Memorandum

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Subject: Non-Residential Lighting Momentum Savings Methodology

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This memo documents the Navigant Consulting, Inc. and Cadeo team's (the research team's) methodology for estimating non-residential lighting Momentum Savings. The team presents the methodology per the Four Question Framework, which is Bonneville Power Administration's (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 Northwest Power and Conservation Council's (the Council's) Sixth Plan period (2010-2015). 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 Council's Sixth 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.

Most Momentum Savings analyses define the market in terms of sales, which is accurate when measure lifetime is relatively comparable between the baseline and efficient replacements. For the non-residential lighting market, however, there are substantial differences in measure lifetimes between baseline and efficient bulbs. For example, the average lifetime of a T12 linear fluorescent lamp is shorter than the average lifetime of an efficient LED luminaire replacement by about 30,000 hours. If the analysis considered only total bulb sales, the results would show a much greater count of inefficient T12 lamps in the market as compared to LED luminaires, but only because consumers using T12s must purchase multiple lamps to every one LED. For this reason, the team defined the non-residential lighting market as the total number of lamps installed in the region (stock), rather than the total volume of lamps sold in any given year (flow).

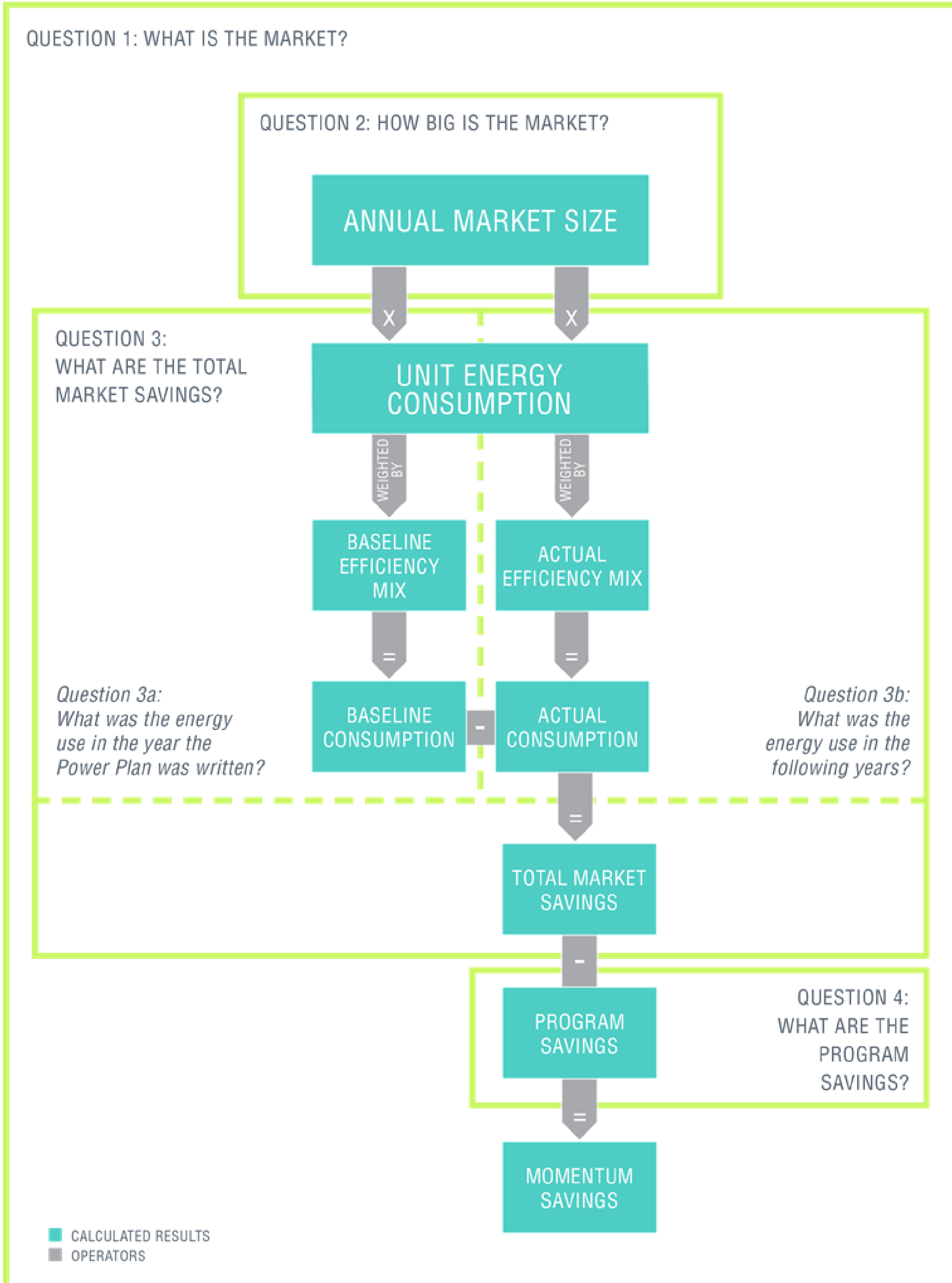
Using this definition of the total number of installed lamps, the research team followed the Four Question Framework to define the non-residential lighting market. **Question 1** describes what elements the non-residential lighting market includes such as geographic scope, sectors impacted, and technology types installed throughout the region.

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[1] included in the commercial, industrial, agricultural, and outdoor lighting sectors. This data informs the stock turnover model that 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 diverse non-residential lighting market. **Question 3** also describes how the team used detailed sales data from regional distributors 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. Figure 1 summarizes how the four questions fit together to estimate Momentum Savings.

[1] 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 share 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. The current analysis does not include lighting controls. 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[2]	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.
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

[2] 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 three distinct sectors: commercial, industrial, and outdoor lighting. Agriculture is included in the industrial sector.

Commercial

The commercial sector covers lighting applications in building types as defined in the Council's Seventh Power Plan (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) data (e.g., manufacturing, food processing, and warehouses) 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.

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 define the various technologies that are eligible for installation. 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 and emerging technologies. The team considers LED lamps, LED luminaires, and tubular LEDs (TLEDs) as emerging technologies; all others are incumbent technologies.

The research team reviewed the following sources to determine which applications to include:

- The US Department of Energy's (DOE's) national lighting model—used to support the Solid State Lighting (SSL) Adoption Report—which is also organized by application
- The Seventh Plan, which focused on a subset of lighting applications
- Program measure offering descriptions
- Manufacturer product categories
- Lamp and fixture type categories in NEEA's 2014 Commercial Building Stock Assessment (CBSA)

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.[3]

[3] 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 Track Small	Display and track lighting **Large:** PAR and R/BR lamps (diameter >2.5") **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 Lamps	Interior Commercial Interior Industrial
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

Application	Description	Eligible Technologies	Sectors
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:

- **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.
- **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.
- **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.
- **New construction** includes all fixtures installed through the addition of new floor space (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.[4] The research team relied on several sources to estimate the total lamps installed in the region, including square footage estimates from the Council's Seventh Plan and lamp and fixture density data from the 2014 CBSA. 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.[5] 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

[4] 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.

[5] 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 Pacific Northwest population and the average number of street and roadway lamps per person [6]

The research team used the data from the Council's Seventh Plan to estimate the total floor space for each commercial building type included in the study. The team also accounted for changes to these totals—through new construction and demolitions—to ensure they accurately represent the floor space for each sector across the region for each year of the study. For industrial floor space, the team used the national Manufacturing Energy Consumption Survey (MECS) data scaled down to the region and then scaled up to include agricultural areas.[7]

The research team calculated a fixture density for each building type in 2014 and assumed the values do not change over time.[8] Table 4 summarizes the data sources for market size (square footage or population) and fixture density for each portion of the non-residential market.

[6] Outdoor lighting density is the average number of street and roadway lamps per person from the Council's 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.

[7] 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.

[8] Overall fixture density at the application or sector level may change over time due to different building type growth and demolition rates, but the team assumes fixture density at the building type level remains constant. 2014 CBSA data is represented in the model as end-of-year 2013.

Table 4: Fixture Density Metrics and Data Sources

Sector	Density Metric	Market Size Data Source	Fixture Density Data Source	Notes/Exceptions
Commercial Interior	Fixtures per square foot	Seventh Plan (square feet)	2014 CBSA	Based on mapping detailed CBSA lighting data to model application and building types. Hospital and University used additional data sources due to the lack of detailed lighting data in the CBSA.[9]
Industrial Interior	Fixtures per square foot	MECS, scaled to Pacific Northwest with census data (square feet)	2014 CBSA (Warehouse)	The 2014 IFSA data did not have sufficient square footage or fixture count data to provide an industrial-specific estimate; the team used CBSA data for the Warehouse building type as a proxy.
Commercial Exterior	Exterior fixtures per interior square foot	Sum of Seventh Plan commercial and MECS industrial square footage (square feet)	2014 CBSA	The 2014 CBSA provides exterior fixture and wattage density relative to interior square footage. While this metric has some uncertainty around it, the team believes this is the best data source available to estimate total exterior fixture counts at this time.
Industrial Exterior	Exterior fixtures per interior square foot		2014 CBSA (Warehouse)	The 2014 IFSA study contained little outdoor lighting data; the team again used CBSA data for the Warehouse building type as a proxy.
Street and Roadway	Fixtures per population	Seventh Plan (population)	Seventh Plan	The Council analyzed several data sources to estimate fixtures per Pacific Northwest population; the team used these estimates directly.

Question 3: What are the total market savings?

Total market savings are the difference between baseline consumption beginning in the year the Council's Sixth Plan was written—calculated in Question 3a—and actual consumption in the years after the Plan was written, calculated in Question 3b. For example, if the analysis finds actual 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 actual 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 modeling how the

[9] The 2014 CBSA used a separate data collection approach for Hospitals and Universities and did not use the same detailed lighting form as other building types. This resulted in non-standard, and in many cases, qualitative or approximate, data on fixture technology type and quantity. Thus, the research team was unable to include these data in the CBSA lighting analyses.

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,[10] leading to answers to Questions 3a and 3b.

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 determines 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 actual energy consumption that drive the Momentum Savings analysis.

Building the Model

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

1. A characterization of the installed stock (size, 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 Using the Model to Refine 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 actual scenarios. In the baseline scenario, the sales mix is frozen, reflecting the concept 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 frozen 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 the actual 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).

[10] Appendix A. 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 the stock turnover model: the 2014 CBSA, 2014 IFSA, and the Seventh Plan.[11] The application shares remained constant within a building type over time, whereas the mix of technologies within each application varied as the stock turned over.

The research team used the following steps to estimate the commercial technology mix for interior lighting applications, assuming that the 2014 CBSA and IFSA data were representative of regional stock at the end of 2013:

1. Mapped each entry from the detailed CBSA lighting data to the corresponding model application and technology (example shown in Table 5)

Table 5: 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 (example shown in Table 6)

Table 6: Example Fixture Application Shares for Assembly and Food Service Building Types

Application	Percentage of Assembly Fixtures	Percentage of Food Service Fixtures
Ambient Linear	45%	30%
Decorative	0%	4%
Downlight Large	29%	31%
General Purpose	11%	22%
High/Low Bay HIGH	2%	0%
High/Low Bay LOW	6%	2%
Track Large	4%	8%
Track Small	2%	4%
Total	**100%**	**100%**

Source: Analysis of 2014 CBSA data

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

3. Calculated the share of fixtures represented by each technology for each application in 2014 using the following equation and the CBSA detailed fixture data. Table 7 shows the technology shares for two applications in the commercial sector.

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 7. Example Technology Shares for Ambient Linear and High/Low Bay Low Applications (Commercial Sector)

Technology	Percent of Ambient Linear Fixtures	Percent of High/Low Bay Low Fixtures
25W T8	4%	0%
28W T8	5%	0%
32W T8	78%	67%
CFL	0%	0%
Halogen	0%	0%
High Pressure Sodium	0%	0%
Incandescent	0%	0%
LED Lamp	0%	1%
LED Luminaire	0%	0%
Mercury Vapor	0%	0%
Metal Halide	0%	5%
Pin CFL	0%	0%
T12	10%	12%
T5 High Output	0%	14%
T5 Standard Output	3%	1%
LED Tubes	0%	0%

Source: Analysis of 2014 CBSA data

For the industrial sector, the research team used the IFSA lighting data to estimate the mix of applications and technologies. The team leveraged the Council's analysis of the IFSA data for the Seventh Plan, which provided some standardization of the fixture descriptions in the raw IFSA data. The team repeated the commercial analysis process of mapping individual site fixture data to applications and technologies to calculate the share of installed watts and fixtures by application and technology for the industrial sector.

For the exterior lighting applications for both commercial and industrial (parking garages, parking lots, and building exterior), the research team relied on 2014 CBSA data. The team categorized CBSA outdoor lighting entries to the building exterior model applications. Table 8 documents these assumptions.

Table 8: 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 2014 CBSA

The Seventh Plan contains estimates of the mix of incumbent technologies in street and roadway lighting and draws on several sources to estimate the LED installed stock penetration in 2015. The analysis cites the 2013 DOE SSL Market Adoption report estimate of a 7.1% penetration of LEDs in the 2013 installed stock. The team combined this data point with the mix of incumbent technologies to estimate the overall mix of technologies in the street and roadway application in 2013 (Table 9).

Table 9: Street and Roadway Installed Stock Technology Mix: 2013

Fixture	Distribution
LED < 400W	7.0%
LED ≥ 400W	0.1%
High Pressure Sodium 100W	50.2%
Metal Halide 200W	13.0%
High Pressure Sodium 250W	12.2%
Metal Halide 400W	16.3%
Metal Halide 1000W	1.3%

Source: Analysis of Seventh Plan and the 2013 DOE SSL Market Adoption report

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 and assumed a single lamp per outdoor street and roadway fixture.

Equation 2: Calculating Technology Share of Lamp Stock

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

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. The team exempted LED technologies from this turnover because they are emerging technologies installed recently and therefore unlikely to be replaced during the modeling period of 2009 to 2015.
- 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.[12] 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.

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

Equation 3: Failure Distribution

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

Where:

- a = application
- g = age
- i = installation year
- s = sector
- 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.[13] 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

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

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 one 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

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

Natural Replacement of Fixtures. For all technologies except LED, 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 (e.g. 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.[14]

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[13] 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.

[14] 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.

Equation 6. Natural Replacement Turnover

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

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

$$\text{Replacements}_{a,s,t,y} = \left(\sum\nolimits_{i,t} \text{Lamp Failures}_{a,i,s,t,y}\right) \times \text{Sales Mix}_{a,t,y,m} + \left(\sum\nolimits_{i,t} \text{Ballast Failures}_{a,i,s,t,y} \times \text{Lamps per Ballast}_{a,i,s,t}\right) \times \text{Sales Mi}$$
$$+ \left(\sum\nolimits_{i,t} \text{Fixtures Replacements}_{a,i,s,t,y} \times \text{Ballasts per Fixture}_{a,i,s,t} \times \text{Lamps per Ballast}_{a,i,s,t}\right) \times \text{Sales Mix}_{a,t,y,m}$$

Where:

m = submarket

Table 10 summarizes the key data inputs and sources for the turnover portion of the model.

Table 10: 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: Seventh Plan hours of use by building type weighted to application level Industrial buildings: IFSA Exterior Lighting: Sixth Plan
Natural Replacement Turnover Rate	Percentage of fixtures replaced each year due to retrofits, renovations or other upgrades	Commercial: Sixth Plan building type rates weighted to application level 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.
- 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.
- 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 provides a snapshot of 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

Using the Model to Refine the 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, manually 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 BPA has collected sales data from 34 unique distributors over the 2010-2015 period.[15]

This sales data is a resource unavailable to many market modelers, and it provides 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 sales data limitations are as follows:

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

- **Technology representativeness.** The sales data is not equally complete for every technology. For example, in the first year of non-residential data collection, very few distributors submitted significant data beyond linear fluorescent and high-intensity discharge (HID). Therefore, the data for these years does not provide a full picture of the relative magnitude of these product sales relative to other technologies (e.g., LED, incandescent, CFL).
- **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 not just the high-level sales but also which lamps are going where—something that sales data cannot inform directly.

To address these limitations, the research team developed a sales allocation process to estimate the share of each technology's sales going to each sector and application. This process also weights the overall sales mix by the known size of each application in the stock, alleviating the issue of technology representativeness in early years. The research team implemented this process in two steps:

- **Step 1: Determine relative size of applications and submarkets for each technology.** Using the 2013 stock application and technology saturation data and the turnover assumptions described above, the team turned over the 2013 stock to calculate the relative size of each application and submarket's lamp sales in 2014 (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 2013
    - The ballast submarket size is equal to the number of ballasts that failed in 2013 multiplied by the number of lamps per ballast
    - The fixture submarket size is equal to the number of fixtures removed in 2013 due to natural turnover multiplied by the number of lamps per fixture

  The team calculated initial application-level sales by assuming like-for-like sales (T12s replace T12s). The research team also needed a way to understand how these application shares could be changing over the modeling period: for example, anecdotal evidence from program activity suggests that the share of T8s going into the High/Low Bay applications increased over the modeling period as HID technology sales declined. The team needed a second point estimate of application shares from a different year to inform these trends rather than assuming the 2014 shares were representative for all years. The team repeated the process described above using estimates of 2010 stock application and saturation from the DOE national lighting model.[16] Then, the team interpolated and extrapolated to estimate sales allocations for each technology and application from 2009 to 2015.

[16] The research team chose to use this national data because it is already broken into applications. The team reviewed the overall technology saturation trends between the 2003, 2009, and 2014 CBSA studies and made some adjustments to individual technology saturations in the national model where the national data did not align with regional trends. For example, national T12 saturation was higher in 2010 than the trend the CBSA studies implies.

- **Step 2: Scale application and submarket-level mixes to align with distributor sales data.** Once these trends in allocations were established, the research team needed to align the technology mixes with the sales mix found in the distributor sales data for the entire non-residential market. The 2010-2015 market sales mixes come directly from distributor data. The team estimated the 2009 market sales mix through the following process:
    - Trending each technology’s share backwards based on 2010-2015 shares
    - Adjusting any negative values to zero
    - Capping CFL, 28W T8, and 25W T8 shares to not exceed 2010 values given these technologies were in a growth stage at this time
    - Re-normalizing so that all technology shares summed to 100%.

  To align the application-level sales estimates with the distributor data, the team multiplied the application-level results by the overall sales mix in 2014 using Equation 8. Finally, the team renormalized each application and submarket so that the technology shares summed to 100%.

Equation 8. Scaling Sales Mixes to Align with Sales Data

$$\text{Sales Mix}_{a,m,t,y} = \text{Like-for-Like Sales Mix}_{a,m,t,y} \times \text{Overall Sales Mix}_{t,y}$$

Where:

a = application

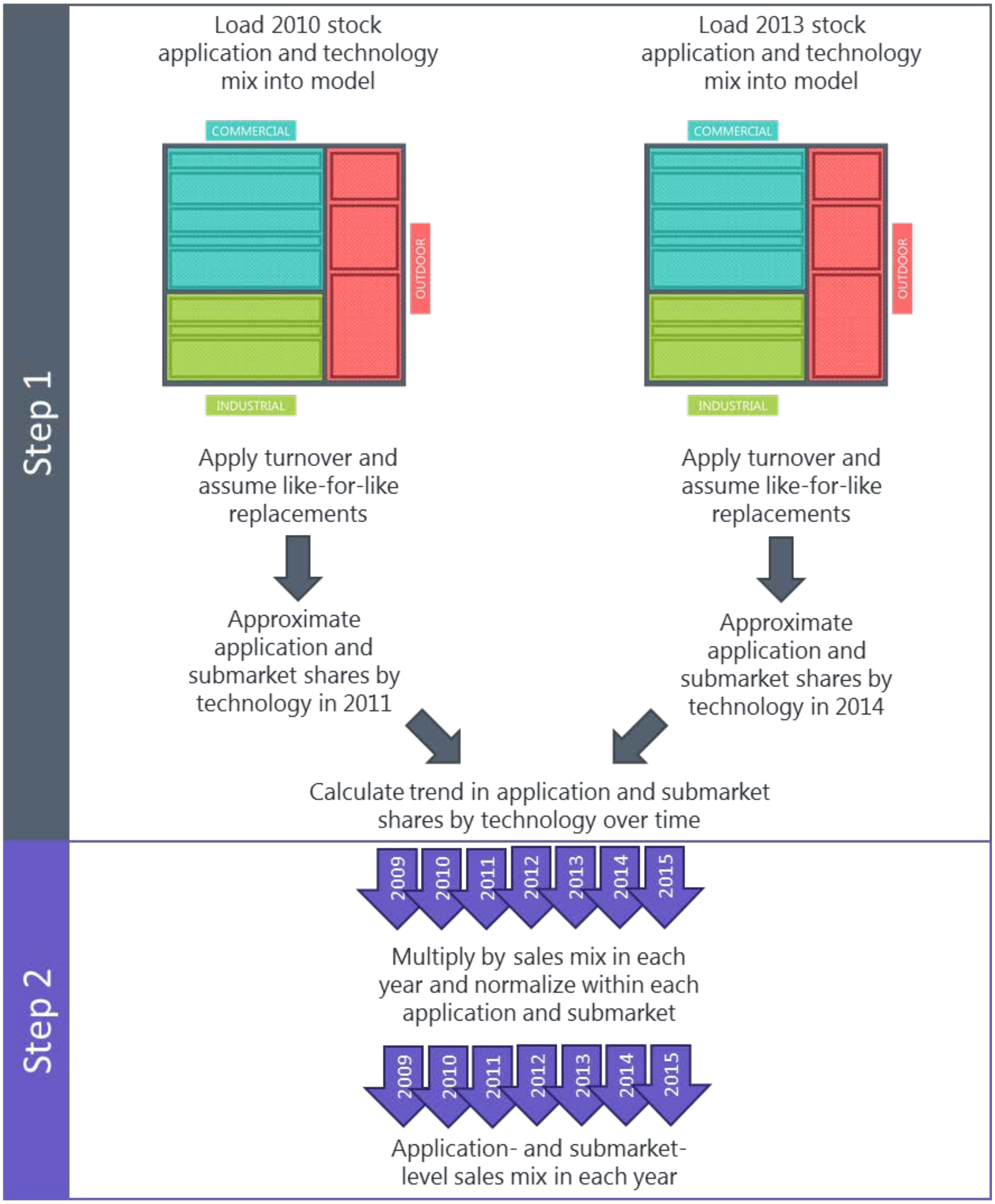
m = submarket

t = technology

y = year

Figure 3 summarizes this process.

Figure 3: Sales Allocation Methodology



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.

Applying Sales Mixes to Model Stock Over Time

The research team used the 2010 stock technology saturations as an estimate for end of year 2008 stock saturation. The model turned over the stock in each year and applied the sales mixes for each submarket and application to the corresponding incoming sales. Due to the complexity of the stock turnover which has so many products of varying lifetime, the stock in 2013 as calculated in the model does not exactly match the input data described previously and used in the sales allocation process. The research team compared the modeled 2013 stock with the 2013 input data. As shown in Table 11, the model is within 1% to 5% of the input technology shares. Given the uncertainty around the technology mixes and the error bounds of the input data, the team chose not to further manipulate sales data or other inputs to improve alignment with the input 2013 stock mix.

Table 11. 2013 Stock Mix Comparison

Technologies	2013 Model Stock Mix	2013 Input Stock Mix
T8	54%	59%
T5	7%	6%
T12	11%	10%
CFL	13%	12%
Halogen	2%	2%
HID	6%	4%
Incandescent	3%	5%
LED	4%	2%

Source: BPA Non-Residential Lighting Model, research team analysis of CBSA, IFSA and 7th Plan data

The team considered iteratively back-calculating the 2008 stock saturations based on the sales data and 2013 stock data, but this approach did not improve the alignment with 2013 data or the trends in stock over time.[17]

Refining Model Sales Mixes to Improve Sales Data Alignment

After running the model using the sales mixes estimated through the sales allocation process, the research team found that this methodology underestimated LED sales relative to the calculated sales allocations based on distributor sales data (for additional detail on why this occurs, see Appendix C). This was especially pronounced in applications where the incumbent technologies have much shorter lifetimes and the initial “like-for-like” assumption did not allocate enough LED sales to the lamp failure submarket, where most sales occur. The team modified the model to automatically adjust submarket-level sales mixes in applications where the modeled sales for individual technologies were higher or lower than the sales allocations at the application level. This greatly improved the modeled sales mixes with respect to the sales allocation targets and overall distributor sales data.

[17] The model cannot simply back-cast from the 2013 stock and prior years’ sales shares alone, because the number of lamps and fixtures failing in each year depends on the mix of technologies in the stock in the prior year.

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 2009, prior to the Council's Sixth Plan. The team then held the 2009 sales 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 actual scenario changes each year, the sales mix in the frozen scenario stays the same. The technology mix in the *stock* did change in both scenarios but less so in the frozen scenario, which drives savings.

Table 12 shows an example of the efficiency mix for the ambient linear application in 2009, the year immediately preceding the Sixth Plan, and the following years.

Table 12: Sales Mix over Time, Ambient Linear

	2009 Sales (Frozen Baseline)	2010 Sales	2011 Sales	2012 Sales	2013 Sales	2014 Sales	2015 Sales
25W T8	5%	5%	4%	4%	4%	4%	3%
28W T8	7%	8%	11%	13%	11%	10%	13%
32W T8	64%	66%	66%	67%	70%	69%	64%
LED Luminaire	0%	0%	0%	0%	0%	1%	2%
T12	21%	19%	16%	13%	12%	11%	9%
T5SO	3%	3%	3%	3%	3%	3%	2%
TLED	0%	0%	0%	0%	0%	2%	6%

Source: Non-Residential Momentum Savings Model

As shown in Equation 9the 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 9: 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 following equation (Equation 10) to calculate the UEC for each lamp type in the application table in Question 1.

Equation 10: 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 A. 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 actual market scenario for the non-residential lighting market, the team ran the model using the actual allocated sales shares over time to come up with 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 in each purchase trigger and application.

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

Calculating Total Market Savings

The research team subtracted the actual 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 11 and Equation 12, isolates first-year savings in each year of the analysis.[18]

Equation 11: Cumulative Savings

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

The busbar factor in Equation 11 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 12).

Equation 12: First-Year Savings

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

Where:

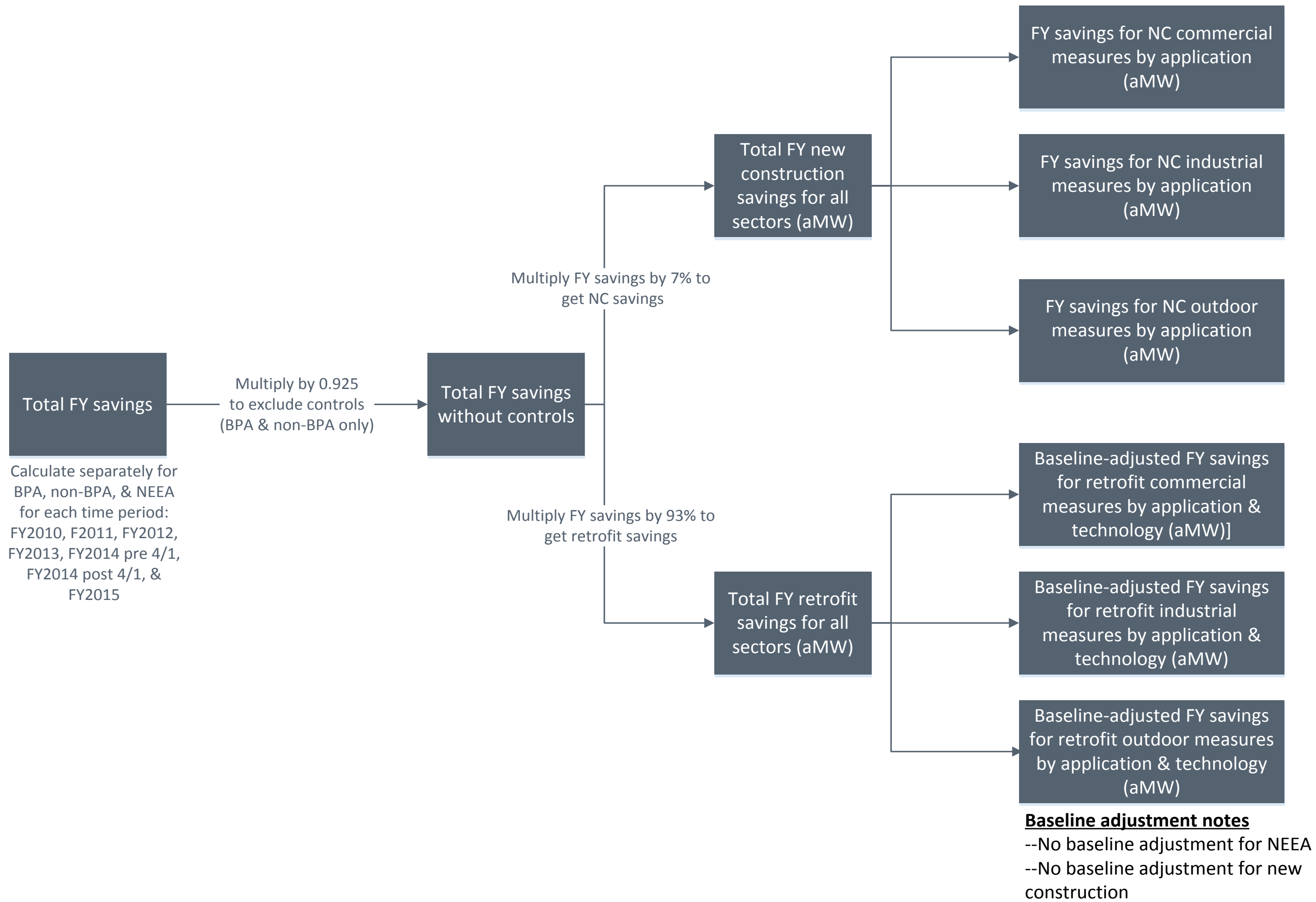
y = year in study period

Question 4: What are the program savings?

The research team followed the process shown in Figure 4 to estimate program savings. This process is detailed below, including caveats by program year. Since the model frozen baseline is based on the current practice in 2009, the research team adjusted program savings that were not claimed relative to a current practice baseline to align with the model baseline.

[18] In contrast to past Momentum Savings analyses, the research team had to calculate savings by monitoring changes in the stock because the conventional methodology—direct comparison of first-year consumption from lighting sales between the baseline and actual cases—overstates savings. This overstatement stems from a difference in sales volume between the baseline and actual cases. In this analysis, the actual case has fewer sales in each year because the market mix is longer lived than in the baseline mix (e.g.., more LEDs and CFLs, etc.). The prevalence of longer lived products in the actual case slows the stock turnover, which results in fewer annual sales than in the baseline. However, this decrease in annual sales does not contribute to real savings as the same number of existing sockets need lamps in both scenarios.

Figure 4: Program Savings Analysis Process



Source: Research team and BPA analysis

Key Assumptions

- 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 2009).[19]
- 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 2009).
- All savings are reported in average megawatts (aMW).
- 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 investor-owned utilities (IOUs) and earlier BPA projects, the research team needed to use the program savings adjustments from BPA's FY2014 and FY2015 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, this is a significant assumption with great uncertainty that directly affects Momentum Savings estimates.

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 (2010-2015). The analysis required the total savings for BPA programs, non-BPA programs (investor-owned utilities, or IOUs), and NEEA programs. Table 13 provides a summary of the data sources for the program savings.

[19] 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 13: 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[20]
Non-BPA	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]
NEEA	Calendar year (January 1 to December 31); the team did not have to convert the savings for the model.	Site energy savings (at the meter level); the team did not have to convert the savings for the model.	NEEA[23]

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 assumed that 7.5% of the total FY savings were savings from controls rather than changing out lamp technology.[24] This assumption applies only to the BPA program savings and non-BPA program savings.

After adjusting for controls, the team adjusted for new construction savings. The team assumed that 7% of the total FY savings without controls were from new construction and 93% of the total FY savings without controls were from existing buildings.[25] 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.

[20] Provided by BPA via email on September 9, 2016.

[21] The Council 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, Summary Workbook from 2014, Tab: Achieved by Sector End Use Chart. This data includes BPA and non-BPA utility savings data at the busbar level. The research team subtracted the BPA savings from the RCP data based on the data provided by BPA via email on September 9, 2016.

[23] Data provided by NEEA via email on September 8, 2016.

[24] This assumption was used in the previous non-residential lighting model and was provided by the Energy Trust of Oregon through an email correspondence.

[25] The research team used the file provided by BPA via email on September 16, 2016 titled "LCData_Latest." The team filtered completion date by 4/1/14 – 9/30/15. The team calculated percentage split using the following columns in the database: CompletionDate, CalculatorType, NC_TotalkWhSavedAdjustedForHVACAndBusbar (new construction savings), and EquipSav_HVAC_MAB_Busbar (existing building 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. The team split the data into savings from commercial, industrial/agricultural, and outdoor lighting. The team used the data sources below for 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 datasets.

- **FY2010-FY2012:** The research team used the BPA lighting calculator data from project files between April 12, 2010 and November 16, 2013; additional details on the source of the data were provided in the Lighting Calculator Data Summary memo submitted by the research team in August 2013[26]
- **FY2013, FY2014 Pre 4/1/14:** The team used a savings midpoint from the FY2010-FY2012 dataset and the FY2015 dataset[27]
- **FY2014 Post 4/1/14:** The team used lighting calculator data[28] from April 1, 2014-September 30, 2014[29]
- **FY2015:** The team used lighting calculator data from October 1, 2014-September 30, 2015[30]

Application Mix

Once the team split savings by sector, it applied an application mix to the total FY new construction savings and total FY existing building savings. The application mix shows the percentage of savings that comes from each application. The team used a variety of sources to calculate the application mix, which are detailed below for each FY. All the data sources below are from BPA program data, which the team used as a proxy for the non-BPA program data and NEEA program data due to the lack of granularity in those data sources.

- **FY2010-FY2013 and FY2014 Pre 4/1/14:** The team used the program data from April 1, 2014-September 30, 2015. The team had to map the program data to convert it into the applications used in the model.[31]

[26] The file behind the 2013 lighting calculator memo is called "Option1LightingData." This file contains BPA program data for FY2010-FY2012, but it is mostly FY2012 data. The team filtered tab "tblLightingSpace," Column F (MeasureCategory) by "Deemed."

[27] The FY2010-FY2012 data comes from the Lighting Calculator Data Summary memo on August 9, 2013, which is supported by the spreadsheet "Option1LightingData." The FY2015 data is based on measures completed between October 1, 2014 and September 30, 2015 in the spreadsheet provided by BPA via email on September 16, 2016 titled "LCData_Latest."

[28] Extract of the lighting projects completed using the BPA Lighting Calculator; template available for download: https://www.bpa.gov/EE/Sectors/Commercial/Documents/BPA%20LC%203.3%20Final.xls

[29] The team used the file provided by BPA via email on September 16, 2015 titled "LCData_Latest." Filtered completion date by 4/1/14 – 9/30/14.

[30] The team used the file provided by BPA via email on September 16, 2016 titled "LCData_Latest." Filtered completion date by 10/1/14 – 9/30/15.

[31] The team used the file provided by BPA via email on September 16, 2016 titled "LCData_Latest." Filtered completion date by 4/1/14 – 9/30/15. The lighting calculator data supporting the August 9,2013 Lighting Calculator Data Summary memo did not have reliable measure-level details to assign application mixes, therefore, the team used the BPA lighting calculator data from April 1, 2014-September 30, 2015 as a proxy.

- **FY2014 Post 4/1/14:** The team used lighting calculator data from April 1, 2014-September 30, 2014 to calculate the application mix. The team had to map the program data to convert it into the applications used in the model.[32]
- **FY2015:** The team used lighting calculator data from October 1, 2014-September 30, 2015 to calculate the application mix. The team had to map the program data to convert it into the applications used in the model.[33]

Key Assumptions

- 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 100% of NEEA savings came from the ambient linear application.[34]
- 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 being 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 actual 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.

Baseline Adjustment Process

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

1. **Created a table to indicate when to adjust and when not to adjust the baseline.** "No adjustment" means the baseline for that FY and application is current practice; therefore, no

[32] The team used the file provided by BPA via email on September 16, 2016 titled "LCData_Latest." Filtered completion date by 4/1/14 – 9/30/14.

[33] The team used the file provided by BPA via email on September 16, 2016 titled "LCData_Latest." Filtered completion date by 10/1/14 – 9/30/15.

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

adjustment is needed to make it comparable to the 2009 frozen baseline. "Adjust" means the baseline for that FY and application is not current practice; therefore, an adjustment is needed to make it comparable to the 2009 frozen baseline.

Table 14: Baseline Adjustment

Fiscal Year	Ambient Linear		General Purpose/ Omnidirectional		All Other Applications
	BPA	Non-BPA (IOUs)	BPA	Non-BPA (IOUs)	BPA and Non-BPA (IOUs)
FY2010	Adjust	Adjust	Adjust	Adjust	Adjust
FY2011	Adjust	Adjust	Adjust	Adjust	Adjust
FY2012	Adjust	Adjust	Adjust	Adjust	Adjust
FY2013	Adjust	Adjust	Adjust	Adjust	Adjust
FY2014 Pre 4/1/14	Adjust	Adjust	Adjust	Adjust	Adjust
FY2014 Post 4/1/14	No Adjustment	Adjust	No Adjustment	Adjust	Adjust
FY2015	No Adjustment	No Adjustment	No Adjustment	No Adjustment	Adjust

Source: Research team analysis of programs' adoption of current practice baselines

2. **Mapped 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. **Calculated 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 come up with a weighted average baseline and efficient wattages within a given FY, sector, and application as detailed in Step 4.
4. **Used 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 them together for all 16 technologies. The team did this calculation for both the baseline wattage and the efficient wattage.
5. **Calculated a baseline adjustment factor for each FY, sector, and application combination.** The team calculated the adjustment factor using the following equation:

Equation 13: 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 2009 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. **Applied the adjustment factor to the program savings for a given FY, sector, and application, when applicable (see Table 14).** The team applied the adjustment factor to the program savings when applicable to adjust the program savings baseline to the 2009 frozen baseline.

Key Assumptions

- The research team did not have detailed program data for years prior to 2014 and thus used the program baseline and efficient technology mixes for 2014 for 2010 through 2013. This makes the baseline adjustment for prior years highly uncertain.
- When this application of 2014 mixes resulted in LEDs in program mixes before LED sales began in an application, the research team removed LEDs from the program mix and renormalized the remaining technologies to 100%.
- The team allowed baseline adjustment factors to be greater than 1.0 (e.g. programs used a baseline more efficient than the frozen baseline), with two exceptions:
    - **Building Exterior LOW**: This application has many different lighting types (wall packs, post-top/low output area lighting, bollards, flood lights etc.) and the research team believes that the difference between the frozen and program baselines is likely because programs focus on a certain subset of building exterior: metal halide is the most common baseline technology in programs, whereas incandescent are a large portion of the frozen baseline. The goal of the baseline adjustment is to make sure the program and frozen baselines are aligned—and in this case the difference does not indicate that program baselines were incongruent, rather programs focused on a subset of the application. The research team applied an adjustment factor of 1.0 for this application.
    - **Building Exterior HIGH**: The adjustment for most years is almost exactly 1.0, but when the LED percentage drops in earlier years (2010 and 2011), the efficient wattage gets much closer to both baselines. This makes the difference in baselines (approximately one watt) more significant. The research team believes this is an issue with lack of data on the program efficient mix in earlier years which should not affect the adjustment factor—not an issue of incongruent program baselines—and used an adjustment factor of 1.0 for these early years.

Calculating Momentum Savings

The research team removed 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.

Appendix A. 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 15 lists the value and unit for the individual tech specs for each of the three submarkets.

Table 15: 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	1,000 hours (lamp)	1,000 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 16 lists the inputs for the lamp specifications.

Table 16: 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 the team developed over the past three years. 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.[35] Second, the team filled in 2015 lumen output with the latest national data (for changing technologies such as LED) or held the data constant (for incumbents). For 2009, the team either backcast or held the lumen output constant depending on whether the 2010-2015 data showed a consistent trend. For some lamp types in the model where BPA did not collect sales data, the team did not estimate tech specs as part of the previous analysis. Figure 5 summarizes these special cases and the source of the tech specs for each product. In this figure, ES Database stands for the ENERGY STAR database of qualified lamps.

[35] 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

Figure 5: Lumen Output Source Data for Select Lamp Types

Lamp Type	Lamp Lumens						
	Sales Year						
	2009	2010	2011	2012	2013	2014	2015
Other LED Lamps							
Decorative (40W equivalent)	Extrapolated				ES Database		
High Output Lamp		2016 DOE National Model					
Incandescent A-type							
100W Incandescent Equivalent							
75W Incandescent Equivalent	Assumed conservative lumen output based on looking at EISA minimums and published values of lumen output						
60W Incandescent Equivalent							
40W Incandescent Equivalent							
Other Incandescent							
Decorative (40W)	Based on National Model efficacy and assumption of 40W incandescent decorative						
Outdoor High Output	Based on online listed output of 500W incandescent lamps						
CFL							
A-Type	Extrapolated				Based on a weighted average of lumen output from sales data collected on CFL A-Type by wattage from 2013-2015		
Decorative (40W equivalent)	Extrapolated			ES Database			
CFL Reflectors							
PAR	Extrapolated	2016 DOE National Model					
R/BR	Extrapolated	ES Database	Extrapolated		ES Database		
Halogen A-type							
100W Incandescent Equivalent							
75W Incandescent Equivalent	Assumed conservative lumen output based on looking at EISA minimums and published values of lumen output						
60W Incandescent Equivalent							
40W Incandescent Equivalent							
Halogen Reflectors							
PAR							
R/BR	Extrapolated	2016 DOE National Model					
MR16							
Other Halogen							
Decorative (40W equivalent)	Set to be the same lumen output as the 40W incandescent decorative lamp						
Outdoor High Output	Extrapolated	2016 DOE National Model					

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 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 national lighting model that Navigant built for the US DOE. These inputs leverage the rich datasets used in DOE rulemaking analysis. When the team adapted these costs to the individual sales categories for incumbent technologies, the team assumed that cost scales linearly with lumen output. The national lighting model determined LED lamp and LED luminaire costs at the dollar/kilolumen level. The equipment cost was determined by multiplying the dollar/kilolumen by the lumen output of each lamp or luminaire. LED luminaire costs are identical in each submarket because the team assumed that LED luminaires compete for every purchase trigger. The national model's first year is 2010, so for 2009 the team backcasted this data. The model annualizes the equipment cost over the lifetime of the lamp.

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 17, 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 17: 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 that is 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 18 list the inputs for the ballast specifications.

Table 18: 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 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 DOE model. The DOE model determined a 2010 equipment cost by technology and sector and assigns a cost decline rate for each technology. The rate of decline is either 0% or 0.5% per year.

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 19).

Table 19. 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 DOE model and varies at the sector and application levels. The DOE analysis estimated 2010 fixture costs by technology and sector and assigned a cost decline rate for each technology. The rate of decline is either 0% or 0.5% per year. The team calculated the cost of LED luminaires at the granular sales data level using the same process as for lamp cost and rolled it up based on mapping, as discussed in the next section.

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.

Mapping Sales Data to Model Technologies and Applications

Between 2010 and 2015, BPA has collected sales data for more than 70 lamp and fixture types and technology combinations. To keep the model size more manageable, the research team collapsed many of these subcategories to align with the technologies and applications in the model. The team varied how each lamp and fixture type in the sales data maps to the model technologies by application and sector so that the rolled up tech specs would vary by application and sector, as applicable. For example, the team mapped different wattages of HID lamps to the Building Exterior High and Building Exterior Low categories to ensure that the high output application wattage and lumen output were higher than those in the low output application. The following sections describe the model technologies in more detail and how the team weighted the detailed sales data to create tech specs for each technology in each application and sector.

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 20 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 20 shows the technology map for all the interior commercial applications. The 16 model technologies are listed in the first row. The number of model technologies that compete in an application ranges from two (Track Small) to 12 (Commercial Building Exterior Low).

Table 20: 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.

For categories where lamp characteristics were not generally improving such as HID technologies, A-type incandescent, and halogen, the average weight of each lower level category for 2010-2015 was used to provide one higher level tech spec for the entire period of 2009-2015. For categories that were changing over time (linear fluorescents, reflectors, and LEDs), the team calculated a tech spec for each year with sales data from 2010 to 2015 and for 2009 by using the 2010 sales splits.

The general equation for the tech spec if two lamp types (x and y) are mapped to one model-level category is shown in Equation 14:

Equation 14: Tech Spec Aggregation

$$\text{tech spec}_{\text{group, application, sector}} = \frac{\left(\text{sales quantity}_x \times \text{tech spec}_x\right) + \left(\text{sales quantity}_y \times \text{tech spec}_y\right)}{\text{sales quantity}_x + \text{sales quantity}_y}$$

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 21 lists the sales category split for the three applications with lumen bins.

Table 21: 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.

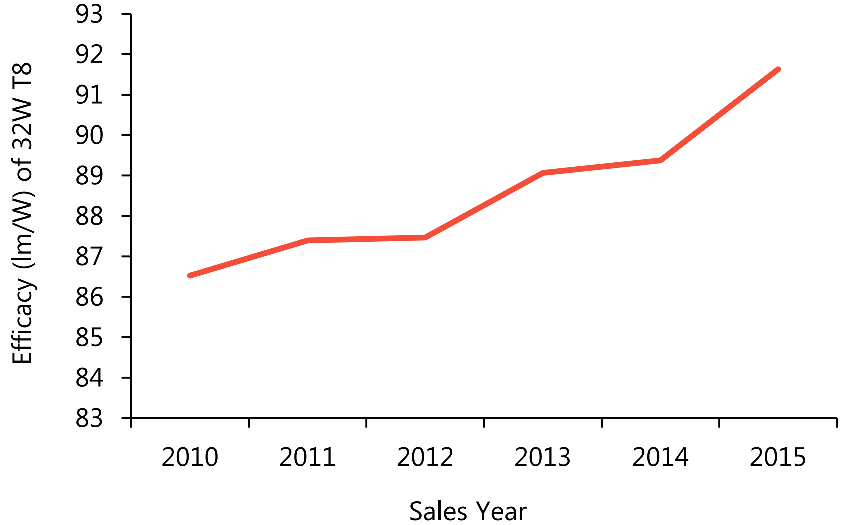
Length Rollup

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.

Efficacy Rollup

In one case, the research team collected sales data for the same lamp at two efficacy levels: the 700 and 800 series 32W T8. Since the model only has one 32W T8 category, the sales of both the 700 and 800 series are mapped to that one model technology. This mapping has an important impact on the efficacy of the 32W T8 since the efficacy varies between the 700 and 800 series. For the case of the 32W T8, the team weighted the tech specs for the 700 and 800 series by the split of 32W T8 between 700 and 800 series for each year. The impact of this roll up on the efficacy of the model-level category is evident in Figure 6.

Figure 6: 32W T8 Rollup of 700 and 800 Series 4-Foot Lamps



The reason the efficacy increases over time is that in the sales data collected for 2010-2015 the percentage of 800 series 32W T8 lamps increased over time, and the 800 series lamps have a higher efficacy than the 700 series. The rolled up 32W T8 tech specs are used for all 32W T8 lamps in all applications unless there are 8-foot T8s mapped to that application. In those cases, the team weighted in the 8-foot T8 tech specs as well.

Lamp Types Not in the Sales Data

In some cases, the research team did not collect sales data for a lamp or technology type that was present in an application. For example, the team did not collect any sales data on decorative lamps, but there is a decorative lamp application. Thus, the team did not weight the tech specs by sales and generated the specs at the model application and sector levels. Other missing gaps are high output TLEDs; high output outdoor halogen, incandescent, and LED lamps; CFL A-type lamps; and halogen MR16s.

Modifications to Individual Technologies

The research team reviewed lumen output data for each application at the fixture level to ensure that all technologies were reasonable replacements. This review led to the following adjustments:

- Revising the number of lamps per fixture for linear fluorescent technologies in the high/low bay applications to better align with metal halide lumen output
- Reducing LED Luminaire lumen output in many applications to account for higher fixture efficiency of LED products relative to incumbents
- Making wattage for high pressure sodium and metal halide lamps equal within applications where both technologies compete; this assumes customers purchase based on wattage, not lumen output, due to the poor light quality of high pressure sodium lamps
- Revising both the halogen and LED lumen output levels within Track Small to reduce the difference between the technologies' lumen output

Appendix B. Historic Stock Model to Determine Initial Age Distribution

To estimate the age of lamps installed in the baseline year (2009), the research team used a stock tracking model to simulate the growth in lamp stocks prior to the baseline year. The model accounts for the lifetimes and survival distributions of various technologies, the historic rate of sales growth,[36] building stock demolition rates, and lamp replacements associated with ballast failure and fixture retrofits. With information about the rate of growth in sales, the model accumulates sales for each technology beginning in 1989 (20 years prior to 2009) and simulates like-for-like replacement for lamp turnover. By tracking these dynamics for 20 years, the model can determine a reasonable approximation of the age distribution of the stock at the beginning of 2009. In addition, the historic stock tracking routine applies the same turnover dynamics as the logic used for the 2009-2020 horizon, ensuring internal consistency.

The pre-2009 stock tracking routine does not make any assumptions about the relative mix of technologies because that adjustment takes place after computing the age distribution. Additionally, the routine does not need to know the absolute quantity of sales for a given technology to determine an age distribution. As such, the pre-2009 stock tracking relies upon a normalized representation of stocks—meaning that the quantity of lamps is not tied to historic quantities but is tied to historic growth rates.

As shown in Figure 7, the historic stock tracking model provides an estimate of how the stock has grown up to 2009 (in a normalized representation) and what percentage of the stock comes from different installation years. This information inherently captures the age of lamps included in the commercial model's baseline year initial lamp stock.

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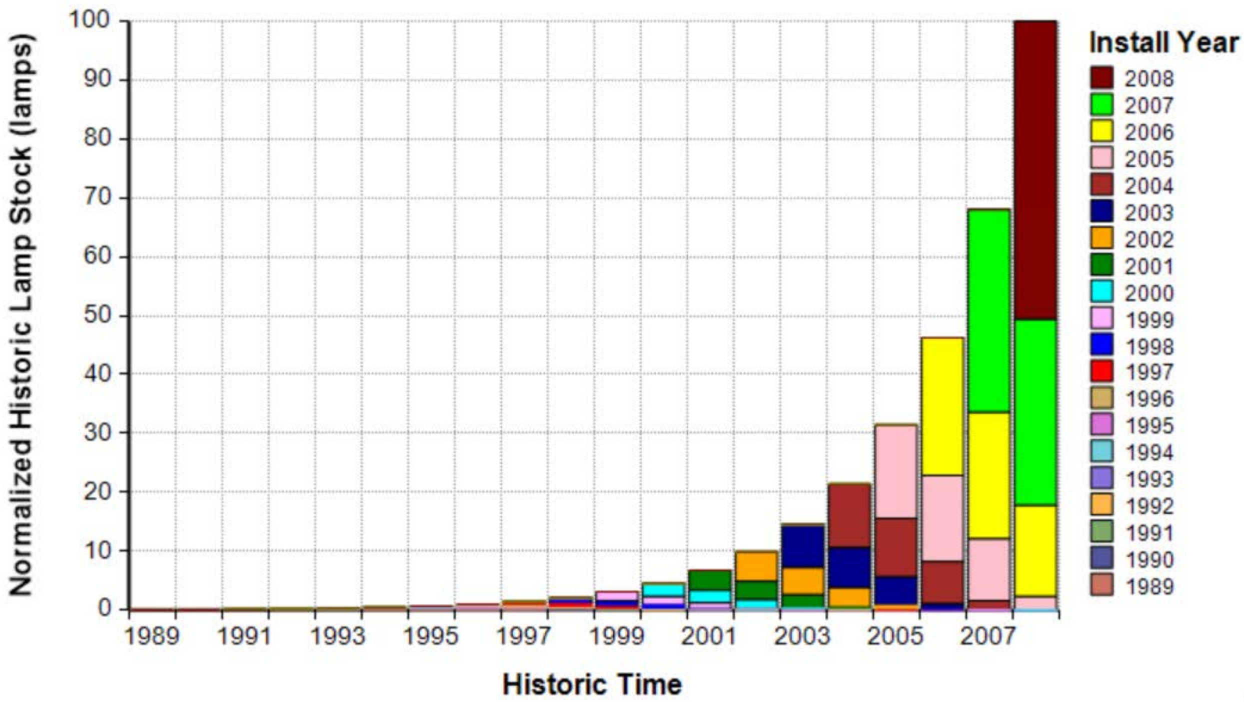
[36] Where data was available, the model used historic growth rates in sales. When data was not available, the model used historic building stock growth rates as a proxy for the growth rate in sales.

Figure 7: Illustrative Normalized CFL Lamp Stock for Historic Years (Lamps)



Source: Non-Residential Momentum Savings Model

By examining the end-of-year 2008 lamp stock (i.e., the beginning of year 2009 lamp stock), the model determines the percentage of that stock coming from various installation years. As shown in Table 22, this information regarding how much of the stock was installed in each year provides an age distribution for the baseline year. The age distributions reflect the different operating hours for each application, the different rated lifetimes for each technology, and the different demolition rates by building type.

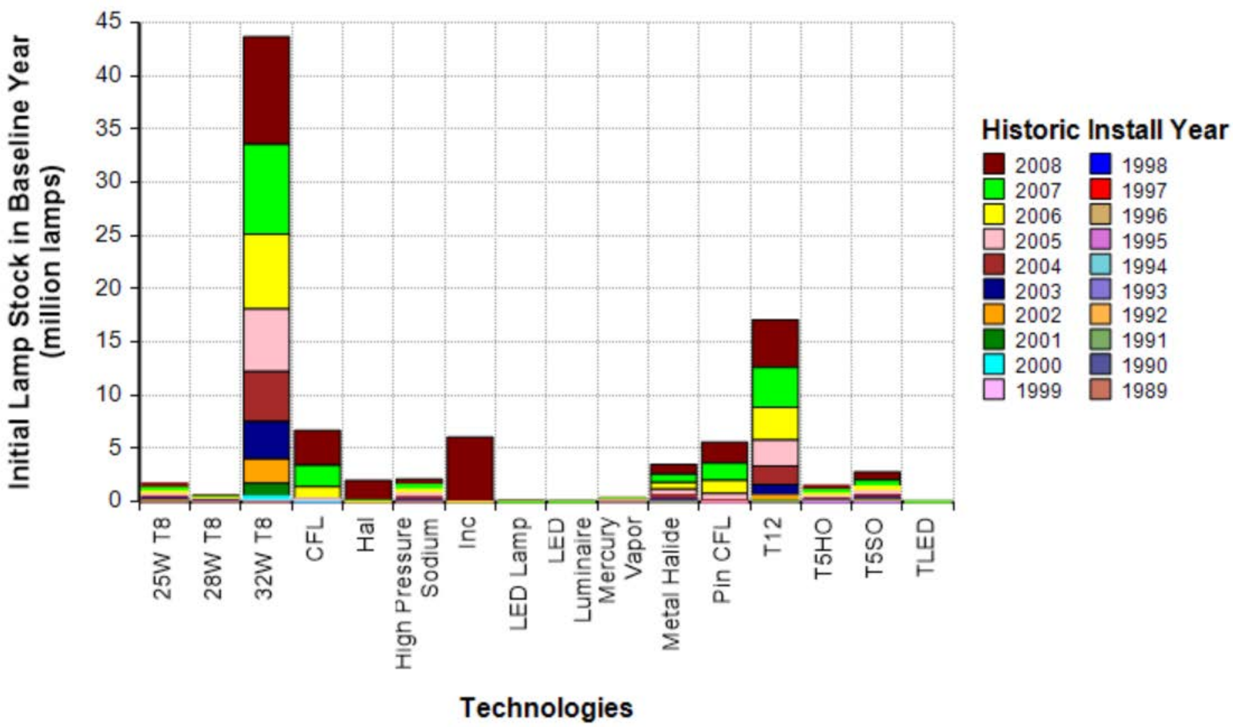
Table 22: Illustrative Base Year Age Distribution of CFLs by Commercial Application

Installation Year (Proxy for Age)	Building Exterior LOW	Decorative	Downlight Large	General Purpose	Track Large
1995	0.0%	0.0%	0.0%	0.0%	0.0%
1996	0.0%	0.0%	0.1%	0.2%	0.0%
1997	0.9%	2.5%	4.5%	5.0%	1.8%
1998	14.4%	15.7%	16.7%	16.8%	14.9%
1999	32.4%	31.1%	30.2%	30.0%	31.2%
2000	52.4%	50.8%	48.5%	48.0%	52.1%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Source: Non-Residential Momentum Savings Model

After determining the age distribution of the baseline year's lamp stock, the model distributes the 2009 lamps stocks across the appropriate installation years. The result is a baseline lamp stock with the correct number of lamps for 2009 and a robust estimation of the age distribution. Figure 8 provides an illustrative example.

Figure 8: Illustrative Lamp Stock in Baseline Year (2009) by Technology (Million Lamps)



Source: Non-Residential Momentum Savings Model

Appendix C. Difference Between Calculated and Applied Sales Mixes

As noted in Question 3, applying the sales mixes estimated in the sales allocation process does not result in modeled sales that align exactly with the sales allocations estimates without adjustment. There are two reasons the actual modeled sales do not exactly match the sales allocation targets before the final adjustment.

Accounting for Stock Turnover Dynamics

The sales allocations process identifies what percent of total sales for each technology go to an application. However, once these mixes are renormalized within each application and submarket, the actual volume of sales over time can result in different total mixes at the application or market level. The following example illustrates this effect.

The product of summed sales allocations (indexed by applications, submarkets and technologies) and the observed sales mix (indexed by technologies) establishes relative share of sales going to each application and submarkets, summing to 100% over all applications, submarkets and technologies in each year. Table 23 provides a simplified summary of this using example data (submarket-level detail omitted for clarity).

Table 23. Simplified Example of Sales Allocation Outputs before Normalization

Technology	Ambient Linear	High/Low Bay High	High/Low Bay Low	Total
T8	55%	5%	10%	**70%**
T5	1%	7%	2%	**10%**
HID	0%	10%	10%	**20%**
Total	56%	22%	22%	**100%**

To apply these data in the model, the research team normalized the mix such that it would sum to 100% over all technologies in each application and submarket. Table 24 illustrates how the example data from Table 23 would be normalized to the application level.

Table 24. Example Normalized Application Sales Mixes

Technology	Ambient Linear	High/Low Bay High	High/Low Bay Low
T8	98%	23%	45%
T5	2%	32%	9%
HID	0%	45%	45%
Total	100%	100%	100%

The model turnover dynamics then dictate the quantity of sales occurring in each application. Table 25 provides example data for the share of lamp sales going to each application.

Table 25. Example Share of Modeled Lamp Sales by Application

Ambient Linear	High/Low Bay High	High/Low Bay Low	Total
52%	24%	24%	100%

When the model aggregates over applications to calculate a total sales mix by technology, the quantity of sales used to weight each application's contribution to the total can differ from the original sales targets. These differences in weighting lead to a simulated technology sales mix that is different from the original sales data mix: note that multiplying the sales mixes in Table 24 and Table 25 yields a different total mix in Table 26 than the starting mix in Table 23.

Table 26. Example Simulated Sales Mix

Technology	Ambient Linear	High/Low Bay High	High/Low Bay Low	Total
T8	51%	5%	11%	**67%**
T5	1%	8%	2%	**11%**
HID	0%	11%	11%	**22%**
Total	52%	24%	24%	**100%**

These variations can also occur at the submarket level.

Variances in Lamps per Fixture

The second complication is that to align with the sales data (which is in lamps) and sum across submarkets, the sales allocations process occurs at the *lamp* level. Different technologies have different numbers of lamps per fixture—and some technologies cannot replace each other without replacing the ballast and/or fixture—so attempting to force a certain lamp sales mix can result in differences in lamp counts. For example, perhaps T5 lamps should be 60% of lamps in the High/Low Bay High lamp submarket. Some of the lamp outflows will be metal halide, and the model must replace the whole fixture and install multiple T5 lamps to replace a single metal halide lamp. The model will do this, and could in doing so inflate the number of T5 lamps relative to the sales allocation target.