				2023*	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	Same as Residential LED PAR38												
Lamp Lumens													
Lamp Efficacy (lm/W)													
CRI													
Correlated Color Temperature (CCT)													
Average Lamp Life (1000 hrs)													
Annual Operating Hours (hrs/yr)													
Lamp Price (2022$)													
Lamp Cost (2022$/klm)													
Labor Cost (2022$/hr)													
Labor Lamp Installation (hr)													
Total Installed Cost (2022$)													
Annual Maintenance Cost (2022$)													
Total Installed Cost (2022$/klm)													
Annual Maintenance Cost (2022$/klm)													

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

DATA SOURCES	2015	2020	2022				2023*	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR*	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	2020 DOE LED Pricing Analysis	Distributor Websites or Product Catalogs			ENERGY STAR, 2020	DOE, 2022	Calculated					
Lamp Lumens								Assume Unchanged					
Lamp Efficacy (lm/W)			Calculated					Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
CRI			Distributor Websites or Product Catalogs				N/A	Assume Unchanged					
Correlated Color Temperature (CCT)													
Average Lamp Life (thousand hours)								Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Annual Operating Hours (h/y)	DOE, 2017												
Lamp Price (2022$)	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	2020 DOE LED Pricing Analysis	Distributor Websites or Product Catalogs			N/A		Model DOE Goals Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Lamp Cost (2022$/klm)	Calculated												
Labor Cost (2022$/h)	N/A												
Labor Lamp Installation (hours)													
Total Installed Cost (2022$)	Calculated												
Annual Maintenance Cost (2022$)													
Total Installed Cost (2022$/klm)													
Annual Maintenance Cost (2022$/klm)													

Commercial Lighting

Data Sources » Commercial General Service 100W Equivalent LED Replacement Lamp in Recessed Can Fixture

DATA SOURCES	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2022 ENERGY STAR	2023 Standard	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Lamp Wattage	2016 EIA Reference Case	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	Distributor Websites or Product Catalogs			ENERGY STAR, 2020	DOE, 2022	Calculated					
Lamp Lumens								Assume Unchanged					
Lamp Efficacy (lm/W)								Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
System Wattage		Calculated											
System Lumens*													
System Efficacy (lm/W)													
Ballast Efficiency (BLE)													
CRI		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	Distributor Websites or Product Catalogs			ENERGY STAR, 2020	N/A	Assume Unchanged					
Correlated Color Temperature (CCT)						N/A							
Average Lamp Life (thousand hours)						ENERGY STAR, 2020		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)				Assume Unchanged	
Annual Operating Hours (h/y)	DOE, 2017												
Lamp Price (2022$)	2016 EIA Reference Case	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	Distributor Websites or Product Catalogs			N/A		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Price (2022$)		N/A						N/A					
Fixture Price (2022$)*													
Lamp Cost (2022$/klm)		Calculated						Calculated					
System (l/b/f) Cost (2022$/klm)		N/A						N/A					
Labor Cost (2022$/h)		2016 EIA Reference Case	2022 RS Means Online					2022 RS Means Online					
Labor System Installation (hours)													
Labor Lamp Change (hours)													
Total Installed Cost (2022$)		Calculated						Calculated					
Annual Maintenance Cost (2022$)													
Total Installed Cost (2022$/klm)													
Annual Maintenance Cost (2022$/klm)													

Data Sources » Commercial LED Reflector Lighting (PAR38)

DATA SOURCES	2012	2018	2022				2023	2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Standard	Typical	High	Typical	High	Typical	High
Lamp Wattage		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	Distributor Websites or Product Catalogs			ENERGY STAR, 2020	DOE, 2022	Calculated					
Lamp Lumens								Assume Unchanged					
Lamp Efficacy (lm/W)								Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
System Wattage		Calculated											
System Lumens*	2016 EIA Reference Case												
System Efficacy (lm/W)													
Ballast Efficiency (BLE)													
CRI		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	Distributor Websites or Product Catalogs			ENERGY STAR, 2020	N/A	Assume Unchanged					
Correlated Color Temperature (CCT)						N/A							
Average Lamp Life (thousand hours)						ENERGY STAR, 2020		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)				Assume Unchanged	
Annual Operating Hours (h/y)	DOE, 2017												
Lamp Price (2022$)	2016 EIA Reference Case	Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	Distributor Websites or Product Catalogs			N/A		Model Reference Scenario, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Price (2022$)		N/A						N/A					
Fixture Price (2022$)													
Lamp Cost (2022$/klm)		Calculated						Calculated					
System (l/b/f) Cost (2022$/klm)		N/A						N/A					
Labor Cost (2022$/h)		2016 EIA Reference Case	2022 RS Means Online					2022 RS Means Online					
Labor System Installation (hours)													
Labor Lamp Change (hours)													
Total Installed Cost (2022$)		Calculated						Calculated					
Annual Maintenance Cost (2022$)													
Total Installed Cost (2022$/klm)													
Annual Maintenance Cost (2022$/klm)													

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

DATA SOURCES	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	2016 EIA Ref. Case	LED Webscrape Database	Distributor Websites			Calculated					
Lamp Lumens						Assume Same as 2022 Typical and High					
Lamp Efficacy (lm/W)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
System Wattage		Calculated									
System Lumens											
System Efficacy (lm/W)											
Ballast Efficiency (BLE)		N/A									
CRI		Distributor Websites									
Correlated Color Temperature (CCT)											
Average Lamp Life (thousand hours)											
Annual Operating Hours (h/y)		DOE, 2017									
Lamp Price (2022$)		LED Webscrape Database	Distributor Websites			Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Price (2022$)		N/A									
Fixture Price (2022$)											
Lamp Cost (2022$/klm)		Calculated									
System (l/b/f) Cost (2022$/klm)											
Labor Cost (2022$/h)		2016 EIA Ref. Case	2022 RS Means Online								
Labor System Installation (hours)		N/A									
Labor Lamp Change (hours)		Assume unchanged									
Total Installed Cost (2022$)		Calculated									
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

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

DATA SOURCES	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Lamp Wattage	2016 EIA Ref. Case	N/A									
Lamp Lumens											
Lamp Efficacy (lm/W)											
System Wattage		LED Webscrape Database	Distributor Websites			Calculated					
System Lumens						Assume Same as 2022 Typical and High					
System Efficacy (lm/W)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Efficiency (BLE)		N/A				N/A					
CRI		Distributor Websites									
Correlated Color Temperature (CCT)											
Average Lifetime (thousand hours)											
Annual Operating Hours (h/y)		DOE, 2017									
Lamp or Luminaire Price (2022$)		LED Webscrape Database	Distributor Websites			Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Price (2022$)		N/A									
Fixture Price (2022$)											
Lamp Cost (2022$/klm)											
System (l/b/f) Cost (2022$/klm)		Calculated									
Labor Cost (2022$/h)		2016 EIA Ref. Case	2022 RS Means Online								
Labor System Installation (hours)		2022 RS Means Online									
Labor Lamp Change (hours)		N/A									
Total Installed Cost (2022$)		Calculated									
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

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

DATA SOURCES	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage	N/A	2016 EIA Ref. Case, 2015 typical	Distributor Websites			Calculated					
Lamp Lumens						Assume Same as 2022 Typical and High					
Lamp Efficacy (lm/W)			Calculated			Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
System Wattage		Calculated				Calculated					
System Lumens											
System Efficacy (lm/W)											
Ballast Efficiency (BLE)		N/A									
CRI		2016 EIA Ref. Case, 2015 typical	Distributor Websites								
Correlated Color Temperature (CCT)											
Average Lamp Life (thousand hours)											
Annual Operating Hours (h/y)		DOE, 2017									
Lamp Price (2022$)		2016 EIA Ref. Case, 2015 typical	Distributor Websites			Calculated					
Ballast Price (2022$)			N/A								
Fixture Price (2022$)											
Lamp Cost (2022$/klm)			Calculated								
System (l/b/f) Cost (2022$/klm)											
Labor Cost (2022$/h)			2022 RS Means Online								
Labor System Installation (hours)		N/A									
Labor Lamp Change (hours)		Chapter 8; Table 8.2.4 of GSFL IRL Preliminary Analysis TSD (DOE, 2013)									
Total Installed Cost (2022$)		Calculated									
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

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

DATA SOURCES	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Lamp Wattage	N/A	N/A									
Lamp Lumens											
Lamp Efficacy (lm/W)											
System Wattage		2016 EIA Ref. Case, 2015 typical	Distributor Websites			Calculated					
System Lumens						Assume Same as 2022 Typical and High					
System Efficacy (lm/W)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Efficiency (BLE)		N/A									
CRI		2016 EIA Ref. Case, 2015 typical	Distributor Websites								
Correlated Color Temperature (CCT)											
Average Lifetime (thousand hours)											
Annual Operating Hours (h/y)		DOE, 2017									
Lamp or Luminaire Price (2022$)		2016 EIA Ref. Case, 2015 typical	Distributor Websites								
Ballast Price (2022$)		N/A									
Fixture Price (2022$)											
Lamp Cost (2022$/klm)											
System (l/b/f) Cost (2022$/klm)		Calculated									
Labor Cost (2022$/h)		2016 EIA Ref. Case, 2015 typical	2022 RS Means Online								
Labor System Installation (hours)											
Labor Lamp Change (hours)		N/A									
Total Installed Cost (2022$)		Calculated									
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

Data Sources » Commercial LED Low-Bay Luminaire

DATA SOURCES	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Lamp Wattage	N/A										
Lamp Lumens											
Lamp Efficacy (lm/W)											
System Wattage	2016 EIA Reference Case	Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)	N/A	Distributor Websites or Product Catalogs		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
System Lumens											
System Efficacy (lm/W)											
Ballast Efficiency		N/A		N/A		N/A					
CRI		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs		Assume Unchanged					
Correlated Color Temperature (CCT)											
Average Lifetime (thousand hours)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Annual Operating Hours (h/y)	DOE, 2017			DOE, 2017							
Lamp or Luminaire Price (2022$)	2016 EIA Reference Case	Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Price (2022$)		N/A		N/A		N/A					
Fixture Price (2022$)											
Lamp Cost (2022$/klm)											
System (l/b/f) Cost (2022$/klm)		Calculated		Calculated		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Labor Cost (2022$/h)		2016 EIA Reference Case		2022 RS Means Online							
Labor System Installation (hours)											
Labor Lamp Change (hours)											
Total Installed Cost (2022$)	Calculated			Calculated		Calculated					
Annual Maintenance Cost (2022$)											
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

Data Sources » Commercial LED High-Bay Luminaire

DATA SOURCES	2012	2018	2022			2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	Typical	High	Typical	High	Typical	High
Lamp Wattage											
Lamp Lumens	N/A										
Lamp Efficacy (lm/W)											
System Wattage											
System Lumens											
System Efficacy (lm/W)		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Efficiency (BLE)	2016 EIA Reference Case	N/A		N/A		N/A					
CRI						Assume Unchanged					
Correlated Color Temperature (CCT)											
Average Lifetime (thousand hours)		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Annual Operating Hours (h/y)	DOE, 2017		N/A	DOE, 2017		DOE, 2017					
Lamp or Luminaire Price (2022$)		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)		Distributor Websites or Product Catalogs		Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Ballast Price (2022$)	2016 EIA Reference Case										
Fixture Price (2022$)						N/A					
Lamp Cost (2022$/klm)		N/A		N/A							
System (l/b/f) Cost (2022$/klm)		Calculated		Calculated							
Labor Cost (2022$/h)						Model, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (Navigant, 2019)					
Labor System Installation (hours)											
Labor Lamp Change (hours)		2016 EIA Reference Case		2022 RS Means Online							
Total Installed Cost (2022$)											
Annual Maintenance Cost (2022$)	Calculated			Calculated		Calculated					
Total Installed Cost (2022$/klm)											
Annual Maintenance Cost (2022$/klm)											

Refrigeration

Data Sources » Commercial Compressor Rack Systems

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Total Capacity (kBtu/h)	ADL, 1996	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Median Store Size (ft^2)	Food Marketing Institute (FMI), 2012	CBECS 2018										
Power Input (kW)	Copeland, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Energy Use (MMWh/y)	ADL, 1996 / NCI Analysis, 2015	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Indexed Annual Efficiency	Calculated											
Average Life (years)	Kysor-Warren, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Total Installed Cost (2022$)	NCI, 2009 / NCI Analysis, 2012	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

Data Sources » Commercial Condensers

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Total Capacity (kBtu/h)	NCI Analysis, 2008 / Heatcraft, 2008 / ADL, 1996	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Median Store Size (ft^2)	Food Marketing Institute (FMI), 2012	CBECS 2018										
Power Input (kW)	NCI Analysis, 2008 / Heatcraft, 2008 / ADL, 1996	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Energy Use (MMWh/y)	NCI Analysis, 2008 / ADL, 1996	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Indexed Annual Efficiency	Calculated											
Average Life (years)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Total Installed Cost (2022$)	NCI Analysis, 2008 / Heatcraft, 2008 / RS Means, 2007	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

Data Sources » Commercial Supermarket Display Cases

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	ENERGY STAR	High	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Median Store Size (ft²)	Food Marketing Institute (FMI), 2012	CBECS 2018										
Case Length (ft)	DOE, 2016: CRE Report / Guidehouse Analysis 2022											
Annual Energy Use (kWh/y)[1,2]	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Energy Use / Case Length (kWh/ft)	Calculated											
Indexed Annual Efficiency[3]	Calculated											
Average Life (years)	DOE, 2007 / NCI Analysis, 2008	DOE, 2016: CRE Report / Guidehouse Analysis 2022										
Retail Equipment Cost (2022$)	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022 / The Restaurant Store										
Total Installed Cost (2022$)	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)[4]	DOE, 2007 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

Data Sources » Commercial Reach-In Refrigerators

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE Report										
Size (ft³)	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE Report										
Annual Energy Use (kWh/y)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022 / ENERGY STAR 2022										
Annual Energy Use / Volume (kWh/y/ft³)	NCI Analysis, 2012	Calculated										
Indexed Annual Efficiency	Calculated											
Average Life (years)	Calculated											
Retail Equipment Cost (2022$)	ACEEE, 2002	DOE, 2014: CRE TSD										
Total Installed Cost (2022$)	ADL, 1996/ Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022 / ENERGY STAR 2022 / The Restaurant Store										
Total Installed Cost (2022$/kBtu/h)	Distributor Web Sites / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$)	Calculated											
Annual Maintenance Cost (2022$/kBtu/h)	NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

Data Sources » Commercial Reach-In Freezers

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	ADL, 1996 / NCI Analysis, 2008	DOE, 2016: CRE Report										
Size (ft^3)	ADL, 1996 / Distributor Web Sites	DOE, 2016: CRE Report										
Annual Energy Use (kWh/y)	ADL, 1996 / NCI Analysis, 2008	DOE, 2016: CRE Report / Guidehouse Analysis 2022										
Annual Energy Use / Volume (kWh/y/ft^3)	NCI Analysis, 2012	Calculated										
Indexed Annual Efficiency	Calculated											
Average Life (years)	ACEEE, 2002	DOE, 2016: CRE Report / Guidehouse Analysis 2022										
Retail Equipment Cost (2022$)	ADL, 1996/ Distributor Web Sites / NCI Analysis, 2008	DOE, 2016: CRE Report / Guidehouse Analysis 2022 / ENERGY STAR 2022 / The Restaurant Store										
Total Installed Cost (2022$)	Distributor Web Sites / NCI Analysis, 2008	DOE, 2016: CRE Report / Guidehouse Analysis 2022										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	NCI Analysis, 2008	DOE, 2016: CRE Report / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	DOE CRE Report 2016 / CCMS 2022 / Guidehouse Analysis 2022											
Size (ft^2)	DOE 2014 WICF TSD / Guidehouse Analysis 2022											
Annual Energy Use (kWh/y)	ADL, 1996 / PG&E, 2004 / NCI Analysis, 2008	DOE CRE Report 2016 / Guidehouse Analysis 2022										
Annual Energy Use / Area (kWh/ft^2/y)	Calculated											
Indexed Annual Efficiency	Calculated											
Insulated Box Average Life (years)	ADL, 1996 / PG&E, 2004	DOE CRE Report 2016 / Guidehouse Analysis 2022										
Compressor Average Life (years)	ADL, 1996 / PG&E, 2004	DOE CRE Report 2016 / Guidehouse Analysis 2022										
Retail Equipment Cost (2022$)	ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008	DOE CRE Report 2016 / Webstaurant 2022 / Guidehouse Analysis 2022										
Total Installed Cost (2022$)	ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008	DOE CRE Report 2016 / Webstaurant 2022 / Guidehouse Analysis 2023										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	ADL, 1996 / FMI, 2005 / NCI Analysis, 2008	DOE CRE Report 2016 / Guidehouse Analysis 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

Data Sources » Commercial Walk-In Freezers

DATA SOURCES	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2022 ENERGY STAR	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Cooling Capacity (Btu/h)	ADL, 1996 / NCI Analysis, 2008	DOE CRE Report 2016 / CCMS 2022 / Guidehouse Analysis 2022										
Size (ft^2)	ADL, 1996 / NCI Analysis, 2008	Guidehouse Analysis 2022										
Annual Energy Use (kWh/y)	ADL, 1996 / PG&E, 2004 / NCI Analysis, 2008	Guidehouse CRE Report 2016										
Annual Energy Use / Area (kWh/ft^2/y)	Calculated											
Indexed Annual Efficiency	Calculated											
Insulated Box Average Life (years)	ADL, 1996 / PG&E, 2004	DOE CRE Report 2016 / Guidehouse Analysis 2022										
Compressor Average Life (years)	ADL, 1996 / PG&E, 2004	DOE CRE Report 2016 / Guidehouse Analysis 2022										
Retail Equipment Cost (2022$)	ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008	DOE CRE Report 2016 / Webstaurant 2022 / Guidehouse Analysis 2022										
Total Installed Cost (2022$)	ADL, 1996 / Distributor Web Sites / NCI Analysis, 2008	DOE CRE Report 2016 / Webstaurant 2022 / Guidehouse Analysis 2023										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	DOE CRE Report 2016 / Guidehouse Analysis 2022											
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Output (pounds [lbs] per day)	ADL, 1996 / NCI Analysis, 2008	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022 / CCMS Database 2022										
Water Use per Hundred Pounds (gal/hundred lbs)	ADL, 1996 / Distributor Web Sites	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022 / CCMS Database 2022										
Energy Use per Hundred Pounds (kWh/hundred lbs)	ADL, 1996 / NCI Analysis, 2008	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022										
Annual Energy Use (kWh/y)	ACEEE, 2002 / NCI Analysis, 2012	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022 / ENERGY STAR										
Indexed Annual Efficiency	Calculated											
Average Life (years)	ADL, 1996/ Distributor Web Sites / NCI Analysis, 2008	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022										
Retail Equipment Cost (2022$)	Distributor Web Sites / NCI Analysis, 2008	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022										
Total Installed Cost (with Bin)	NCI Analysis, 2008	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	ADL, 1996 / NCI Analysis, 2008	DOE, 2022: ACIM TSD / Guidehouse Analysis, 2022										
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
Cooling Capacity (Btu/h)	DOE, 2014: CRE Report / Guidehouse Analysis 2022											
Size (ft^3)	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Annual Energy Use (kWh/y)	ADL, 1996 / NCI Analysis, 2008	DOE, 2014: CRE Report / Guidehouse Analysis 2022 / ENERGY STAR 2022										
Annual Energy Use / Volume (kWh/ft^3/y)	Calculated											
Indexed Annual Efficiency	Calculated											
Average Life (years)	ACEEE, 2002	DOE, 2014: CRE Report / Guidehouse Analysis 2022										
Retail Equipment Cost (2022$)	ADL, 1996 / Distributor Web Sites	DOE, 2014: CRE Report / Guidehouse Analysis 2022 / KaTom Restaurant Supply										
Total Installed Cost (2022$)	DOE, 2014: CRE Report / Guidehouse Analysis 2022											
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	DOE, 2014: CRE Report / Guidehouse Analysis 2022											
Annual Maintenance Cost (2022$/kBtu/h)	Calculated											

Data Sources » Commercial Refrigerated Vending Machines

DATA SOURCES	2012 Installed Stock Average	2018 Installed Stock Average	2022 Low	2022 Typical	2022 High	2022 ENERGY STAR	2030 Typical	2030 High	2040 Typical	2040 High	2050 Typical	2050 High
Cooling Capacity (Btu/h)	DOE, 2015: BVM TSD / Guidehouse Analysis, 2015	DOE, 2022: BVM TSD / Guidehouse Analysis, 2022										
Can Capacity	DOE, 2015: BVM TSD	DOE, 2022: BVM TSD										
Size (ft³)	DOE, 2022: BVM TSD / Guidehouse Analysis, 2022											
Annual Energy Use (kWh/y)	DOE, 2015: BVM TSD	DOE, 2022: BVM TSD										
Annual Energy Use / Volume (kWh/ft³/y)	Calculated											
Indexed Annual Efficiency	Calculated											
Average Life (years)	DOE, 2015: BVM TSD	DOE, 2022: BVM TSD										
Retail Equipment Cost (2022$)	DOE, 2015: BVM TSD	DOE, 2022: BVM TSD										
Total Installed Cost (2022$)	DOE, 2015: BVM TSD	DOE, 2022: BVM TSD										
Total Installed Cost (2022$/kBtu/h)	Calculated											
Annual Maintenance Cost (2022$)	DOE, 2015: BVM TSD / Guidehouse Analysis, 2015	DOE, 2022: BVM TSD / Guidehouse Analysis, 2022										
Annual Maintenance Cost (2022$/kBtu/h)	DOE, 2022: BVM TSD / Guidehouse Analysis, 2022											

Commercial Ventilation

Data Sources » Commercial Constant Air Volume Ventilation

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
System Airflow (CFM)	CBECS 2003 & BED 2007	CBECS 2018										
System Fan Power (kW)	ASHRAE 90.1-2007	ASHRAE 90.1-2016	ASHRAE 90.1-2019	ASHRAE 90.1 2019 / Guidehouse Analysis 2022								
Specific Fan Power (W/CFM)												
Annual Fan Energy Use (kWh/y)												
Average Life (years)	ASHRAE: Service Life Database											
Total Installed Cost (2022$)	2022 RS Means Online											
Annual Maintenance Cost (2022$)	2022 RS Means Online / Guidehouse											
Total Installed Cost (2022$/thousand CFM)	Calculated											
Annual Maintenance Cost (2022$/thousand CFM)	Calculated											

DATA SOURCES	2012	2018	2022				2030		2040		2050	
	Installed Stock Average	Installed Stock Average	Low	Typical	High	ENERGY STAR	Typical	High	Typical	High	Typical	High
System Airflow (CFM)	CBECS 2003 & BED 2007	CBECS 2018										
System Fan Power (kW)	ASHRAE 90.1-2007	ASHRAE 90.1-2016	ASHRAE 90.1-2019	ASHRAE 90.1 2019 / Guidehouse Analysis 2022								
Specific Fan Power (W/CFM)												
Annual Fan Energy Use (kWh/y)												
Average Life (years)	ASHRAE: Service Life Database											
Total Installed Cost (2022$)	2022 RS Means Online											
Annual Maintenance Cost (2022$)	2022 RS Means Online / Guidehouse											
Total Installed Cost (2022$/thousand CFM)	Calculated											
Annual Maintenance Cost (2022$/thousand CFM)	Calculated											

Data Sources » Commercial Fan Coil Unit

<table>
<tr><th rowspan="2">DATA SOURCES</th><th>2012</th><th>2018</th><th colspan="4">2022</th><th colspan="2">2030</th><th colspan="2">2040</th><th colspan="2">2050</th></tr>
<tr><th>Installed Stock Average</th><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>System Airflow (CFM)</td><td colspan="12">Product Literature</td></tr>
<tr><td>System Fan Power (kW)</td><td rowspan="3">ASHRAE90.1-2007</td><td rowspan="3">ASHRAE90.1-2016</td><td rowspan="3">ASHRAE90.1-2019</td><td colspan="9" rowspan="3">ASHRAE90.1 2019 / Guidehouse Analysis 2022</td></tr>
<tr><td>Specific Fan Power (W/CFM)</td></tr>
<tr><td>Annual Fan Energy Use (kWh/y)</td></tr>
<tr><td>Average Life (years)</td><td colspan="12">ASHRAE: Service Life Database</td></tr>
<tr><td>Total Installed Cost (2022$)</td><td colspan="12">2022 RS Means Online</td></tr>
<tr><td>Annual Maintenance Cost (2022$)</td><td colspan="12">2022 RS Means Online / Guidehouse</td></tr>
<tr><td>Total Installed Cost (2022$/thousand CFM)</td><td colspan="12">Calculated</td></tr>
<tr><td>Annual Maintenance Cost (2022$/thousand CFM)</td><td colspan="12">Calculated</td></tr>
</table>

Appendix B
References

Guidehouse
1200 19th Street, NW, Suite 700
Washington, D.C. 20036

And

Leidos
11951 Freedom Drive
Reston, VA 20190

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