Solid State Lighting in Residential Buildings

Kevin Willmorth, Lumenique, LLC
Victor Zaderej, Molex Inc.
William Miller, Oak Ridge National Laboratory

ABSTRACT

Reducing energy-use in our homes and businesses is the single largest opportunity for reducing loads placed on existing power production infrastructures, as well as reducing overall dependence on non-renewable and environmentally hazardous energy resources. To realize these potential gains, we have addressed energy-use through optimizing design features and adopting new technologies that more efficiently create desired results with less energy.

In the United States, commercial lighting accounts for 20% of all energy and 38% of electrical energy consumption.(Energy Information Administration 2003) Currently, commercial lighting system efficacies average 60 lm/W (lumens per watt). This translates to a conversion-efficiency (electrical energy into useable light) of roughly 15%. Current and near term improvements are expected to improve average luminaire efficacies to 85 lm/W producing a reduction of energy consumed for commercial lighting of 29% .

In a 2001 survey of residential energy use by the US Energy Information Administrtation, lighting represented 8.8% of all electrical power consumption (Energy Information Administration 2001). However, residential lighting is inefficient, depending on obsolete incandescent sources and low efficiency fluorescent lighting producing efficacies of less than 15 lm/W and conversion efficiencies of no more than 3.8%. Because of this, residential structures consume nearly five times the energy for the light delivered than commercial buildings. Bringing efficiencies of residential lighting to the current commercial level of 60 lm/W would result in a 75% reduction of energy consumption used for residential lighting.

Schaad LLC, the TVA, the Department of Energy, and Oak Ridge National Laboratories have joined forces under the Zero Energy Building Research Alliance to build and field test two pairs of energy saver homes. Several building envelope types, space conditioning methods, and lighting technologies will be evaluated over a two-year period.

One home of an identical pair is entirely lit using Solid State Lighting (SSL) provided by Molex Inc. of Lisle, IL and designed by Lumenique of Germantown, WI. The lighting in this home will be compared to the lighting in a “sister” home which was fitted with compact fluorescent lights (CFL). Factors such as energy use, lighting quality, and maintenance requirements will be evaluated over the two year period.

Initially, the home will be lit with fixtures that utilize a unique AC LED produced by Seoul Semiconductor that does not utilize electronics to convert the AC line voltage into DC as do most other SSL devices. As the technology for Solid State Lighting improves during the two-year period, the home’s lighting will be updated so that additional data can be collected on its performance and quality.

Information collected from this evaluation will be used to help builders, lighting designers, and home owners to make their lighting decisions based on actual data. The desired result of this evaluation will be to expedite the energy saving implementation of Solid State Lighting into our work places and homes.

Introduction

This paper describes an approach to incorporating a combination of lighting design and advanced LED technology in an effort to optimize energy-use for illumination in a subject home. The subject home is constructed by the ZEBRAlliance, and includes all areas of building technologies and the composite impacts on energy-use for residential structures.

The subject home is included in the construction of four evaluation homes started in 2008 and completed in early 2010. The homes were constructed by Schaad Companies, the Alliance private sector partner who specializes in commercial construction, residential and commercial real estate development, and property management. After the construction of the homes is finished, ORNL and TVA researchers will collect data and make adjustments to the houses' components in order to achieve the optimal quality and efficiency of the homes. These four research homes are expected to be the first to use several newly emerging products such as the Climate Master ground-source integrated heat pump and residential Solid State Lighting products produced by Molex Inc. of Lisle, Illinois. If these new components successfully demonstrate their energy saving capabilities and perform as expected, they will promoted to builders, developers, architects, and homeowners as good options to reduce energy demand.

This paper describes the approach taken in one of the four homes, including lighting design that incorporates LED technology, and design approaches that further reduce energy-use through eliminating unnecessary and undesirable illumination.

ZEBRAlliance - Background

The Zero Energy Building Research Alliance or ZEBRAlliance (ZEBRAlliance 2010) is both a research project and a residential efficiency education campaign. The members of the Alliance consist of Schaad Companies, Tennessee Valley Authority (TVA), Oak Ridge National Laboratory (ORNL), BarberMcMurry Architects, and the Department of Energy. ZEBRAlliance will integrate the components of ORNL's energy-efficient technologies into the construction of the homes to be used as test markets to gauge the integral success and affordability of the components and the houses. Through the focused efforts of the Alliance members, new energy-efficient components will be tested in order to provide homeowners with information on how to buy the best energy-efficient technologies for their homes.

The Emergence of Solid State Lighting

Solid-state lighting technology is founded on the discovery of semiconductor materials capable of producing photons (light) from the movement of electrons from one state to another. LEDs generate a narrow band of light energy depending on the materials used to create the semiconductor die within an LED. The earliest LEDs emerged in 1962 (Schubert 2003, 9), producing red light used for indicator lighting and electronic displays. In 1993, Sangi Nakamura developed the first bright blue Indium Galium Nitride LED source (Schubert 2003, 15). This source, when covered with phosphors that convert blue to white light, form the foundation of white light solid-state light sources used in general illumination.

Theoretically, if 100% of all electrical energy consumed by a light source were converted to visible light, 683 lm/W could be achieved (Ohno 2004, 89). However, in practical application an assumed optimum conversion efficiency of 50% is accepted as a benchmark, or 340 lm/W.

Conventional fluorescent lamp technology has attained a level of 105 lm/W in white light. 160 lm/W has been achieved in limited spectral distribution sources such as Low Pressure Sodium. Incandescent sources produce light by heating an element, or a filament, until it generates visible light. This technology achieves an efficacy of 15 lm/W, converting just 3% of its energy to light with the remaining 97% emitted as heat.

Development efforts in LED sources produced rapid improvements in color and intensity. By 2006, a wide range of LED sources became available that eclipsed incandescent lamp efficacy and are equal to compact fluorescent lamp efficacies. Current technology LEDs achieve efficacies of 85 to 135lm/W, and are expected to reach 180lm/W by FY2014 (DOE 2010)

. As LED light output increases, more applications become potential targets for adoption. Initially, low-level lighting effects, accent lighting, display, automotive and task lighting became early application markets. In time, this expanded to exterior area and roadway lighting, and parking garages. Most recently, improvements in the technology have made it practical for consideration in general interior illumination.

Advantages of LED Sources in Residential Application

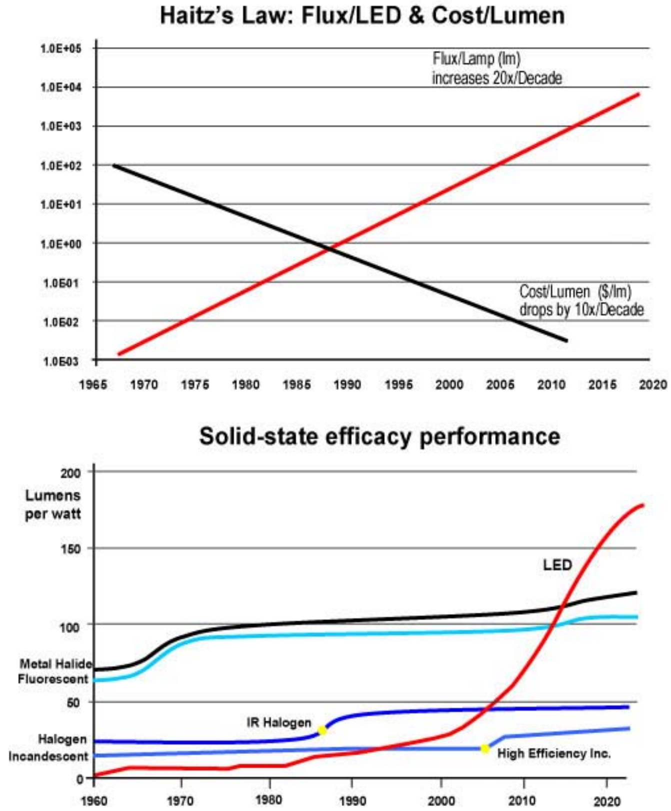
In residential applications, incandescent lighting is preferred for its low initial cost, ease of maintenance, and lighting qualities – regardless of the energy consumed. While CFLs have been deployed for over 30 years, issues of poor color quality, shorter than expected life, lack of control, long start up time, mercury content, and cost combine to make it a less than desirable choice.

LED technology does not suffer the liabilities of mercury content, which is a serious issue in the residential market, where failed lamps are generally disposed of in regular trash. LEDs also offer usable life seven times that of the highest quality CFL source, and produce more desirable color qualities. LEDs are more optically controllable, offering greater application efficiencies. LED products are instant-on devices, reaching full light output in seconds. Further, compared to a typical incandescent lamp, LEDs generate more than five times the light for each watt consumed, producing an energy savings of 75% to 80%.

A typical high-quality LED light source suitable for residential application will provide between 35,000 and 60,000 hours of service life. With the average lamp in a home being used for less than 1000 hours per year (Tribwell & Lerman 1996), the life of an LED light source will be between 44 and 75 years, or more than 18 to 30 times the life of an incandescent lamp. Additionally, unlike fluorescent lamps, LEDs do not suffer any loss of life or performance from frequent switching.

Compared to other household expenses the cost of energy used for lighting is small and hidden within electrical costs. Because of this, the largest liability of LEDs is their initial cost. Based on a simple one-for-one replacement from incandescent to LED, payback periods are very long. Further, residential customers are not trained to evaluate investment returns in meaningful terms. However, the cost of LEDs and supporting hardware are dropping rapidly. LED technology is expected to reach an acceptable price for the residential market within the next three years.

Figure 1. Comparison of LED Performance Improvements and Capability vs. Conventional Sources



The continued combination of efficiency gains and cost reductions for light produced is rapidly improving the suitability of LEDs as a preferred light source against existing lighting technologies. Compared to conventional sources, LED technology has or will soon surpass all other commercially available light sources.

Lighting in the Home

Lighting of single family homes and small multi-family residences has evolved over time. Additions of down and accent lighting has steadily increased the use of energy. Because of this, addressing only the sources applied, and not the design of the illumination system will only result in incremental gains. Due to the potential of LED technology to enhance lighting effect, including addition of color, uses in furniture, cabinetry and architectural features, it is possible that energy gains may ultimately be consumed by additional lighting effects and features.

Employing Human Perception and Enhanced Visual Interest to Reduce Energy Use

Human visual perception includes factors of illuminance, contrast (highlight and shadow), and focus. The most efficient approach is one that seeks to attain the highest level of perception and function, with the least amount of energy possible. This reductive approach eliminates energy-use by lighting that is not necessary to the function of the spaces involved.

Luminaire manufacturers can produce high efficiency numbers by producing light in an uncontrolled manner. The result is a lighting system with high individual luminaire efficacies that waste energy illuminating surfaces in excess of that needed to support good vision and an attractive space. The result is a high objective performance, with very low subjective qualities.

The use of drama and shadow – or the application of darkness using directional light control is an effective method of enhancing perception, while simultaneously reducing energy consumed. Residential spaces can be easily defined by function (kitchen, dining, etc..) facilitating specific approaches to each. For example, living and entertainment areas require very little general illumination. Television screens self illuminate, requiring only minor surrounding wall surface illuminance to support viewing quality, while occasional reading tasks can be accommodated by portable task lights - eliminating the need for filling the whole space with light. Conversely, kitchens require greater illuminance levels on both horizontal and vertical surfaces best accommodated with a combination of under-cabinet illumination for counter tasks, while cabinet and general illumination from overhead.

Figure 2. Comparison of Illumination Design Approaches

An "efficient" design on the left uses (6) 12W "high efficiency" luminaires rated at 52 lm/W to produce an average of 12 footcandles (Fc), using 72 Watts. The space looks flat, with very little focus. The space on the right uses (10) less efficient 39lm/W sources consuming 4W. The result is lower average illuminance (5Fc) but provides greater definition of the space, reinforcing vision within the 3D space, while reducing energy consumption by 48%

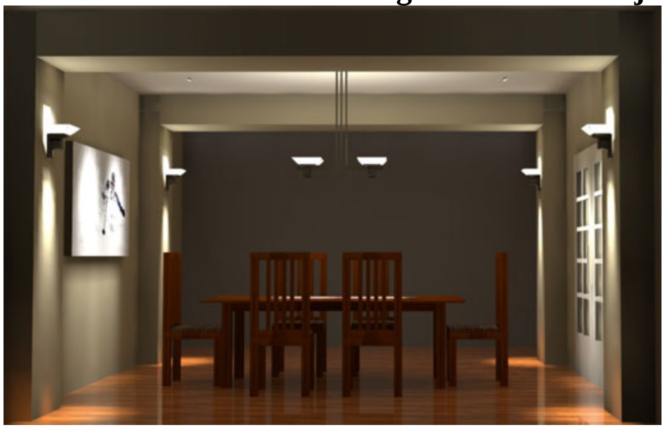
Figure 3. Test Applications Applying LEDs for Enhanced Presence and Efficiency

In Figure 3 below, the application on the left, the original lighting system used Halogen PAR consuming 305 Watts. An LED update illuminates the hall and stairs with accent and drama and reduced energy consumption by 86%. In the application on the right, conversion of halogen lamps to LED sources with the addition of wall accent lighting reduced the total energy used over the halogen pendant by 82%.

Figure 4. Test Application in a Living Room Applying LEDs for Enhanced Presence and Efficiency

This living space utilizes just (7) 5W LED lamps for wall and table illumination, with the addition of (2) 7W LED accent lights for visual interest. The total energy to illuminate this 250 s.f. space with dramatic impact and interest is 49 watts - less than 0.2 Watts per square foot.

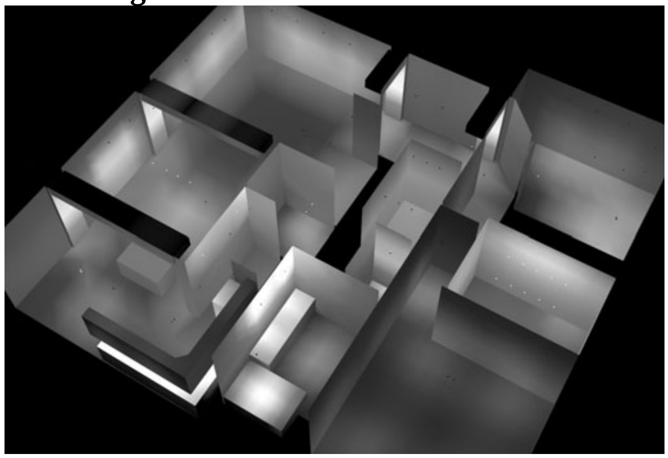
Figure 5. Rendered Results for Dining Area of the Subject Home



A rendering created using lighting evaluation software demonstrates the effect of the proposed design approach on the ZEBRA dining room, and illustrates the application of focused applied lighting to create visual impact with minimal energy use. This 195 s.f. space is illuminated using (22) 4.5W LED sources for an applied 0.5 Watts per square foot.

Since the goal is to establish the minimum use of energy through application of light on target surfaces, generalized watts-per-square-foot budgets become irrelevant and misleading. In order to develop a lighting scheme using this approach with unfamiliar new sources or technology, the use of computer modeling software is often necessary.

Figure 6. Rendered Brightness Patterns of Lower Level of the Subject Home



A rendering generated using AGI32 lighting calculation software accurately depicts brightness patterns. This type of simulation makes it possible to better visualize the lighting effect. Additional use of lighting software to evaluate light levels on horizontal and vertical surfaces provided information necessary to develop a lighting system that optimizes energy use with little or no waste.

Applicable Standards

Power density limits for single family residential lighting have not been widely applied. Lighting codes for residential occupancies are focused primarily on mandating the use of energy efficient sources.

Both ASHRAE 90.1 2008 – Multi-Family Residential 0.7 W/s.f. and IECC 2009 – Multi-Family Residential 0.7 W/s.f. power density allowances address the non-residential portions of these structures. ASHRAE includes a budget of 2.0 watts per square foot for residential spaces, assuming that lighting use (duty cycle) reduces this significantly. The NEC assumes a load of 3.0 W/s.f. for single and two family dwellings, also assuming that lighting use is a portion of this due to demand factoring.

Minimum light level requirements offered by the IES in Recommended Practice RP-11 for interior living space were used in the design of the lighting system for this home to establish minimum recommended illuminance levels for the specific rooms and areas as follows:

Table 1. Minimum Recommended Illuminance Levels by IES RP-11

Room/Area	Min Fc Recommended	Calculated Fc Applied	Note
Living spaces	5	3	Does not include portable
Dining Room	10	10	27+Fc at table surface
Office	20	12	Does not include portable task
Laundry	20	15	
Garage	5	5	
Bedrooms	5	2	Does not include portable
Kitchen	20	20	Counter top

Source: IES Residential Lighting Committee 1995, 9

The Molex Module

The LED module utilized in the design of the subject lighting system is the Transcend light module produced by Molex Inc. This module incorporates 120VAC LED arrays manufactured by Seoul Semiconductor. The advantage to these modules over other LED systems is that they require no external voltage conversion or power regulation. Further, the modules are configured to plug into a standard GU24 bi-pin socket, commonly used for other efficient lamps, such as CFL. This precludes end-user downgrade of the efficient system to incandescent, as there are no incandescent lamps sharing this socket configuration.

In order to facilitate the installation of these modules into luminaires with little or no thermally active features, a novel combination of plated plastics and aluminum heat spreader is utilized.

The LED within the modules incorporates several LED die, connected in series on opposing poles to the AC sine wave. The result is a device that emits light at a frequency of 120Hz. Light output is roughly 150lm, with each module consuming 4.5 Watts. The RM2 reflector module incorporates high efficiency optics. The resulting efficacy is 30 lm/W, equivalent to the system efficacy of residential grade CFL products. However, unlike the fluorescent luminaires, these modules are more directional, offering an opportunity to eliminate glare and unwanted brightness, while focusing light energy onto target surfaces within the design.

Figure 7. Molex Modules Employed in the Study Home

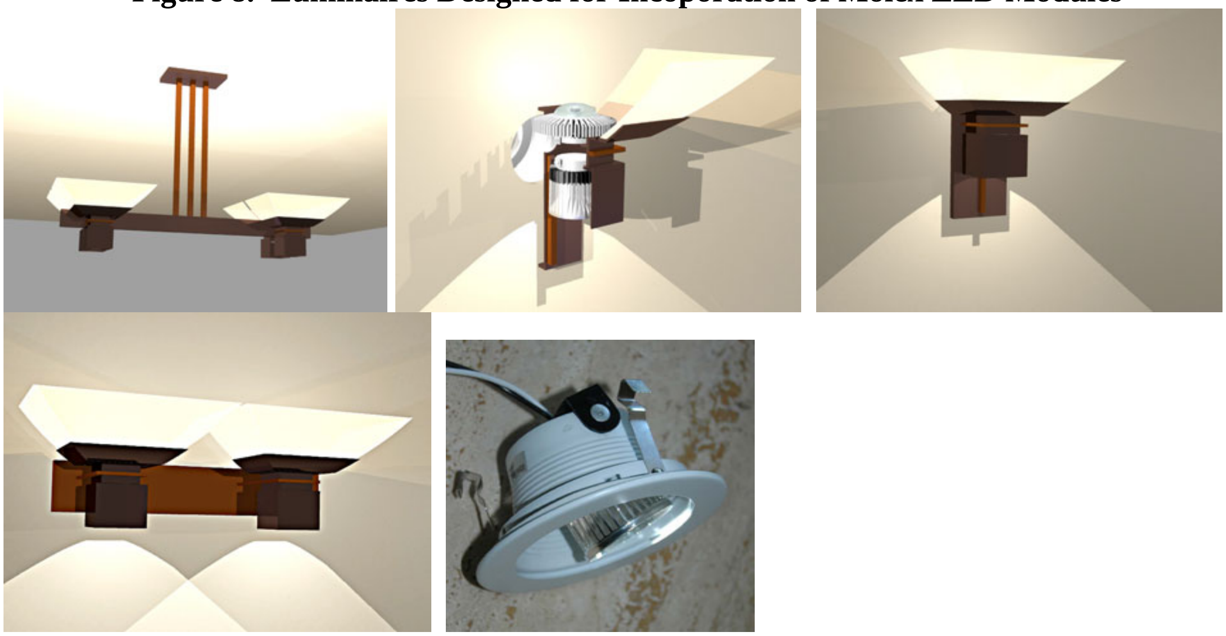
The light sources used throughout the design, specifically the RM2 reflector module, with a 25 degree beam spread (left), and the PM3 “puck” module with its wide diffuse distribution (right). In many products, both components were used in combination to produce and up/down lighting effect.

Future versions of modules of similar configuration, sharing the GU24 socket, are planned to produce 360-400 lumens utilizing Bridgelux LED arrays driven by on-board drivers, consuming roughly 7W, for an improvement in efficacy to 57lm/W. These modules may be applied to the study residence to evaluate performance against the AC LED products.

Luminaire Design

In order to deploy an LED solution in context to residential design, compatible with the expectations of customers reviewing the spaces, luminaire designs were developed to efficiently utilize the LED modules in familiar fixture configurations. Wall sconces, a dining table pendant, and exterior wall lighting incorporate indirect and diffuse lighting through luminous areas to create a sense of space, while downlighting presents higher horizontal illumination. Downlights are configured in familiar baffle trim with adjustable aiming to facilitate directing light on target surfaces.

Figure 8. Luminaires Designed for Incoporation of Molex LED Modules



Renderings illustrating the range of luminaires used in the subject home, incorporating the Molex modules in custom fixtures.

Summary of Costs, Energy Use, and Payback Analysis

The connected load for the lighting system design in the subject home is less than 0.3 W/s.f., with portable lighting included. To achieve this result, the approach to lighting layout and design included departures from normal residential design, including the use of custom luminaires to utilize the LED modules. At this time, very few LED sourced products are available for the residential market, beyond a small range of downlights and under-cabinet lighting. There are no suitable decorative luminaires incorporating LEDs of suitable style and scale.

Generally, residential lighting products are manufactured in China, Mexico, or Taiwan, by very high volume producers. These products are exceptionally low cost. At this time, few of these providers have integrated LED products into their offering. Further, the Molex Transcend module was not available to these manufacturers during the completion of this project, necessitating a custom approach to obtaining the required luminaires.

Because of this, cost justification for the luminaires was not evaluated on an ROI basis. However, there were no features within the products produced that could not be duplicated at similar cost and end user pricing as currently available products. Therefore, establishing an actual payback for the investment is not possible. In order to realize a reasonable payback for an LED system over incandescent or fluorescent products now common in the market, the cost of LED modules and fixtures housing them will need to reach parity with current fluorescent products in both light output per watt consumed and cost per lumen delivered. Current and near term development of luminaires and LED modules is expected to meet this requirement within the two-year test period for the study residence.

Table 2. Comparison of Light Sources, Costs, and Payback Potential

Product	Initial Cost	Luminaire Lumens	Watts	Cost per lumen delivered	System Efficacy	Annual Energy + Lamp Cost (1800 Hours)	Payback Period
50W Incandescent Downlight	$ 24.00	650	50	.04	13 lm/W	$ 12.91	Base
18W CFL Downlight	$ 36.00	700	20	.051	35 lm/W	$ 6.14	2.51 Years
4.5W LED Module Downlight **2010**	$ 55.00	135	4.5	.41	30 lm/W	$ 8.31*	n/a*
7W LED Module Downlight **2012**	$ 36.00	500	7	.072	71 lm/W	$ 3.31	3 Years

**Includes the requirement of additional fixtures needed to achieve minimally comparable light levels on target surfaces due to low initial lumen output. Payback exceeds 10 years.*

A comparison of various light sources used on residential downlighting indicates both efficacy differences and potential for payback in the near and medium term.

Performance Monitoring and Evaluation

To evaluate the performance of the lighting system in actual application, the subject home will be operated using automatic controls to simulate lighting use over a period of 2 years. The subject home is circuited to isolate load areas into groups, with the living/dining area, kitchen, master bedroom suite, and office areas to be tracked individually. A sister home, illuminated with CFL products using a conventional lighting design, separated into identical load areas, will be tracked using an identical automatic use schedule.

In addition to energy use, illuminance levels will be monitored throughout the study period to evaluate lumen depreciation, and color shift. Further, visitor comments will be recorded and logged for both the SSL and the sister CFL home.

At the mid-point of the LED test home period, it is anticipated that an upgrade to the higher performing 7W, 400lm modules will be installed to replace the initial 4.5W RM2 modules used in the downlight positions of luminaires throughout the home. This will be accomplished to compare performance, and demonstrate benefits produced by emerging new technologies, and to upgrade the design to meet Energy Start core requirements. This final state of the design will represent a realistic state of the art for LED application in residential application, meeting all efficiency standards anticipated to be in place at the end of the test period for the SSL subject home. The result of this upgrade will be a modest increase in total energy use of 36%, to realize a significant improvement in illumination levels of 62%. Comparative study of visitor comments and illumination level studies will be completed at the conclusion of the study period with conclusions and recommendation developed from the study results.

In addition to the energy consumed directly by the lighting system, indirect effects on air conditioning and heating loads will be evaluated during the study period.

The Future Potential of SSL

Of all sources that solid-state lighting competes with, the incandescent lamp presents the greatest opportunity, and the greatest challenge. The characteristics of LEDs in light intensity, directional control, color, instant on, tolerance of frequent switching, and dim-ability make them a superior technology to the compact fluorescent lamp. Further, LED products contain no mercury and provide service life that is 25X that of incandescent and 5X that of fluorescent lamps. Add to these attributes compact source size which is ideal for residential scale lighting fixtures and low heat in the light pattern and you have an optimized illumination source.

The incandescent lamp presents a difficult challenge based solely on one factor – low initial cost. Incandescent luminaires are inexpensive to manufacture, and the application of very low cost off-the-shelf lamps, allow the end use customer to fit light output to personal taste with a quick trip to the local home hardware store.

While modern compact fluorescent products have just now begun to make headway into this market, residential consumers prefer subjective decision making over cost/benefit analysis. Given the choice, residential customers will continue to choose incandescent sources over current energy saving CFL alternatives, even if costs were not an issue. The CFL lamp produces only one advantage over incandescent – energy savings – while delivering harsh light, poor color performance, poor dimming characteristics, long warm up time, and shortened life when switched frequently.

Solid-state lighting costs are projected to drop significantly, while lumen delivery is forecast to continue to improve. In the commercial markets, which make objective decisions based on operating costs, solid-state lighting is beginning to realize strong growth.

Within the period of the study residence, the cost/benefit of solid-state against CFL products of similar light output are emerging, favoring the solid-state solution for its subjective advantages over the CFL product. With higher efficacies, and the deployment of new product designs that deliver this advantage more effectively than retrofitting of existing incandescent products, the likelihood of solid-state taking a leading role in the displacement of all incandescent sources in the residential market is very high.

Conclusion

Solid State Lighting (SSL) is quickly evolving into the next generation of energy efficient lighting. The transition is occurring today in commercial applications, expanding rapidly as efficiencies and costs of SSL products advance. This is expected to reach the residential market within the next five years.

Although SSL can and will be used for retrofitting existing light fixtures, the benefits of this new lighting technology are not fully realized unless light sources are optimized through proper luminaire design. Simple application of SSL technology to replace existing low efficiency sources, applied in inefficient designs, will significantly reduce the impact of SSL in reducing energy consumption, with a resulting negative impact on cost justification over the low cost incandescent infrastructure.

Evaluation of the benefits and differences in the use of Solid State Lighting in the ZEBRA Alliance homes will provide a controlled environment in which energy use, light quality, and longer term performance can be measured, the design approach evaluated, and homeowner reaction collected. Information gathered from this effort, including critique and evaluation of the approach taken, will be published so that builders, architects, lighting designers, and consumers might use this information to advance positive discoveries and make improvement where needed. The result of this study and effort will be an advancement of lighting quality, and reduction in energy use, through demonstration of methods and technologies that deliver these improvements.

References

DOE. Department of Energy – Energy Efficiency and Renewable Energy. *Solid-State Lighting Research and Development: Multi-Year Program Plan March 2010,* Washington DC: Department of Energy

Ohno, Y. 2004. *Color Rendering and Luminous Efficacy of White LED Spectra*, for SPIE Vol. 5530 Gaithersburg, MD: National Institute of Standards and Technology

Schubert, F. 2003. *Light Emitting Diodes*, Cambridge, UK: Cambridge Press

Tribwell, S., and Lerman 1996. *Baseline Residential Energy Use Study,* for Tacoma Public Utilities, Tacoma, WA: Resource Power Supply Expansion Project

Energy Information Administration. *Electrical Consumption (kWh) by End Use for All Buildings, 2003*, http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/2003set19/2003exel/e05a.xls. Washington DC: Energy Information Administration

Energy Information Administration. *End Use Consumption of Electricity 2001*, http://www.eia.doe.gov/emeu/recs/recs2001/enduse2001/enduse2001.html Washington DC: Energy Information Administration

IESNA Residential Lighting Committee. 1995. *RP-11 Design Criteria for Lighting Interior Living Spaces*, New York: Illuminating Engineering Society

ZEBRAlliance. *ZEBRAlliance: Building Smart 2010*, http://www.zebralliance.com/about.shtml Oak Ridge TN: ZEBRAlliance