DESIGN INTEGRATED APPROACH TO APPLYING SOLID-STATE LIGHTING FOR ILLUMINATION OF OFF-GRID DWELLINGS

K. Willmorth
Lumenique, LLC

Abstract

When it is desirable to produce illumination from alternative energy sources, or where circumstances prohibit connection to a utility power grid, the selection of light sources requires the same careful consideration for energy use as any high efficiency application. However, with the high initial cost of energy generation on-site, the need for conservation is amplified. Whether the alternative source is from wind, solar photo-voltaic, or fuel generation, producing the greatest illumination result from the smallest possible electrical load reduces initial infrastructure costs, as well as operational costs. Reducing energy use also reduces the additional impact of losses from voltage conversion and power conditioning. Further, when the power source available is DC, any efficient lighting system that can operate directly from the raw generated power, or directly from batteries without conversion losses, offers an additional advantage over AC lighting systems requiring higher AC voltages.

Solid-state lighting offers several advantages in off-grid application, which will be explored in this paper. While the cost of solid-state lighting systems remains higher initially for the general market, application in off-grid applications offers a greater potential, due to the comparatively higher cost of energy production and system maintenance. Further, an optimized design approach, from exploiting the inherent advantages of LED light sources, is critical in optimizing investment in solid-state lighting.

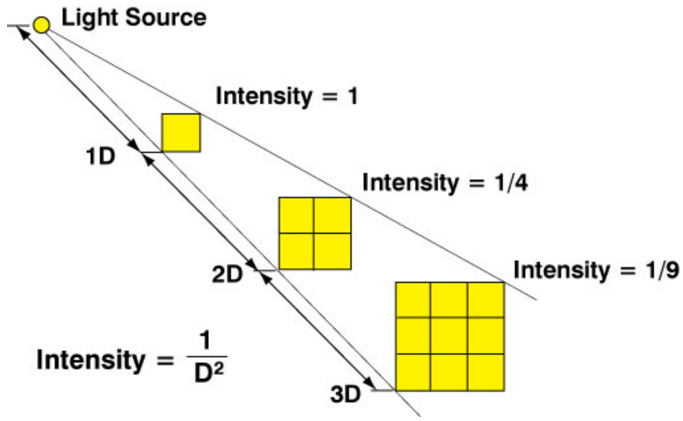
This paper addresses several key strategies for deploying an effective lighting system using solid-state lighting technology. These approaches apply universally to any illumination system, from remote single room dwelling in a developing nation to high end zero-energy commercial facility.

Core Design Approach – Focus on Task Lighting over General Illumination

At the core of any efficient lighting system design is the recognition of the physics of illumination that dictate important considerations in optimizing energy use for achieving a desired target illuminance. The significance of separating the general illumination needs from task visual demands is the most overlooked factor impacting the use of energy in general lighting systems. The key factor in optimizing energy use for lighting is consideration of the significance of the physical distance between light source and target surface, and its impact on lighting power required to attain a given illuminance result.

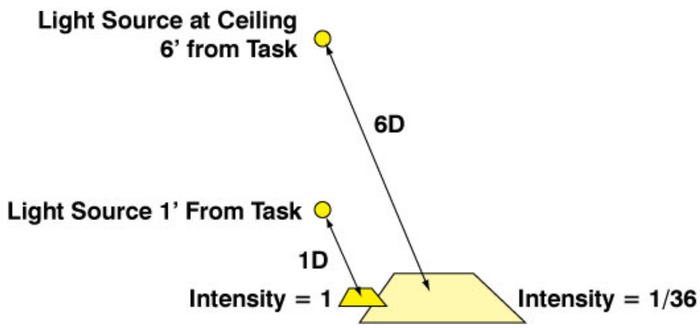
The Inverse Square Law establishes that light intensity is reduced by the square of the distance from source to object - which supports the use of task lighting for any high level illuminance need:

Figure 1. Inverse Square Law



Light sources nearer the surface or object to be illuminated produce higher illuminance than those further distant. Because the effect of distance is exponential, greater efficiency can be realized from locating the source nearer the target surface than can be attained from selection of higher efficiency light sources. The higher the desired target illuminance, the greater the effect of distance will be on energy consumption.

Figure 2. Task vs. General Illumination



Light sources further away spread light over a larger area, with less intensity on the target surfaces. Lighting placed nearer the target surface produces a smaller lighted area of higher intensity. This improves efficiency, while enhancing lighting quality in the space overall by reducing brightness, glare, and unnecessary over-illumination

Optimization of lighting energy use should include an approach that separates the two components in the illumination: General illumination for seeing objects, providing a sense of space, and safe navigation; and Task Illumination for executing visually difficult work, high precision tasks, reading, or other activities that demand high levels of performance. Factors of age, size of the task performed (text size included), and subject contrast, also impact the amount of light needed to provide good visual performance. While it is possible to fill a room with the amount of light needed for the most demanding task, this approach significantly increases energy use. Providing a lower level ambient general illuminance level, supplemented by targeted task lighting reduces energy consumption, increases visual comfort.

The following table outlines areas within a home in both average general illumination and task illuminance:

Table 1. Minimum Recommended Illuminance Levels (Derived from IES Residential Lighting Committee 1995, 9, and Lumenique recommendations)

Room/Area	General Illumination Lux	Task Lighting Required
Living spaces	50	Provide local portable task lighting of 500Lux where needed
Dining Room	100	Provide table surface lighting of 250Lux
Office	200	Provide local task lighting of 500Lux on critical surfaces
Laundry	200	No other task lighting required
Garage	50	Provide local task lighting of 1000Lux on work surfaces
Bedrooms	50	Provide local portable task lighting of 500Lux
Kitchen	200	Provide counter top surface illumination of 400Lux

Note that if task illuminance were applied as general illumination, from sources located at the ceiling level, the amount of energy required increases exponentially. A lower general illumination level with proper glare and brightness control, combined with localized task illumination from nearby sources optimizes light control and energy use.

Optimizing Lighting System Performance Through Application of Solid-State Lighting

There are several advantages to solid-state lighting in off-grid lighting system application. Light Emitting Diodes (LEDs) are specifically well suited to operation from Direct Current (DC) power sources, including PV Solar panels, batteries, or portable generators. LEDs are low voltage devices, typically operating at between 3VDC and 24VDC, requiring little more than current limiting electronics to operate efficiently and to protect them from high inrush or energy spikes.

However, the most significant advantages of LEDs, is their high luminous efficiency, directional light output, and ease of controllability.

Source Efficacy

LEDs produce more light per watt consumed than incandescent sources by a factor of 5X to 7X. To realize 750 lumens from an Incandescent lamp typically requires 60 Watts of energy, or 12.5 lm/W (lumens per Watt). Quality LEDs generate source efficacies from 45 to 135 lm/W, representing a reduction of between 75% and 92% over incandescent sources. Fluorescent sources deliver similar efficacies, up to 105lm/W, but are more difficult to control in directional lighting application.

Optical Efficiency

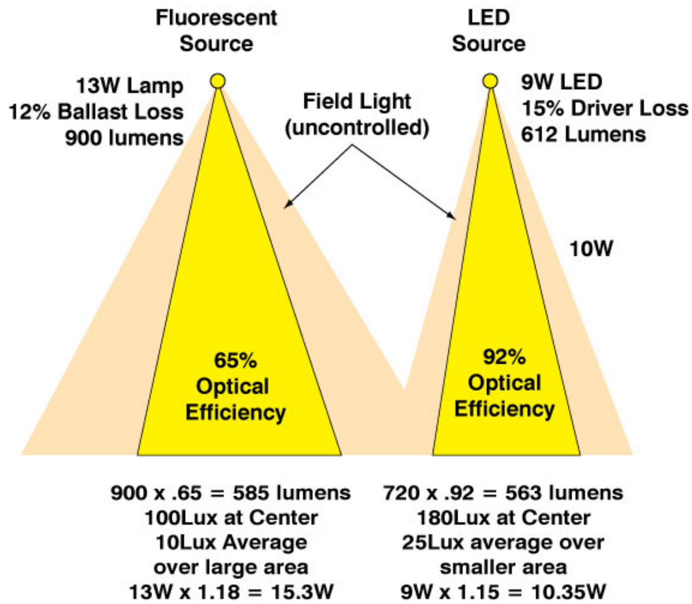
The directionality of LEDs used in solid-state lighting product, compared to the omni-directional character of fluorescent and high intensity discharge (HID) sources, produces an advantage in optical efficiency when directional control is desirable. Where an efficient compact fluorescent luminaire attains optical efficiencies of 65% or less, well designed LED products achieve optical efficiencies of 80% to 92%, delivering more light on target surfaces. In addition to improvements in total efficiency, LED optical systems produce a tighter beam pattern, focusing more total light output into desired lighting zones, with less light wasted, or scattered.

Electronic Efficiencies

For applications where DC power is available, operating LEDs without inverters, using high efficiency current limiting drivers, produces the lowest system power loss. Quality DC current control drivers provide protection of the LEDs from over-current and transient voltage spike conditions, and are between 92% and 98% efficient. Simple resistive current limiting circuits reduce efficiency and increase thermal gains, resulting in system efficiencies as low as 35%. For grid tied systems using inverters and distribution of AC line voltage power (120VAC+), a combination power supply/driver, or external power supply to convert incoming alternating current high voltage power to low voltage DC power is required. High quality systems utilize high quality transformers, capacitors, and other circuit components to produce a smooth, consistent output voltage with minimal harmonic distortion (<8%) and a high power factor (>80%), with efficiencies as high as 92%. Simple rectified switch mode resistive power supply/driver combinations using electrolytic capacitors operate at significantly lower efficiencies, often as low as 40%.

Efficient electronic operating components of LED systems must be well matched to the load connected to them, or efficiency will suffer. Universal power supply/drivers, with a wide load rating vary from 45% to 80% efficient depending on applied load. Efficiencies of >85% require careful matching of power supply and driver design load and applied load.

Figure 3. Composite Efficiencies



The composite effect of tighter optical control, higher optical efficiency, and excellent source efficacy produces significant improvements in delivered illuminance over less effective technologies. Additionally, ballast and driver losses increase power requirements over source energy use. In this example, the LED system produces 80% more light at the center of the light pattern and 150% more light in the pattern area than the fluorescent system, using 32% less energy.

Application Approach

Integration of solid-state lighting into an effectively defined task/general illumination lighting system requires careful attention to lighting layout. Use of focused light sources, with less uncontrolled, or wasted spill light, can result in unforeseen under-lighting and potential issues of poor uniformity, resulting in an unattractive final result.

In Figure 4 below, application of tightly controlled optics required additional sources to support minimum general illumination levels, while delivering higher target surface illuminance. However, taking advantage of the higher directional control efficiency, and controlling spill light, results in lower energy consumption overall.

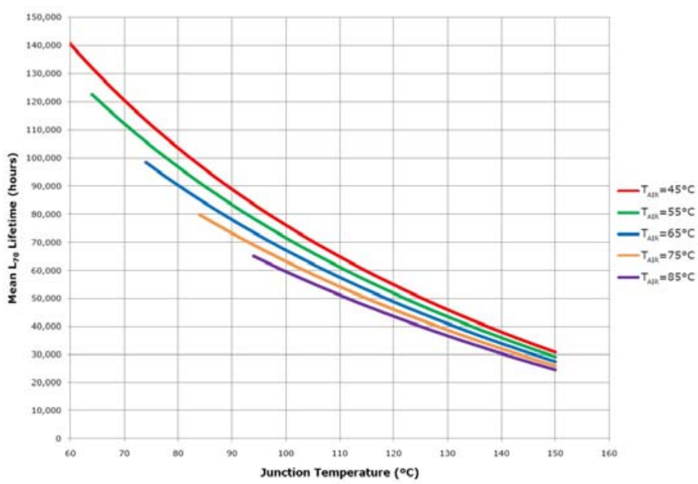
Figure 4. Application Comparison - Simulated

In this example, an "efficient" design on the left uses (6) 12W "high efficiency" luminaires rated at 52 lm/W to produce an average of 120 lux, consuming 72 Watts. The space on the right uses (10) 39lm/W sources consuming 4W each, for a total of 40 watts. The result is a lower average light level (50 lux) but higher illuminance on the art, table and planters; enhancing 3D perception of the space while reducing energy consumption by 48%

The Final Link – Controls

Like incandescent lamps, solid-state lighting systems do not suffer any ill effects from frequent switching. Further, when dimmed, thermal management designed to control heat at full LED power levels results in lower operating temperatures, which significantly extends LED life, and electronics degradation. Where fluorescent source life is shortened when frequently switched, LEDs are able to be frequently cycled from on-to-off, and are able to be dimmed without starting at full light output. Unlike all other conventional sources, solid-state lighting does not lose efficiency when dimmed, and can actually improve in efficiency in systems with high normal operating temperatures.

Figure 4. Effect of Heat on LED Life



LED service life is significantly impacted by operating temperatures. Dimming and frequent switching reduces the thermal load on LEDs and electronic components, extending their life.

With a high tolerance for switching, solid-state lighting systems support the use of occupancy controls, daylight controls, and individual lighting controls, producing further energy savings and service life benefits (optimizing investment recovery). The electronic nature of solid-state systems, instant on-off response, and relatively low operating load (for the light delivered) enable a level of integration in control strategies impossible with fluorescent or HID systems.

Lighting system controls incorporating occupant controlled dimming, daylight sensing, occupancy sensing, and automatic load shedding control increase total system performance, as well as increase system longevity from minimizing both in-service demand (time), as well as lowering operating temperatures when maximum illumination is not required.

Special Considerations for Low Cost Off-Grid Lighting in Developing Nations

The use of an LED based lighting operated from batteries and/or small PV solar panels requires a very high diligence in energy conservation, amplified by the negative impact of the use of lower cost (lower efficiency) LEDs and energy sources. General illumination is significantly reduced in favor of more concentrated focus on essential task lighting to maximize benefits at lowest cost. Further, with less competition from surrounding light sources, task illuminance levels are reduced significantly. Counter-intuitively, these simpler lighting systems demand greater design consideration than more developed and complex systems, as each light source represents a higher degree of impact in context to the application.

Several key issues must be considered when applying LEDs in small applications, and applications of limited general illumination or ambient light.

- LEDs are intense light sources, with small source presence. The potential for permanent eye damage is high if glare and visibility of the light source is not controlled.
- Task focused lighting too-often produces extreme contrast in the visual field from a lack of background illumination. For this reason, consideration of glare, and emission of a small portion of light into the surrounding environment should be considered.
- Low cost LEDs are more sensitive to thermal conditions, not less. Failing to properly control heat will cause more rapid degradation in performance than with more expensive packaged LED products.
- All LEDs are sensitive to voltage spikes, such as arcing of a battery connection, which can destroy an LED instantly. Some protection should be provided to protect the LEDs from these conditions.
- While high end systems might use integrated LED systems in disposable assemblies, this approach may not be appropriate in markets where re-purchase of an entire fixture due to the failure of an LED would be considered a hardship. Modular, replaceable elements are a preferable solution to disposable systems.
- LEDs require a minimum voltage at which they will begin to operate. When operating from batteries, the LED may stop functioning regardless of remaining usable battery charge falling below the minimum voltage required by the LED itself. Consider use of current controls to maintain LED current throughout the full range of a battery system’s discharge profile to extend useful light performance.

- Controls should be integrated in all solid-state systems to cut power drain when in the “off” position. This is critical in any system operating from batteries as the primary power source.

Implications for Grid Tied Systems

Grid tied systems that utilize inverters to operate lighting loads from common power distribution circuits within a stricture include additional system losses that will reduce total lighting efficiency. Losses from voltage conversion to high voltage, in addition to high voltage AC to DC conversion, compound energy consumption without delivering illuminance benefits. If battery storage is utilized to deliver low DC voltage to the LED lighting system, losses from battery drain and grid source recharging during low solar contribution will also reduce total system efficiency. The most effective strategy in reducing the impact of these losses, and optimizing the potential revenue generating energy being delivered into the grid, is to minimize the use of energy for lighting overall using the strategies described in this paper.

Conclusion

Regardless of the economies involved, or budget available for initial construction, long term benefits of alternative energy approaches rest first on sound energy conservation approaches, that do not waste energy unnecessarily.

The fundamentals of successful off-grid lighting system design are consistent with conventional lighting practice. However, due to the first-cost of alternative energy sources, energy conservation becomes an even higher priority. In this pursuit, separating general illumination from higher illuminance task demands, coupled with selection of high performance lighting products that efficiently deliver light with minimal losses from uncontrolled (spill) light, produces an effective strategy for attaining high visual performance with minimal energy demand. Beyond these objectives, reduction in parasitic or system support losses is an additional area of potential gain.

Solid-state lighting offers several advantages in reaching these objectives. LEDs are high efficiency light sources that deliver light that is easily controlled using efficient optics. Solid-state lighting requires minimal conversion and power supply conditioning when used in DC low voltage systems. Finally, solid-state lighting and LEDs are both easily controlled optically and electrically, that are tolerant of frequent switching, making them ideal for automatic (daylight, occupancy, time, etc..) and manual user control application to optimize energy savings even further.

As the cost of LEDs, and solid-state lighting systems continues to improve, they will become the preferred source for many general illumination applications. In off-grid application, where the cost benefit balance favors efficiency, and where lower cost alternatives require expensive supporting power supplies, solid-state will produce realizable gains than might be generally accepted in grid-tied, or fully grid dependant building applications.

References

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Author Background

Kevin Willmorth has been involved with lighting for 30 years. His experience includes lighting design consulting, product design, marketing, business strategy, and editorial writing. His past positions include VP of Design and Marketing for Kim, Winona, and Visa Lighting, VP and Director of Product Management with Renaissance Lighting, VP of Design – Lighting, for Atlandia Design, and was sole proprietor of Kevin L. Willmorth Lighting Design Consultant. He currently owns Lumenique, LLC, offering product design, prototype development, testing, product evaluation, and strategic consulting to manufacturers and technology providers, lighting application design, and technology evaluation for building owners. He is also editor of Architectural SSL magazine and provides editorial content on the topic of lighting to all Construction business media publications including Architectural Products and Illuminate. Kevin is a regular presenter at solid-state conferences, including DOE workshops, LEDs, ArchLED, and Strategies in Light.