Updated National Lighting Usage Estimates Incorporating Two New Regional Metering Studies

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ABSTRACT

This paper presents the methods and results of a multi-project effort to integrate new sources of primary data on residential lighting hours-of-use (HOU) into a model that estimates residential lighting energy use at the regional level. The paper addresses statistical methods and issues of bias in such analyses and explores the practical benefits and limitations of the approach. The context for this methodological work is the U.S. Department of Energy (DOE) Residential Lighting End Use Consumption Study, which was completed and published in late 2012 with a vision that it would be updated periodically as new data became available. The estimates for lighting usage in the study were extrapolated from a regression model for HOU as a function of characteristics of the home and occupants, as well as by characteristics specific to the lamp and fixture. This model was applied to household characteristics and lighting inventory profiles from existing national and regional survey data. The DOE study funded a metering study of households in a new three-state region. Additionally, in late 2013 Tennessee Valley Authority (TVA) initiated a metering study of households designed to leverage the national lighting study estimation framework. In 2014-2015 the DOE Study estimates were updated to expand the source data for the hours of use regression model from the region of the original DOE study to also include the new data from the mid-Atlantic and TVA.

Introduction

For many years most residential lighting usage studies have been conducted on a regional or utility territory basis as part of energy efficiency program baseline potential studies or impact evaluations. These studies used inventories of lighting stock in homes and metered usage from samples of the installed lamps. The data collected from these studies have been used in analyses that help determine the potential energy savings that can be expected to be realized through various lighting efficiency program constructs, or for evaluating the impacts of these programs.

A residential lighting usage study using loggers or meters for a U.S. level sample has never been attempted. Policy makers and economists interested in energy consumption by residential lighting at the national level have had to construct estimates by extrapolating lamp penetration and usage estimates from regional studies, technical reference manuals (TRM), or by applying usage assumptions to household survey data.

The DOE Residential Lighting End-Use Consumption Study (DOE 2012) was an initiative of DOE's Solid-State Lighting Program with a primary objective of developing a better understanding of lighting consumption in residential dwellings in the United States. The study did not attempt to collect lighting inventory and usage data countrywide because that would have been cost prohibitive. Rather, the aim was to conduct a rigorous analysis bringing together many regional studies that had been conducted in recent years, and to produce both national and regional estimates of lighting usage that spanned the country, even for regions where no lighting data had been collected or made available for analysis.

A framework was developed in the DOE Study that allowed for estimation of lighting usage at various levels:

- For the United States as a whole and various regions within
- By certain household characteristics e.g., dwelling type
- By location within the home e.g., kitchen fixtures
- By certain lamp characteristics e.g., CFL, incandescent, or other technology
- By certain combinations of these factors

In this paper we refer to the original analysis conducted in 2011-2012 as "DOE Study v1.0" (DOE 2012) and the currently unpublished 2014-2015 update as "DOE Study v2.0". In referring to the overall study without respect to the estimates from the original study or the update, we use "DOE Study". All of the lamp usage data in the 2012 DOE Study v1.0 came from a single study in California, with the vision that it would be updated periodically as new data became available. The DOE Study took the first step in this direction by using project funds to collect data from a sample of approximately 180 homes in the eastern U.S., but funds were not available to conduct the analysis of the data collected, so the update was on hold until funding was secured for this analysis.

Methodology

Overview of DOE Study Analysis Framework

The lighting usage model developed for the DOE Study uses a "bottom-up" methodology that estimates HOU and energy consumption for individual lamps through a regression model relating usage recorded from loggers to attributes of the fixtures, their locations in the homes, and the households. These estimates are produced for all lamps in modeled household lamp inventories for a representative sample of U.S. households. The design of the model allows for the incorporation of new data so that lighting estimates can be updated to improve the accuracy of regional and overall national estimates.

The model was designed to account for variation in lighting usage not only by geography, but also by structural and demographic characteristics of homes as well as attributes of the lamps themselves. For the model to be based on actual data collected from U.S. households, the following data elements were sought:

- **Household survey data** capturing the variability in the structural characteristics of the U.S. housing stock as well as the demographic and behavioral attributes of the households that occupy the homes
- **Lighting inventory data** capturing the variability in the number of lighting fixtures by location in the home, and the characteristics of those fixtures and the lamps installed in them
- **Lighting usage data** capturing the variability in the operating hours of lamps in residences by lamp type, location, and fixture characteristics

The ideal data source would be a single study that includes all of these data and represents the whole of the United States, but one does not exist with geographic coverage outside of individual utility territories or regions of a small number of states. Therefore, data from independent studies containing varying data elements from different regions of the country were collected. As a result, most regional studies had data elements that did not fit neatly together. For instance, a study from one region may not have demographic data from the households in the study, and another region may not have recorded as many lamp and fixture characteristics as another regional study did.

To solve this problem, separate data sources were identified that contained survey fields in common that allowed data to be extrapolated from more comprehensive data sets to less comprehensive, and individual lighting studies were expanded to represent the entire country. For example, if one data set had all three of the types of data elements listed above, and another data source contained just household survey data and lighting inventories, then the lighting usage data would be extrapolated from the first study to the second, controlling for patterns in usage with respect to the lamp and fixture characteristics, as well as the makeup of the household.

We acknowledge that this approach only mitigates risk of bias in HOU estimates with respect to the linked characteristics. In other words, it controls for population level differences in household characteristics and lighting inventories. It does not control for regional drivers of HOU other than the differentiable household and fixture characteristics distributions in different geographic areas. In other words, if there is a characteristic of the residential population in California that drives their lighting usage lower than other areas, and that effect is not explained through the variation in the regression covariates listed below in this paper, the extrapolated estimates may reflect any such bias to some degree.

Data Sources - DOE Study v1.0

Household Survey Data Sources. The U.S. Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS) is a national survey that collects household characteristic information including how those households use energy. EIA publishes anonymized responses to the RECS for researchers and policy makers on its website. The 2009 RECS data (EIA 2009) – the most recent at the time of the DOE Study – were used to account for region-to-region variation in characteristics, such as the type and size of the home and number of household occupants. The 2009 RECS did not collect detailed information on the different types of rooms within homes, which was sought because lighting usage is dependent on the types of spaces where fixtures are located. The United States Census Bureau's American Housing Survey (AHS) (United States Census Bureau 2009) contains more detailed data on the number of rooms by type (e.g., kitchen), so the 2009 AHS was used in the DOE Study to supplement the RECS data.

Lighting Inventory Data Sources. In 2008, Nexus Market Research (NMR) led a Multi-State CFL Modeling Study that included more than 9,300 telephone surveys and 1,400 onsite lighting inventory surveys in 16 different geographic areas. The study was commissioned by 14 entities including electric utilities, energy service organizations, public service commissions, and state agencies. This study did not have a national sample design, but the collection territories did cover several parts of the country. Importantly, the data collection protocol was similar across the 14 sponsoring entities so the data elements were consistent.

NMR data were used in the DOE Study to account for the numbers and associated attributes of lamps (e.g., on/off control type) and fixtures (e.g., ceiling fixture) in homes with respect to the data elements captured in the RECS and AHS data. Each of the RECS sample households was mapped to either an individual NMR study that was geographically relevant, or an average of multiple NMR studies. For example, if an individual RECS sample household record was for a single-family home with two adults, one child, three bedrooms, and two bathrooms, the DOE Study matched an average lighting inventory profile for homes with those exact characteristics to augment the RECS data. Lighting inventory data were not available from Tennessee or neighboring states, so an overall average lighting inventory profile from the NMR studies was originally taken to represent households in TVA states.

Lighting Usage Data Sources. During 2008 to 2009, a study was conducted in California by KEMA (now DNV GL) for the California Public Utilities Commission (CPUC) in which household characteristics and detailed lighting inventories were collected onsite from a random sample of over 1,200 residences throughout the state (CPUC 2010). These inventories included detailed information on all lighting fixtures in the residence, including location, switch type, fixture type, light source type, light source wattage, dimmability, and socket base type. In addition, HOU data was metered for a random sample of up to seven lighting fixtures per residence resulting in more than 8,000 lighting fixtures in the study. The large sample size and scope (coverage of residence types, room types, and lighting inventory) made this data set perhaps the most comprehensive to date. As part of the CPUC study, a statistical model was developed for estimating residential lighting end-use consumption as a function of lighting attributes and household characteristics data.

The DOE Study v1.0 utilized the statistical model developed in the CPUC study to estimate HOU for households nationwide, taking into account the structural characteristics of homes (from RECS/AHS), characteristics of their occupants (from RECS/AHS), and the lighting inventories in service (from the NMR studies).

New Data Sources for DOE Study v2.0

TVA Lighting Data. DNV GL, on behalf of Tennessee Valley Authority (TVA), collected lighting usage data between late 2013 and early 2014 from a sample of households in the TVA service area. The study was designed to leverage the DOE Study framework, through calibration of the DOE Study average daily HOU estimates using the new usage data collected within the TVA service area. At the time that the study was conceived, preparations were underway for fielding onsite data collection for a residential HVAC study, and detailed lighting inventory data were already being collected. It was decided to target a subsample of these homes for recruiting to additionally allow the DNV GL field engineers to install light loggers on a random sample of fixture groups in their homes.

Seventy homes were targeted for this “piggyback” study. It was known going in that this sample size would not be large enough to serve as a robust stand-alone lighting study for a large number of cuts in the data (e.g., ceiling fixtures with CFL lamps in dining rooms in multi-family homes). However, paired with the DOE Study data as a backbone, updated HOU regression models using the TVA data could provide usage calibrations that could be applied to the detailed DOE Study HOU estimates.

Mid-Atlantic Lighting Data. In addition to making use of the TVA data, the updated DOE Study v2.0 incorporated data that DNV GL collected in 2012 from the Mid-Atlantic Census Division, which consists of New York, New Jersey, and Pennsylvania. This area was targeted because of its high population density. The data collection effort was part of the scope of work for the original DOE Study v1.0, but timing and budget did not allow for its incorporation into the estimates at that time. The analysis and incorporation of the Mid-Atlantic data was put on hold until additional funding was secured for an update, which came through the TVA Study. The Mid-Atlantic data was collected using the same protocols as both the California Residential Lighting Metering Study and the TVA Study, which enabled the data to be analyzed with minimal marginal cost above the update to the DOE Study using the TVA data alone.

HOU Estimation Procedure – DOE Study v1.0

The Hours of Use (HOU) estimation framework leveraged the regression model produced as part of the CPUC’s Upstream Lighting Program Impact Evaluation conducted over 2008-2009, relating annualized HOU for a lamp to operational and locational characteristics of the lamp as well as household characteristics. The process used to link data sources together so the CPUC HOU model could be applied throughout the country to estimate lamp hours is described in the following steps:

1. RECS data were expanded to include more detail about the rooms located within the homes in that data set. This was accomplished by merging average room profiles from the AHS to the RECS and controlling for high-level household characteristics such as the number of total rooms and the type of dwelling (e.g., single-family home).
2. The combined RECS-AHS data were expanded again by adding more detail about the number of lamps and fixtures and associated attributes (e.g., ceiling fixture, non-ceiling fixture) to each of the rooms/spaces within the RECS sample homes. This was done by merging the NMR lighting inventory data to the RECS-AHS data, controlling for room type and high-level household characteristics.
3. Lighting usage for all lamps in the combined RECS-AHS-NMR data were estimated by merging the statistical model parameters from the CPUC study to the lamp and household attribute variables in the combined RECS-AHS-NMR data.

Figure 3 summarizes this estimation process. The modeled relationships between lighting usage of lamps and attributes of those lamps and the households in which lamps were installed were extracted from the CPUC study and applied to synthetic survey data designed to capture the variability of those attributes throughout the U.S.

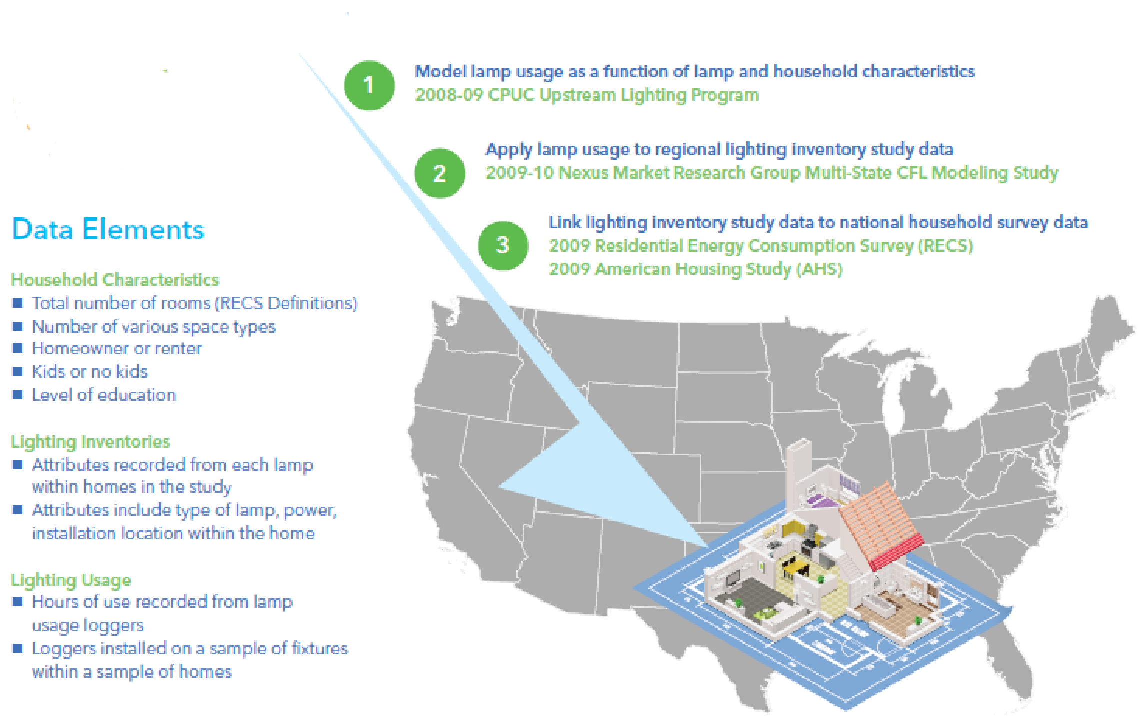

Figure 1: Process for Estimating HOU for Lamps in the DOE Study v1.0

Additional details regarding the original DOE Study methodology are documented in the project report (Gifford et al. 2012).

HOU Estimation Procedure – DOE Study v2.0

The updated DOE Study estimation procedure carried forward the approach of v1.0, with some modifications to make use of the new sets of household characteristics, lamp inventories, and logger data collected in the TVA and Mid-Atlantic studies. This involved combining all of the new data together with those of DOE Study v1.0, annualizing and fitting new lamp usage models for TVA and the Mid-Atlantic region, and aggregating the new results in each of the geographic domains forming a partition of the U.S.

Combining Data from the Different Studies. The data collected from the TVA study were combined with data used in the original data analysis, the Mid-Atlantic data collected in 2012, as well as the logger data from the CPUC study from which the HOU regression model was derived. It was important that all of the variables had the same categorization (i.e., categorical variable names needed to have exactly the same number of possible response categories and numerical ranges needed to match) across all of the studies so that the usage regression model could be fit in a consistent manner across the three study areas with logger data (California, TVA, and the Mid-Atlantic). In cases where households had missing values for numbers of rooms, number of residents, and composition (whether the household had children under the age of 17), a regression-based imputation procedure was used to estimate the missing values.

Annualization. We annualized the logger data from the TVA and Mid-Atlantic studies and computed average daily HOU from the raw percent-on lamp usage data that was recorded. The majority of the loggers were actively recording state change for fixture groups for about six months out of the year. We used sinusoidal regression models to extrapolate usage for the remaining duration of the year. In instances where a particular logger showed an unreasonable level of seasonality (fitting to the noise), or the sinusoidal shape parameter was insignificant, a straight mean-based extrapolation was used instead. Figure 2 shows the average annualized lamp utilization (percent-on) for the TVA study. Note that the fit of the model is attributed to the portion of the year where the most loggers were installed and actively collecting data.

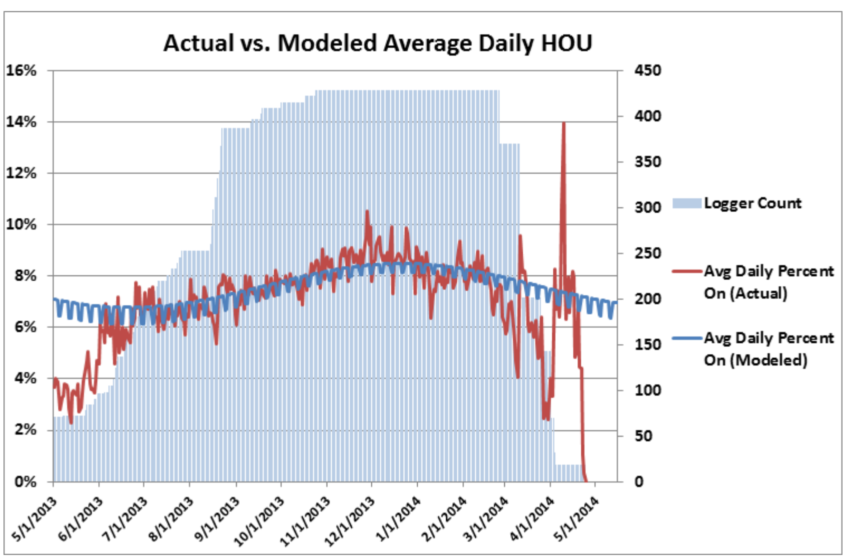

Figure 2: Sinusoidal regression model average predicted lamp utilization (blue curve) versus actual utilization (red). The vertical light blue bars represent the count of active loggers in the field.

HOU Regression Modeling. After the logger data from the TVA and Mid-Atlantic studies was annualized, the next step was to fit regression models relating household and lighting space characteristics to the average daily HOU for the lamps from the studies. The model structure from the CPUC study was used in fitting the models for the TVA and Mid-Atlantic usage data, separately, with separate models for each lamp type (CFL, Incandescent, Other).

The predictor variables used in the models were the following numeric variables or categorical variables represented in the model with binary indicator variables for the categories. The parameter estimates will be published in the forthcoming DOE report for the study updates.

- CFL saturation (numeric)
- Total number of sockets (numeric)
- Number of CFLs (categorical)
- Own/rent status (TVA data was all owner-occupied)
- Household composition (kids/no kids)
- Number of bedrooms (categorical)
- Number of bathrooms (categorical)
- Education level (categorical)
- Room type (categorical)
- Fixture location (ceiling/non-ceiling)

Many other explanatory attribute variables were considered in the CPUC study (e.g., dwelling type), but were not found to contribute a statistically significant improvement to the fit of the models (CPUC 2010 135-136)

Aggregating the HOU Estimates. There were two separate avenues to consider following for the regression analysis of the annualized average daily HOU data. The first was to fit separate models for each region and afterwards apply weights to the resulting estimates associated with the regional models (e.g., the HOU for a given combination of cross-categorical factors for a given state could be the straight average of the model from the CPUC, TVA, and Mid-Atlantic studies). The second approach that was considered was to include geographic region indicator variables directly into the model as fixed effects and potentially interactive terms of each of the predictor variables with the new regional indicator variables. With all predictor variables interacted with the regions, the two approaches would become identical.

We chose the first approach of having separate models for each region/lamp type combination because there was so much more data from the CPUC study than for the other regions. The second approach without a full set of interactive terms would result in more or less the same California HOU distribution with a fixed HOU differential across all of the cross-categorical factors. The separate models for separate regions approach that we took provides improved regional specificity in the HOU distributions, but with the drawback of being based on a smaller number of loggers. To leverage the other logger data to provide a more stable HOU distribution by analysis factors, we used a weighted approach of 80 percent TVA, 10 percent Mid-Atlantic, and 10 percent CPUC for the geographic domains intersecting with the TVA service area; 10 percent TVA, 80 percent Mid-Atlantic, and 10 percent CPUC for the Mid-Atlantic states; and 100 percent CPUC for California. All other geographic domains used weights of one-third for each of these three logger data studies. In further updates to this study a different approach may be taken if seen to be beneficial.

The weighted HOU model was applied to the lamp inventory and household characteristics data extrapolated to each geographic domain in the U.S. The weighted inventory profiles were identical to those of the DOE Study v1.0 except for the domains in the TVA and Mid-Atlantic areas.

Results

The average daily HOU estimates increased across the board for each lamp type in each region between the DOE Study v1.0 to v2.0, except in RECS Domain 26, California. The updated overall U.S. average daily HOU estimate for CFL lamps is 2.19, up from 1.92 in the v1.0 estimates. The incandescent and other lamp type HOU estimates were 1.43 and 1.76 hours per day, up 0.20 and 0.25 hours per day, respectively. Table 1 shows the original and updated DOE Study estimates by geographic (RECS) domain and lamp type. The bold domains correspond with regions intersecting with the TVA and Mid-Atlantic study areas. The results presented in this paper are preliminary and may be adjusted with further updates before the next DOE Study report and data tool are posted.

Table 1: DOE Study v1.0 and v2.0 Average Daily HOU by Lamp Type and RECS Domain

RECS Domain	CFL		Incandescent		Other Lamp Type	
	DOE Study 1.0	DOE Study 2.0	DOE Study 1.0	DOE Study 2.0	DOE Study 1.0	DOE Study 2.0
01. CT, ME, NH, RI, VT	1.95	2.21	1.26	1.45	1.49	1.77
02. MA	2.05	2.32	1.31	1.52	1.51	1.79
03. NY	**1.99**	**2.24**	**1.31**	**1.51**	**1.54**	**1.84**
04. NJ	**1.87**	**2.09**	**1.22**	**1.40**	**1.46**	**1.71**
05. PA	**1.95**	**2.19**	**1.24**	**1.42**	**1.48**	**1.74**
06. IL	1.93	2.17	1.21	1.39	1.34	1.62
07. IN, OH	1.97	2.19	1.24	1.43	1.43	1.70
08. MI	2.00	2.23	1.27	1.46	1.46	1.73
09. WI	1.86	2.10	1.20	1.38	1.37	1.63
10. IA, MN, ND, SD	1.89	2.14	1.18	1.36	1.41	1.66
11. KS, NE	1.88	2.12	1.19	1.36	1.39	1.65
12. MO	1.83	2.06	1.16	1.32	1.35	1.59
13. VA	**1.77**	**1.97**	**1.18**	**1.35**	**1.40**	**1.62**
14. DE, DC, MD, WV	1.82	2.02	1.20	1.37	1.40	1.62
15. GA	**1.81**	**2.43**	**1.20**	**1.53**	**1.51**	**1.85**
16. NC, SC	**1.89**	**2.52**	**1.23**	**1.58**	**1.63**	**1.99**
17. FL	1.91	2.13	1.22	1.40	1.59	1.82
18. AL, KY, MS	**1.90**	**2.54**	**1.21**	**1.56**	**1.52**	**1.90**
19. TN	**1.99**	**2.67**	**1.25**	**1.64**	**1.53**	**1.98**
20. AR, LA, OK	2.02	2.66	1.28	1.64	1.58	1.96
21. TX	1.96	2.19	1.27	1.46	1.59	1.85
22. CO	1.84	2.06	1.17	1.36	1.44	1.69
23. ID, MT, UT, WY	1.92	2.16	1.22	1.40	1.48	1.74
24. AZ	1.82	2.06	1.16	1.33	1.59	1.80
25. NV, NM	1.83	2.05	1.19	1.37	1.59	1.81
26. CA	1.91	1.91	1.24	1.24	1.61	1.61
27. AK, HI, OR, WA	1.93	2.16	1.22	1.42	1.53	1.80
Overall United States	**1.92**	**2.19**	**1.23**	**1.43**	**1.51**	**1.76**

As in the CPUC HOU study where logger data was collected from over 8,000 lamps in over 1,200 homes, the HOU by CFL lamps was generally higher than the corresponding usage for incandescent and other lamp types, even after controlling for fixture location. This could indicate that CFL lamps tend to be installed in greater usage fixtures or there could be an increased usage effect associated with high efficiency lamps being in service. Besides the possibility of there being a rebound effect (households increase lamp usage due to the new lamp being more efficient), there are two common explanations for this phenomenon:

1) People tend to put CFLs into greater-use fixtures because they know they get more savings there. There is significant household-to-household variation in HOU for a given fixture/location type. Within a fixture/location type, households install CFLs more often for those at the higher end of the HOU spectrum.
2) People buy a package of CFLs and replace whatever burns out with a CFL from the package. More frequently used bulbs get replaced by CFLs faster. The location/fixture type with the greatest overall use tends to get filled with CFLs first, but still within any type, more frequently used sockets get replaced with CFLs faster.

There has not been a conclusive study confirming or denying the rebound effect associated with lamp replacement to date. Such a study may involve metering fixture usage both before and after a replacement of the lamp with a more efficient technology. This would be challenging in that a large number of fixtures would need to be metered over a time period so that a sufficient number of natural lamp replacements would be made to the more efficient technology across different segments of a population. Additionally, a metering device capable of measuring wattage at the socket may be required so that the technology change could be measured and pinpointed to a specific interval. This would be more costly than using logger devices which simply record the state change from off-to-on and vice versa, with wattage recorded for the lamp separately.

Conclusions and Next Steps

The results of the update to the DOE Residential Lighting End Use Consumption Study demonstrated that data from new lighting studies in new regions, conducted under the specified data collection protocols, can indeed be incorporated into the analysis framework. The framework can facilitate multiple modeling approaches for average daily HOU. The HOU estimates following this update are now more aligned with results from studies outside of California. This addresses a criticism of the first version of the study – that national estimates based on an extrapolation of the HOU results from California to the U.S. is inappropriate because the California estimates were on the low end of the spectrum of average daily HOU among other recent residential HOU studies.

While these current results are encouraging, new data and models must continue to be incorporated into the study on a regular basis or the lighting usage estimates will become out of date and irrelevant. Among the recommended next steps for the DOE study are to:

- Identify additional lighting data from regional studies and funding sources for further updates
- Test additional model structures with regional effects included in the model parameterization as additional data becomes available
- Expand categorization to include LEDs along with CFLs and incandescent lamps

While the focus on this analysis approach is on residential lighting usage, it can be adapted to other sectors or to different end uses. Such a study could also make use of regional end use studies linked to EIA or other population survey research data using a national stratified sample design for extrapolating the results throughout other regions of the U.S. For weather-dependent end uses (e.g., HVAC), weather data along with penetration/saturation and relevant building and population characteristics should be used in the extrapolation procedure.

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