FINAL REPORT

Residential Lighting Hours-of-Use Quick Hit Study

MA20R21-E

Date: March 31, 2020

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Massachusetts Residential Lighting HOU Quick Hit Study 2020 (MA19R12-E)

The overall objectives of this study were to explore the relationship between saturation and hours of use (HOU) and provide inputs into the PA and EEAC Consultant consensus process to update HOU estimates for program supported LEDs, taking into account the increasing saturation of LEDs.

Approach

This study re-analyzed metered HOU data collected as part of the 2014 Northeast HOU study to take into account the effects of efficient lamp saturation on HOU, as well as exploring and addressing the distribution of HOU. The revised model was applied to recent lighting inventory data (RLPNC 18-10) to produce estimated HOU values. The study also calculated the percentage of sockets whose HOU rounds to zero by room type and by efficient vs inefficient lamps to account for the distribution *bump* at zero. Using the state-wide collaborative process, the PAs and EEAC consultants then came to a consensus on how the HOU values would be implemented.

Key findings

The models revealed a positive and statistically significant relationship between saturation and HOU. HOU initially declines at low levels of saturation but as saturation levels increase HOU also begins to increase for each room type. The result was that recent increases in saturation lead to higher estimated HOU.

Historical Method
Historically, HOU were based on efficient or all lamp HOU.

Inefficient HOU were not used. At the time, efficient saturation was relatively low.

New Method
PAs and EEAC Consultants agree to based on inefficient or a combination of efficient and inefficient HOU.

This change is due to increased levels of efficient saturation and observed replacement of lamps.

Conclusions & Decisions

The key findings were provided to the PAs and the EEAC consultants. The PAs and the EEAC consultants agreed to change methods to use inefficient HOU or a weighted average of efficient and inefficient HOU based on the program design and lamps that were likely to be replaced.

Consensus Recommendations

- Use results of updated model produced as part of this study
- Use inefficient HOU (2.6) for direct install and turn-in
- Use mid-point of efficient and inefficient HOU (2.7) for upstream

Implications

- Adjusted for cross-sector sales, HOU for upstream is 3.0 for the cycle
- Switch to inefficient lamps decreased HOU for most years and delivery methods
- Decreases ranged from 0% to 6%

1 EXECUTIVE SUMMARY

The Massachusetts Program Administrators (PAs) last directly measured residential lighting hours of use (HOU) as part of the 2014 Northeast Residential Lighting HOU Study (2014 HOU Study).[1] At the time, compact fluorescents (CFLs) were the dominant technology in the marketplace, and PA efforts to support LEDs were in their infancy. Since then, the residential lighting market has undergone a period of rapid change, with LEDs now the dominant technology and CFLs no longer supported by the PAs. In addition, steady increases in efficient lamp saturation driven by LED adoption, observed as part of nearly annual market assessments, led the PAs and Energy Efficiency Advisory Council (EEAC) Consultants to consider what impact these market changes may have had on HOU. In addition, EEAC Consultants were concerned that the level of skewness in HOU distribution present in the 2014 HOU Study data was unaccounted for and might have impacted the 2014 HOU Study results.

The PAs and EEAC Consultants directed DNV GL and NMR (DNV GL team) to investigate what impact, if any, increases in saturation of efficient lamps may have had on HOU for three distinct program delivery channels: upstream, direct install, and turn-in. The EEAC Consultants had theorized that customers choose to install energy efficient lamps in higher-use sockets first, and that average HOU of energy efficient lamps would tend to decline as saturation increases.

1.1 Overview of objectives and approach

The overall objective of this study was to explore the relationship between saturation and HOU, and based on that, help the PAs and EEAC Consultants agree on updated HOU estimates for program-supported LEDs for the 2019, 2020, and 2021 program periods. The study was designed to explicitly take into account the effects of saturation on HOU and update HOU estimates for three general program models: upstream, direct install, and turn-in. The study included new analysis of the 2014 metering data together with lamp inventory data collected at the end of 2018 as part of the 2018-19 Residential Lighting Market Assessment Study (RLPNC 18-10).[2]

In order to explore the relationship between HOU and saturation, the DNV GL team:

1. Explored the distribution of HOU in the 2014 HOU Study data. Developed the appropriate transformation needed to conduct an unbiased HOU analyses.
2. Revised the model for HOU as a function of known lamp, application, and household characteristics, explicitly taking into account the effect of efficient lamp saturation on HOU, as well as exploring and incorporating HOU data transformation to address the distribution of HOU.
3. Applied the revised model to the most recent lighting inventory to produce a current data set with estimated HOU.
4. Used the data set from Step 2 to estimate the appropriate HOU for each current lighting program
5. Assessed the percentage of sockets whose HOU round to zero, presenting the results by room type and by efficient vs. inefficient lamps; assessed changes in distribution with zero usage sockets removed from the sample.

[1] http://ma-eeac.org/wordpress/wp-content/uploads/Northeast-Residential-Lighting-Hours-of-Use-Study-Final-Report1.pdf

[2] http://ma-eeac.org/wordpress/wp-content/uploads/RLPNC_1810_LtgMarketAssessment_FINAL_2019.03.29.pdf

1.2 Key findings

- **HOU distribution was right skewed and bounded between zero and 24 hours of use per day.** While the validity of ordinary least squares (OLS) regression does not hinge on the normality of the underlying distribution, significant departures from a normal distribution can yield estimates and inferences that lack the typically assumed characteristics of OLS regression. Therefore, a transformation was performed on the 2014 HOU data to find a transformation which would allow the HOU distribution to more closely approximate normality.
- **Updated model found smaller difference between efficient and inefficient HOU.** The 2014 Northeast HOU study provided a point estimate for inefficient lamps (2.3) that was 23% lower than efficient lamps (3.0). Using the model created as part of this study and the 2018 saturation values, the difference was smaller with a 10% difference in HOU between inefficient (2.58) and efficient (2.86).
- **Saturation and demographic factors significant in model.** Room type, education, tenure, the total number of sockets, and efficient lamp saturation variables for each room type were all found to be significant in the model and were used in the final model.
- **Changes in saturation by room type decreased HOU.** When the revised model was applied to the most recent lighting inventory data, estimated efficient HOU decreased relative to original lighting data included in the 2014 study. This was driven by relative changes in and the inventory of efficient lamps across room types. The number of efficient lamps in rooms with lower HOU is higher in the 2018 saturation data compared to the data used for the 2014 study.
- **HOU appears to increase as energy efficient saturation by room type increases.** Models prepared as part of this study to explore the relationship between HOU and saturation revealed a positive and significant relationship between saturation and HOU. This relationship persisted across a variety of models and variable combinations. This finding is counterintuitive and runs counter to a previous study conducted in California, and it highlights the complexity of the relationship between HOU and individual behavior. Possible explanations include customers with higher overall HOU tending to purchase more energy efficient lamps, and snapback behavior with customers increasing the use of lamps as saturation increases and the cost to operate lamps decreases. With no strong or compelling reasoning behind this phenomenon, care must be taken when drawing any conclusions. Additional work needs to be performed to develop a more complete understanding of the relationship.
- **Inefficient lamps comprised a greater proportion of rarely used lamps (less than 0.5 daily HOU).** Overall, 20% of lamps were used for less than 30 minutes a day, based on weighted metering data (pre-modeled). Efficient lamps accounted for 45% of the low-use lamps, which was lower than their portion of the entire sample of metered lamp (52%). Not surprisingly, closets had the highest proportion of low-use lamps (66%), and kitchens and the home's exterior tied for the lowest proportion of low-use lamps (10%). Inefficient lamps accounted for the majority of low-use lamps in all room types except kitchens and basements.
- **Efficient lamps account for a sizeable portion of replaced lamps.** Based on lamp replacement behavior observed as part of the 2018-19 Market Assessment Study, 43% of replaced medium

screw-base lamps were efficient (33% CFLs and 10% LEDs) and 57% were inefficient (46% incandescent and 11%).[3]

- **Consensus process considered both inefficient and efficient HOU, adjusted for saturation rates in the 2018 to 2019 Lighting Market Assessment (RLPNC 18-10).** At a meeting led by the DNV GL team, the PAs and EEAC Consultants agreed to the use of the rounded inefficient HOU (2.6) for direct install and turn-in programs and combined efficient and inefficient HOU (2.7 – unadjusted for cross-sector sales and 3.0 after adjusting for cross-sector sales) for upstream programs for the full 2019 to 2021 program cycle.

1.3 Recommended updated impact factors

Recommendation: The PAs and EEAC Consultants should apply the consensus-derived HOU for the 2019 to 2021 program cycle.

Rationale: The re-analysis of the original 2014 metering data considered additional factors and relied on a modelling approach more appropriate to the distribution of HOU. The PAs and EEAC Consultants carefully considered the results and reached consensus on recommended values.

Table 1-1 provides the recommended HOU impact factor updates by measure and initiative. For context, the table also includes the assumed values from the 2019-2021 plan and the percentage change in HOU.

Table 1-1. HOU impact factors (planned and updated)

Measure	Delivery Method	Initiatives	Year	Residential Daily HOU****		
				2019 -21 TRM	Updated Value	% Change (decrease)
LED Lamp – General Service Lamp	Direct Install	RES_NH, RCD, & IECD**	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp – Reflector	Direct Install	RES_NH, RCD, & IECD**	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp – Specialty	Direct Install	RES_NH, RCD, & IECD**	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp – General Service Lamp	Upstream	RES_RETAIL	2019 2020 2021	3.2 3.1 3.0	**3.0**	(6.3%) (3.2%) 0
LED Lamp - Reflector	Upstream	RES_RETAIL	2019 2020 2021	3.2 3.1 3.0	**3.0**	(6.3%) (3.2%) 0
LED Lamp - Specialty	Upstream	RES_RETAIL	2019 2020 2021	3.2 3.1 3.0	**3.0**	(6.3%) (3.2%) 0

[3] Excludes empty sockets, linear fluorescents, and pin-based lamps.

LED Lamp – General Service Lamp	Turn in	RES_RETAIL***	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp - Reflector	Turn in	RES_ RETAIL	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp - Specialty	Turn in	RES_ RETAIL	2019 2020 2021	2.7	**2.6**	(3.7%)

***Source:** **https://www.masssavedata.com/Public/TechnicalReferenceLibrary**.

****Single-family only for RES NH&R = Residential New Homes & Renovations; RCD = Residential Coordinated Delivery (excluding High Rise measures), IECD = Income Eligible Residential Coordinated Delivery, RES_RETAIL = Residential Retail**

*****The turn-in program was not included in the three-year plan and was new to the portfolio for 2019. The turn-in program was using the HOU for direct install as a placeholder awaiting results from this study.**

******Residential Retail hours have been adjusted for assumed cross-sector sales of 7% with 7 HOU per bulb. Without this adjustment planned values were 2.9, 2.8, and 2.7 for 2019, 2020, and 2021, respectively. The revised value was 2.7 for all three years.**

1.4 Methodology overview

The study relied on data from the 2014 Northeast HOU Study and more recent lighting saturation data collected as part of the 2018-19 Residential Lighting Market Assessment. [4,5] The 2014 HOU study estimated HOU as a function of lamp, application, and household characteristics. The HOU distribution in the 2014 HOU study was assessed and a transformation was created. This transformation was used in all subsequent models and analyses. The model constructed for this study has been applied in the original study and subsequent analysis to estimate program lamp average HOU using onsite inventory data from the 2014 HOU study and the 2018-19 Market Assessment.

This study was designed to address 2 potential weaknesses of the 2014 modeling effort.

1. The ordinary least squares (OLS) regression may not be appropriate for the untransformed HOU data. OLS regression assumes the unexplained variation (residual error) has a normal distribution, whereas the HOU data are highly skewed and bounded between 0 and 24 hours per day, resulting in similarly non-normal residuals.

The 2014 study tested the effects of saturation on HOU, however, the efforts yielded no significant relationship. Because of the potential influence of the non-normal error terms this study revisited the relationship of HOU and the saturation of efficient lamps. Accordingly, the new HOU model included the following steps:

1. Identify an appropriate transformation of the HOU data such that the transformed data is approximately normal.
2. Fit a new regression model using the transformed HOU data, exploring various ways to capture the effect of increasing saturation.
3. Apply the new model to 2018-19 inventory data to estimate HOU for various conditions.
4. In consultation with the PAs and EEAC, recommend and finalize updated HOU values based on the new results.

1.4.1 Limitations

The current study had several limitations, none perhaps as obvious as the vintage of the data.

- **The HOU data used to construct models does not reflect current market conditions.** When the 2014 HOU Study was conducted, CFLs were the dominant efficient lamp technology, the PAs heavily supported CFLs, and PA efforts to support LEDs were in their infancy. Therefore, nearly all of the efficient lamps in the 2014 HOU data set were CFLs. The PAs no longer support CFLs and have been exclusively supporting LEDs since 2017.
- **Differences in behavior between CFL and LED users.** The analysis performed for this study assumes that household deployment of LEDs follows a similar pattern to the deployment of CFLs at corresponding saturation levels.
- **No time series available.** The data available from the 2014 HOU Study represents a single period of measurement. This lack of time-series data provides limitations to the interpretation of the findings.

[4] http://ma-eeac.org/wordpress/wp-content/uploads/Northeast-Residential-Lighting-Hours-of-Use-Study-Final-Report1.pdf
[5] http://ma-eeac.org/wordpress/wp-content/uploads/RLPNC_1810_LtgMarketAssessment_FINAL_2019.03.29.pdf

- **The models developed are not causal.** Values are based on observations of the data available but do not indicate that increased saturation causes increased HOU. This inability to assess causality is primarily due to a lack of time series data.

2 INTRODUCTION

2.1 Study purpose, objectives, and research questions

The DNV GL team carried out the Hours of Use Update – Quick Hit Study (MA20R21-E) from December 2019 through March 2020. The study's overall purpose was to support the PAs and EEAC Consultants in updating HOU by providing analysis to facilitate the arrival of a consensus for HOU estimates for upstream, direct install, and turn-in programs. Its objectives are as follows:

1. Explore the distribution of HOU in the 2014 HOU Study data. Developed the appropriate transformation needed to conduct an unbiased HOU analyses.
2. Revise the model for HOU as a function of known lamp, application, and household characteristics, explicitly taking into account the effect of efficient lamp saturation on HOU, as well as exploring and incorporating HOU data transformation to address the distribution of HOU.
3. Apply the revised model to the most recent lighting inventory to produce a current data set with estimated HOU.
4. Use the data set from Step 2 to estimate the appropriate HOU for each current lighting program.
5. Assess the percentage of sockets whose HOU round to zero, presenting the results by room type and by efficient vs. inefficient lamps; assess changes in distribution with zero usage sockets removed from the sample.

2.2 Organization of memo

The remainder of this memo is organized as follows:

- Section 3: Methodology and approach
- Section 4: Analysis and results
- Section 5: Consensus discussions and decisions
- Section 6: Conclusions and recommendations

3 METHODOLOGY AND APPROACH

The tasks for this study fell into three broad categories,

1. Identify and assemble data sources.
2. Develop a new HOU model to the 2014 metering data, accounting for energy efficient saturation effects.
    a) Fit a regression model to the transformed data.
3. Apply the new model to recent inventory data to estimate current HOU.

3.1.1 Data sources

The data used for this study includes the following:

- 2012-2013 lighting data from the 2014 Northeast Residential Lighting HOU Study
- 2018-2019 lighting data from the 2018-19 Market Assessment Study

3.1.2 Data transformation

In order to normalize the data, the team assumed a two-part distribution:

1. A fraction of values equal to exactly 0 or 24 hours per day (or round to one of those bounds to the nearest hour)
2. The remaining values can be transformed into a continuous, approximately normal distribution.

Estimating chance of HOU = 0 or 24. Due to the bounded nature of the HOU distribution, the DNV GL team used several different discrete logistic models (i.e., trinomial and binomial models) to explore the probabilities that a lamp's HOU is zero, 24 hours, or something in between. Due to the limited number of observations at exactly zero HOU and none at 24 HOU, rounding to the nearest whole-hour and binomial logistic models were also explored in addition to the proposed trinomial models. The binomial model that yielded the best results used the dichotomy of lamps that rounded (to the nearest whole number) to zero and all other rounded non-zero HOU values. This model was a function of various lamp, household, and application characteristics.

Transforming non-zero and 24 HOU. We used a standard transformation approach due to Box and Cox [Box, G. E. P. and Cox, D. R. (1964). An analysis of transformations, *Journal of the Royal Statistical Society*, Series B, *26*, 211-252.], identified the best transformation from the power transformation family. This family of transformations showed promise when looking at the unweighted distributions; however, to formalize the approach, the team used a Box Cox transformation and the log-likelihood as the metric to determine if the transformation brings the data closer to being approximately normal. The form of a Box Cox transformation was:

$$y = \frac{\left(x^{\lambda} - 1\right)}{\lambda}$$

Where x = HOU and y = transformed HOU, and the goal of the analysis was to find the λ which maximizes the log likelihood function.

3.2 Regression of transformed HOU on lamp variables

An OLS regression was performed using the transformed HOU variable as the dependent variable and various lamp, household, and application characteristics as the independent variables. The model was built using data from the 2014 metering data, which included data from MA, RI, CT, and NY (split into upstate and downstate). In order to mirror the work that was done in the 2014 Northeast Residential Lighting HOU Study all states were included in the MA model, with the exception of those lamps in the downstate region of NY as this geographic area had previously been shown to have HOU patterns which differed statistically significantly from the other northeastern states. Models were also explored using MA-only data; however, given the poorer performance of these models, they were generally used to assess the robustness of any effects. Once the model was created, we input the data collected at the end of 2018 as part of the 2018-19 Residential Lighting Market Assessment Study (RLPNC 18-10) and projected values for HOU where calculated. The mix of saturation levels by room type from the 2018-2019 study is assumed to be more representative of the current market than data collected in the 2014 study. While the model has inherent limitations because it was designed using an older data set, the use of the 2018 saturation data could blunt this effect.

4 ANALYSIS AND RESULTS

4.1 Results of data transformation

Consideration was given to the implications of the HOU distribution, which is right skewed yet bounded between zero and 24 hours of use per day. The validity of ordinary least squares regression does not hinge on the normality of the underlying distribution, particularly with large sample sizes. However, significant enough departures from normality can yield estimates and inferences that lack the typically assumed characteristics of OLS regression. Transformations were explored for lamps that fell into the "between" HOU category, these transformations would attempt to convert the HOU values to a distribution that more closely approximates a normal distribution.

A standard approach that is used to find a power transformation which gives the "best" approximately normal distribution is a Box Cox analysis. In the Box Cox analysis done here, the measure of normality is log likelihood of the transformed data being from a normal distribution. The form of a Box Cox transformation is:

$$y = \frac{\left(x^{\lambda} - 1\right)}{\lambda}$$

Where the goal of the analysis is to find the λ which maximizes the log likelihood function. In the analysis performed, the selected $\lambda = 0.25$ was consistent with the hypothesized transformation explored on the unweighted data during the planning stages of the study.

In Figure 4-1 and Figure 4-2 (below) the differences between the weighted HOU data and the transformed HOU data are clearly illustrated, with the transformed data appearing roughly normally distributed (symmetric and bell shaped). It should be noted that it is still possible for the OLS regression performed on the transformed data to yield results that are outside of the zero to 24 hours of use range, since the normal distribution is unbounded. Another consideration when using transformed data is converting back to the original scale, a reverse transform is applied to return an unbiased estimate of HOU from the values generated by the model.

Figure 4-1. Weighted HOU Histogram with Untransformed Data

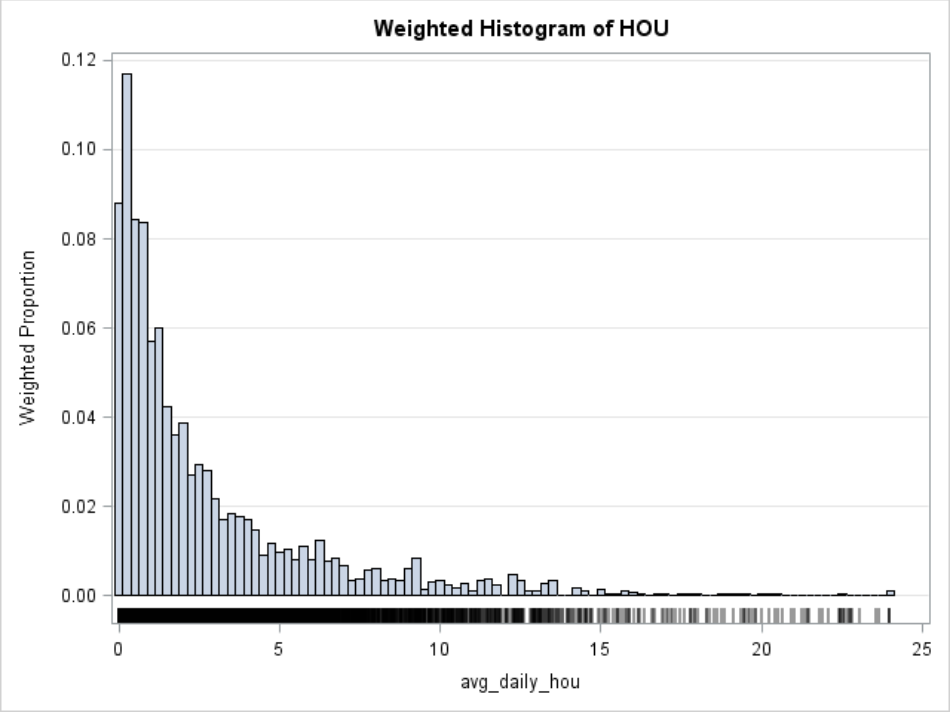
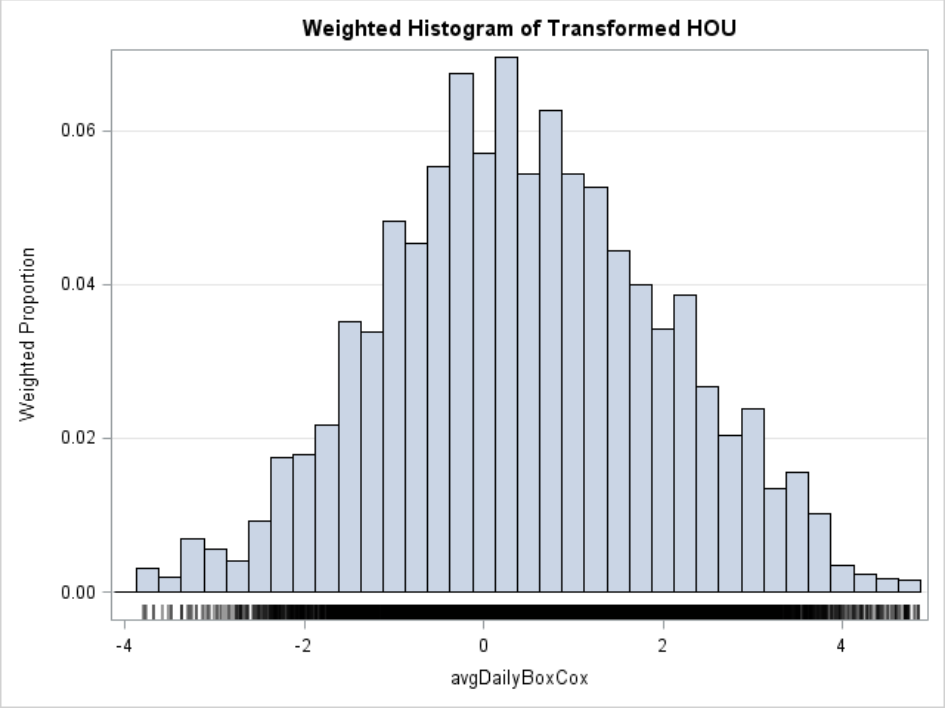


Figure 4-2. Weighted HOU Histogram with Transformed Data



4.2 Discrete model

Due to the bounded nature of the HOU distribution, the DNV GL team attempted a trinomial model to explore the probabilities that a lamp's HOU are zero, 24 hours, or non-zero. However, because there were very few true 0 HOU lamps and no true 24 HOU lamps, we were unable to estimate a model with a lot of detail.

To overcome this issue, a model was attempted that used a dependent variable that could take on one of three values if HOU rounded (to the nearest hour) to zero, 24, or non-zero. Again, the model was abandoned because of the relatively small number of lamps with HOU greater than or equal to 23.5 hours per day.

Based on the low number of lamps with zero or near 24-hour usage, the team focused on developing a binomial model where the dependent variable is either zero when HOU rounds (to the nearest hour) to zero, or is one when HOU is greater than or equal to 0.5 hours per day (rounds to one hour).

The model used the number of total rooms, a room type variable, a state variable, and the square of the proportion of sockets in the home that were filled with an energy efficient lamp as regressor variables. While all these variables were significant, the saturation variable coefficient had an unexpectedly positive sign. This means that an increase in saturation was associated with an increase in the odds a lamp was used for more than 0.5 hours per day compared to the odds the lamp was used for less than 0.5 hours per day.

Table 4-1. Odds Ratio Estimates from Binomial Model

Effect	Point Estimate	95% Confidence Limits	
		Lower	Upper
TOTAL_ROOMS	0.96	0.94	0.98
Bathroom vs Other	1.28	1.04	1.59
Bedroom vs Other	1.16	0.95	1.42
Dining vs Other	2.31	1.78	2.99
Exterior vs Other	4.69	3.14	6.99
Kitchen vs Other	4.43	3.36	5.86
Living vs Other	3.04	2.39	3.87
Percent of EE Sockets (squared)	2.38	1.67	3.41
CT vs MA	1.70	1.41	2.06
RI vs MA	2.05	1.57	2.69
UNY vs MA	1.60	1.32	1.93

Table 4-1 shows some, but not all, associated odds ratios and their confidence intervals. In the model, both total rooms and percentage of energy efficient sockets were continuous variables and therefore the associated odds ratios are just the comparison of the odds at single level and the odds at a unit decrease from that level. Here we can see that an increase in saturation is associated with an increase in the odds of being in the "over 0.5 HOU" group. While this was counterintuitive, the total rooms odds ratio estimate was in line with expectation. Homes with higher numbers of rooms had higher odds of having low-use lamps.

The binomial model did not shine any additional light on the relationship between saturation and HOU. If anything, the counterintuitive result only highlighted the complexity of the relationship and the behaviors of individuals. In the future, this type of model could be used on a data set in which LEDs are the dominant energy efficient lighting technology; such a model could also potentially assist in determining whether the technology differences are one of the potential drivers of the positive relationship.

4.3 Regression on the non-zero values

The next focus of the analysis was the creation of models for the non-zero hours of use values. Several models were specified using the transformed HOU variable from the Box-Cox analysis as the dependent variable, and combinations of lamp, application, and household characteristics as independent variables. The idea behind this analysis was that, after transforming the data, a latent relationship between saturation and HOU could be identified and used to inform the future values used by the PAs.

Initial results from the models showed a positive relationship between saturation and HOU. This result runs counter to a previous study conducted in California and was unexpected but aligned with findings of the discrete model described above.[6] Additional specifications and restrictions on the model were explored to elucidate the causes of this counterintuitive relationship. The DNV GL team tried numerous approaches to adjust the models to further explore this relationship, including:

- Rolling saturation into a single overall house wide value
- Including a saturation measure for each room type
- Developing models which excluded exterior lamps
- Developing models for bedrooms alone
- Lastly, including occupancy data

The sections that follow summarize the results of these models.

4.3.1 Relationship between HOU and efficient saturation

Various models yielded different results but were consistent in showing a positive and significant relationship between saturation and HOU. The persistence of the positive effect across different models and room types indicates a potentially robust result. Figure 4-3 shows the average daily HOU by saturation deciles and room type. As shown, there is a general decline in HOU between the first and second (or third) deciles. This initial decline in HOU is likely the result of customers choosing to install efficient lamps first in higher use sockets, and then moving to lower usage sockets with subsequent purchases. This finding is in line with expectations and earlier work in California.

However, after this initial decrease, HOU generally increases until a peak in the eighth or ninth decile. This behavior runs counter to earlier work in California and is somewhat counterintuitive. However, the persistence of the effect across different model specifications and room types may mean it merits further attention. Further, the work conducted in California was based on moving from no efficient lamps to low levels of saturation, whereas the work for this study looked at the relationship across a wide range of saturation from low to close to 100%. Possible explanations include:

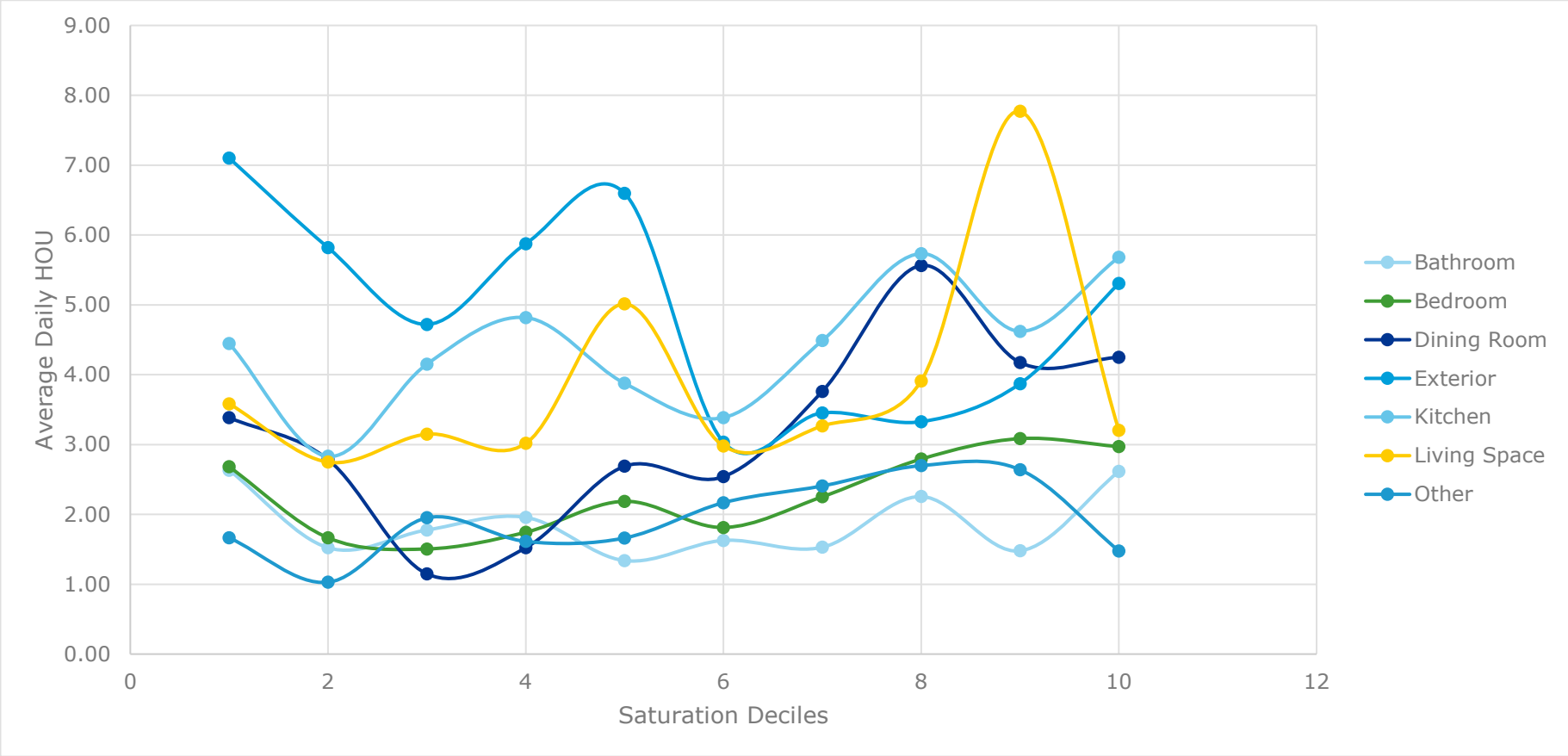
- Customers with higher overall HOU tending to purchase more energy efficient lamps

[6] KEMA. 2014. *California Upstream and Residential Lighting Impact Evaluation Work Order 28 (WO28) Final Report.* Available at http://www.calmac.org/publications/WO28_-_California_Upstream_and_Residential_Lighting_Impact_Evaluation_Final_Report.pdf

- Observation of snapback behavior with customers increasing the use of lamps as saturation increases and the cost to operate lamps decreases
- Energy efficient lamps likely to be replacing high-use CFLs that burn out
- Low-use sockets continuing to be the least likely lamp to be replaced in a home because these lamps burn out and need replacement less frequently than high-use sockets
- True near-zero sockets being rare within homes

Unfortunately, with the data available for this study, we were unable to determine specifically what drove differences, or lack of differences, in HOU. It is possible that the addition of HOU data collected in different time periods would have helped to increase the understanding of the relationships and causal factors.

Figure 4-3. Average Daily HOU by Saturation Deciles and Room Type



4.3.2 Overall, whole home model

Table 4-2 provides the estimated coefficients for the final regression model, along with the standard error, the associated t-value, and p-value. (See section 4.3.3 below for more information on tested model specifications.) Because this model was performed on the transformed data, coefficients do not translate directly into a linear increment in HOU. Still, the directionality is maintained between the non-transformed and the transformed data, so positive (negative) parameter estimates correspond to an increase (decrease) in HOU as that parameter increased (decreased). This model used saturation by room type for the living space, bathroom, bedroom, and other room types. However, kitchen, dining, and exterior room types were combined into a single saturation variable. This was done because these variables show marginal significance and a similar coefficient magnitude. Creating a single combined variable allowed for better estimation and stronger significance. The single room type saturation values were also interacted with a dummy variable which indicated if the lamp that observation represented was in that room type. The combined saturation variable has no such interaction because it was built into the creation of the combined variable (i.e., the value for that variable would be zero if the lamp was in a different room type).

Table 4-2. Regression Estimates on Transformed HOU[7]

Parameter	Estimate	Standard	t Value	Pr > |t|
Intercept	-0.034	0.109	-0.310	0.7561
state CT	0.569	0.069	8.240	<.0001
state RI	0.637	0.088	7.200	<.0001
state UNY	0.425	0.067	6.320	<.0001
state MA	0.000	.	.	.
education - Advanced or Grad Degree	0.197	0.065	3.050	0.0023
education - Bachelor's Degree	0.178	0.074	2.410	0.0162
education - HS or GED	-0.086	0.079	-1.080	0.2792
education - Less than HS	0.271	0.182	1.490	0.1367
education - Some College	0.000	.	.	.
Room 2 - Bathroom	0.058	0.119	0.490	0.6244
Room 3 - Bedroom	0.035	0.122	0.280	0.7777
Room 7 - Dining	0.758	0.112	6.800	<.0001
Room 8 - Exterior	1.903	0.131	14.520	<.0001
Room 12 - Kitchen	1.336	0.119	11.220	<.0001
Room 13 - Living Space	0.887	0.126	7.020	<.0001
Room 15 - Other	0.000	.	.	.
TOTAL_SOCKETS	-0.002	0.001	-2.300	0.0218
own_rent 1 - Own	-0.416	0.076	-5.490	<.0001
own_rent 2 - Rent	0.000	.	.	.
EESockets_perLS*LS_dummy	0.741	0.177	4.180	<.0001
EESockets_perBT*BT_dummy	0.237	0.185	1.280	0.2006

[7] Categorical variables that were used as independent variables in the model have a reference case set by the modeler. An estimated value of 0.000 for a categorical variable indicates that the corresponding value was used as the reference case.

Parameter	Estimate	Standard	t Value	Pr > |t|
EESockets_perBR*BR_dummy	0.771	0.174	4.420	<.0001
EESockets_perKDREXT	0.343	0.115	2.980	0.0029
EESockets_perOther*OtherDummy	0.600	0.163	3.670	0.0002

4.3.3 Additional model specifications explored

Here we briefly discuss a few of the other model specifications that were explored to help understand the complex relationships revealed as part of this study. While these additional models yielded little insight, it is important to document the rationale and results of each.

Excluding exterior lamps. Exterior lamps have the highest average HOU by room type, and because those exterior lamps also saw an increase in HOU as saturation increased, it was decided to remove that room type and re-run the model. The positive relationship between HOU and saturation was still present when exterior lamps were removed.

Bedroom-only model. Likewise, a bedroom-only model was created. The positive relationship between saturation and HOU was still present and significant in the bedroom only model.

Inclusion of occupancy. Occupancy data was included in both the overall model and the bedroom-only model to see if that variable might capture some latent effect that was not being controlled. The occupancy coefficient was not significant in either model, and its inclusion in the models did not result in a sign change in the saturation coefficient.

Additional models were attempted that used only MA data. The MA-only models all had poorer performance, and still showed a significant positive effect between saturation and HOU. Initial models also considered home type but once room type and saturation were added the home type variable was no longer significant. Given the nature of a quick-hit study, the work here was not meant to be exhaustive and additional model specifications could be explored in the future. Looking at single- versus multi-family homes, controlling for income, or looking at the various PA programs separately could potentially deepen the PA and EEAC Consultants' understanding of the effects of saturation on HOU.

4.3.4 Adjusting results for current saturation

The DNV GL team built the models using the original 2014 HOU Study data. To produce updated HOU that reflects current household characteristics, we applied the model to the detailed lighting inventory and demographic data from the 2018-19 Residential Lighting Market Assessment, providing an estimated HOU for each observation. This estimated HOU was then averaged together to give a recommended HOU value.

Table 4-3 provides the HOU estimates based on the new model using the original 2014 HOU Study saturation and the updated 2018 saturation data. As the table shows, applying the model to the more recent saturation data results in a decrease in both efficient and inefficient bulb HOU. At first this seems counter to the findings of the model that show a positive relationship between HOU and efficient lamp saturation. However, the change in HOU demonstrated here are driven primarily by changes in the count of sockets and saturation by room type. Efficient lamps were more prevalent in higher HOU room types in 2014 compared to 2018. As efficient lamps become more ubiquitous in lower HOU room types this has an effect of decreasing HOU. Since inefficient HOU also dropped, this is an indication that the socket counts in 2018 and 2014 were not uniformly distributed. Put another way, while HOU is positively correlated with saturation by

room type, HOU by room type still varies. As more efficient (or inefficient) lamps are installed in lower HOU room types, overall efficient HOU decreases.

Table 4-3. HOU adjusted for changes in saturation

Bulb Type	HOU estimate w/ 2014 data	HOU estimate w/ 2018 data
Efficient Bulb	3.19	2.86
Inefficient Bulb	2.67	2.58
Difference	0.52 (16%)	0.28 (10%)

4.3.5 Adjusting for snapback

The 2014 HOU Study authors put forth three possible theories to explain the difference in HOU between efficient and inefficient lamps:

1. **Differential socket selection.** When households target installing efficient lamps in fixtures that are used more frequently in any given room.
2. **Shifting usage.** When households install efficient lamps in a socket and then increase usage of that socket compared to other sockets containing inefficient lamps.
3. **Snapback (increased usage).** When households choose to operate lamps for longer periods as a result of lowering operating costs.

Absent evidence supporting any of these three possibilities, the authors assumed all were equally likely. As only one of the theories was excluded from saving calculations (snapback) the 2014 HOU study recommended HOU values equal to the value of energy efficient HOU minus one-third the difference between energy efficient HOU and inefficient HOU.

In the model produced as part of this study, energy efficiency saturation is explicitly incorporated into the model which partially, if not entirely, adjusts for the first two effects. Therefore, we assume snapback accounts for one-half the estimated difference between energy efficient and non-energy efficient lamps.

4.3.6 Summary of model results

The results from this analysis for each of the models specified are included in Table 4-4, note that our recommended model is bolded in the table. For context, the results of the 2014 HOU Study model are also included in the table. It is interesting to note that the updated models produced as part of this study found the difference in HOU between efficient and inefficient lamps to be much less than that found as part of the 2014 HOU study. As shown in the percent different column, the 2014 Northeast HOU study found a difference in HOU between efficient and inefficient lamps of 23% compared to only 10% for the recommended model produced by this study.

Table 4-4. Estimated HOU Values

Model	States	R-Squared	Non-EE Lamps HOU	EE Lamp HOU	% Diff.	Snapback Adjusted HOU (EE)

With Room Saturation	All	0.193	2.61	2.91	10%	2.85
With Combined Kit_DR_EXT	All	0.193	2.58	2.87	10%	2.81
With Combined Saturation	All	0.186	2.79	2.97	6%	2.94
With Combined Saturation interacted with Deciles	MA	0.148	2.42	2.75	12%	2.68
With Combined Kit_DR_EXT and Total Sockets	**All**	**0.194**	**2.58**	**2.86**	**10%**	**2.80**
2014 NE HOU	*All*	*0.26*[8]	*2.3*	*3.0*	*23%*	*2.9*

4.4 Adjusting for cross-sector sales

It is understood that commercial customers purchase a portion of the lamps supported by the Retail Products Initiative. These lamps are ultimately installed in commercial applications instead of residential applications. Therefore, the program adjusts the HOU for lamps sold through the upstream program to adjust for higher HOU found in commercial applications. As detailed in the August 2, 2018 memo, "MA RLPNC Cross-Sector Sale HOU Update," the PAs assume that 7% of lamps sold through the Retail Products Initiative ultimately are used in commercial settings. The memo further details the sales weighted HOU for cross-sector sales is equal to 2,559 hours per year. We used this value to update the Retail Products Initiative HOU to adjust for cross-sector sales. The adjusted value is 3.0 hours per day.

4.5 Replaced lamp types

The newly developed regression model identified differences in HOU between energy efficient and inefficient lamp types. Therefore, it is important to understand what type of lamps customers are replacing. To help provide this context to the PAs and EEAC Consultants during discussions, the team pulled in data from the 2018-19 Market Assessment on observed lamp replacement behavior. These observations were from on-site visits completed in late 2018 with a sample of panel households. For more details on methods, please see the 2018-19 Market Assessment report. As Table 4-5 shows, 43% of lamps replaced between 2018 and 2019 were efficient lamps. NMR has also completed a set of panel visits with residential baseline participants in March 2020; the data from these visits was not final in time for discussions but preliminary results from January showed very similar proportions of efficient and inefficient lamps being replaced.

[8] The 2014 HOU study provided a pseudo-R squared for hierarchical regression model. The stand-alone regression model had an R-Squared of 0.14.

Table 4-5. Screw-based replaced lamps by type (2018-19)[9]

CFL	LED	Incandescent	Halogen
33%	10%	46%	11%
Efficient		**Inefficient**	
43%		**57%**	

4.6 Inspection of near-zero-use lamps

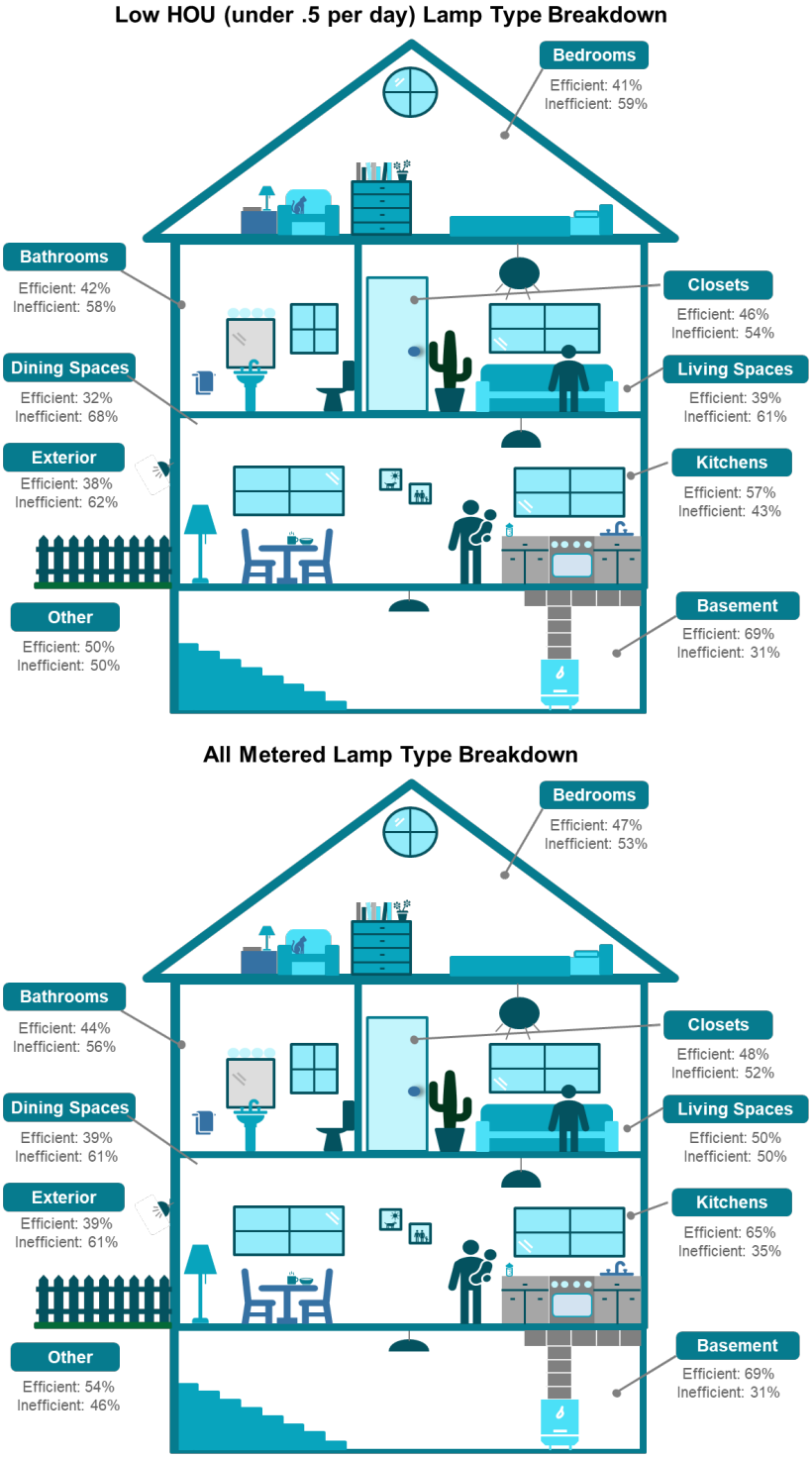
The team identified low-use lamps and their characteristics within the data set in order to assess whether low-use lamps were overrepresented based on efficiency or room. Low use was defined as any lamp with an HOU of 0.5 or less, which accounted for 20% of all lamps in the HOU data set. Low-use efficient lamps accounted for 9% of the sample while low-use inefficient lamps made up 11% of the sample (Table 4-4). Fewer than one-third of lamps in most rooms were low-use, with the exception of closets, where 66% of lamps were low-use. The exterior and kitchen housed the smallest percentage of low-use lamps with 10% of those areas' lamps being used less than half an hour a day. Energy efficient lamps made up a smaller portion of the low-use sample (45% of low-use lamps) compared to the entire sample of metered lamps (52%) (Figure 4-4). This same pattern held for most room types, but the kitchen and the basement had higher proportions of low-use EE lamps due to linear fluorescent tubes.

[9] Excludes linear and empty sockets. See Table 5 in 2018-19 Market Assessment.

Table 4-6. Low-Use Lamps Across HOU Sample

Room	Low-Use Lamp Count	% Low-Use Lamp in Room	% EE Low-Use Lamp in Room	% non-EE Low-Use Lamp in Room
Basement	44	31%	22%	9%
Bathroom	160	24%	10%	14%
Bedroom	197	23%	10%	13%
Closet	72	66%	30%	36%
Dining Room	69	16%	5%	11%
Exterior	23	10%	4%	6%
Kitchen	68	10%	6%	4%
Living Space	108	14%	6%	8%
Other	197	28%	14%	14%
Total Low-Use Lamps	**938**	**20%**	**9%**	**11%**
Total Lamps Across HOU Sample	**4,462**	**100%**	**52%**	**48%**

Figure 4-4: Comparison of EE and IE Lamp Proportions, Low-use and Full Sample of Metered Lamps



5 CONSENSUS DISCUSSIONS AND DECISIONS

The team met with the PAs and EEAC Consultants three times to discuss the results presented above in this memo. The first meeting took place on February 20, 2020, the second on February 24, 2020, and the third on February 27, 2020. During the first two meetings, the team presented preliminary results and received feedback and direction for additional exploration of the data.

During the third meeting, the PAs and EEAC Consultants discussed the methods, data, and results and agreed to HOU estimates for three initiatives (single-family only direct install, upstream, and turn-in). This report documents the decisions and rationale made at that meeting. Table 5-1 provides a summary of updated values and 2019-2021 planning values by initiative and year.

- **Time period of decisions.** The PAs and EEAC Consultants agreed to lock-in the HOU estimates for the 2019 – 2021 program period. Therefore, each program only has one estimate which is set for 2019, 2020, and 2021.

  The ***rationale*** for this decision was that the PAs and EEAC Consultants did not believe additional new information would be available to update HOU estimates in future years.

- **Direct install (2.6 HOU per day).** The PAs and EEAC Consultants agreed to use the inefficient HOU estimate from the recommended model produced as part of this study, rounded to the nearest tenth. This value was 2.6 hours per day.

  The ***rationale*** for this decision was that the direct install program is an early replacement program that targets replacing all remaining inefficient lamps in customer homes. As the program does not replace efficient lamps, the inefficient HOU value was decided to be most appropriate. Prior to this, the programs used the "all-bulbs" HOU value of 2.7 from the 2014 HOU Study.

- **Upstream (2.7 HOU per day – 3.0 after adjusting for cross-sector sales).** The PAs and EEAC Consultants agreed to use the weighted average of inefficient and efficient HOU estimates from the recommended model produced as part of this study, rounded to the nearest tenth. Values were weighted based on the proportion of inefficient (57%) and efficient (43%) lamps observed replaced as part of the 2018-19 Market Assessment. The calculation was as follows: 57% x 2.58 + 43% x 2.86 = 2.7. After adjusting for cross-sector sales the value increased to 3.0.

  The ***rationale*** for this decision was that the upstream program lamps are primarily installed as replace on failure and are likely to be installed roughly in proportion to the lamps that are replaced in a given year. Prior to this, the programs used the Efficient Bulb value of 3.2 from the 2014 HOU Study (adjusted for cross-sector sales).

- **Turn-in (2.6 HOU per day).** The PAs and EEAC Consultants agreed to use the inefficient HOU estimate from the recommended model produced as part of this study, rounded to the nearest tenth. This value was 2.6 hours per day.

  The ***rationale*** for this decision was that the turn-in program provides LEDs in exchange for inefficient (halogen or incandescent) lamps and is intended to capture few to no efficient lamps (CFLs or LEDs). As the program is not targeting replacement of efficient lamps, the inefficient HOU value was decided to be most appropriate.

Table 5-1. Hours-of-use impact factors (planned and updated)

Measure	Delivery Method	Initiatives	Year	Residential Daily HOU****		
				2019 -21 TRM	Updated Value	% Change (decrease)
LED Lamp – General Service Lamp	Direct Install	RES_NH, RCD, & IECD**	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp – Reflector	Direct Install	RES_NH, RCD, & IECD**	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp – Specialty	Direct Install	RES_NH, RCD, & IECD**	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp – General Service Lamp	Upstream	RES_RETAIL	2019 2020 2021	3.2 3.1 3.0	**3.0**	(6.3%) (3.2%) 0
LED Lamp - Reflector	Upstream	RES_RETAIL	2019 2020 2021	3.2 3.1 3.0	**3.0**	(6.3%) (3.2%) 0
LED Lamp - Specialty	Upstream	RES_RETAIL	2019 2020 2021	3.2 3.1 3.0	**3.0**	(6.3%) (3.2%) 0
LED Lamp – General Service Lamp	Turn in	RES_RETAIL***	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp - Reflector	Turn in	RES_ RETAIL	2019 2020 2021	2.7	**2.6**	(3.7%)
LED Lamp - Specialty	Turn in	RES_ RETAIL	2019 2020 2021	2.7	**2.6**	(3.7%)

*Source: https://www.masssavedata.com/Public/TechnicalReferenceLibrary.

**Single-family only for RES NH&R = Residential New Homes & Renovations; RCD = Residential Coordinated Delivery (excluding High Rise measures), IECD = Income Eligible Coordinated Delivery, RES_RETAIL = Residential Retail

***The turn-in program was not included in the three-year plan and was new to the portfolio for 2019. The turn-in program was using the HOU for direct install as a placeholder awaiting results from this study.

****Residential Retail hours have been adjusted for assumed cross-sector sales of 7% with 7 HOU per bulb. Without this adjustment planned values were 2.9, 2.8, and 2.7 for 2019, 2020, and 2021, respectively. The revised value was 2.7 for all three years.

6 CONCLUSIONS AND RECOMMENDATIONS

This study found no evidence of declining HOU as energy efficient saturation increases toward high levels, and in fact, models suggest that the opposite is true. This result is contrary to the effects that have been seen in an earlier study in California and are also seen in this study for lower saturations, which show declining HOU with increasing saturation in the range from around 0 to around 30% saturation. Reasons for this behavior at higher saturations are uncertain. These results suggest that we may not see additional decreases in HOU as EE saturation continues to rise.

Initial concerns among EEAC Consultants that lamps being supported by the programs were likely to be installed in low-use sockets may be unjustified. While energy efficient saturation continues to reach new heights, a sizeable share of replaced lamps continues to be efficient lamps (43%). In addition, higher-use inefficient lamps are more likely to fail than low-use lamps.

Finally, the difference in HOU between efficient and inefficient lamps based on the updated model produced as part of this study (10%) was less than that identified in the 2014 Northeast HOU study (23%). This means that the difference in usage between efficient and inefficient lamps may have been overestimated by the 2014 HOU Study.

6.1 Consensus-derived recommendations

The study yields the following recommendation:

Recommendation: The PAs and EEAC Consultants should apply the consensus-derived HOU listed in Table 5-1 for the 2019 to 2021 program cycle.

> *Rationale: The re-analysis of the original 2014 metering data considered additional factors and relied on a modeling approach more appropriate to the distribution of HOU. The PAs and EEAC Consultants carefully considered the results and reached consensus on recommended values.*

The study also offers some additional considerations. As demonstrated in this study and historical work, the relationship between HOU and saturation is complex. While this study provided information to help the PAs and EEAC Consultants assess the current state of the market, it may be worth considering other potential approaches for future research. Given the nature of a quick-hit study, the work here was not meant to be exhaustive and additional model specifications could be explored in the future. Looking at single versus multi-family homes, controlling for income, or looking at the various PA programs separately could potentially deepen the PAs' and EEAC Consultants' understanding of the effects of saturation on HOU.

In addition, the PAs and EEAC Consultants should consider developing a socket turnover model that leverages the annual panel visit data. This turnover model would factor in data on replace on failure, early replacement, historical changes in socket saturation, observed lamp failures, and HOU. Ultimately, this socket turnover model would be able to help ascertain updated HOU based on reported useful lives and other factors known for the residential lighting market. Separate models could be prepared for upstream, direct install, and turn-in program delivery designs.

APPENDIX A. DATA SOURCE DETAILS

The data used for this study includes the following:

- 2012-2013 lighting data from the 2014 Northeast Residential Lighting HOU Study
    - Area – including State
    - Total number of sockets
    - Total number of rooms
    - Total number of fixtures
    - Percentage of CFL sockets – Whole House
    - Percentage of EE sockets – Whole House
    - Percentage of CFL sockets – Bedroom
    - Percentage of EE sockets – Bedroom
    - Percentage of CFL sockets – Bathroom
    - Percentage of EE sockets – Bathroom
    - Percentage of CFL sockets – Kitchen
    - Percentage of EE sockets – Kitchen
    - Percentage of CFL sockets – Living Space
    - Percentage of EE sockets – Living Space
    - Percentage of CFL sockets – Dining Room
    - Percentage of EE sockets – Dining Room
    - Percentage of CFL sockets – Exterior
    - Percentage of EE sockets – Exterior
    - Percentage of CFL sockets – Other
    - Percentage of EE sockets – Other
    - Multi-Family or Single-Family Home
    - Home type (more detail) – SF, MF 2-4, or MF 5+
    - Education
    - Own or Rent indicator
    - Under 18 in home indicator
    - Average daily HOU
    - Average annual HOU
    - Efficient lamp indicator
    - Lamp type
    - Fixture type
    - Lamp Shape
    - Socket type
    - Control type
    - Room type
    - Weights
- 2018-2019 lighting data from the 2018-19 Market Assessment Study. Data mirrored that of the above, with the exception of no "under 18 in home" indicator.

APPENDIX B. REVERSING THE TRANSFORMATION

After the estimated regression model was applied to the inventory data, a reverse transform was applied to return an unbiased estimate of HOU for those conditions based on the model. The regression model for the non-zero values was a standard OLS regression model. To account for the effects of using the data from other states, a state variable was added. The non-zero HOU regression model was done on the transformed HOU values, this has the effect of making the conversion back to the original scale more complex than sampling inverting the function used to make the conversion. In this case with a $\lambda = 0.25$ to convert the function the following relationship was used, where y is the model point estimate and σ is the model's root mean squared error[10]:

$$x = \left(\frac{1}{4}y + 1\right)^4 + \frac{3}{8}\sigma^2\left(\frac{1}{4}y + 1\right)^2 + \frac{3}{256}\sigma^4$$

It should also be noted that it is still possible for the OLS regression performed on the transformed data to yield results that are outside of the zero to 24 hours of use range, since the normal distribution is unbounded. In the event that a HOU value was calculated outside of those values it would be coded at either 0 or 24, as appropriate.

[10] Freeman, Jade. & Modarres, Reza. (2006). Inverse Box-Cox: The power-normal distribution. Statistics & Probability Letters 76, 764-772.

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