I Know What You Lit Last Summer: Results from California's Residential Lighting Metering Study

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ABSTRACT

California recently conducted a large-scale comprehensive residential lighting metering study. The primary goal of the study was to produce estimates of annual and peak lighting use by dwelling type, room type and fixture/lamp type. In addition, the study provided whole-house lighting inventory data that has been used to determine the remaining potential for energy efficient lighting applications in the residential sector. These results are being used by California's regulators, planners and implementers to design future strategies for residential lighting programs.

The study included 1,200 households recruited randomly throughout California over three overlapping waves of data collection, beginning in July 2008 and ending in December 2009. Up to seven meters were installed in each household participating in the study – up to four meters per home were reserved for fixtures containing CFLs, and the remaining meters were installed on fixtures containing other types of lamps. A randomized meter installation protocol was used by the surveyor to determine which specific fixture groups to meter. Meters were installed for at least six months during the 2008-2009 data collection period.

In addition to estimating average hours of use (HOU) for CFLs, the study produced estimates of HOU by fixture type, room/location, dwelling type, home size, income, education, and other demographic characteristics. HOU estimates were also developed for different levels of CFL saturation to aid in the transferability of California-specific results to areas with more, less or similar market penetration. This paper will discuss the methods used to calculate HOU and presents results for various segments of interest.

Study Background

This study was conducted on behalf of the California Public Utilities Commission (CPUC) to support the impact evaluation of the 2006-2008 Upstream Lighting Program. The Upstream Lighting Program was sponsored by the three electric investor-owned utilities (IOUs) of California – Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E).

Households were recruited from IOU customer databases by random sampling. Each of the three participating IOUs provided the name, address, and telephone information for a total of 20,000 randomly selected residential customers.[1] Targets for recruiting and scheduling were established for 37 different regions throughout the IOU's service territories. These regions consisted of groups of counties or groups of zip codes within a county, depending on population

[1] The surveys were conducted in three waves. In the first wave, 300 households were recruited and in the second wave another 300 households were recruited. A random sample of 10,000 IOU residential customers was used to recruit the first 600 households. In the final wave, a total of 600 households were recruited and a second random sample of 10,000 IOU residential customers was used for recruiting.

density. Targets were set for each region based on the percent of households within each region and the overall target for each IOU. Figure 1 displays the sampling targets for the full sample.

Households were recruited by a cold call during which they were informed of the study and invited to participate. Participants received $100 for their participation in the study – $50 after an initial inventory and installation visit, and another $50 after the meters were removed. Depending on the size of the home, the initial visit could last up to two hours. Up to seven meters were installed on different fixtures and the metering period was six months.

Lighting Inventory

A whole-house inventory was collected for each household recruited into the study. This involved recording information about every lamp[2] installed inside and outside of each home. For each lamp, the following characteristics were recorded:

- Location in home by room type
- Type of heating and cooling system serving space in which it is located
- How the fixture is controlled (by switch, dimmer etc)
- The type of fixture it is installed in
- Number of watts
- Lamp type (Incandescent, CFL, Halogen etc)
- Lamp shape type or Bulb type (Spiral, globe, tube, etc)
- Base type (small screw-in, pin, standard-medium screw, etc.)

In addition, information on incandescent lamps and CFLs contained in storage for future use was also collected (i.e., wattage, type, shape, and base type).

Meter Installation Protocols

As mentioned above, up to seven meters were installed in each household participating in the study – up to four meters per home were reserved for fixtures containing CFLs, and the remaining meters were installed on fixtures containing other types of lamps.[3] When completing the lighting inventory, surveyors entered a room and started recording information about each fixture group in a clock-wise direction from the entrance where they first walked into the room. A fixture group was defined to consist of all fixtures in a room that are operated by the same switch.

A randomized meter installation protocol was used by the surveyor to determine which specific fixture groups to meter. First, the surveyor would determine the total number of fixture groups in the home. Then, the surveyor would look up a randomized starting number on a table created uniquely for each site and meter every nth fixture group according to protocol.

[2] Use of the word lamp in this paper is consistent with the lighting industry use. A lamp in this sense is also known as a bulb in colloquial language. Here, a bulb is the glass casing encapsulating the filament or cathode.

[3] Analysis of non-CFL fixtures was not undertaken as part of the CPUC impact evaluation of the 2006-2008 Upstream Lighting Program. However, this analysis will be undertaken for use in future program planning and evaluation studies.

Figure 1. California Residential Lighting Metering Study Sample Design

Region	IOU		
	PG&E	SCE	SDG&E
Alameda Region	60		
Butte Region	24		
Contra Costa Region	40		
Desert South West Region		20	
El Dorado Region	20		
Fresno Region	36		
Humboldt Region	12		
Kern Region	24	8	
LA Central Region		64	
LA Coastal Region		44	
LA Inland Empire Region		76	
LA North Region		24	
Merced Region	12		
Monterey Region	24		
Orange North Region		72	
Orange South Region		12	16
Riverside West Region		36	
San Bernardino Region		64	
San Diego City Region			72
San Diego Coastal			36
San Diego NE Region			48
San Diego SE Region			36
San Diego South Region			32
San Francisco Region	36		
San Joaquin Region	16		
San Mateo Region	28		
Santa Barbara Region	16	8	
Santa Clara Region	60		
Solano Region	20		
Sonoma Region	36		
Tulare Region	4	16	
Tuolumne Region	12		
Ventura Region		36	
TOTAL	**480**	**480**	**240**

Source: KEMA, Inc.

The protocol requires that only one meter is installed per fixture group, and a fixture group was not eligible for metering if all the sockets in the group were burned out or empty or the entire fixture group was not in use. In addition, if both CFLs and non-CFLs were being used within the same fixture group, then the fixture group was considered to be CFL fixture group. Surveyors provided documentation for cases where it was technically infeasible to install meters on fixture groups selected by the random protocol. In these cases, the surveyor used the protocol to select the replacement fixture group for the one that was infeasible. Finally, if a home did not have four CFL fixture groups, then the meters were installed on additional non-CFL fixture groups, again selected by the protocol. Appropriate weights were developed and applied to the final metering results.

Average Daily Hours-of-Use (HOU)—Methods

Estimates of the average daily hours-of-use (HOU) for residential lighting were derived from the analysis of logger data collected during 2008-2009. Table 1 shows the numbers of sites visited and the number of meters installed/removed in each month for each wave during the 2008-2009 monitoring period.

Residential lighting HOU estimation consisted of the following steps:

1. Annualization. Because each logger collected data for only a portion of the year, a procedure was required to annualize the logger data. Annualization allows the seasonality and level of use indicated by each logger to be applied to the full year, rather than having different logger samples represent different parts of the year. Annual average HOU per day was estimated for each logger, by fitting a sinusoid curve to the daily hours of use data.
2. Weighting. Sample expansion weights were calculated for each metered home, fixture group, and lamp.
3. Analysis of Covariance (ANCOVA). A model was fit across the annualized loggers to calculate annual hours of use as a function of dwelling unit characteristics, room type, fixture type, lamp type, and IOU.
4. Projection to Full Inventory Sample. The estimated model was applied to each lamp observed in the full inventory of each metered home, providing an estimate of annual hours of use for each lamp in the inventory.
5. Calculation of Averages. Applying the premise weights to the inventory estimates, average annual hours of use were calculated for CFLs and non-CFLs by various breakdowns, including IOU, room type, dwelling unit type, and heating/cooling type.

Below, we discuss the annualization process and the ANCOVA modeling procedures in more detail.

Table 1. Residential Lighting Metering Study Sample Sizes by Month/Year

	2008						2009											
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
# Sites Per Month																		
Wave 1	26	191	92				-26	-191	-92									
Wave 2				118	181	15					-118	-181	-15					
Wave 3									188	76	213	133		-24	-231		-155	-200
Total # Cumulative Sites Per Month	**26**	**217**	**309**	**427**	**608**	**623**	**597**	**406**	**502**	**578**	**673**	**625**	**610**	**586**	**355**	**355**	**200**	**0**
# Meters Per Month																		
Wave 1	174	1280	622				-174	-1280	-622									
Wave 2				814	1249	104					-814	-1249	-104					
Wave 3									1297	524	1470	918		291	64	-524	-1470	-2570
Total # Cumulative Meters Per Month	**174**	**1454**	**2076**	**2890**	**4139**	**4243**	**4069**	**2789**	**3464**	**3988**	**4644**	**4313**	**4209**	**4500**	**4564**	**4040**	**2570**	**0**

Site/meter added

Site/meter removed

Source: KEMA Inc.

Annualization

Because each logger collected data for only a portion of the year, a procedure was required to annualize the logger data. Annualization allows the seasonality and level of use indicated by each logger to be applied to the full year, rather than having different logger samples represent different parts of the year. For each logger, a sinusoid model was fit, of the form:

$$H_d = \alpha + \beta \sin(\theta_d) + \varepsilon_d$$

Where

H_d = hours of use on day d
θ_d = angle for day d, where θ_d is 0 at the spring and fall equinox, $\pi/2$ d = December 21, and $-\pi/2$ for d = June 21,
α and β are coefficients determined by the regression
ε_d = residual error.

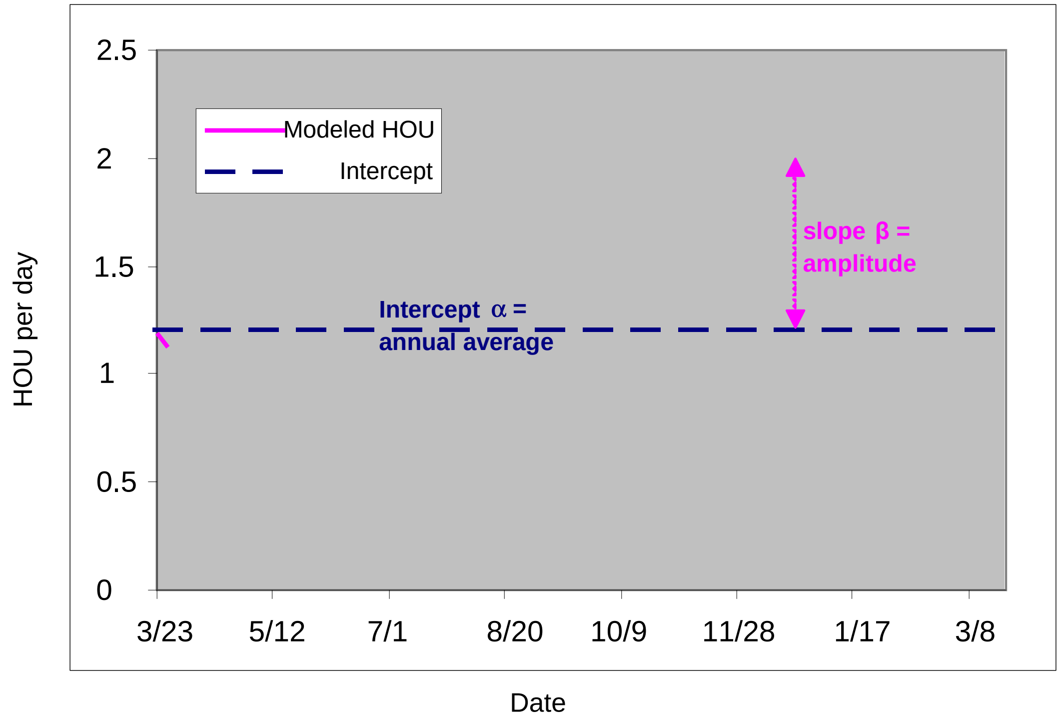
Fits that resulted in sine coefficients greater in magnitude than +10, or with standard error of the sine coefficient β greater than 1 were classified as "poor." For these cases, the average slope coefficient of "good fit" loggers (all that were not "poor") from the same room type was assigned. The intercept for each poor fit was set such that the average modeled value was equal to the observed average value over the period for which the logger had data. This approach ensured that the "level" information from the logger was included in the analysis sample, but treated the "slope" information as uninformative. Classification of fits as good or poor and transfer of average slopes from good fits to poor fits was conducted separately for weekdays and weekends.

The sinusoid shape is very close to the shape of hours of darkness, and gives very similar estimates (Figure 2). Other studies have used daily hours of daylight. The two are very closely correlated. Ultimately, we worked with the sinusoid because it has the advantage of a very simple analytic form, as well as some convenient features. In particular:

- The intercept of the weekday (weekend) model is the average weekday (weekend) use over the year.
- The slope of each daytype's model (i.e., weekday or weekend) is the difference between use on the solstice (the days of maximum and minimum daylight) and the average use.

The average annual daily hours of use is calculated by averaging the weekday and weekend/holiday intercepts in proportion to the number of each daytype in the year.

Figure 2. Illustration of Sinusoidal Model



Source: KEMA, Inc.

Analysis of Covariance (ANCOVA) Model

Overall statewide and IOU-specific estimates of HOU can be generated directly from the metering sample. For smaller subgroups, however, the direct expansion estimates have high variance because of small sample sizes with particular combinations of characteristics. Alternative estimates are provided by leveraging the entire sample, via an Analysis of Covariance (ANCOVA) model. The ANCOVA model provides the incremental effect of each dimension on hours of use, and allows all loggers in the sample to inform each IOU's estimate, while still retaining the differences among the IOUs. The ANCOVA model provides several benefits:

- It describes factors that affect lighting use.
- It provides more robust estimates for each small subgroup, compared to taking direct weighted average from the loggers that fall in that subgroup.
- It provides a basis for leveraging the full inventory sample, rather than calculating averages only from the metered loggers.
- It provides a basis for transferring estimates from this sample to other populations.

On the other hand, for estimates that do not involve taking small subsets of the data, the ANCOVA-based leveraged estimates tend to have higher variance than the direct expansion estimates using the metered loggers only.

The HOU ANCOVA model was tested with variables that were likely to affect lighting usage or might be correlated with lighting use drivers. Final variables included in the model are listed and described in Table 2. Additional variables tested that were found not to be statistically significant in the model included:

- Dwelling unit type
- Fixture type
- Heating system type
- Cooling system type
- Lamp type (e.g., twister/spiral, A-line, globe, reflector)
- IOU-discounted v. non-IOU discounted CFL

Table 2. Variables Used in HOU ANCOVA

Variable	Description	Levels
CFL Saturation	Ratio of MSB CFLs and applicable MSB sockets.	Numeric
Number of Sockets	Total number of applicable sockets in the premise.	Numeric
Number of CFLs	Total number of CFLs in the household.	1-2
		3-4
		5+
IOU	Which utility serves the household.	PG&E
		SCE
		SDG&E
Own/Rent	Household is owned or rented.	Own
		Rent
Dwelling Type	Dwelling unit type.	Single Family
		Multifamily
		Mobile Home
Household Composition	Household has kids or no kids.	Kids
		No Kids
Number of Bedrooms	Number of bedrooms in the household.	1
		2-3
		4+
Number of Bathrooms	Number of bathrooms in the household.	1
		2
		3+
Education Level	Highest education level of the respondent.	Less than HS
		HS Graduate
		College
		Post Graduate
Room Type	Type of room or location in which the bulb was found.	Bedroom
		Bathroom
		Dining Room
		Garage
		Hall/Entrance
		Kitchen
		Living Room
		Other
		Office
		Exterior
Fixture Type	Type of fixture in which the bulb was found.	Ceiling
		Other

There are differences in average hours of use across these dimensions. However, these differences are accounted for by the other variables included in the model.

ANCOVA results are shown in Tables 3 and 4 below. As anticipated, HOU declines with increasing CFL saturation. However, the general decline had a different pattern for very small numbers of CFLs in use: homes with three or four CFLs in use had much higher average use than those with one or two, or with five. These differences are captured by the categorical CFL count variable.

Even after accounting for all the other factors in the list, there were still statistically significant differences by IOU. These terms were therefore retained in the model.

Table 3. HOU ANCOVA Model Dependent Variable = Annual Average Hours of Use per Day Analysis of Variance

Variable Name	***p*-value**
Intercept	<.0001
CFL Saturation	0.1362
Number of Sockets	<.0001
Number of CFLs	0.1921
IOU	0.0007
Household Composition	0.0026
Room Type	<.0001
Number of Bedrooms	0.0400
Number of Bathrooms	0.0012
Education Level	0.0317
Fixture Type	0.0090

Average Daily Hours-of-Use (HOU)—Results

Average daily residential HOU estimates were produced directly from the metering sample results (direct expansion), as well as from the ANCOVA model (leveraged expansion). Results were produced for CFLs overall, as well as for a variety of different CFL types (e.g., twister/A-lamp shaped CFLs, globe-style CFLs, reflector-style CFLs, other). A comparison of the direct and leveraged expansion results is presented in Table 5.

Table 4. HOU ANCOVA Model Parameter Estimates

Variable Name	Level	Coefficient	Std Error	t-stat	*p*-value
Intercept		3.483	0.316	11.020	<.0001
CFL Saturation		-0.423	0.226	-1.870	0.062
Number of Sockets		-0.004	0.002	-2.030	0.042
Number of CFLs	1-2	0.001	0.272	0.000	0.997
	3-4	0.301	0.172	1.750	0.080
	5+				
IOU	PGE	0.212	0.139	1.520	0.128
	SCE	0.494	0.139	3.560	0.000
	SDGE				
Household Composition	Kids	0.325	0.107	3.040	0.002
	No Kids				
Room Type	Bedroom	-2.191	0.191	-11.500	<.0001
	Bathroom	-2.304	0.203	11.350	<.0001
	Dining Room	-1.854	0.335	-5.530	<.0001
	Garage	-1.752	0.375	-4.680	<.0001
	Hall/Entrance	-2.226	0.241	-9.240	<.0001
	Kitchen	-1.139	0.243	-4.700	<.0001
	Living Room	-1.459	0.202	-7.220	<.0001
	Other	-2.022	0.230	-8.800	<.0001
	Office	-2.133	0.289	-7.390	<.0001
	Exterior				
Number of Bedrooms	1	-0.878	0.241	-3.640	0.000
	2-3	-0.320	0.140	-2.280	0.023
	4+				
Number of Bathrooms	1	0.753	0.200	3.760	0.000
	2	0.396	0.149	2.650	0.008
	3+				
Education Level	Less than HS	-0.115	0.207	-0.550	0.579
	HS Graduate	0.429	0.183	2.340	0.019
	College	0.213	0.122	1.750	0.081
	Post Graduate				
Fixture Type	Ceiling	-0.297	0.114	-2.610	0.009
	Other				

Table 5. Statewide Residential Average Daily Hours-of-Use (HOU): Comparison of Direct Expansion and Leveraged Expansion Results

	Direct Expansion (Metering Sample Results)			**Leveraged Expansion** (ANCOVA Model Results)		
	HOU	90% CI +/-	90% CI +/-%	HOU	90% CI +/-	90% CI +/-%
Overall	1.9	0.1	3%	1.9	0.3	16%
Twister/A-Line	2.0	0.1	4%	1.9	0.3	16%
Reflector	2.0	0.4	21%	1.9	0.3	17%
Globe	1.3	0.3	24%	1.5	0.3	20%

As shown, the direct expansion results produced more precise estimates for CFLs overall as well as for twister/A-line shaped CFLs. This is because the underlying metering sample size for these categories is very large. As a result, the sample provides a good representation of the distribution of these bulbs across homes and deployment conditions, and also provides a well-determined estimate. However, for the other types of CFLs, the underlying sample sizes were a lot smaller and, as a result, the direct expansion results are less precise. The ANCOVA results for a particular category essentially "borrow" information from the other categories that indicates differences in use associated with home, room, fixture, and occupant characteristics. For the categories with small sample sizes, the leveraged estimate is more robust and more precise compared to the direct expansion estimate.

The average daily residential HOU estimates developed through this evaluation were found to be about 20% lower than was found in previous studies. This is likely attributable to increasing saturations of CFLs in homes. The analysis found that HOU tends to decline as saturations increase; however, this relationship was observed only for larger numbers (5 or more) of CFLs installed. This finding confirms that initial CFL installations tend to go into higher use fixtures.

Statewide HOU results for various segments of interest are presented in Table 6. As shown, average daily residential HOU for all CFLs are:

- ***Highest for households living in SCE's service territory (2.1) and lowest for households living in SDG&E's service territory (1.5)***. Since CFL saturation is similar across households in both service territories, the main difference appears to be dwelling type – i.e., homes in SDG&E's service territory are larger and have more sockets than homes in SCE's service territory.
- ***Highest in smaller homes, multi-family dwellings and rental properties.*** Average daily CFL HOU is highest in multi-family dwellings (2.1) and rental properties (2.0). In addition, dwellings with only one bathroom have the highest average daily CFL HOU (2.2) and dwellings with three or more bathrooms have the lowest (1.4).
- ***Lowest for the most highly educated households (1.4)***. Households with post-graduate education levels have the lowest average daily CFL HOU, which could be a factor correlated with dwelling type and size.
- ***Highest for CFLs located outdoors (3.9), in kitchens (2.5) and in living rooms (2.3).*** Average daily HOU is lowest for CFLs located in garages (1.2), hallways (1.2), bathrooms (1.4), and offices (1.6).

Conclusions

The CPUC has used the results of this study to evaluate the ex-post impacts of the 2006-2008 Upstream Lighting Program. The average daily residential HOU estimates developed through this study were found to be about 20% lower than was assumed in the ex-ante estimates. In addition, the CPUC and the IOUs plan to use the results of this study to inform future estimates of energy savings achievable from residential energy efficient lighting measures. Finally, these results will also be used by the CPUC and the IOUs to help design programs targeted to reach the segments of households and residential lighting applications with the highest energy savings potential.

Table 6. Average Statewide Residential Daily Hours-of-Use (HOU)

Segment	Level	Average Daily HOU	90% CI +/-	90% CI +/- %
Overall		1.9	0.1	3%
IOU	PG&E	1.8	0.1	5%
	SCE	2.1	0.1	5%
	SDG&E	1.5	0.1	8%
Own/Rent	Own	1.9	0.1	4%
	Rent	2.1	0.1	6%
Education	Less than high school	1.9	0.2	10%
	High school	2.0	0.2	10%
	College	2.0	0.1	4%
	Post graduate	1.4	0.1	8%
Dwelling Type	Multifamily	2.0	0.1	6%
	Mobile home	1.9	0.3	17%
	Single family	1.8	0.1	4%
Number of Bathrooms (proxy for home size)	1	2.2	0.1	6%
	2	2.1	0.1	5%
	3+	1.4	0.1	7%
Room/Location	All Exterior	3.9	0.4	9%
	All Interior	1.7	0.1	3%
	Bathroom	1.4	0.1	8%
	Bedroom	1.7	0.1	6%
	Dining	1.9	0.3	16%
	Garage	1.2	0.4	29%
	Hall	1.2	0.2	13%
	Kitchen	2.5	0.2	8%
	Living	2.3	0.2	8%
	Office	1.6	0.2	13%
	Other	1.4	0.2	12%

References

KEMA, Inc. 2010. **Final Evaluation Report: Upstream Lighting Program, Volume 1.** Oakland, Calif.

KEMA, Inc. 2010. **Northwest ENERGY STAR® Homes Energy Analysis: 2006 - 2007: Final Report**. Portland, Ore.: Northwest Energy Efficiency Alliance.

Snedecor, G.W. and W.G. Cochran. 1967**. Statistical Methods, 6th Edition**. Ames, Iowa: Iowa State University Press.