What Light through Yonder Window Breaks? Methods to Study the Effects of Urban Canyons on Lighting Usage

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ABSTRACT

A 2013 article in the New York Times explored how shadows affect urban households, observing that *"in a city forever sprouting new buildings, the quest to reach higher often comes at the cost of stealing somebody else's light*" (Buckley 2013). What the article describes is known as the *urban canyon effect*, the conditions created by streets cutting through dense blocks of structures to form human-made canyons. Urban canyons can affect radio reception, wind, temperature, air quality, and—most relevant to our research—light. The nature of urban canyons also tends to limit glazing in high-rise apartments to one or two sides of a unit. A recent lighting hours-of-use (HOU) study in four Northeastern states provided the opportunity to explore the relationship between available natural light and use of electric lights in high-rise apartments in Manhattan - an area replete with urban canyons. For this exploratory study, the authors collected glazing and solar shading data for a sample of 130 high-rise units to determine if the availability of direct sunlight, and of ambient light generally, has an effect on lighting HOU. The results provide useful insights into quantifying the effect of urban canyons on HOU, which is potentially of interest for programs in densely-populated cities worldwide, and for economic data collection methods in these areas.

Introduction

The High-Rise Solar Shading Analysis was an exploratory effort undertaken as an add-on to the broader Northeast Residential Lighting Hours-of-Use Study (NMR 2014). The study grew out of a desire to represent high-rise apartment dwellers in the overall HOU study while trying to account for the urban canyon effect, which is caused by streets cutting through dense blocks of structures to form human-made canyons. While the urban canyon affect had been studied in the past in relation to radio reception, wind speed, temperature, and air quality, no one had ever studied the effects on urban dwellers lighting usage. In addition to urban canyon affect, the design of typical high-rise apartments also tends to limit glazing (i.e., windows) to one or two sides of a unit. To explore the effects of shading on lighting HOU, the evaluation team collected glazing and solar shading data for 130 high-rise apartment units in Manhattan to determine if the availability of direct sunlight, and of ambient light generally, has an effect on residential lighting use in high-rise apartments. The team developed a regression model to quantify the relationship.

Project Background

As noted in the introduction, the solar shading analysis was an add-on to the Northeast Residential Lighting Hours-of-Use study (HOU Study), one of the largest and most comprehensive residential lighting HOU studies ever conducted. This is one of three papers being presented at IEPEC

Long Beach 2015 on this study. The other two are *A Lighting Study to Stand the Test of Time: Exploring the Results of a Residential Lighting Study Designed to Produce Lasting Data*, Barclay, et al., an exploration of the larger study and *Are You Turned On? A Hierarchical Modeling Approach for Estimating Lighting Hours of Use*, Correia, et al., which focuses on specific modeling techniques applied to the data. The larger study included on-site visits to 848 homes in Connecticut, Massachusetts, Rhode Island, and New York.[1] Each site required two visits: the first to collect a detailed lighting inventory and install time-of-use light meters (loggers) and the second, occurring several months later[2], to collect the lighting loggers. The team installed 5,730 loggers overall, an average of seven per home. Technicians placed the loggers on unique circuits (a circuit is a set of bulbs or fixtures operated by the same switch) throughout each home. In multi-family homes, technicians installed, where possible, one logger in each of the following room types: living spaces, bedrooms, bathrooms, and kitchens, and two loggers in other room types. In single family homes, technicians also tried to place one logger each in dining rooms and on the exterior. The team theorized that HOU would be different for high-rise homes, and that the urban canyon effect would be a driver of differences. To explore this, NYSERDA funded an oversample of 121 high-rise apartments in Manhattan for additional solar shading data collection in addition to HOU metering. The HOU study did indeed find that high-rise households in Manhattan use lighting significantly more than the region overall (3.9 hours per day on average versus 2.7 hours for the region comprising Connecticut, Massachusetts, Rhode Island, and Upstate New York). Using the model described below, the team determined that solar shading effects explain some of this difference.

Sample Design

To recruit the high-rise oversample, the evaluation team developed a list of high-rise buildings in Manhattan using the Primary Land Use Tax Lot Output (PLUTO™) database maintained by the City of New York Department of City Planning. The PLUTO data files contained information for 859,324 building locations across five boroughs in New York City (NYC).[3] While Manhattan had the smallest number of total building locations, it had by far the greatest number and percentage of residential high-rises.[4] Given this, the evaluation team chose to limit the oversample to Manhattan, where the evaluators identified 25,771 residential high-rise buildings with 868,942 units.[5] Based on the data contained within the PLUTO database, the evaluation team developed an initial sample stratified by age of building (vintage) and height, with a goal of completing visits to low-income households in proportion to their share of total units. Abt SRBI, NYSERDA's survey contractor, sent samples of addresses from the PLUTO database to Telematch. The team used matched telephone numbers to conduct a CATI survey to recruit high-rise respondents. Using this sample the team recruited 121 high-rise respondents to participate in the study with the solar shading data collection. The team also collected solar shading data at an additional nine high-rise sites that had been part of the Downstate New York[6] sample, for a total of 130 sites.

Manhattan Data Collection Considerations

Economic and efficient data collection in Manhattan required unique approaches compared to the site visits for other areas included in the project. The team hired local technicians to perform the visits

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[1] 848 includes the 121 visits of the high-rise oversample.

[2] Loggers were in the field for an average of 143 days, with 84% collecting data for at least 121 days and 31% for at least 151 days.

[3] Each location may have multiple buildings.

[4] For the purposes of this study, high-rise buildings were defined as four stories or higher.

[5] Manhattan had 25,771 residential high-rises, 46% of the total number of buildings, versus 18,386/33% in Brooklyn, the second highest total of the five boroughs.

[6] Includes New York City and Westchester County

and paid for their travel to the sites via stored value cards (Metrocards) for the New York MTA public transit system. This ensured that the technicians would be familiar with Manhattan geography and travel on the MTA. It also greatly reduced or eliminated costs to the project for hotel rooms, car rental, travel cost and time, parking, and traffic delays.

Without a vehicle to transport equipment to sites, the team had to limit data collection tools to what one person could easily transport on the subway (Figure 1). Each technician was provided with a backpack to carry various hand tools, data collection forms, and other necessary items, including a small folding stepstool to help reach ceiling fixtures. For solar shading data tools, the team provided each technician with a digital camera, tape measure, compass, and a device called the SolarPathfinder ™ (described below), which, among other benefits, folds into a compact carrying case.

Collecting the solar shading data added time and complexity to the already difficult and often lengthy process of the lighting inventory and logger placement. The team took care to devise a procedure that would be as simple, quick, and non-intrusive as possible, while still allowing for collection of all pertinent data.

By our choice of local technicians, careful consideration of a manageable equipment package, and straightforward data collection procedures, the team was able to keep costs low for this exploratory metric.

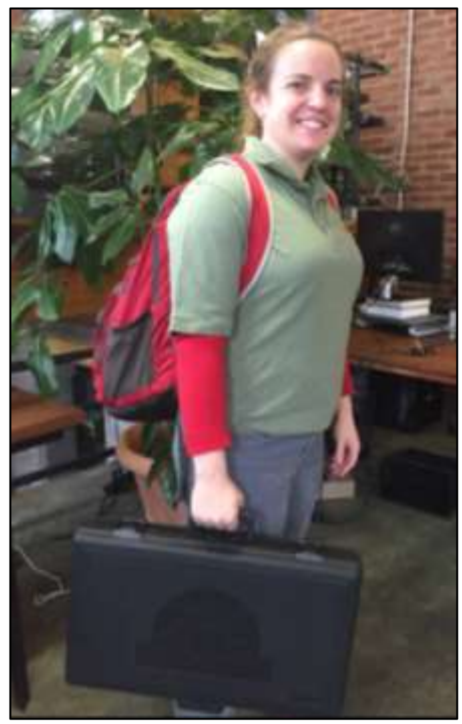

Figure 1: On-site Equipment

Solar Shading Methodology

Glazing

The number, size, and direction of windows are important factors that determine how much of the available ambient light enters a home. Project technicians sketched the layout of apartments, identified the orientation of the walls, measured the exterior walls and windows, and recorded the presence of light obstructions like blinds, curtains, and window air conditioners.

Solar Shading

The other factor that determines available ambient light is exterior shading. Solar exposure was measured using the Solar Pathfinder,™ [7] a simple mechanical device used primarily in the solar energy industry for the purpose of shade analysis (Figure 2). The Pathfinder provides a method for measuring a full year of solar availability or shading based on a reflected image overlaid on a sun path diagram. Instead of relying on shadows, the Pathfinder uses a highly reflective convex dome that provides a panoramic view of the entire site. This makes it possible to use the Pathfinder during any daylight hour or time of year. More details on the operation of the Pathfinder device and the principles behind it can be found at the Solar Pathfinder website.[8]

Technicians placed the Pathfinder on the sill of the window where solar exposure was to be measured, and photographed the Pathfinder as well as the view out the subject window (Figure 3). Technicians generally did not take Pathfinder photos at north-facing windows, which have no direct sun exposure. Using these photos and the Solar Pathfinder Assistant software, the team calculated the percentage of available direct sunlight reaching the window (Figure 4). The software requires the user to trace the unobstructed area reflected on the dome. This is the area where one can see the sky between the adjacent buildings in Figure 2 and Figure 3. Based on values entered for location and tilt of the "collector" (in this case a window perpendicular to the ground), the software outputs the expected sun hours per day reaching the location of the Pathfinder in each month of the year, and the daily average for the year.

The Pathfinder provides a measure of solar exposure at a particular point. It does not account for the size or number of windows, the layout of the interior of a home, or the behavior of the inhabitants. It was also not always possible to obtain a photo from every window. Technicians focused on getting at least one photo from each side of the house expected to receive the most sun (south-, southeastern, or southwestern-facing). As a proxy measure of available sunlight at a site, the team calculated solar exposure using the photo from the window with the greatest solar exposure.

[7] http://www.solarpathfinder.com/PF

[8] http://www.solarpathfinder.com/pdf/pathfinder-manual.pdf

A photo of the Solar Pathfinder on the sill of a southeast-facing window. The curved lines on the Pathfinder template indicate the position of the sun at all hours of the day and all months of the year. Any point on the diagram that shows open sky indicates that there is direct sun at the Pathfinder's location at that date and time.

Figure 2: Solar Pathfinder

The view out the window from the Solar Pathfinder photo in Figure 2. One can see how the gap of sun in the "canyon" of buildings along the street is represented in the reflection on the Pathfinder's dome

Figure 3: View Out SE-facing Window

Solar Site Analysis Report 1

Image File 145-SE-1-SP.JPG

Solar Obstruction Data

Month	Actual Unshaded Solar Radiation Azimuth=180.0 Tilt=90.0 kWh/m² /day	Actual Shaded Solar Radiation Azimuth=180.0 Tilt=90.0 kWh/m² /day
January	3.02	0.00
February	3.58	0.20
March	3.68	0.92
April	3.03	1.06
May	2.81	0.69
June	2.60	0.59
July	2.79	0.68
August	3.08	1.01
September	3.42	1.06
October	3.68	0.38
November	3.08	0.00
December	2.76	0.00
Totals	**37.37**	**6.90**
	Effect: 87.47%	**Effect: 11.74%**
	Sun Hrs: 3.11	**Sun Hrs: 0.54**

Notes: [None]

By tracing the area of sky present in the Solar Pathfinder photo, the Solar Pathfinder Assistant software calculates the amount of direct sunlight reaching the measured location.

Figure 4: Solar Pathfinder Assistant Report

Solar Shading Analysis

Glazing

The mean value for the glazing area of the 130 sites was 10% of the total wall area. Wall area includes all boundary walls of the unit, not just exterior walls. Manhattan's characteristic street grid is aligned roughly on the NE-SW axis. Most buildings north of Houston Street are aligned to the street grid, leading to a prevalence of glazing on the NE-SE-SW-NW sides (Table 1). The design of typical high-rise apartments in Manhattan also tends to limit glazing to one or two sides of a unit.

Table 1: Window Orientation (n = 130)

Orientation	Percent of total window area
North	3%
Northeast	26%
East	3%
Southeast	15%
South	2%
Southwest	30%
West	2%
Northwest	19%

To facilitate regression modeling, glazing values were divided into classes for both overall and southerly glazing (Table 2 and Table 3).

Table 2: Overall Glazing Classes (n = 130)

Glazing % of wall area	Glazing Class	Count
0 – 10%	1	81
11% - 20%	2	40
21% - 30%	3	6
> 30%	4	3

Table 3: Southerly Glazing Classes (n = 130)

Glazing % of wall area	Glazing Class	Count
0 – 10%	1	110
11% - 20%	2	17
21% - 30%	3	3

Solar Exposure

Solar exposure is measured relative to the maximum solar insolation[9] at a given location and tilt angle. As calculated with the Solar Pathfinder Assistant software, the maximum annual average daily solar insolation in Manhattan for an object at the ideal tilt angle of 40.7 degrees relative to the ground is

[9] Solar insolation is a measure of solar radiation energy received during a given period of time on a given surface area.

4.6 kWh/m^2 (also referred to as “sun hours” per day). For an object perpendicular to the ground, such as a window, the maximum is 3.1 kWh/m^2 per day. This can also be expressed as the effective solar radiation percentage, or the average percentage of the day during which there is no shade. The maximum effective percentage for a window in Manhattan is 67% (3.1/4.6). The team was able to collect reliable solar exposure measurements at 101 sites. The annual average insolation was 0.97 sun hours per day, or 21%. Solar exposure data were also divided into four classes based on a scale of 0-100% as a percentage of the theoretical maximum insolation (Table 4).

Table 4: Solar Exposure Classes (n = 101)[10]

Percent of maximum insolation	Class	Count
0 – 25%	1	48
26-50%	2	30
51-75%	3	20
76-100%	4	3

In further anticipation of regression modeling, the team created a variable defined as the sum of all classes. The variable was equal to the sum of the glazing class, south-facing glazing class, and solar exposure class for each site. Values ranged from three to ten; therefore, a simplified variable called the “binned sum of class values” was created taking only the values one, two, or three. See Table 5 for more details. The motivation for creating this variable is that it combines the different glazing variables and amount of solar exposure into one variable as opposed to three. This is desirable because a combination of glazing and solar exposure dictate useable ambient light. For example, a site with a large amount of glazing that is mostly shaded by a big tree and a large building will not receive much ambient light in the home; similarly, a site with a high amount of solar exposure but very low glazing will also not receive much ambient light. However, a site with a large amount of glazing and high solar exposure should receive a good amount of ambient light in the home. This variable allows us to capture those differences.

Table 5: Binned Sum of Class Values

<table>
<tr><th>Sum of Class Values</th><th>Count</th><th>Binned Sum of Class Values</th><th>Count</th></tr>
<tr><td>3</td><td>31</td><td>1</td><td>31</td></tr>
<tr><td>4</td><td>25</td><td rowspan="2">2</td><td rowspan="2">49</td></tr>
<tr><td>5</td><td>24</td></tr>
<tr><td>6</td><td>10</td><td rowspan="5">3</td><td rowspan="5">21</td></tr>
<tr><td>7</td><td>4</td></tr>
<tr><td>8</td><td>5</td></tr>
<tr><td>9</td><td>1</td></tr>
<tr><td>10</td><td>1</td></tr>
</table>

[10] Technicians obtained usable solar exposure data from 101 of the 130 sites. Reasons for failure to collect solar shading data included lack of time, darkness (PathFinder photos can only be taken during daylight hours), technician error, and obstructions within the site that prevented technicians from taking photos near windows.

Regression Model

To determine which solar shading variables were important predictors of HOU, the team performed variable selection using a stepwise linear regression analysis, accepting or rejecting variables based on the Akaike information criterion (AIC), which is a measure of the relative quality of a statistical model, balancing both the goodness of fit and parsimony of the model (Akaike 1974). While AIC does not tell us about the absolute quality of a particular model, it does allow for comparisons between candidate models, with the model having the lowest AIC being the preferred model. Note that when using AIC as a model-building criterion, it is possible to accept a variable into the model that is not statistically significant; thus, the AIC provides a more flexible approach than simply retaining only statistically significant variables, which is important given the exploratory nature of this analysis. However, because it also rewards parsimonious models, it ensures that highly uninformative variables are not added to the model, making it a better alternative than using R^2 or adjusted R^2 for model building.

Prior to the variable selection procedure, four variables were dropped in a preliminary phase: %North-, %South-, %East-, and %West-facing glazing. These variables were excluded due to the NE-SW axis on which the Manhattan grid is aligned, which translates to very few sites having windows facing directly north, south, east, or west.[11]

In the stepwise regression, the team began by forcing the model to contain the same household and logger explanatory variables as the HOU models presented in the associated Northeast Residential Lighting Study (except the home type variable, as all sites in this subsample were multifamily). Given the relatively small sample size for this subtask, the team believed it would be useful to apply the information obtained from the entire Northeast regional study about important predictors, so these variables were used regardless of their AIC-based classification. Specifically, the base solar shading model had the following variables:

- Room type
- Efficient bulb indicator
- Low-income indicator
- Household education
- Rent/own indicator
- Anyone under 18 years of age indicator

The goal of the variable selection procedure, therefore, was to determine which, if any, of the solar shading variables were also important predictors of HOU in addition to the base variables listed above. The variables selected into the model via the stepwise procedure were:

- %Northwest-facing glazing
- %Northeast-facing glazing
- %Southwest-facing glazing
- %Southeast-facing glazing
- Binned sum of class values

The final model also included an interaction term between the binned sum of class values variable and each of the directional variables. All variables used in the model are described in Table 6.

[11] Only 20% of the sample had glazing facing any of the four cardinal directions.

Table 6: Variables Used in Solar Shading Regression Analysis

Variable	Description	Levels
Room Type	Room/location the bulb was located.	Bedroom
		Bathroom
		Kitchen
		Living Space
		Dining Room
		Exterior
		Other
Efficient Bulb	Whether the bulb was efficient or non-efficient.	Yes
		No
Income	Household income.	Low Income
		Non-Low Income
Education	Education level of the respondent.	Less than High School
		High School or GED
		Some College
		Bachelor's Degree
		Advanced or Graduate Degree
Rent/Own	Whether household is owned or rented	Rent
		Own
Under 18	Anyone under 18 years of age in the household	Yes
		No
%NW Glazing	% of total glazing facing NW	Continuous
%NE Glazing	% of total glazing facing NE	Continuous
%SW Glazing	% of total glazing facing SW	Continuous
%SE Glazing	% of total glazing facing SE	Continuous
Total of Glazing Class Values	Binned variable summarizing the sum of all glazing class values (See Table 5)	1
		2
		3
Interactions		
%NW Glazing × Total of Glazing Class Values		
%NE Glazing × Total of Glazing Class Values		
%SW Glazing × Total of Glazing Class Values		
%SE Glazing × Total of Glazing Class Values		

Table 7 summarizes the marginal effects of each of the solar shading variables selected into the model. Given the relatively small sample size and exploratory nature of this solar shading analysis, the team advises a more qualitative interpretation of the numbers in Table 7. For the sake of clarity, however, the values in Table 7 should be interpreted as follows: Holding all other variables in the model constant, for every 10% increase in %NW glazing, there is an expected increase in HOU of 0.31 hours (or about 19 minutes per day). Similarly, holding all other variables in the model constant, for a 10% increase in %SE glazing there is an expected decrease in HOU of 0.14 hours (or about 8 minutes per day). More qualitatively, however, the general trend seen in Table 7 is that sites with a high proportion of their glazing facing the NE and SE have slightly lower HOU, while sites with a high proportion of glazing facing the NW and SW appear to have a slightly higher HOU. Naturally, the team does not believe that an increase in NW or SW glazing is itself a cause of higher lighting usage; intuitively speaking, any increase in glazing should allow more ambient light in the home, however minimal, and result in less of a need to use artificial light. Rather, the observed relationship is likely because an increase in NW or SW glazing is associated with a *decrease* in NE and SE glazing, as these variables are negatively correlated (see Table 8), and households in Manhattan appear to benefit more from easterly glazing than they do from westerly glazing. Evaluators speculate that this could be due to people being home more during the first few hours of daylight (before leaving for work/school) than they are during the last few hours of daylight (after school/work) and are thus able to benefit more from ambient light coming into the home from easterly windows than from westerly windows. This would be particularly true in the winter months, when the sun sets roughly around the time (and in many cases before) people would be arriving home from work. However, given the data available for this study, this is not a hypothesis evaluators were readily able to test.

Additionally, and as expected, the binned sum of class values variable also proved to be quite informative. Consider a site with a binned sum of class values equal to one. As described briefly above, this means that particular site has a small percentage of glazing wall area, a small percentage of southerly glazing wall area, and a small amount of solar exposure. Unsurprisingly, the model suggests that such a home would have a higher HOU than a site with a binned sum of class values equal to two or three. On the other end of the spectrum, a residence with a binned sum of class values equal to three would have a large percentage of glazing wall area, a large percentage of southerly glazing wall area, and a large amount of solar exposure; the model suggests that these homes have a significantly lower HOU than homes with a value of one or two for this variable. Formally, the results in Table 7 say that holding all other variables in the model constant, sites in Level 2 of the binned sum of glazing class variable would have 0.6 HOU less than sites in Level 1, while sites in Level 3 would have 2.3 HOU less than those in Level 1. Again, while these are the formal interpretations of the values below, the team advises the more qualitative interpretation, given the nature of the study—specifically, that HOU tends to decrease as glazing and insolation increase together.

Table 7: Marginal Effects of Solar Predictors from Regression Analysis

Variable	Level	Coefficient	Std Error	p-value
%NW Glazing		0.031	0.011	0.006
%NE Glazing		-0.018	0.015	0.232
%SW Glazing		0.018	0.012	0.135
%SE Glazing		-0.014	0.010	0.180
Total of Glazing Class Values	1	--	--	--
	2	-0.569	0.819	0.488
	3	-2.285	1.054	0.030

Table 8: Correlations Between Occurance of Easterly and Westerly Facing Windows

	Northwest Facing	Southwest Facing
Northeast Facing	-0.29	-0.47
Southeast Facing	-0.19	-0.18

Sensitivity Analysis

To examine the effect of forcing our model to contain the same household-level and logger-level explanatory variables from the Northeast Residential Lighting report, the team also performed the stepwise procedure across *all* explanatory variables—both solar-specific and non-solar-specific variables. In doing so, the team found that the model with the lowest AIC additionally excluded the Income and Own/Rent variables from the model.

The results from this model, however, are nearly identical to those seen in the previous approach. The marginal effects of the solar shading variables in this model are presented in Table 9:.

Table 9: Marginal Effects of Solar Predictors from Updated Approach

Variable	Level	Coefficient	Std Error	p-value
%NW Glazing		0.029	0.011	0.006
%NE Glazing		-0.013	0.013	0.324
%SW Glazing		0.018	0.012	0.139
%SE Glazing		-0.014	0.010	0.182
Total of Glazing Class Values	1	--	--	--
	2	-0.617	0.772	0.424
	3	-2.090	0.932	0.025

Again, increases in easterly glazing tend to result in lower operating hours, whereas increases in westerly glazing have the opposite effect—likely because increased westerly glazing is associated with having less easterly glazing. Similarly, as glazing and insolation increase together, as measured by the binned sum of class values variable, lighting usage decreases, since more ambient light is able to enter into the home.

Conclusions

Based this exploratory analysis, it is apparent that the direction of glazing and insolation/amount of glazing play a role in lighting usage in Manhattan high-rises. The effects, however, were modest and likely do not fully explain the differences found between usage in Downstate New York/Manhattan and the rest of the Northeast region (discussed in detail in the full Northeast Residential Lighting Study). In addition, based on research conducted after the study, the authors suspect that the number of occupants is a strong predictor of hours of use, but these data were not collected as part of this study. To make a fair comparison, future studies should incorporate occupant counts and solar data for all sub-regions participating in all areas of study in order to compare the effect of solar shading variables between high-rise and non-high-rise households.

At a broader level, it is intuitive that the amount of natural light available in a home will affect the occupants' use of electric lighting during daylight hours. This method was an initial attempt to quantify the natural light available to high-rise buildings and to measure its effects on HOU. This method could be applied in non-high-rise structures as well, though the effects are likely more pronounced and predictable in areas with the regular pattern of "urban canyons" found in Manhattan. Administrators of energy efficiency programs in densely-populated urban areas should consider incorporating these factors and their effects on HOU in program design and planning.

References

Akaike, H. 1974. "A New Look at the Statistical Model Identification." IEEE Transactions on Automatic Control 6: 716-723.

Buckley, Cara. 2013. "In the Shadow of Rising Towers, Laments of Lost Sunlight in New York." *The New York Times*. December 19.

NMR. 2014. *Northeast Residential Lighting Study*. Prepared for Sponsors in Connecticut, Massachusetts, New York, and Rhode Island.