Bonneville Power Administration Non-Residential Lighting Market Model Methodology

May 2022

Contributors

Kate Bushman, Nolan Kelley, Ethan Wilkes, and Rob Carmichael, Cadeo Group

Please refer questions to the BPA Project Lead, Juan Carlos Blacker, at jcblacker@bpa.gov

Acknowledgements

This model is a direct result of the diligent and thoughtful engagement from countless individuals. Bonneville Power Administration's Market Research Team would like to thank everyone who provided feedback and recommendations throughout model development, including the members of the Expert Panel: Chris Meek, Geoff Cooper, Wesley Whited, John Morris, Paul Sklar, Greg Brown, and Kathryn Bae. BPA would also like to acknowledge the team that originated this model, led by Laura Tabor.

Introduction

As a public energy provider in the Pacific Northwest (the region), Bonneville Power Administration (BPA) aims to continually improve the regional body of knowledge about energy consumption and savings. This helps BPA and other regional organizations better track, understand, and account for energy consumption and energy efficiency activities in the region. These efforts serve to facilitate regional power planning, support program efforts, and help the region understand the impact new technologies have on the market. To achieve this improved insight, BPA develops quantitative models that characterize the energy consumption of different regional markets. These market models calculate the size of a market year-over-year and estimate the change in energy consumption over time. They also account for the program savings (through regional utility incentive programs or market transformation initiatives) and quantify Momentum Savings, defined as cost-effective energy savings resulting from newly installed energy efficiency measures that are above the Northwest Power and Conservation Council (the Council) baseline and not included in program savings.[1]

This memo documents the Cadeo team's (the research team's) methodology for estimating non-residential lighting Momentum Savings. BPA and its contractors originally developed this methodology for BPA's 2009-2015 Non-Residential Lighting Momentum Savings Model, and subsequently updated the methodology for the 2016-2021 Non-Residential Lighting Momentum Savings Model. The team presents the methodology per the Four Question Framework, which is BPA's standard analytical framework for estimating Momentum Savings.

Momentum Savings Analysis Framework

The research team answered four key questions to calculate non-residential lighting Momentum Savings over the Council's Seventh Power Plan action plan period (2016-2021). These questions are as follows:

1. What is the market?
2. How big is the market?
3. What are the total market savings?
4. What are the program savings?

Answers to these questions provide the data necessary to estimate Momentum Savings—the energy savings that occur above the Seventh Plan frozen baseline and that are not directly incented by programs or claimed as part of the Northwest Energy Efficiency Alliance's (NEEA's) net market effects.

The research team followed the Four Question Framework to define the non-residential lighting market.

Question 1 describes what elements the non-residential lighting market includes such as geographic scope, sectors impacted, and technology types installed throughout the region.

---

[1] "Methods for Calculating Momentum Savings", August 2016, https://www.bpa.gov/EE/Utility/Momentum-Savings/Documents/Methods_for_calculating_Momentum_Savings.pdf, accessed February 6, 2022

Question 2 uses several regional sources to estimate exactly how big the non-residential lighting market is as well as the number of installed fixtures[2] included in the commercial, industrial, agricultural, and outdoor lighting sectors. This data informs the stock turnover model the team built to estimate the changes in the efficiency mix of sales and installed lamps and fixtures over time, addressing **Question 3.** The model incorporates the total number of installed fixtures across the many sectors, application types, and technology types that make up the non-residential lighting market. **Question 3** also describes how the team used detailed sales data from regional distributors along with regional stock assessment data to calibrate this model.

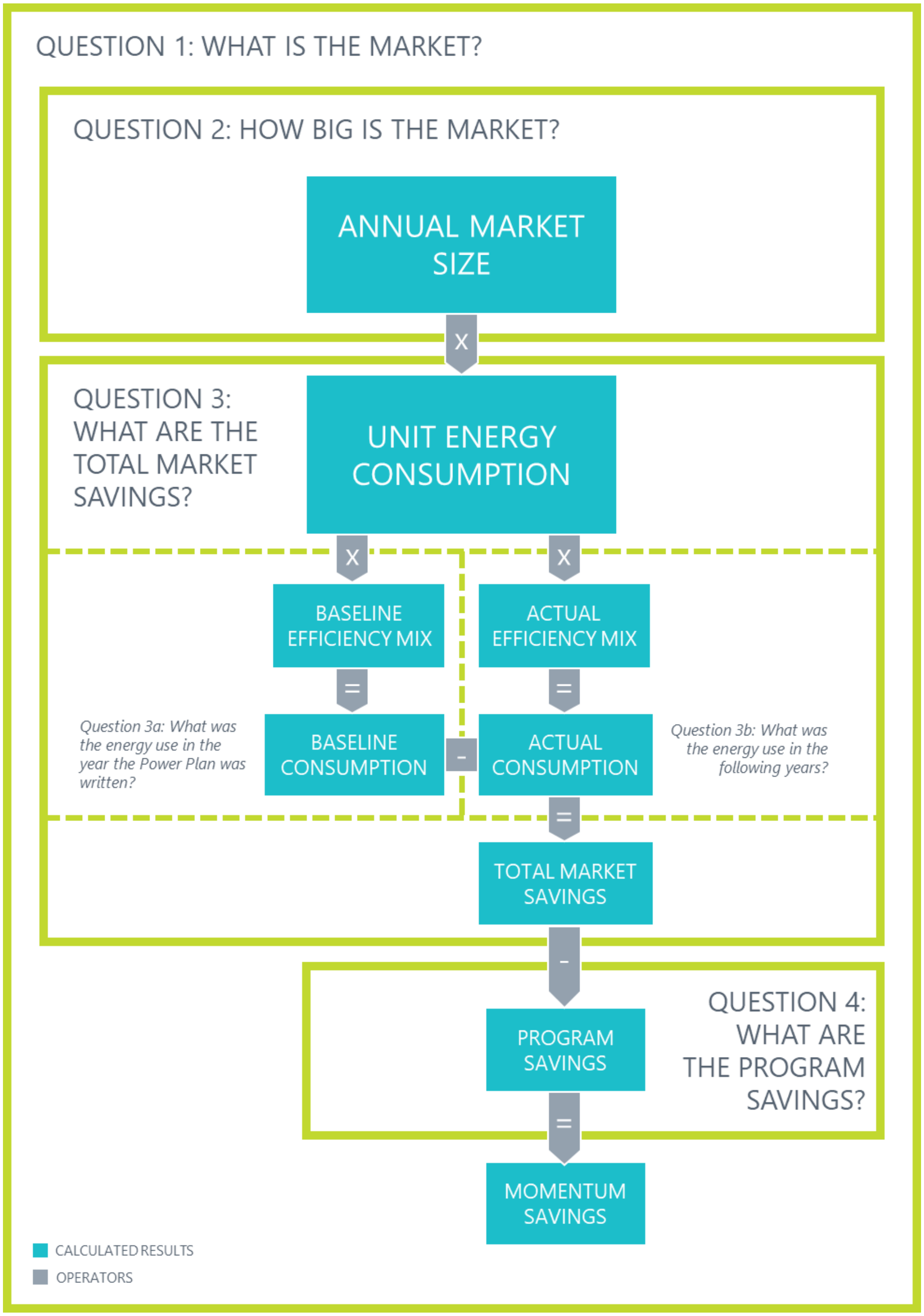
Question 4 defines the programmatic savings across the region during the study period that the team removes from the total market savings to arrive at Momentum Savings.

Answers to these questions are necessary interim steps of the methodology to estimate Momentum Savings and are shared in this memo for transparency. These steps are not used for other program reporting or auditing purposes. Figure 1 summarizes how the four questions fit together to estimate Momentum Savings.

---

[2] The research team had to first identify the total number of installed fixtures throughout the region; thus, Question 2 defines the market in terms of fixtures. The team then used a stock turnover model (defined in Question 3) to distribute the total fixtures across the various technology types for the study. Since the number of lamps per fixture depends on the technology type, only then could the team estimate the market size in terms of lamps.

Figure 1: Overview of the General Momentum Savings Analysis Framework



Question 1: What is the market?

Question 1 of the Four Question Framework defines the various elements and dimensions of the non-residential lighting market, including technologies, sectors, applications, and geographic boundaries. Table 1 defines the unit of account, dimensions, and scope of the overall market used in this study.

Table 1: Market Definitions

Dimension	Scope of Model	Notes
Unit of Account	All installed **lamps** in the geographic, sector, application, and technology scopes listed below	The model tracks sales of lamps, ballasts, and fixtures. Lamp characteristics and assumed average number of lamps per ballast and fixture dictate ballast and fixture consumption. Thus, the primary unit of account is lamps.
Geographic Scope	Oregon, Washington, Idaho, and Western Montana[3]	Consistent with the regional power plan; the research team did not vary stock or sales mixes by this dimension.
Sector	Interior and exterior lighting in commercial, industrial, and agricultural buildings; outdoor lighting	Agriculture uses the same sales and stock mix as industrial.
Building Type	All commercial building types	Applies to commercial sector only; the research team did not vary sales mixes by this dimension. Stock inputs began at the building type level, but the team aggregated all data to the sector level for the analysis.
Application	Dominant lighting applications in each sector; specific exclusions include exit signs, refrigerated case lighting, and railway and airfield lighting	Defined as a common lighting need in the market that can be met by several competing technologies; may be further divided by lumen bins.
Technology	Dominant technologies within each application	Defined as an individual technology that is modeled as a distinct product choice within appropriate applications. The model includes lighting technologies only and does not include controls.
Purchase Triggers	New construction, maintenance, and natural replacement	Lamp and ballast burnout drive maintenance; retrofit, renovation, and system turnover drive natural replacement. LED technologies can only leave the stock due to maintenance (lamp or driver burnout).

Unit of Account

The unit of account is the metric the research team uses to quantify the non-residential lighting market. In this analysis, the unit of account is the installed **lamps** in each year of the analysis. That is, the research team defines the market as the total number of lamps in service each year of the analysis period. The model also tracks total installed fixtures and ballasts since the number of lamp installations depends on the characteristics of the installed fixtures (e.g., linear fixtures can have anywhere from one to eight lamps

---

[3] The sales mix reflects sales from all of Montana, but the stock and sales market size only represents Western Montana.

depending on the application). The number of lamps per fixture also affects the number of ballasts per fixture, which in turn affects the total wattage and lumen output of the fixture, lamp, and ballast system.

Sector and Building Type Definitions

The team sought to define comprehensive and mutually exclusive sectors that represented all non-residential lighting applications in the Pacific Northwest. The results include four distinct sectors: commercial, industrial, agricultural, and outdoor lighting. The agricultural sector includes indoor agriculture buildings only. Other agricultural buildings, such as food or crop processing facilities, are included in the industrial sector.

Commercial

The commercial sector covers lighting applications in building types as defined in the Seventh Plan and includes any exterior lighting associated with these buildings. Table 2 provides the list of commercial building types.

Table 2: Building Types Included in the Commercial Sector

Commercial Building Types
Office*
Retail*
School K-12
University
Warehouse
Grocery*
Restaurant
Lodging
Hospital
Residential Care
Assembly
Other

**The research team collapsed granular categories in the Office, Retail, and Grocery sectors from the Seventh Plan for conciseness.*

Industrial

The industrial sector covers lighting applications in building types as defined by the Industrial Facilities Stock Assessment (IFSA) conducted by NEEA and includes any exterior lighting associated with these buildings. This category also includes agricultural building stock because the research team did not have enough data to effectively distinguish between the two. The exception to this is indoor agriculture, specifically where crops are grown indoors, which is included in a separate sector.

Agricultural

For the purposes of this Momentum Savings model, the agricultural sector includes only buildings used for indoor agriculture. The model's characterization of stock in this sector is based on data sources that focus exclusively on the cannabis industry.[4]

Outdoor Lighting

The team included outdoor lighting applications not associated with buildings, such as street and roadway lights.

Application and Technology Definitions

Applications provide a useful framework for non-residential lighting because they segment the various technologies that are eligible for installation. Applications are specific uses of lighting technologies in specific spaces that share some characteristics such as installation practices, wattage, lamp type, or other characteristics. For example, only a small set of technology types work as large downlights, as defined in Table 3. The team defined the major applications and eligible technologies that can be installed within them to understand the correlation between incumbent (less efficient) and efficient technologies.

BPA determined the model's applications based on the following sources:

- The US Department of Energy's (DOE's) national lighting model, which is also organized by application
- The Seventh Plan, which focused on a subset of lighting applications
- Efficiency program measure offering descriptions
- Manufacturer product categories
- Lamp and fixture type categories in NEEA's 2014 and 2019 Commercial Building Stock Assessments (CBSAs)

Table 3 provides a complete list of the applications covered in this study, the eligible technologies within each application, and which applications are included in each sector.[5]

---

[4] Cannabis industry square footage is defined as square feet of lit canopy, and is segmented into spaces utilized for propagation, vegetation, and flowering.

[5] Commercial and industrial have both interior and exterior applications in the model. The outdoor sector consists of only outdoor lighting applications not associated with buildings (e.g., street lighting) and is mutually exclusive of the exterior lighting in the other sectors.

Table 3: Summary of Application Definitions and Eligible Technologies

Application	Description	Eligible Technologies	Sectors
Ambient Linear	Low bay linear lighting lamps and luminaires	Linear Fluorescent LED Tubes LED Luminaires	Interior Commercial Interior Industrial
General Purpose/ Omnidirectional	Omnidirectional lamps used for general purpose lighting	Incandescent LED Halogen CFL	Interior Commercial Interior Industrial
Downlight Large	Directional lamps (pin and screw base) and downlight luminaires **Large:** PAR and R/BR lamps	Incandescent LED Lamps Halogen CFL LED Luminaires	Interior Commercial Interior Industrial
Track Large	Display and track lighting **Large:** PAR and R/BR lamps (diameter > 2.5")	Incandescent LED Lamps Halogen CFL LED Luminaires	Interior Commercial Interior Industrial
Track Small	Display and track lighting **Small:** MR16 lamps	Incandescent LED Lamps Halogen CFL LED Luminaires	Interior Commercial Interior Industrial
Decorative	Decorative mini-base lamps	Incandescent LED Lamps Halogen CFL	Interior Commercial
High/Low Bay	Bay lighting with ceiling height of at least 15 feet and/or lumen output of at least 5,000 lumens per fixture	Linear Fluorescent Metal Halide High Pressure Sodium Mercury Vapor LED Luminaires LED Tubes LED Lamps	Interior Commercial Interior Industrial

Application	Description	Eligible Technologies	Sectors
Parking Garage	Ceiling and wall lighting in parking garages	Incandescent Linear Fluorescent LED Tubes Metal Halide High Pressure Sodium LED Luminaires LED Lamps	Commercial Exterior
Building Exterior	Exterior lighting associated with buildings: wall packs, walkway lighting, exterior sales, and flood lights	CFL High Pressure Sodium Metal Halide LED Luminaires Halogen Incandescent Linear Fluorescent	Commercial Exterior Industrial Exterior
Parking Lot	Exterior lighting in parking lots, including area lighting	High Pressure Sodium Metal Halide LED Lamps LED Luminaires Linear Fluorescent Mercury Vapor Halogen Incandescent	Commercial Exterior Industrial Exterior
Street and Roadway	Street and roadway lighting	High Pressure Sodium Metal Halide LED Luminaires	Outdoor
Other	Other outdoor lighting, including signage and stadium lighting	Linear Fluorescent LED Tubes LED Luminaires Metal Halide High Pressure Sodium Incandescent Halogen	Outdoor

Purchase Triggers

A purchase trigger occurs any time there is an opportunity to purchase a lighting technology. When a fixture is replaced, a lamp or ballast burns out, or a new building is constructed, the consumer must make a choice as to what lighting option to install. The research team identified four main purchase triggers for lighting technologies:

1. **Lamp maintenance** involves the replacement of a lamp or bulb that has burned out at the end of its average lifetime; also referred to as naturally occurring lamp failure.
2. **Ballast and lamp maintenance** involves naturally occurring ballast failure where the entire lighting ballast fails. In this case, the consumer replaces both the ballast and the lamps associated with the ballast.
3. **Natural replacement** involves early retirement fixture purchases, or replacements of ballasts and/or lamps before the end of their average lifetime. The lamp or ballast has not yet failed, but a consumer still decides to upgrade to a more efficient alternative. Projects of this type include retrofits, major renovations, and tenant improvement upgrades.
4. **New construction** includes all fixtures installed through the addition of new floor area (new construction and additions) to the market.

Question 2: How big is the market?

This analysis defines the size of the market as the estimated total number of lamps installed in each sector of the non-residential market across Oregon, Idaho, Washington, and Western Montana.[6] The research team relied on several sources to estimate the total lamps installed in the region, including square footage estimates from the Seventh Plan and lamp and fixture density data from the 2014 and 2019 CBSAs. There are three factors that influence the number of lamps installed: the total space that requires lighting (usually in square feet), the density of fixtures within that space (i.e., fixtures per square foot), and the number of lamps in each fixture.[7] The number of lamps per fixture depends on the technology, making the total lamps dependent on the technology mix, which is addressed in Question 3. Question 2, therefore, defines the size of the market as the total number of fixtures installed in each sector and later applies lamps-per-fixture within the stock turnover model, which is discussed at length in Question 3.

At a high level, the research team used three different types of density:

- For **interior** lighting, fixture density is expressed as interior fixtures per interior square foot of building space
- For **exterior** lighting (associated with buildings), fixture density is expressed as exterior fixtures per interior square foot of building space

---

[6] While the market size is Western Montana only, the research team used sales data and stock saturation data for the entire state of Montana, assuming that the efficiency mix does not vary across the state.

[7] Lamp density depends on the technology and application type shares defined within the stock turnover model. The research team calculated a lamp per fixture density based on these shares to get to the total count of installed lamps. See Question 3 for more details.

- For **outdoor** lighting (not associated with buildings), fixture density is expressed as fixtures per population, such that the total installed stock is the product of the total regional population and the average number of street and roadway lamps per person [8]

The research team used the data from Seventh Plan to estimate the total floor area for each commercial building type included in the study.[9] The team also accounted for changes to these totals—through new construction and demolitions—to ensure they accurately represent the floor area in each sector across the region for each year of the study. For industrial floor area, the team used the national Manufacturing Energy Consumption Survey (MECS) data scaled down to the region and then scaled up to include agricultural areas.[10] For Street and Roadway stock, the team validated the existing model inputs, which were based on the DOE National Lighting Market Model and Census data by comparing these estimates to BPA's Outdoor Lighting Stock Assessment.

The research team calculated a fixture density for each building type in each year based off the 2014 and 2019 CBSAs.[11]

Question 3: What are the total market savings?

Total market savings are the difference between baseline consumption beginning in the year the Seventh Plan was written—calculated in Question 3a—and actual market consumption in the years after the Plan was written, calculated in Question 3b. If the analysis finds market energy consumption to be lower than the baseline energy consumption in any given year, the difference is the total market savings.

The research team arrived at the baseline consumption and the market consumption estimates by mapping all the installed fixtures defined in Question 2 into the many building types, application types, and technology types that make up the diverse non-residential lighting stock and then modeling how the installed technology shares change over time. The team then multiplied these shares by the unit energy consumption (UEC) of each technology to estimate the total energy use of the market in each year.

This process required the use of a stock turnover model to accurately identify how the mix of technologies within the installed lamps in the various dimensions of the market changes over time. This section defines this process and how the stock turnover model calculates energy consumption in the non-residential lighting market,[12] leading to answers to Questions 3a and 3b.

---

[8] Outdoor lighting density is the average number of street and roadway lamps per person from the Seventh Plan. The plan assumed 81 streetlights per 1,000 people based on a regression analysis using data from the Pacific Northwest National Laboratory (PNNL) and other sources. For more information, see: Seventh Power Plan, "com-streetlight-7P_V9.xlsx," "7PSourceSummary" tab.

[9] After reviewing the 2021 Plan commercial building estimates, BPA decided to continue using the 7th Power Plan commercial building stock estimates for consistency with model baseline assumptions. Additionally, the 2021 Plan stock includes secondary impacts from climate change which may not align with BPA's assumptions. During the 2021 Plan Period, BPA will determine which climate scenario best aligns with BPA expectations and revisit commercial building stock assumptions for future modeling efforts.

[10] The research team estimated regional industrial square footage using manufacturing employment data from the US census. Then, the team estimated the relative size of the agricultural lighting market by comparing the volume of agricultural and industrial sector lighting program participation and scaled up regional square footage accordingly.

[11] To develop the model input, the team applied 2014 CBSA values in 2014 and prior years, applied a linear interpolation between the 2014 and 2019 CBSA values for the interstitial years, and then held the 2019 values constant through 2021.

[12]

The Stock Turnover Model

The purpose of a stock turnover model is to identify how consumers adopt technologies and how these adoptions impact the size and efficiency mix of the stock—in this case total lamp installations—over time. For the non-residential lighting market, this model estimates the size and efficiency mix of each application defined in Question 1. The results are the total installed lamp counts by technology required to properly calculate the baseline energy consumption and market energy consumption that drive the Momentum Savings analysis.

Building the Model

The research team first had to build the stock turnover model using several sources and assumptions, which led to three primary input areas:

1. A characterization of the installed stock (quantity, mix, and age of the lamps in the stock) for at least one year in the analysis period—explained in the Stock Characterization: Application and Technology Shares section
2. An estimate of how fast the existing stock turns over each year due to the four purchase triggers in each year—described in the Turnover section
3. An efficiency mix of sales in each year of the analysis period—provided in the Sales Efficiency Mix section

With these inputs, the model estimates how the mix of installed technologies in the stock changes over time in both the baseline and market scenarios. In the baseline scenario, the sales mix is frozen, reflecting an assumption that sales into the market will not get more efficient. Yet, even in the baseline, lamps and ballasts burn out, renovations occur, and new buildings require lighting. Thus, if the baseline sales mix is more efficient than the existing stock, the stock in the baseline scenario will get more efficient over time—just at a slower rate than might be observed in the actual market stock.

These changes in the installed technology mix affect total lighting energy consumption. This stock data multiplied by the UEC of each technology yields the consumption in each case (described in the Question 3a: What was the energy use in the year the plan was written? and Question 3b: What was the energy use in the following years? sections below).

Appendix 1. Technical Data offers additional detail around the technology-specific data supporting consumption calculations.

Stock Characterization: Application and Technology Shares

After defining the market size in fixtures as described in Question 2, the research team then defined the portion of total lamps and fixtures in the stock belonging to each application and then applied the share of technologies—or technology mix—to each defined application (as seen in Table 3). The team used the most up-to-date data available to apply the technology mix to beginning of the stock turnover model analysis period. These data sources included the 2014 CBSA, 2014 IFSA, and the Seventh Plan, all of which informed the characterization of the stock in the model prior to the beginning of the Seventh Plan period.[13] A critical component of this model update involved calibrating the model to align the modeled stock in 2019 with the 2019 CBSA's estimated stock mix of technologies.

The research team applied the same methodology used in the Sixth Plan model to estimate the commercial technology mix for interior lighting applications, assuming that the 2014 CBSA and IFSA data were representative of regional stock in 2014, and that the 2019 CBSA was representative of regional stock in 2019. The team:

1. Mapped each entry from the detailed CBSA lighting data to the corresponding model application and technology (example shown in Table 4).

Table 4: Example of CBSA Data Mapped to Model Application and Technology

CBSA Database Fields					Mapped Fields	
Fixture Category	**Fixture Type**	**Lamp Type**	**Lamp Details**	**Watts Per Lamp**	**Application**	**Technology**
Linear Fluorescent	LF Ceiling Mount	Fluorescent T8	HP	25	Ambient Linear	25W T8

2. Calculated the share of fixtures (application share) in the stock that belong in each application by building type using the detailed CBSA fixture data.
3. Calculated the share of fixtures represented by each technology for each application in 2019 using Equation 1 and the CBSA detailed fixture data. The team calculated a range of values representing the 95% confidence interval. Table 5 shows the technology shares for the ambient linear application in the commercial sector as an example of the results of these calculations. The model Export Tables include technology shares for all major applications.

---

[13] The CBSA/IFSA took place during 2013 to 2014. For purposes of this study, the research team defines this data as the technology mix at the beginning of 2014.

Equation 1: Technology Fixture Share

$$\text{Technology Fixture Share}_{a,b,t,y} = \text{Application Share}_{s,b} \times \text{Technology Share}_{a,s,y}$$

Where:

a = application

b = building type

s = sector

t = technology

y = year in study period

Table 5. Example: Technology Shares for Ambient Linear Application (Commercial Sector)

Technology	2019 CBSA Stock Application Technology Mix (Bottom of 95% Confidence)	2019 CBSA Stock Application Technology Mix (Top of 95% Confidence)
25W T8	0.0%	4.7%
28W T8	0.9%	14.4%
32W T8	54.6%	62.5%
LED Luminaire	1.2%	6.4%
T12	4.4%	12.2%
T5HO	0.0%	4.5%
T5SO	0.0%	3.7%
TLED	14.3%	23.1%

Source: Analysis of 2019 CBSA data

For the industrial sector, the team updated industrial building stock using new data from the 2014 US Energy Information Administration (EIA) MECS and 2013–2015 manufacturing employment from the US Census.[14] The EIA last published the MECS in 2010, so the team updated the industrial floorspace estimates back to 2011, impacting a portion of the Sixth Plan Period (2011–2015) as well as the first two years of the Seventh Plan action plan period (2016 and 2017). It was important to incorporate the most accurate information back to 2011 to ensure that the model characterized the Seventh Plan baseline year (2015) as accurately as possible. The team calculated industrial building stock by multiplying the total amount of national manufacturing floorspace in the US from the EIA MECS report by the percentage of US manufacturing employees in the region from the Census. The team used the percentage of US manufacturing *employees* in the region as a proxy for the percentage of floor area in the region because region-specific estimates were not available. The team also used the new data to update industrial building stock projections through 2035. The calculation methodology is consistent with previous model updates—the addition of the new, more recent data was the only update.

---

[14] The US Census tracks establishments across years in the 1989–2015 business information tracking series.

For the exterior lighting applications for both commercial and industrial (parking garages, parking lots, and building exterior), the research team relied on 2019 CBSA data. The team categorized CBSA outdoor lighting entries to the building exterior model applications. Table 6 documents these assumptions.

Table 6: Exterior Lighting Classification

CBSA Outdoor Lighting Use Type	Model Application
Walkway	Building Exterior
Parking Lot	Parking Lot
Signage	Other
Façade	Building Exterior
Other	Other
Sporting Field	Other
Unknown	Other
Exterior Sales	Building Exterior

Source: Analysis of 2019 CBSA

For street and roadway lighting, the model draws on several sources to estimate the installed stock mix of technologies. The analysis cites the 2013 DOE Solid State Lighting (SSL) Market Adoption report, the DOE National Lighting Market Model, and US Census data. The team validated the model estimates by comparing the 2019 modeled stock technology mix against the results of BPA's Outdoor Lighting Stock Assessment study.

After characterizing the stock into application and technology shares, the research team applied a lamps-per-fixture equation using data from the CBSA on the average number of lamps per fixture for each technology type. For some technologies, this varies by application—for example, the average 32W T8 fixture in the ambient linear application has fewer lamps (one or two) than the average 32W T8 fixture in high bay lighting (four to eight). The research team made some adjustments to the lamps-per-fixture data from the CBSA to ensure that all technologies had similar lumen output. The team applied these lamps-per-fixture estimates at the application level, assuming that applications would be similar across building types and sectors. The team used CBSA data for the industrial sector applications and assumed a single lamp per outdoor street and roadway fixture. Equation 2 calculates the technology share of the lamp stock for each year in the study period.

Equation 2: Calculating Technology Share of Lamp Stock

$$\text{Technology Lamp Share}_{y} = \text{Application Share}_{s,b} \times \text{Technology Share}_{a,s,y} \times \text{Lamps per Fixture}_{a,t}$$

Where:

a = application

b = building type

s = sector

t = technology

y = year in study period

Turnover

As discussed in the definition of purchase triggers in Question 1, lamps enter the market through lamp failure, ballast failure, natural replacement of fixtures, and new construction. Each of these purchase triggers creates a submarket, which is the subset of total market sales that result from that trigger. The research team considers the sales due to the new construction and natural replacement purchase triggers a single submarket with the same mix of technologies in sales. The model applies these purchase triggers as follows:

- All fixtures except LED technologies—regardless of year installed—are subject to the natural replacement turnover. That is, if the natural replacement turnover rate is 5%, the model removes 5% of all installed fixtures and fills the stock with new sales using the sales mix for the natural replacement and new construction submarket. In previous iterations of the model, the team exempted LED technologies from this turnover because they were considered emerging technologies installed recently and therefore unlikely to be replaced during the previous modeling period of 2009 to 2015. For the current model update, affecting 2016–2021, however, the team phased in the ability for LED technologies to turn over by allowing pre-2015 vintage LEDs to turn over according to their estimated lifetimes.
- A subset of the remaining ballasts not removed through natural replacement of fixtures fail according to their vintage, rated lifetime and operating hours. When a ballast fails, the model replaces both the ballast and associated lamps with the sales mix for the ballast maintenance submarket.
- A subset of the remaining lamps not removed through natural replacement of fixtures or ballast replacement fail according to their installation year, rated lifetime, and operating hours. The model replaces these burned-out lamps with the sales mix for the lamp maintenance submarket.

The remainder of this section describes the inputs driving turnover in more detail.

Lamp Failure. For lamp failure, the lifetime and operating hours of each unique lamp type (e.g., incandescent general-purpose lamp, LED reflector lamp, etc.) in the stock determine the frequency with which it fails, on average. For example, if an incandescent general-purpose lamp has a lifetime of 1,000 hours and the research team assumes lamps of this type operate (are turned on) for 500 hours per year, then the team can expect these bulbs to fail, on average, after they have been in the stock for two years. Using the count and age of each lamp type in the stock, the stock turnover model determines the number of failures by lamp type and the corresponding number of replacement lamps in any given year.

Equipment does not always fail exactly at its rated lifetime. To account for this, the model employs failure distributions for each technology that assign the percentage of lamps of a certain age that will fail in any given year. The research team estimated failure rates using a Weibull distribution having a mean value equal to each lamp's expected lifetime, along with a shaping factor of five.[15] The Weibull distribution assumes that a greater portion of lamps fail after the expected lifetime as opposed to a normal distribution, which would assume equal numbers of lamps failing before and after the mean (expected) lifetime.

Lamp replacement sales are calculated as shown in Equation 3 through Equation 7.

---

[15] The value of the shaping factor is consistent with the US DOE lighting market model.

Equation 3: Failure Distribution

$$\text{Failure Distribution}_{a,g,t,y} = \text{Weibull Distribution (Mean Lifetime}_{a,t,y=i}\text{, Shaping Factor)}$$

Where:

a = application

g = age

i = installation year

t = technology

y = year in study period

The model tracks the age of every installed lamp, which enables it to apply the appropriate failure percentage to each age cohort.[16] For every year of the study period, the model predicts the quantity of lamps that fail from each age cohort.

Equation 4: Lamp Failures by Vintage

$$\text{Lamp Failures}_{a,i,s,t,y} = \text{Lamp Stock}_{a,i,s,t,y} \times \text{Failure Distribution}_{a,g,t,y=i}$$

Where:

a = application

g = age

i = installation year

s = sector

t = technology

y = year in study period

Ballast Failure. For ballast failures, the model uses a simplified approach that assumes a constant fraction of ballasts fail in each year. This fraction is 1 divided by the rated ballast lifetime for each technology. The research team assumes that with each ballast replacement, the associated lamps are replaced as well.

Equation 5: Ballast Failures

$$\text{Ballast Failures}_{a,i,s,t,y} = \text{Ballast Stock}_{a,i,s,t,y} \times \frac{1}{\text{Ballast Lifetime}_{a,t,s,y=i}}$$

Where:

a = application

---

[16] An age cohort is all the lamps installed in a given year. The failure rate is a function of lamp age as shown in Equation 3.

i = installation year

s = sector

t = technology

y = year in study period

Natural Replacement of Fixtures. For all technologies, the model calculates the number of fixtures replaced each year using Equation 6. The research team investigated varying the application of this turnover rate by technology or vintage (so that older fixtures or certain technologies would have a higher chance of turning over). Given the lack of detailed primary data on turnover rates with this level of granularity—and, in the case of varying by vintage, the additional computational burden required—the team chose to use a single turnover rate for all technologies and vintages (the model does not track fixture vintage) to avoid false precision and keep the model a more reasonable size.[17]

Equation 6. Natural Replacement Turnover

$$\text{Natural Replacement Turnover}_{a,s,y} = \text{Fixture Stock}_{a,s,y} \times \text{Natural Replacement Turnover Rate}_{a,s}$$

Where:

a = application

s = sector

y = year in study period

Total Replacement Sales from All Purchase Triggers. All lamp and ballast failures and natural turnover fixtures are then subject to replacement. Upon replacement, a fixture or lamp and ballast system can switch from one technology to another based on the assumed sales mix across technologies within each submarket.

Equation 7: Replacements

$$\begin{gathered}\text{Replacements}_{a,s,t,y} = \left(\textstyle\sum_{i,t} \text{Lamp Failures}_{a,i,s,t,y}\right) \times \text{Sales Mix}_{a,t,y,m} + \\ \left(\textstyle\sum_{i,t} \text{Ballast Failures}_{a,i,s,t,y} \times \text{Lamps per Ballast}_{a,i,s,t}\right) \times \text{Sales Mix}_{a,t,y,m} + \\ \left(\textstyle\sum_{i,t} \text{Fixtures Replacements}_{a,i,s,t,y} \times \text{Ballasts per Fixture}_{a,i,s,t} \times \text{Lamps per Ballast}_{a,i,s,t}\right) \times \text{Sales Mix}_{a,t,y,m}\end{gathered}$$

Where:

a = application

i = installation year

---

[17] Turnover rates for each application are based on a weighted average of building type-level turnover rates. Tracking fixture vintage is possible but adding this complexity would dramatically increase the size of the model. This would make the model less accessible (some computers may not have enough memory to run larger models) and increases run time.

m = submarket

s = sector

t = technology

y = year in study period

Table 7 summarizes the key data inputs and sources for the turnover portion of the model.

Table 7: Turnover Inputs and Sources

Input	Description	Source
Lifetime	Rated lifetime of lamps and ballasts in hours; varies by technology and application	DOE input assumptions for SSL Market Model
Hours of Use	Annual operating hours of lighting equipment; varies by sector and application	Commercial buildings: 2014 and 2019 CBSA Industrial buildings: IFSA Exterior Lighting: 2014 and 2019 CBSA
Natural Replacement Turnover Rate	Percentage of fixtures replaced each year due to retrofits, renovations or other upgrades	Commercial: 2019 CBSA and Sixth Plan Industrial: Sixth Plan value for warehouse building type Outdoor: Sixth Plan
New Construction and Demolition Rates	Number of fixtures added to or removed from the stock due to new construction or demolition of building stock	Seventh Plan floor space estimates by building type multiplied by fixture density

Together, these inputs drive how much the stock grows or shrinks each year and what fraction of lamps, ballasts, and fixtures will fail and require replacement. From this data, the model calculates the total sales of lamps, ballasts, and fixtures in each year as follows:

- The **natural replacement turnover rate** determines the number of fixtures replaced in each year, making up one part of the fixture submarket.[18]
- The **lifetime in hours** of the lamp or ballast divided by the **annual hours of use** by sector and application equals the **expected lifetime in years** for each technology in each application and sector. This is the lifetime used to calculate the failure distributions described above and dictates the number of lamps and ballasts that fail each year. This drives the size of the lamp and ballast submarkets.
- The **new construction rate** determines how many fixtures will be added to the stock in each year through new buildings, which makes up the remainder of the fixture submarket.

---

[18] Turnover rate is difficult to research, and while the 2019 CBSA did collect data on lighting system turnover, there are limitations associated with applying those data in the model. The detailed model input documentation workbook contains more explanation of these limitations. The team also considered the potential impact of COVID-19 on turnover rate but did not have adequate data to support any adjustments.

- The **demolition rate** determines how many fixtures will be removed from the stock in each year due to the demolition of existing buildings.

Figure 2 shows how, in each year, failures in the existing stock drive the next year's sales, which in turn determine the mix of technologies installed in the next year. New construction and demolitions also affect the stock and sales in each year. This process applies for the entire modeling period.

Figure 2. Illustration of How Stock and Sales Interact in Model

Source: BPA Non-Residential Lighting Model development

Sales Efficiency Mix

The efficiency mix of sales flowing into the market in each year is the percentage of lamps that each technology makes up in the sales. This mix varies by application and submarket. There are three possible methods for determining efficiency mix: using technology shares from available sales data, estimating technology shares based on available data and professional judgment, and building economic logic within the model to estimate technology shares. Actual sales data is the most direct, and through this and prior projects NEEA and BPA have collected sales data from 47 unique distributors that the team uses to characterize sales over the 2010 to 2020 period.[19]

These sales data are a resource unavailable to many market modelers, and provide a clear, high-level target for the non-residential share of market sales. There are two main limitations to using this data directly for each individual purchase trigger and application: technology representativeness and allocation granularity. The implications of these limitations are as follows:

- **Representativeness.** The sales data is an attempted census of all non-residential lighting sales through the distributor channel in the region. The team believes the dataset to be representative of the distributor sales channel. However, the data set does not include sales via online or brick and mortar retailers (e.g., Amazon, Home Depot). Through prior market research, BPA determined that the distributor channel represents most lighting product sales, and so the model has

---

[19] For additional information on this data collection and data cleaning analysis, see: Non-Residential Lighting Distributor Sales Data Gaps memorandum.

historically used the distributor sales data set to represent the total market sales mix of technologies.

- **Allocation granularity.** To understand the large-scale changes happening across the market, it is important to understand what is happening at a more granular level than the current sales data can provide. For example, lamps may be going to industrial, outdoor, or commercial applications, which have a variety of operating hours and conditions, at varying rates. To be more accurate in estimating energy consumption and savings, the research team needed to assess the high-level sales and which lamps are going where—something that sales data cannot inform directly.

To address these limitations in this model update, the team applied two analytical steps. First, the team allocated sales across applications and submarkets. Second, the team calibrated the model to align the model stock with the 2019 CBSA, thus correcting for any potentially inaccurate trends implied by the sales data and ensuring that technology/application trends are anchored to an empirical observation of installed stock. The research team implemented this process in two steps:

- **Step 1: Allocate sales across applications and submarkets.** Using the 2015 stock application and technology saturation data and the turnover assumptions described above, the team turned over the 2015 stock to calculate the relative size of each application and submarket's lamp sales in 2016 (each year's sales are driven by stock changes in the prior year). Turning over the stock applied the lifetime and turnover assumptions to calculate the volume of each submarket's lamp sales as follows:
  - The lamp submarket size is equal to the number of lamps that failed in 2015
  - The ballast submarket size is equal to the number of ballasts that failed in 2015 multiplied by the number of lamps per ballast
  - The fixture submarket size is equal to the number of fixtures removed in 2015 due to natural turnover multiplied by the number of lamps per fixture

  The output from the sales allocation process is the sales mix for each application and submarket over time. Each year, the model summed all the lamp failures from all sectors within each application and submarket and applied the application- and submarket-specific sales mix to determine the number of new lamps of each technology type in that year.

- **Step 2: Apply calibration adjustments to align modeled stock with 2019 CBSA.** The team applied adjustments at two levels in the model to keep the estimated stock mix of technologies at the application level within the error bounds of the 2019 CBSA. In an iterative process, the team adjusts application-technology level sales mixes to target 2019 stock mixes that align with the CBSA and calibrates the proportion of incoming product flow by technology dedicated to each application to achieve total-market alignment with the 2019 CBSA. These adjustments preserve year-over-year directional trends in sales but scaled up or down technology shares to allow for alignment with the 2019 CBSA stock saturations of technologies. Detailed documentation of calibration adjustments is included in the Model Input Documentation Workbook.

Applying the Model's Results

The results of the stock turnover model are twofold: (1) an actual market scenario, and (2) a frozen baseline scenario. The resulting differences in stock energy consumption between these two scenarios directly equate to savings in the non-residential lighting market as described in Questions 3a and 3b, which are discussed below.

Question 3a: What was the energy use in the year the plan was written?

The research team used the stock turnover model to estimate the total stock and sales technology mixes of the non-residential lighting market in 2015, prior to the Seventh Plan. The team then held the 2015 sales mix estimates as frozen for each subsequent year of the study to compare each year to the actual market scenario. That is, while the sales mix in the market scenario changes each year, the sales mix in the frozen baseline scenario stays the same. The technology mix in the *stock* did change in both scenarios but less so in the baseline scenario, which drives savings.

Table 8 shows an example of the efficiency mix in the market scenario for the ambient linear application in 2015, the year immediately preceding the Seventh Plan, and the following years. The model Export Tables include all modeled sales mixes by application.

Table 8: Sales Mix over Time, Ambient Linear

	2015 (Frozen Baseline)	2016	2017	2018	2019	2020	2021
25W T8	2%	1%	1%	1%	1%	1%	1%
28W T8	5%	5%	7%	12%	12%	11%	11%
32W T8	76%	62%	52%	39%	36%	34%	34%
LED Luminaire	3%	4%	5%	7%	11%	11%	11%
T12	5%	4%	5%	4%	3%	2%	2%
T5HO	2%	1%	1%	2%	2%	1%	1%
T5SO	0%	0%	0%	0%	0%	0%	0%
TLED	7%	22%	28%	35%	36%	41%	41%

Source: Non-Residential Momentum Savings Model

As shown in Equation 8, the research team calculated market energy consumption based on the resulting installed lamp stock technology mix and the UEC of each lamp type and age cohort. The model determined the number of installed lamps by simulating stock turnover, whereas the UEC came directly from input assumptions.

Equation 8: Energy Consumption

$$\text{Annual Energy Consumption}_{s,y} = \sum_{a,b,i,t} \left(\text{Installed Lamps}_{a,b,i,s,t,y} \times \text{Unit Energy Consumption}_{a,b,s,t,y=i} \right)$$

Where:

a = application

b = building type

i = installation year

s = sector

t = technology

y = year in study period

Unit Energy Consumption

Understanding how much energy one unit (lamp) consumes is a key input for calculating how much the entire lighting market consumes and must be calculated for each lamp type included in the study. The team used the Equation 9 to calculate the UEC for each lamp type in the application table in Question 1.

Equation 9: Unit Energy Consumption

$$UEC = \text{Average Wattage}_{a,b,s,t,y=i} \times \text{Annual Operating Hours}_b$$

Where:

a = application
b = building type
s = sector
t = technology
y = year in study period
i = installation year

See

Appendix 1. Technical Data for a more detailed account of the technology specifications used in the UEC calculation.

Question 3b: What was the energy use in the following years?

In the market scenario for the non-residential lighting market, the team ran the model using the market allocated sales shares over time to produce the total stock and technology mixes for each year of the study. This allowed the model to estimate the efficiency mix in each application and submarket, effectively determining the market shares of incoming products for each purchase trigger and application.

The research team then calculated total energy consumption in the stock in the market scenario using the UEC for each technology in each year and the modeled technology mixes.

Calculating Total Market Savings

The research team subtracted the market scenario stock energy consumption from the frozen baseline to arrive at the cumulative savings in each year. It is important to note that direct comparisons of stock energy consumption in any given year yield **cumulative** energy savings—savings that includes efficiency improvements in prior years. In contrast, Momentum Savings and program savings are **first-year** savings, so an adjustment was necessary. To arrive at the first-year savings, the team deducted the prior year's cumulative savings. This approach, shown in Equation 10 and Equation 11, isolates first-year savings in each year of the analysis.

Equation 10: Cumulative Savings

$$\text{Cumulative Savings} = (\text{Baseline Stock Consumption} - \text{Market Stock Consumption}) \times \text{Busbar Factor}$$

The busbar factor in Equation 10 converts energy savings at the customer meter to the generation source. The research team used a busbar factor of 1.09056 per BPA's guidance.

In 2010, the cumulative savings are equal to the first-year savings. For all other years, the team calculated first-year savings as the difference between the cumulative savings in that year minus the cumulative savings of the prior year (Equation 11).

Equation 11: First-Year Savings

$$\text{First-Year Savings}_y = \text{Cumulative Savings}_y - \text{Cumulative Savings}_{y-1}$$

Where:

y = year in study period

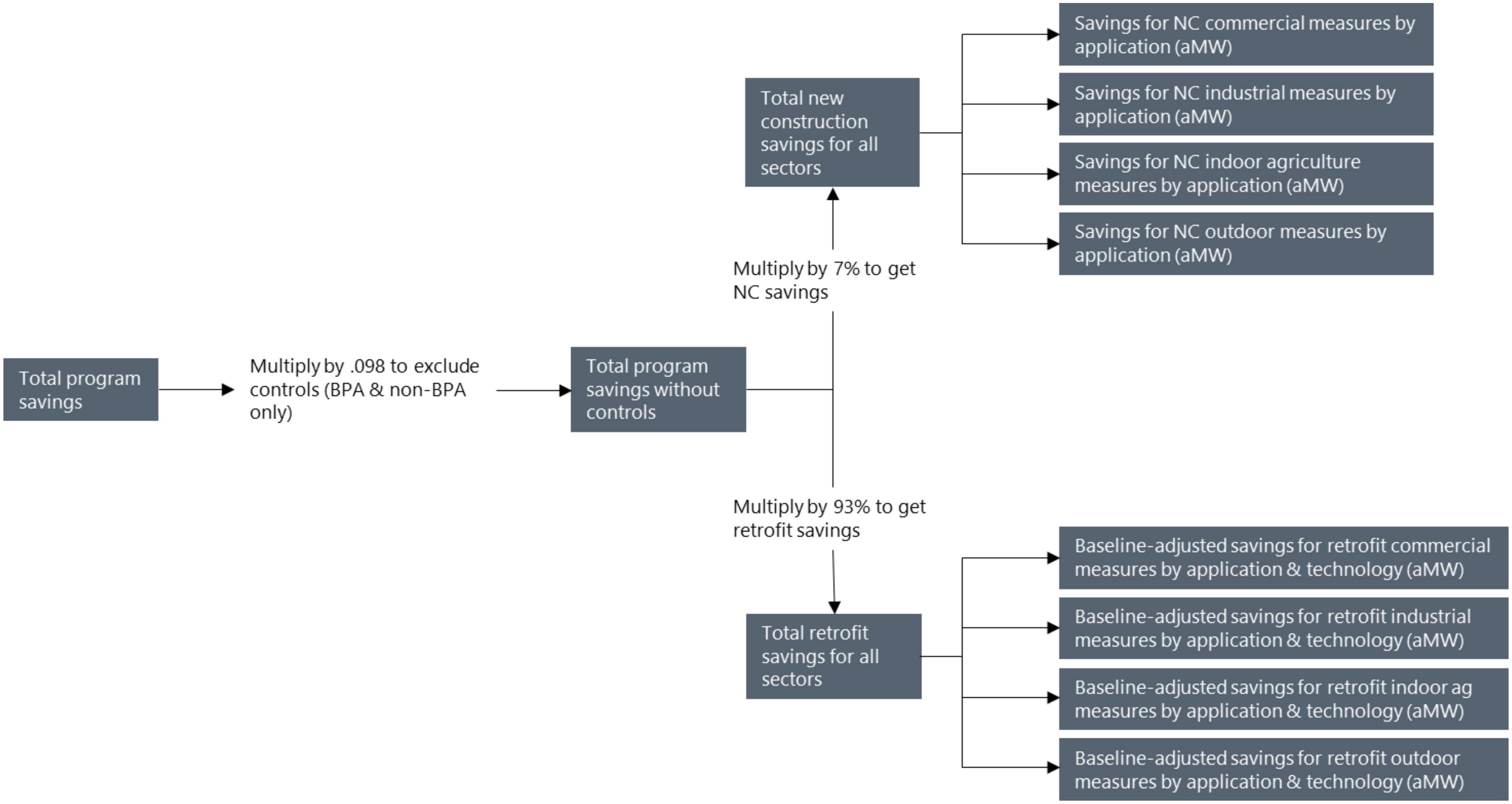
Question 4: What are the program savings?

The last step in the Momentum Savings analysis involves subtracting all reported regional non-residential lighting program savings from the total market savings calculated in Question 3. After subtracting the program savings, the remaining savings are regional Momentum Savings.

Calculating regional program savings is complex because program funders use different processes or data sources to calculate their program savings. Therefore, the research team performs an analysis to align regional program savings with the market model's inputs. The alignment includes using a single consistent baseline, the Seventh Plan baseline, to avoid double counting of Momentum Savings and program savings. The resulting program savings calculated by the model are "adjusted program savings" and are used solely as an interim step in calculating Momentum Savings, not for other reporting purposes.

The research team followed the process shown in Figure 3 to estimate program savings, using the 2019 adjustment factors as examples. This process is detailed in the sections that follow. Since the model frozen baseline is based on the current practice in 2015, the research team adjusted program savings that were not reported relative to a current practice baseline to align with the model baseline.

Figure 3: Program Savings Analysis Process (2019 adjustment factors)



Baseline adjustment notes:

- No baseline adjustment for NEEA
- No baseline adjustment for new construction

Source: Research team and BPA analysis

Key Assumptions

Below is a list of key assumptions utilized in the design of this model:

- The team did not apply a baseline adjustment to new construction savings because new construction savings are claimed against energy code lighting power density levels, and the team assumed that energy code requirements are at least as efficient as the frozen baseline (sales in 2015).[20]
- The team did not apply a baseline adjustment to the NEEA program savings because NEEA used a current practice baseline or one that is more efficient.
- The team did not apply a baseline adjustment to linear fluorescent savings claimed relative to a current practice baseline because this baseline is at least as efficient as the model frozen baseline (sales in 2015).
- All savings are reported in average megawatts.
- All savings data inputted into the model are at the meter (site) level. The model converts them to busbar savings as needed to compare to the total market savings.
- Due to limitations in data from non-BPA programs, the research team needed to use the program savings adjustments from BPA's lighting calculator data to estimate both the application mix and application-specific adjustment factors for all other lighting program savings. As lighting program baselines and project types have changed over this period due to federal standards regulating T12s and the emergence of LEDs, The use of BPA utility program savings as a proxy for non-BPA utility program savings is a significant assumption with high uncertainty that directly affects Momentum Savings estimates. BPA validated this assumption by requesting more granular program savings estimates from the largest non-BPA utilities and comparing those estimates against the model assumptions. These granular comparisons confirmed expectations regarding savings from new and existing construction, savings from Indoor Agriculture, sectoral savings, etc. This comparison did not yield any significant disparities, though it did indicate that year-over-year sector and application mixes may vary by utility.

Total Fiscal Year Savings

The team's first step to estimate program savings was to obtain the total savings for each program year included in the analysis (2015–2021). The analysis required estimating the total savings for BPA programs, non-BPA programs (investor-owned utilities), and NEEA programs. Table 9 provides a summary of the data sources for the program savings.

---

[20] This is based on the research team's professional judgement. New construction program baselines are driven by code, which is expressed as lighting power density rather than a technology mix. This difference in metrics makes it difficult to make a direct comparison to confirm that code is more efficient than the frozen baseline; however, because new construction is the most efficient part of the market, the team believes this is a reasonable simplifying assumption.

Table 9: Data Sources for Program Savings

Entity	Data Year	Data Type	Data Source
BPA	Fiscal year (October 1 to September 30); the team converted it to calendar year (January 1 to December 31) for the model.	Busbar level; the team converted the savings to the site level (at the meter level).	BPA internal savings tracking summaries.
Non-BPA and NEEA	Fiscal year (October 1 to September 30); the team converted it to calendar year (January to December 31) for the model.[21]	Busbar level; the team converted the savings to the site level (at the meter level).	Regional Conservation Progress (RCP) data, which includes both BPA and non-BPA utility savings data; the team subtracted out the BPA savings to determine the non-BPA savings.[22]

Source: Research team and BPA analysis

Accounting for Controls and New Construction Savings

The team's next step to estimate program savings was to adjust the total fiscal year (FY) savings for controls. To adjust for savings from controls, the team calculated the annual percentage of total savings associated with controls using the BPA detailed program data. This assumption applies to the BPA program savings and non-BPA program savings and results in reducing total program savings.

After adjusting for controls, the team adjusted for new construction savings. The team calculated the annual percentage of total savings associated with new construction measures using the BPA detailed program data. It was important to divide the total FY savings into savings from new construction and existing buildings because the team did not apply a baseline adjustment to new construction savings.

Accounting for Savings at the Sector Level

After accounting for controls and new constructions savings, the research team accounted for the split of savings by sector by splitting the data into savings from commercial, industrial, indoor agriculture, and outdoor lighting. The data source used for this split is BPA's detailed lighting calculator data, which contains summary data from BPA program projects that utilize the BPA Lighting Calculator. The team used this source to allocate savings associated with all entities (BPA, non-BPA, and NEEA). The team used BPA data as a proxy for non-BPA program savings and NEEA program savings due to the lack of granularity in those data sets.

---

[21] Council staff noted to the team on October 13, 2016, that some utilities report savings in a fiscal year (October-September) while other utilities report savings in a calendar year (January-December). For the purposes of this analysis, the research team assumed that all of the RCP data corresponds to the fiscal year.

[22] The RCP data comes from https://rtf.nwcouncil.org/about-rtf/conservation-achievements/previous-years

Application Mix

After splitting savings by sector, the team applied an application mix to the total new construction savings and total existing building savings. The application mix shows the percentage of savings that comes from each application.

Key Assumptions

The team used BPA Lighting Calculator data to determine the application mix, once again using BPA data as a proxy for the non-BPA program data and NEEA program data due to the lack of granularity in those data sources.

- Due to the lack of granularity in the non-BPA program data, the team used the BPA program data as a proxy to determine the application mix for non-BPA program data.
- The team assumed that 5% of total non-BPA program savings is associated with indoor agriculture measures. This assumption is based on a single utility that provided BPA with indoor agriculture savings detail and represents a conservative extrapolation to Oregon and Washington non-BPA territories.
- The team assumed 100% of NEEA savings came from the ambient linear application.[23]
- The BPA Lighting Calculator data for new construction measures only shows the savings—not the measure-level details (e.g., baseline fixture details, efficient fixture details). Thus, the team used the retrofit data as a proxy for the new construction data to determine the application mixes.
- There are six applications that depend on wattage: High/Low Bay LOW, High/Low Bay HIGH, Building Exterior LOW, Building Exterior HIGH, Street and Roadway LOW, and Street and Roadway HIGH. The team used stock data to determine the split between high and low wattage fixtures in these applications.

Baseline Adjustment

The team's final step to estimate program savings was to adjust the baseline assumed in the program data to the model frozen baseline, thus adjusting the savings estimate. This adjustment is needed so that all savings are compared against the same baseline and can be compared to each other (e.g., savings from the total market and the program). This method allows for an apples-to-apples comparison of the existing equipment in the program data (the program baseline) to the frozen baseline.

Due to the limited granularity in the non-BPA program savings data, the team used the BPA baseline adjustment as a proxy for the non-BPA program savings. The team did not adjust the baseline for the NEEA program savings because NEEA uses either a current practice baseline or one that is more efficient. The team used the same data sources for the BPA program data as noted in the Application Mix section.

---

[23] NEEA savings are reported for linear fluorescent lamps (28W and 25W lamps) only.

Baseline Adjustment Process

The research team followed these steps to complete the baseline adjustment:

1. **Determine when to adjust and when not to adjust the baseline.** Since the beginning of the Seventh Plan Period, both BPA and non-BPA utility programs have applied a current practice baseline for Ambient Linear and General Purpose lamps and fixtures. Therefore, no adjustment is needed to make them comparable to the 2015 frozen baseline. For all other applications, programs apply a pre-conditions baseline in calculating savings, which means the baseline for those applications is not current practice; therefore, an adjustment is needed to make it comparable to the 2015 frozen baseline.
2. **Map the baseline and efficient technology names in the BPA program data to one of the 16 technologies in the model.** The naming conventions of the technologies in the program data differ from the naming conventions used in the model, which required the team to map the program data baseline and efficient technologies to one of the 16 technologies in the model (e.g., metal halide, incandescent). The non-BPA program data does not have technology-level data; therefore, the team used the BPA technology mix as a proxy. The BPA program data also does not list the baseline wattage; therefore, the team was not able to split out the T5 and T8 technologies any further (e.g., 32W T8, 28W T8) using the available information in the program data. The team instead used stock data to split out the T8s into 32W, 28W, and 25W lamps and T5s into high output T5s and standard output T5s.
3. **Calculate the percentage of savings from each baseline technology and from each efficient technology within a specific FY, sector, and application**. The purpose of this exercise was to use the percent savings to produce a weighted average baseline and efficient wattages within a given FY, sector, and application as detailed in Step 4.
4. **Use the wattage assumptions for the technologies in the model to determine a weighted average wattage for both the baseline technology and the efficient technology in each FY, sector, and application.** The team determined a weighted average baseline wattage and weighted average efficient wattage for every unique combination of FY, sector, and application by multiplying the percent savings of each technology by the wattage of the technology in the model and summing all 16 technologies. The team did this calculation for both the baseline wattage and the efficient wattage.
5. **Calculate a baseline adjustment factor for each FY, sector, and application combination.** The team calculated the adjustment factor using Equation 12:

Equation 12: Baseline Adjustment Factor Calculation

$$\text{Baseline adjustment factor} = \frac{\text{Wattage}_{\text{Baseline, Frozen}} - \text{Wattage}_{\text{Efficient, Program Data}}}{\text{Wattage}_{\text{Baseline, Program Data}} - \text{Wattage}_{\text{Efficient, Program Data}}}$$

Where:

- $\text{Wattage}_{\text{Baseline, Frozen}}$ = Weighted average baseline wattage from the 2015 frozen baseline for a given FY, sector, and application (calculated from the frozen baseline scenario within the model)

- $\text{Wattage}_{\text{Efficient, Program Data}}$ = Weighted average efficient wattage from BPA program data for a given FY, sector, and application (see Step 4 above)
- $\text{Wattage}_{\text{Baseline, Program Data}}$ = Weighted average baseline wattage from BPA program data for a given FY, sector, and application (see Step 4 above)

6. **Apply the adjustment factor to the program savings for a given FY, sector, and application.** The team applied the adjustment factor to the program savings to adjust the program savings baseline to the 2015 frozen baseline.

Calculating Momentum Savings

The research team subtracted the savings associated with programs calculated in Question 4 from the team's estimates of total market savings calculated in Question 3 to arrive at an estimate of non-residential lighting Momentum Savings.

Table 10 below shows non-residential lighting Momentum Savings for the Seventh Power Plan action plan period (2016–2021). Additional detailed results are available in the model Export Tables. The team calculates BPA's share of the total regional savings by multiplying the total regional savings by 42%, which represents BPA's share of regional electricity generation.

Table 10. Non-Residential Lighting Momentum Savings, aMW 2016-2021

	2016	2017	2018	2019	2020	2021	Seventh Power Plan Total
Total Regional	-12.4	-16.4	25.9	27.9	23.9	11.7	60.6
BPA	-5.2	-6.9	10.9	11.7	10.0	4.9	25.4

Source: Non-Residential Lighting Market Model

These results indicate that the non-residential lighting market has undergone significant transformation during the model analysis period, resulting in meaningful energy savings beyond those directly associated with regional energy efficiency programs. Additional detailed model results are available in the Non-Residential Lighting Export Tables workbook, and additional discussion of the results is included in the Non-Residential Lighting Market Model Executive Summary.

Appendix 1. Technical Data

The majority of the technical data used in this study relates to the technical specifications of all the different lamps, ballasts, and fixtures competing in the stock turnover model. The technical specifications (tech specs) include lifetime, labor cost, equipment cost, efficacy, lumen output, and wattage. Additional technical data includes HVAC interaction factors and the sales categories that compete in each technology category within an application.

Lifetime drives how often lamps and ballasts burn out, and wattage dictates the energy consumption of each technology. The team used lumen output and efficacy data to derive wattage estimates for each technology and to ensure all technologies in each application had similar lumen outputs. Since the forecasting part of the model uses economic logic to determine what portion of sales go to each technology when equipment fails or is replaced, the team also needed data on first cost and operating cost. Wattage drives operating cost, while equipment and installation costs drive first cost; equipment and installation costs are not insignificant for some applications such as streetlights.

For each of the three submarkets—lamp, ballast, and fixture—the team developed tech specs at the year, sector, application, and technology levels. The tech specs can be defined as the value that represents that general category but not any given lamp on the shelf or available online. This is because within a subcategory of lamps there can be some variation in the actual specifications. There are six tech specs necessary for the model. Table 11 lists the value and unit for the individual tech specs for each of the three submarkets.

Table 11: Tech Specs by Submarket

	Lamp (y, s, a, t)	Ballast (y, s, a, t)	Fixture (y, s, a, t)
Efficacy	lm/W (lamp)	Ballast efficiency (%)	1.0
Lifetime	hours (lamp)	hours (ballast)	N/A (retrofit rate)
Lumen Output	lm/lamp	lm/lamp * lamps/ballast	lm/lamp * lamps/ballast * ballasts/fixture
Watts	W/lamp=lumen output/efficacy	Watts/lamp * lamps/ballast	Watts/lamp * lamps/ballast * ballasts/fixture
Equipment Cost	$/lamp	$/ballast + $/lamp*lamps/ballast	$/fixture+ $/ballast*ballasts/fixture+ $/lamp*lamps/ballast
Labor Cost	$/lamp	$/ballast	$/fixture

Lamp Specifications

The research team first calculated all lamp specifications except for labor cost at the level of granularity of the sales data. The granular level of the sales data, in many cases, maps more closely to a given lamp on a shelf or online (i.e., 400W metal halide lamp). For LED luminaires, the sales data is at a luminaire category level such as LED track lighting luminaires. Developing the technical specifications at the sales level allows flexibility to roll up those categories into the model separate from an input value at the general category level. For example, both a 40W and 100W A-type incandescent fit within the category "General Purpose" and technology type "Incandescent." However, the 40W A-type has different technical specifications than a 100W A-type. The sales level granular lamp tech specs are agnostic of the purchaser and thus do not vary by application or sector: that is, a 250W metal halide lamp has the same wattage, efficacy, lumen output, and equipment cost whether it is installed in a low bay commercial warehouse, high bay industrial facility, or parking lot. Differences by application and sector do arise from differences in mapping subcategories of lamps to each application, which is discussed in the next section. Table 12 lists the inputs for the lamp specifications.

Table 12: Inputs for Lamp Specifications

Inputs for Lamp Specifications	Sales Level				Application Level
Input	Lamp lumen output	Lamp efficacy	Equipment cost	Lifetime	Labor cost
Unit	lm/lamp	lm/W	$/lamp to purchase	1,000 hours	$/lamp to install

Lamp Lumen Output

Lumen output is a unique characteristic of a lamp or luminaire. For some technologies where the sales data was for a specific wattage, the lumen output correlates with that wattage. For example, a 100W incandescent has a different lumen output than a 40W incandescent. For other more general categories, such as a halogen R/BR reflector, the team used a representative lumen output to approximate the mix of lamps in that category (e.g., R60, BR40, and BR60).

There are two main data sources for lumen output. The team used the lumen output data for 2010-2014 from previous Momentum Savings research. This analysis relied on data from DOE rulemakings for incumbent technologies and a combination of qualified product list databases and webscraping for LED technologies. The 2014 and 2015 BPA Lighting Market Characterization reports summarize these methods in more detail.[24] In this model update, the team used the 2019 DOE SSL report, with supporting data from the DLC QPL and Energy Star, to update lumen assumptions for 2015-2019.

Lamp Efficacy and Wattage

The research team used the same data sources for efficacy as for lumen output and calculated wattage by dividing lumen output by efficacy for each lamp type. Additional nuances for the lamp efficacy data are as follows:

- Manufacturers may report LED lamp efficacy based on the mean lumen output or the initial lumen output. For incumbent technologies, the team used mean lumen output. For LED lamps and

---

[24] Bonneville Power Administration, "Northwest Nonresidential Lighting Market Characterization," 2014. https://www.bpa.gov/EE/Utility/research-archive/Documents/Northwest_NonRes_Lighting_Market_Characterization.pdf

Bonneville Power Administration, "2015 Non-residential Lighting Market Characterization," 2015. https://www.bpa.gov/EE/Utility/research-archive/Documents/Momentum-Savings-Resources/2015_Non-Res_Lighting_Mkt_Characterization.pdf luminaires, the team used the listed lumen output provided by manufacturers and assumed that this represented the mean lumen output.

- Ballast efficiency is included in the lamp efficacy estimates—thus, the average lamp wattage represents the power draw of that lamp type given the average mix of ballasts with which it could be paired. This is relevant for linear fluorescent and HID systems, where technology progress and standards have led to changes in ballast efficiency over time. The team derived ballast mixes for these technologies using ballast sales data from 2010 to 2012. However, while the CBSA has some data on ballast efficiency mixes in the stock, there is not sufficient data to justify an adjustment to differentiate ballast efficiency in new versus existing fixtures. Thus, the team made the simplifying assumption that a lamp replaced due to maintenance is installed into a fixture with a ballast that has the same efficiency and lifetime of the average new ballast sold for that technology.
- For CFL and LED decorative lamps, lamp efficacy was determined by dividing the lumen output by lamp wattage in the ENERGY STAR database.

Equipment Cost

For equipment cost data, the research team relied upon inputs from the DOE's SSL Market Adoption Reports, published in 2016 and 2019. The team estimated LED equipment cost within the application-technology pairs based on these data sources. The team started with three years of data from the DOE SSL Reports - 2015 from the 2016 report, 2017 from the 2019 report, and 2020, a projection from the 2019 report. Next, the team estimated the percent change year-over year from these reports. Finally, the team used the 2015-2017 trend to project 2015-2017, 2017-2020 to project 2017-2019 and held 2019-2021 flat based on expert panel input. For non-LED equipment costs, the team relied on the forecast from the previous model update, which was based on the DOE National Lighting Model, and applied an adjustment to account for inflation, which relied on Producer Price Index data from FRED. The team did not update 2009-2015 costs, which were derived from the DOE National Lighting Model in a previous model update.

Labor Cost

The research team also leveraged data from the DOE lighting model for labor cost estimates. In most cases, the team held labor cost constant across applications and sectors. However, labor cost varies by application and sector, as shown in

Table 13, for HID and the LED luminaire equivalent. In this case, lamps are cheaper to install in interior applications than exterior applications in the outdoor sector. As with the equipment costs, the model annualizes labor cost based on the lamp lifetime to account for the fact that labor costs over a given period will decrease if CFLs or LEDs with longer lifetimes replace incumbents with shorter lifetimes.

Table 13: Examples of Labor Cost

Technology	High/Low Bay (LOW and HIGH)	Building Exterior (LOW and HIGH)	Parking Lot	Parking Garage	Street and Roadway (LOW and HIGH)
Metal Halide	$18	$54	$54	$54	$54
High Pressure Sodium	$18	$54	$54	$54	$54
Mercury Vapor	$18		$54		
LED Luminaire	$18	$54	$54	$54	$54

Source: Research team analysis of DOE data

Lamp Lifetime

One of the most important technical specifications is lamp lifetime. This determines the turnover in the lamp submarket or maintenance submarket. The research team used the lamp lifetime data from the DOE model. For the incumbent technology, the DOE model determined a 2010 value and annual rates of increase that vary by technology category. A lifetime value for all years was determined for the LED lamps and luminaires with some increasing over time and others held constant.

Lamp Operating Costs

Wattage and the electricity costs determine the lamp operating costs. In the forecast period, the model competes the technologies against one another based on the sum of the annualized labor cost, annualized equipment cost, and yearly operating costs.

Ballast Specifications

Ballast specifications drive the costs and turnover in the ballast submarket. While some of the technologies do not have ballasts (such as screw in lamps), HID, linear fluorescent, and pin CFLs do have ballasts. As LED lamps and TLEDs may have various ballast or driver configurations, the team made the following assumptions:

- TLEDs installed in the lamp submarket are those that can integrate with the existing ballast (may be known as instant fit or plug and play).
- TLEDs installed in the ballast submarket do not have a ballast and an electrician wires them directly to the power source (also known as ballast bypass). This leads to an associated labor cost and a lifetime associated with that wiring set, which is the same as a linear fluorescent ballast replacement.
- Higher output LED lamps can have external drivers similar to a ballast. In the ballast submarket, the team assumed that these lamps would have a driver installed similar to the ballast of the technology that they are replacing and that labor costs and lifetime are the same. The team did not find significant price differences between lamps with integrated and external drivers and thus

assumed that equipment cost for this external driver is part of the lamp cost. The result is that the ballast cost for LED lamp replacements is zero.

Table 14 list the inputs for the ballast specifications.

Table 14: Inputs for Ballast Specifications

Inputs for Ballast Specifications	Sector and Application Level			Technology Level
Input	Lamps per ballast	Equipment cost	Labor cost	Lifetime
Unit	Lamps/ballast	$/ballast to purchase	$/ballast to install	1,000 hours

Lamps per Ballast

Based on the stock mapping and lamps per fixture data in the 2019 CBSA, the research team assumed that all applications and technologies have only one ballast per fixture, except for linear fluorescent fixtures with more than four lamps in the High/Low Bay HIGH application. The team assumes these fixtures have two ballasts per fixture in both the commercial and industrial sectors. The team calculated the lamps per ballast by dividing the lamps per fixture by the number of ballasts per fixture. Since the model does not force lumens to remain constant in lamp, ballast, or fixture replacements, it is important that the lamps competing in a single application have roughly equivalent lumen output at either the ballast or fixture level. For example, if a consumer decides to replace a failed T12 ballast and the corresponding two T12 lamps with a T8 ballast and two lamps, the lumen output of that combination needs to be a reasonable substitute for that of the T12 fixture.

Equipment Cost

The equipment cost for the ballast comes from the previous model update, which was based on the DOE National Lighting Model. The team applied an adjustment to account for inflation, which relied on Producer Price Index data from the Federal Reserve Economic Data developed by the Research Department at the Federal Reserve Bank of St. Louis. For additional detail on equipment cost input development, see the Non-Residential Lighting Model Input Documentation workbook.

Labor Cost

The team set up the model logic such that when a ballast fails, the lamps associated with the ballast are replaced in addition to the ballast. The equipment costs for the lamps associated with the ballast are included in the overall cost of a ballast replacement, and there is not a separate labor cost to account for the lamp replacement.

Ballast Lifetime

The ballast lifetime drives the ballast submarket and is from the DOE model. The DOE model provides a 2010 ballast lifetime and an improvement rate in the ballast lifetime. The 2010 ballast lifetime is either 50,000 hours for all linear fluorescent and pin base CFLs or 75,000 hours for all HID lamps such as metal halide, high pressure sodium, and mercury vapor. The improvement rate for both groups is 0.5% per year.

Fixture Specifications

The research team assumed that all lamp types except for LED luminaires require a fixture. The team did not analyze fixture specifications as part of previous Momentum Savings research except for LED luminaires. Thus, the team relied on the fixture specifications in the DOE lighting model. For LED lamps including TLEDs, the fixture cost is the same as the incumbent technology. All the fixture specifications vary at the sector and application level (Table 15).

Table 15. Inputs for Fixture Specifications

Inputs for Fixture Specifications	**Sector and Application Level**			
Input	Ballasts/fixture	Equipment cost	Labor cost	Lifetime for annualizing costs
Unit	Ballast/fixture	$/fixture to purchase	$/fixture to install	150,000 hours

Ballasts per Fixture

The ballast per fixture is set to one in all cases except for High/Low Bay HIGH fixtures in commercial and industrial where it is set to two ballasts per fixture because the lamps per fixture is close to six lamps.

Equipment Cost

The fixture equipment cost for all incumbent technologies is from the previous model update, which was based on the DOE National Lighting Model. The team applied an adjustment to account for inflation, which relied on Producer Price Index data from the Federal Reserve Economic Data.

Labor Cost

The fixture labor cost is from the DOE model and varies at the sector and application levels. It ranges from $2 to $225 depending on the sector and application, with the two drivers being lamp type and lamp location—either interior or exterior. It does not change over time.

Lifetime

Turnover in the fixture submarket only occurs due to retrofit rates. The model does not incorporate fixture failure in the model in a similar way to lamp or ballast failure. However, the model needed to annualize fixture labor costs and equipment costs in a similar manner to lamp and ballast equipment and labor costs. For this reason, the model uses a fixture lifetime of 150,000 hours for all technologies to annualize the upfront costs.

HVAC Interaction Factor

The research team used the most recent HVAC interaction factors available through the RTF for commercial buildings. The RTF derived these interaction factors from building simulations for the entire region. The team used the regional weighted average values for each building type and used the warehouse building type for the industrial sector. There is no HVAC interaction for exterior and outdoor lighting.

Sales Data Analysis

Model Technology Definitions

The research team defined model technologies after reviewing several sources, such as policy initiatives that could change the overall technology deployment over time, and regional stock data. The model's technologies include HID, linear fluorescent, halogen, incandescent, CFL, and LED lamps and luminaires. Table 16 provides more detail. To limit the model's size, the team only split two of the linear fluorescent technologies into different wattage groups. The team split T5 into T5SO (28W) and T5HO (54W) and T8 into 32W, 28W, and 25W.

Next, the team defined which technologies compete in each application and sector. The 2013 CBSA provided information on technologies available in that year. Due to significant improvements in LEDs since that time, the team added at least one LED technology such as an LED lamp, LED luminaire, or TLED to each application independent of whether it was present or not in the 2013 CBSA stock analysis. Table 16 shows the technology map for all the interior commercial applications. The 16 model technologies are listed in the first row.

Table 16: Commercial Interior Technology Map

Application	32W T8	28W T8	25W T8	T12	T5SO	T5HO	CFL	Pin CFL	Hal	Inc	HPS	MH	MV	LED Lamp	LED Luminaire	TLED
Ambient Linear	■	■	■	■	■										■	■
General Purpose							■		■	■				■		
Downlight Large							■	■	■	■		■		■	■	
Track Large							■		■	■				■	■	
Track Small									■					■		
Decorative							■		■	■				■		
High/Low Bay LOW	■			■	■	■					■	■	■	■	■	■
High/Low Bay HIGH	■			■	■	■					■	■	■		■	■

Since the model technology categories are fewer than the sales data categories, the team needed to roll up the lamp tech specs at the sales level to determine the lamp tech spec at the higher level category. To do this, the team weighted the lamp tech specs of each subcategory mapped to that application by the sales quantities for each subcategory. This way the model-level category matches closely with the sales data. The team weighted to roll up lamps split by lumen output and wattage, efficacy level, length, bulb type, and application type in the sales data as necessary for each mapping.

Lumen Output and Wattage Rollup

Many of the general lamp categories in the sales data have subcategories of lamps grouped by wattage. These categories include all HID lamps, A-type incandescent, halogen, LED lamps, and linear fluorescent lamps. For example, the research team calculated weighted average specifications based on all wattages of A-type incandescent lamps (40W, 60W, 75W, and 100W) for the incandescent technology in the general purpose application.

In some cases, the team needed to map different wattage levels to the model-level categories using lumen bins. The team determined the lumen bin cutoff for the three applications with HIGH and LOW lumen bins. The lumen bin cutoffs are as follows:

- High/Low Bay is 15,000 lumens and above in HIGH
- Building Exterior is 7,000 lumens and above in HIGH
- Street and Roadway is 25,000 lumens and above in HIGH

The team mapped the individual lamp wattage subcategory using the mean lumen output determined in the lamp tech specs. The team split LED luminaires by specific application if no lumen output information was available from the sales categories. Table 17 lists the sales category split for the three applications with lumen bins.

Table 17: Mapping Technologies and Applications

Technology	**High/Low Bay LOW** *< 15,000 lm*	**High/Low Bay HIGH** *≥ 15,000 lm*	**Building Exterior LOW** *< 7,000 lm*	**Building Exterior HIGH** *≥ 7,000 lm*	**Street and Roadway LOW** *< 25,000 lm*	**Street and Roadway HIGH** *≥ 25,000 lm*
High Pressure Sodium	<250W	-	70W	-	100-250W	-
	-	≥ 250W	-	>70W	-	-
Metal Halide	<250W	-	≤ 150W	-	150-250W	-
	-	≥ 250W	-	>150W	-	≥ 400W
Mercury Vapor	<250W	-	-	-	-	-
	-	≥ 250W	-	-	-	-
LED Luminaire	Low Bay 5,000-15,000	-	LED Wall Packs, LED Post-Top, and Bollard	-	LED Post-Top and Bollard	-
	-	High Bay >15,000	-	LED Canopy Fixtures, LED Area, and Parking Lot	-	LED Roadway

Lamp Shape Rollup

For the reflector category for incandescent, halogen, CFL, and LEDs, the sales data is at the lamp shape level (i.e., R/BR, PAR). For the Downlight Large and Track Large applications, the research team rolled up all reflector lamp shapes into the model-level technology. The MR16 lamps are the only shape included in the Track Small application.

Length Rollup

For the T12 and T8 categories with sales data for both 4-foot and 8-foot lamps, the research team determined the sales amount by which to weight the tech specs by doubling the sales quantities of the 8-foot lamps and keeping the sales quantities of the 4-foot lamps the same. The team halved the wattage and lumen output tech specs of the 8-foot lamps for the roll up. The two applications with 8-foot lamps are High/Low Bay HIGH and High/Low Bay LOW. The model considers all linear fluorescents as 4-foot lamps.

Appendix 2. Sensitivity Analysis

In prior iterations of this model, sensitivity was analyzed by allowing the user to adjust inputs up or down by a margin of their choosing. Because this approach does not factor in the appropriate level of change for each input variable, sensitivity scenarios were developed to reflect the potential variation in inputs due to uncertainty.

Where possible the research team uses a confidence interval-based approach to calculate high and low scenarios. Where insufficient data exists to calculate a confidence interval of appropriate magnitude, the research team leveraged relevant research, publications, and analysis of a variety of data to estimate appropriate scenarios.

Sensitivity Scenarios

Below are brief descriptions of each input for which sensitivity scenarios were developed.

HVAC Interaction Factor

HVAC interaction factor in the model is taken from the Council HVAC Interaction Factor Analysis. The Council's HVAC interaction factors used in the model were based on two prior sets of data which were combined. Because the property types do not align perfectly between the Council's analysis and the model, the research team matched property type where possible, applying an interaction factor of 0 when outdoors, and otherwise applying an average differential between the old and new data sets from the Council's analysis. Note that this scenario does not include a confidence interval-based approach but instead relies on the variation in Council data sets used for calculation of general HVAC interaction factors.

Market Wattage

2019 CBSA data is used to calculate standard deviations of wattage by technology type & application. Not all technology-application pairings are present in the most recent CBSA. To address this, some standard deviation values are interpolated. A confidence level of 95% is applied within this analysis.

Facility Operating Hours

2019 CBSA data is used to calculate standard deviations of hours of use by technology type & application. A confidence level of 95% is used to determine high and low scenarios.

Lamps per Fixture

2019 CBSA data is used to calculate standard deviations of lamps per fixture which is then used to calculate a 95% confidence interval. The confidence interval forms the basis for the high and low scenarios included in the model.

Lamp Saturation

Lamp saturation is more complicated than other inputs. Lamp saturation scenarios required making adjustments to LED technology saturations (based on their respective 95% confidence intervals) and adjusting other technology saturations to reflect a complete mix.

These saturations reflect the 2019 mix of products in the stock and so would be leveraged in the model during the calibration process that connects the 2014 and 2019 CBSAs. Because the saturations would require recalibration to be tested, they are not immediately comparable to other input scenarios as the change in input is not a ceteris paribus adjustment to a single input but rather a calibration of the entire modeled plan period between 2015 and 2019.

Building Stock

Building stock within the model is taken from the Council's Seventh Power Plan. The only scenario the research team developed for this model input reflects the 2021 Plan stock. In this scenario, only 2021 square footage within the model is leveraged as a variable input (meaning all other years remain at Seventh Power Plan levels). No confidence intervals are used as this scenario merely reflects the different between two assessments of stock.

Lamp Lifetime (Hours)

Lamp lifetime scenarios impacts the model through the level of turnover of pre-2015 LED products. Because of that the high and low scenarios reflect only changes to LED technology lifetime. Further, uncertainty surrounding lifetimes is highest around LEDs, as they have experienced substantial changes in quality and durability as technology has matured.

Precise data relating to the lifetimes of LEDs are difficult to find. The best source is the Department of Energy and National Lab estimates of uncertainty surrounding LED lifetimes, which were used to approximate reasonable uncertainty bounds that are applied within the model to create a high and low scenario.

Fixture Density

Fixture density is calculated based on the 2019 CBSA at the building type level. Because different building types contain many different application and space uses, there is very high variability in the number of fixtures per square foot of building space. Although high and low scenarios based on a 95% confidence interval are contained within the model, their results are not directly comparable to other scenarios due to the extremely high uncertainty surrounding fixture density within any one property type. No property type has a fixture density uncertainty margin of less than 80%, meaning that the number of fixtures (and consequently consumption and savings) within the model is highly impacted by these scenarios.

Sensitivity Analysis Results

The impact of these scenarios on market scenario total consumption is shown below. Additional detailed outputs of each sensitivity scenario are included in the Analytica model. Hours of use produces the highest impact on total consumption, total market savings, and momentum savings within the model and is consequently an area of interest for additional research in the future.

Figure 4. Impact on Total Market Consumption by Sensitivity Scenario