California Lighting Model

Erik Kolderup, Eley Associates, San Francisco, CA
Charles Eley, Eley Associates, San Francisco, CA
Lisa Heschong, Heschong Mahone Group, Sacramento, CA

ABSTRACT

This paper describes a model used to evaluate the long term electric energy savings and demand reductions from potential policy scenarios directed toward residential and commercial lighting in California. At the core of the model are estimates of base case lighting characteristics, market shares and energy use patterns in California, broken down by building type, space type, and lighting application. These basecase data were developed from end-use surveys of more than 700 homes and 50 million ft^2 of commercial (nonresidential) space.

The model uses a relational database which is organized by building type, space type, and lighting applications within spaces. Lamp, ballast and control technologies are linked to the lighting applications. The model is built around the concept of market shares, e.g. if porch lighting is a residential application, the market for this application could be split between incandescent, compact fluorescent, etc. Potential policy scenarios are characterized through their ability to shift market shares over time. The model projects energy use and electric demand over a 15 year period, based on current building stock as well as projections of future construction, demolition and renovation. The model estimates macro impacts for the state as a whole as well as average per dwelling unit impact for housing and per square foot impact for nonresidential buildings.

Introduction

The California Lighting Model (CLM) was developed in response to California Senate Bill 639 which required that the Energy Commission recommend ways to improve the efficiency of lighting in the state. The CLM is a tool to evaluate and compare alternative public policy options. For each policy option, the model can quantify lighting energy use by building type, space type, and lighting application. Estimates of statewide impact are developed by combining the per-building estimates with projections of building stock over a 15 year time period. The impact of changes in technologies, market penetration, and design practices can be estimated and applied to projected changes in new and existing building stocks. In examining public policy options, any of these parameters can be adjusted, and the resulting lighting energy use differences calculated.

The model is based on average values generated from a comprehensive survey of existing lighting characteristics and energy use, and of numbers and types of buildings. The CLM is built in Microsoft Access using a relational database structure. This structure allows the model to be efficiently manipulated to correspond to various policy scenarios, and so to calculate the energy demand differences between them. The structure of the model determines the analysis options and capabilities available for study.

There are actually two California Lighting Models: one for residential buildings and one for commercial buildings. The emphasis of this paper is on the residential model with only passing reference to the commercial model.

Residential Model

Data Sources

The structure of the models was strongly driven by the available data. The major source of residential data was an on-site survey of more than 16,000 fixtures in 683 California homes in southern California (Goett, 1993). In generating this data for Southern California Edison (SCE), a trained auditor spent about an hour in each home taking an inventory of all lighting fixtures inside and out. Furthermore, the occupants were interviewed about the hours of use for each fixture and their lamp purchasing habits.

Lighting hours of operation were monitored for a subset of the lighting sockets (Goett, 1993). Data were collected from about 360 hourly interval monitors for a period of 4 to 8 months from a sample of more than 2,600 residential fixtures. The time-of-use interval data was taken from five main residential room types: living room, kitchen/dining, hallways, bedrooms, and bathrooms. The SCE inventory and monitored data provided the most thorough and reliable description of the characteristics of residential lighting in California, and this data set was the primary source of information for the model.

A second source of data was a study in the Tacoma, Washington area (Tribwell, 1996). The local utility monitored 80% of the lighting fixtures in 161 homes for a total of 2,641 monitored fixtures. The lighting loggers monitored elapsed and total run time, but not time-of-use or interval data as in the SCE study; without interval data, it was not possible to generate hourly load shapes for lighting end-uses from this data. The Tacoma data was used primarily to compare self-reported hours of operation against monitored results and to evaluate geographic differences.

Database Structure

The general structure of the database is shown in Figure 1. The boxes represent the primary database tables. The lines represent links between the tables. These links are themselves database tables that contain multiple sets of relationships. The structure of this model was strongly driven by the available data.

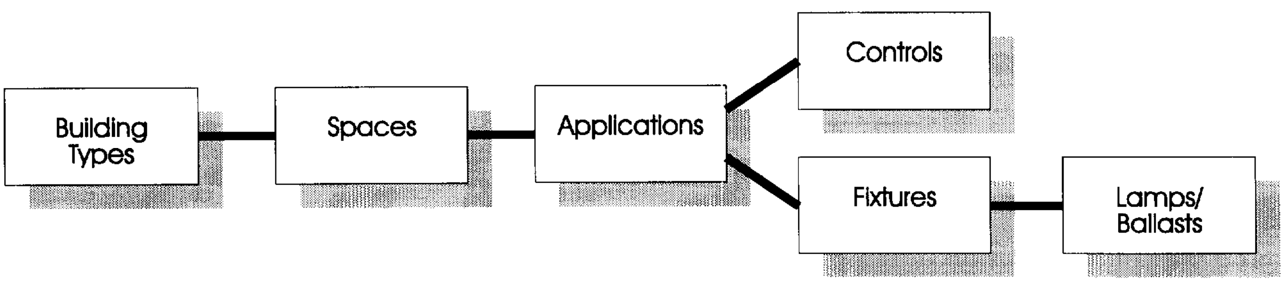

Figure 1. Database Structure - Residential Buildings

In the residential model, the *Building Types* table contains just two records: for single-family and multi-family dwellings. The *Spaces* table has nine records: bath, bedroom, den, hall, kitchen/dining, living, garage, utility, and yard. The surveyors found it difficult to distinguish between breakfast nooks, dining areas, and kitchens so these spaces were grouped into one category called Kitchen/Dining.

The *Applications* table has a record for each lighting application. In the residential model, 30 lighting applications were studied. A fixture type within a given room type was used to define an application. The survey data is divided between nine fixture types in nine room types. Without aggregation, this would yield a total of 81 lighting applications. The incidence of many of these was quite small, however, and were grouped into "Other, Indoor" and Other, Outdoor". This aggregation reduced the number of residential lighting applications to 30. The *Applications* table has key information that drives the model, including average lumen output and hours of operation.

Hours of operation were determined from the self-reported data in the SCE inventory (Goett 1993). These values were adjusted, however, to account for typical differences between self-reported data and monitored data. A correction factor was calculated for each residential space by comparing monitored and self-reported data. Data from both the SCE (Goett 1993) and Tacoma (Tribwell 1996) studies were used in determining the adjustments. Table 1 shows the average lighting hours for residential spaces. These average values are generated from data in the model which is more finely tabulated by lighting application.

Table 1. Average hours of Lighting Operation by Residential Space

Residential Space	*Hours/Day*
Bedroom	1.4
Bathroom	2.0
Den	2.0
Hall	2.2
Garage	2.3
Living	2.6
Utility	2.6
Yard	3.1
Kitchen/Dining	3.4

The *Controls* table has a record for each type of control. Example controls include dimmers, photocells, and motion detectors. The table has information on the effectiveness of the controls, expressed as a time correction factor (TCF). The self-reported data was not used to determine the time correction factors. Instead, monitored data from the Tacoma study was analyzed. The control multipliers shown in Table 2 are relative to a standard on/off switch which is assumed to have a TCF of 1.0. While some controls result in a reduction in lighting hours (TCF < 1.0), other controls result in significantly longer hours of operation. For instance, outdoor photocells increase hours of use by a factor of almost 4.0. The level of certainty with the TCF values is low, since the number of monitored automatic controls is quite small.

Table 2. Time Correction Factors for Residential Controls

Control Type	*Time Correction Factor (TCF)*
Motion Detector, indoor	0.46
3-Way Switch, low hours	0.57
Scheduler, yard	0.84
Dimmer	0.92
On-Off Switch (base)	**1.00**
Timer	1.10
Motion Detector, yard	1.14
3-Way Switch, high hours	1.25
Photo-sensor, indoor	2.37
Scheduler, indoor	2.61
Photo-sensor, outdoor	3.94

The *Fixtures* table has a record for each type of fixture. Examples include ceiling recessed cans and ceiling recessed troffers/coves. The *Lamps/Ballasts* table has a record for each unique lamp/ballast combination. The key information in the lamps table is the efficacy, expressed in lumens per watt. The efficacy data were developed by the research team based on a literature survey of performance data. These data were used to back-calculate the light lumens per application which is a key driver of the model.

The relationships between the primary tables are provided by link tables. To illustrate, consider the relationship between building types and spaces. A record would exist in the BldgType_Spaces links table for each connection between a building type and a space. In the residential model, the links table would have information about the number of each space type in the building type. For instance, single-family homes in California have an average of 2.64 bedrooms.

Algorithms

Once the model is populated with data, energy use may be calculated. The first step is to calculate the average watts per fixture (Wf), based on the lumen method. This is achieved with a simple equation that does not consider the coefficient of utilization or other factors

$$W_f = L_f \cdot \sum_{l=1}^{\text{NmbrLamps}} \frac{SL_{f,l}}{E_l}$$

where

W_f Average power (watts) for fixture "f".

$S_{f,l}$ Share of lamp/ballast "l" for fixture "f". The original equation assumes that this share is the ratio of watts provided by lamp/ballast "l" to the total watts provided by all lamp/ballasts associated with fixture "f".

E_l Efficacy of lamp/ballast "l". The units are lumens/watt.

L_f Average lumens for fixture "f". This information is stored in the fixtures table.

$SL_{f,l}$ Share of lumens produced within fixture "f" that are provided by lamp/ballast "l".

The average watts per application (Wa) is then calculated by multiplying the average watts per fixture times the share for that fixtures type.

$$W_a = \sum_{f=1}^{NmbrFixtures} S_{a,f} \cdot W_f$$

where

W_a Average watts for application "a".

$S_{a,f}$ Share of fixture "f" that meets the needs of application "a:. All the shares for a particular application sum to one. The equation assumes that these shares are the ratio of watts of fixture "f" to the total watts for application "a".

The annual energy use for each application is then calculated by multiplying the average watts per application times the operating hours for the application. This is adjusted by an average energy control factor for the application (shown in the equation below as a separate summation).

$$kWh_a = \frac{W_a \cdot H_a \cdot 365 \cdot \sum_{c=1}^{NmbrControls} \left(S_{a,c} \cdot ECF_c\right)}{1000}$$

where

kWh_a Annual electricity use (kWh/y) for application "a".

H_a Daily hours of use for lighting application "a". This is stored in the applications table.

$S_{a,c}$ Share of control type "c" for application "a". The equation assumes that this is a share of lighting power. This is stored in the links table between applications and controls.

ECF_c Energy control factor for control type "c". This is stored in the controls table, which means that it is the same for all applications.

Once the power and energy use for each application is known, it is very straightforward to calculate the power and energy use for each space and building type.

	Power (W)	Energy (kWh)
Space Calculations	$W_s = \sum_{a=1}^{NmbrApplications} S_{s,a} \cdot W_a$	$kWh_s = \sum_{a=1}^{NmbrApplications} S_{s,a} \cdot kWh_a$
Building Calculations	$W_b = \sum_{s=1}^{NmbrSpaces} S_{b,s} \cdot W_s$	$kWh_b = \sum_{s=1}^{NmbrSpaces} S_{b,s} \cdot kWh_s$

where

W_s Electric power for space "s" in watts.

kWh_s Electric energy for space "s" in kWh/year per space.

W_b Electric power for space "b" in watts.

kWh_b Electric energy for space "b" in kWh/year per dwelling unit or household.

$S_{s,a}$ Number of applications of type "a" in space "s". This is stored in the links table between spaces and applications. These shares may sum to a number greater than one.

$S_{b,a}$ Number of spaces of type "s" in building "b". This is stored in the links table between buildings and spaces. These shares may sum to a number greater than one.

The residential model yields power (W) and energy (kWh/y) values per dwelling unit. The model then produces Statewide projections by multiplying these per dwelling unit or per square foot values times projections of residential dwelling units in California. These projections are contained in the *Forecasts* table for each building type and for a 15 year time horizon. This information is combined with projections of electricity costs to produce estimates of annual energy costs for lighting. The model has the capability of tabulating results separately for different utility service territories, but this feature was not used. The model has the capability to consider changes in the allocation of room types and fixture types over time, but this capability was not used for lack of data.

Calibration

Lighting energy use predicted by the basecase model was compared to other data sources. According to the model, the average residential dwelling unit in California uses 1,704 kWh/y-du for lighting[1]. These compare favorably with the Tacoma study, which found an average of 1,818 kWh/y-du. A more direct analysis of the SCE data (eliminating the averaging necessary for the model), yielded an estimate of 1,726 kWh/y-du.

Commercial Model

The commercial buildings model is similar in concept to the residential model but has several important differences. These are:

- Projections of building stock are expressed in square feet instead of number of dwelling units.
- The primary tables in the model are different, reflecting differences in available data.
- The constant in the commercial model is lumens/ft^2 of light output at the space level, as opposed to lumens/application in the residential model.
- Lighting controls are assessed in terms of both a power reduction factor and a time reduction factor since many commercial building controls result in reduced power, e.g. lumen maintenance.
- With the residential model, a building type can have more than one of each space type, while with the commercial model, the space shares must equal one.

The primary tables in the commercial building model are shown as boxes (see Figure 2). The relationships between the primary tables are shown as lines and embodied as links tables, similar to the residential model.

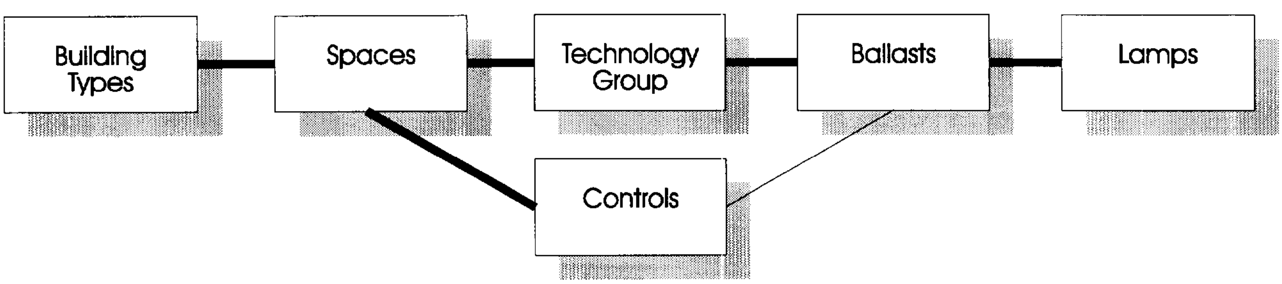

Figure 2. Database Structure - Commercial Buildings

[1] The estimate for single-family homes is 2076 kWh/y-du while the estimate for multi-family housing is 1084 kWh/y-du (du = dwelling unit).

Scenarios

A scenario is an alternative future that would result from some type of intervention in the marketplace. The intervention could take many forms, from the implementation of codes or standards, to public awareness campaigns or the development and introduction of new technologies. Each policy scenario can be characterized as a change or shift from one technology or product to another. This change can occur all at once, but more commonly there would be a penetration rate. Several common penetration rates were used in the development of the policy scenarios (See Figure 3).

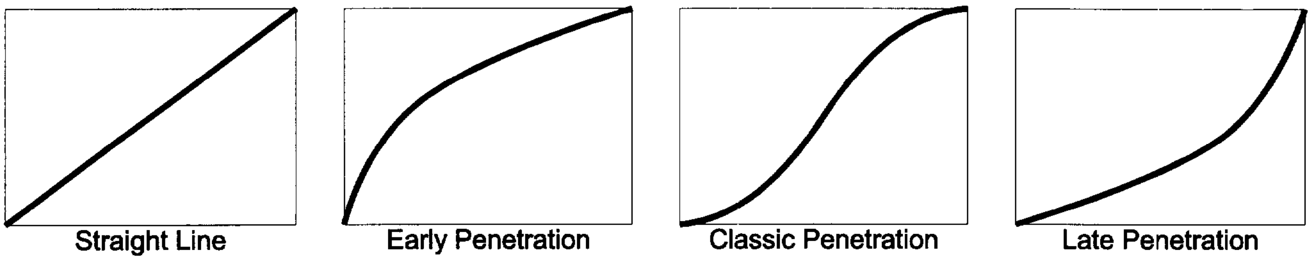

Figure 3. Penetration Curves

In the CLM, a scenario is characterized as a set of market shares for different years in the future. For simplicity, the shares were typically set for 1995 and 2010 and one of the penetration curves (see Figure 3) was used to set the shares for the intermediate years.

Process of Developing Scenarios

The process of developing the scenarios involved several (sometimes iterative) steps. The first step was to develop an idea for a public policy, for instance, improving the knowledge of lighting designers through training programs. A short written description of the policy was developed, and then the team would estimate the impact of the scenario by describing how market shares would shift. The shift in market shares was first described in simple words and then more precisely described using a set of pseudo code (see Table 3). This pseudo code was then used to create a new scenario.

The model is intended to be used by technical staff and programmers that are familiar with the underlying concepts and principles. It is not an end-use application that can be used widely by anyone in the industry (like a spreadsheet program). Once a scenario was described in words and in pseudo code, the process to create a new scenario would begin, using the following steps.

- Create a new scenario based on an existing scenario. A form was created for this purpose. The new scenario begins its life as a clone of an existing scenario (the basecase is a scenario, too).
- The newly created scenario is then modified with the different assumptions about the future that are expected if the proposed policy were implemented. A form (see Figure 5) was developed to assist. This form can be used to implement the pseudo code statements in Table 3.
- Typically, the previous step would be done for the year 2010. The form shown in Figure 6 would then be used to interpolate the intermediate years based on one of the penetration curves.
- The above process would be repeated for each shift in market shares until all the necessary adjustments are made.

- The form shown in Figure 4 may be used to develop more complex scenarios. With this editor, the user is not limited to shifts in market share that can be described with the pseudo code. Just about any change in market share can be accommodated.

Once a scenario is created, it can be compared to the basecase or to another scenario to obtain the impact over the 15 year study period. This impact data was reviewed by the project managers at the CEC, key members of the LEAGue advisory committee and other interested individuals. Comments from the group were then used to make refinements and adjustments to the scenarios. Another paper in these proceedings describes this process in more detail (Heschong 1998).

Table 3. Pseudo Code for Specifying Scenarios

Example Command	*Result*
INCREASE < Fluorescent, 1-19 W > BY <50%> IN <Lamps_Ballasts> FOR <2005>	The penetration of fluorescent lamps (<19 W) will be increased to 50% of saturation for the year 2005. All other shares will be reduced proportionally so that the sum for each fixture equals unity.
REDUCE < Incandescent 51-100W> BY <25%> IN <Lamps_Ballasts> FOR <2010>	The penetration of incandescent lamps between 51 W and 100 W will be reduced 25% of the way to zero for the year 2010. All other shares will be increased proportionally so that the sum for each fixture equals unity.
INTERPOLATE_ BETWEEN <1995> AND <2010> STEP <5> FIT <STRAIGHT_LINE> IN <Lamps_Ballasts>	Shares for 2000 and 2005 will be created to represent mid points between 1995 and 2010. This will be applied to all

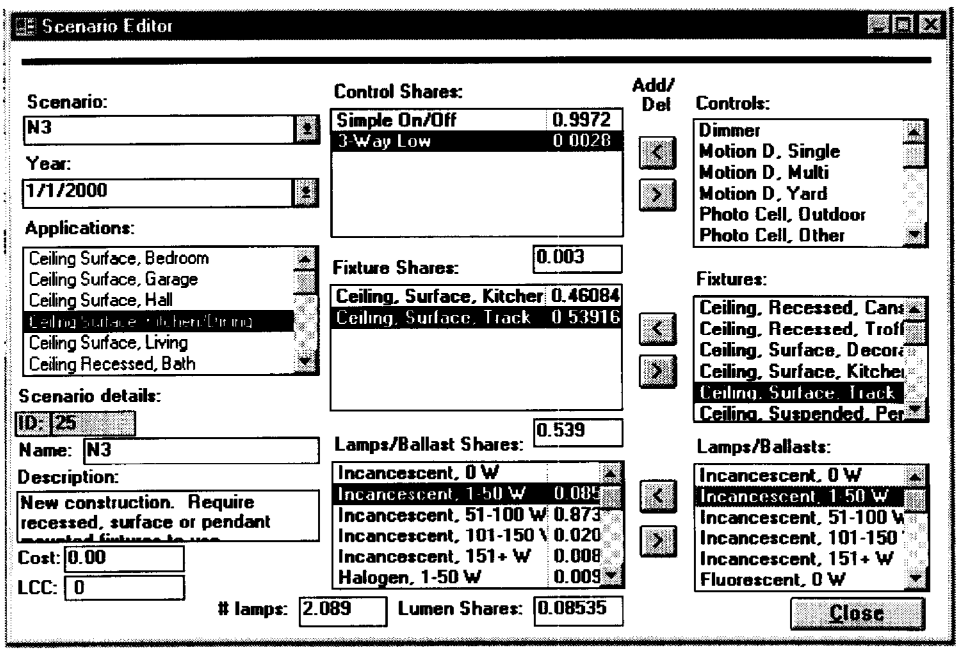

Figure 4. Scenario Editor

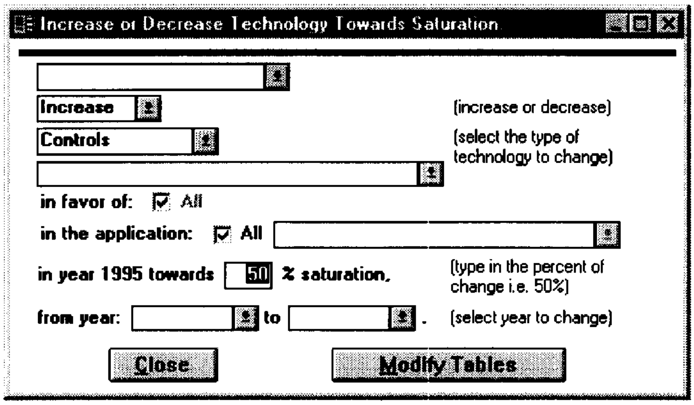

Figure 5. Increasing/Decreasing Shares Towards Saturation

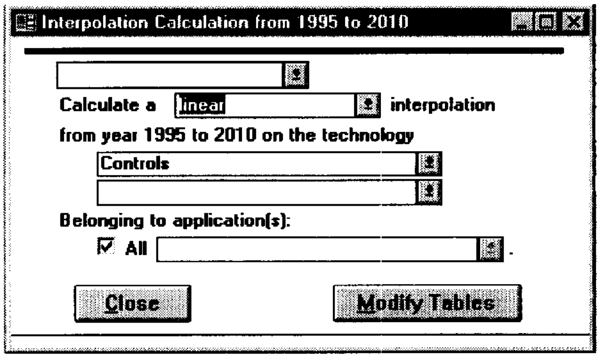

Figure 6. Applying Penetration Curves

Results

The following paragraphs provide a brief description of the residential scenarios that were analyzed. The scenarios that apply only to new construction are identified with an "N" while those that apply to the total stock are identified with a "T".

Table 4. Residential Scenarios

N1 Outdoor Lighting Efficacy	Wall and ceiling mounted outdoor fixtures gradually change from incandescent to compact fluorescent sources.
N2 Outdoor Induction Lamps and Controls	This is a more aggressive version of the previous scenario. In this scenario, all wall, ceiling and lantern mounted outdoor fixtures change from incandescent to electrodeless fluorescent (induction) lamps, which have advantages for outdoor applications over compact fluorescents.
N3 CFL Ceiling Fixtures	This scenario assumes that all indoor ceiling mounted fixtures throughout the house are installed with fluorescent lamps, except for fixtures with large incandescents (150+W), which are converted to halogen lamps, and chandeliers, which are not affected. An early penetration is assumed.
N4 Fluorescent Kitchen Fixtures	This scenario calculates the savings potential of expansion and increased enforcement of the Title 24 requirement for fluorescent fixtures in kitchens.
N5 Fluorescent Bathroom Vanity Fixtures	This scenario assumes that all bathroom vanity fixtures shift from incandescent to fluorescent sources, with a late penetration curve.
N6 Fluorescent Garage and Utility Fixtures	This scenario assumes that all garage and utility room fixtures are either required to be of fluorescent efficacy or greater, or to have an automatic control.

Table 4. Residential Scenarios (continued)

T1 Outdoor Lighting Efficacy and Controls	This scenario assumes that 50% of the incandescent lumens in outdoor wall and ceiling fixtures are converted to compact fluorescents.
T2 CFL Lamps in Torchiers	This scenario assumes that torchiers lamps (defined as floor lamps which have tungsten halogen or incandescent bulbs greater than 150 watts) are replaced with compact fluorescent lamps, a more efficacious source.
T3 CFL Lamps in Torchiers, Floor and Table Lamps	This scenario builds on the previous one which replaced compact fluorescent lamps in most torchiers, and further assumes that 80% of the lumens in all table and floor lamps, except for task lamps and small table lamps (which generally have shorter hours of operation), are converted to compact fluorescents from incandescent.
T4 Time Limiting Controls	This scenario assumes that 80% of all on/off switches on hard-wired fixture types (i.e., all except floor and table lamps) are replaced with time limiting controls which automatically turn off unneeded lights.
T6 CFL lamps in all Applications	This scenario assumes that 75% of all incandescent lumens, in all fixture types, are converted to fluorescent sources, following a late penetration curve.
T7b Replace Floor and Table Lamps with Torchiers	This scenario assumes that the popularity of torchiers continues to increase, resulting in twice as much wattage for floor lamps in bedrooms and living rooms. Given the high wattage of current torchier lamps over standard incandescent floor or table lamps (300-500 watts vs. 75-150 watts), this seems an appropriate and even conservative assumption. This scenario attempts to quantify what is viewed by some as a disturbing trend in residential lighting purchases by homeowners.
T8 Replace Long Burning Incandescent Lamps with Tungsten Halogen Infrared Technology	This scenario assumes that lamps in those fixtures which are on for more than 3 hours per day are replaced with an improved tungsten halogen lamp with an efficacy of 22 lumens per watt.
T9 Replace Long Burning Incandescent Lamps with CFLs	This scenario follows the same format as T8 above, but instead replaces long-burning incandescents with compact fluorescents (CFLs) instead of tungsten halogen IR lamps.
N1, N4 & N5: T-24 Standards for Kitchens, Bathrooms and Outdoor Lighting	This scenario assumes fluorescent lighting for most kitchen ceiling fixtures and bathroom vanity fixtures, and 50% of outdoor fixtures using fluorescent sources by changing the requirements and enforcement for Title 24 standards for residential new construction. It models the energy impacts of a more rigorous interpretation of current Title 24 standards for kitchens and bathrooms, and 50% of outdoor fixtures using fluorescent sources.
N1, N3, N4, & N5: T-24 Standards for all NEC Required Fixtures	This scenario is very similar to the one above, except that it models the energy impacts of having all residential fixtures required by the National Electric Code (NEC) be required to use efficient sources.
T1 & T2: Appliance Standards for Portable and Outdoor Lighting	This scenario looks at the impact of instituting appliance standards for both portable lighting fixtures and outdoor lighting fixtures for the residential market.

Conclusions

Interventions which effect the entire residential market, such as marketing campaigns or appliance standards, have a vastly greater impact than approaches that only effect residential new construction, such as Title 24 energy standards requirements. While the new construction residential scenarios have the ability to save from approximately 0.5% to 1.5% of current residential lighting energy use, the "all building" residential scenarios have the potential to effect from 7% to 21% of current residential lighting energy use, or about a 14 times larger impact.

Residential lighting in general is operated for very few hours per day. In order to achieve significant and cost effective savings, residential lighting efficiency programs should either target those lighting fixtures which operate for the longest hours, or where there are the greatest number of inefficient fixtures.

Outdoor lighting meets both of these criteria. Outdoor lighting efficiency measures show the greatest savings for the residential new construction approaches considered in this study, and almost ten times those savings when applied to all homes.

Targeting residential lighting fixtures which operate for three or more hours per day for replacement with more efficient light sources shows even greater potential savings. Placing tungsten halogen infrared lamps in these fixtures can save about 12% of current residential lighting energy use, while using compact fluorescent lamps in these fixtures has the potential to save 21%.

Targeting table lamps and floor lamps for replacement with more efficient sources also has considerable impact, since there is such a huge number of these fixtures. Automatic controls which can eliminate unnecessary hours of operation also have the potential to save considerable residential energy. It is also clear that current trends in increased energy use for lighting in residences, such as the increased use of powerful halogen torchiers, could significantly reduce any gains from an aggressive lighting efficiency program, and could completely cancel any gains from a modest program.

Potential energy savings from the "all building" residential scenarios are on a par with those considered for commercial buildings. This similarity in energy savings potential exists in spite of the fact that commercial lighting hours of operation are 4 times longer than residential. The similarity in savings exists primarily because the residential sector is so large, with 3 times as much installed wattage as the commercial sector, and because residential lighting currently uses much less efficient sources than commercial, and so there is much greater potential for savings from efficiency improvements.

The model proved to be very useful in meeting the needs of the Energy Commission. The model could also easily be adapted for other geographic areas and/or purposes, provided data is available to make adjustments. The tools used to create the scenarios could also be used to adjust the underlying data for different jurisdictions.

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