LED Efficacy: What America Stands to Gain

Impressive gains in the efficacy of LED (light-emitting diode) lighting technology have been realized in the past decade, as evidenced by the high-performing products now gaining share in growing numbers of lighting market niches. Research and development investments made through the U.S. Department of Energy (DOE) Solid-State Lighting Program, in partnership with industry and academia, are widely credited with spurring the technology advances underlying this success.

Given the magnitude of progress made to date, should DOE continue driving for big gains in LED lighting efficacy? This important question is asked periodically of DOE leadership. As stewards of the taxpayer dollar, DOE must regularly evaluate the impacts of its R&D investments.

This white paper considers the projected impacts of future efficacy gains in advancing major national goals, as well as in strengthening the competitive positioning of U.S.-based manufacturers. Taken together, these benefits provide compelling reasons for industry and government to keep targeting the aggressive but achievable LED lighting efficacy goals identified by DOE. Indeed, as the paper concludes, bold forward leaps in technology will be a matter of urgency if the nation is to fully realize the benefits of LED lighting.[1]

Efficiency First

Energy efficiency has motivated DOE investment in solid-state lighting (SSL) technology since the inception of the program. Some of the first questions addressed in forming program goals and strategies were these: *Just how efficient can LED technologies become? Can we get there cost-effectively within a reasonable period of time?*

DOE has evaluated the technological challenges underlying these questions and established aggressive yet achievable efficacy goals, expressed in lumens of light output per watt of electric power, as well as cost goals, expressed in dollars per kilolumen.[2] The industry and research communities, with targeted support from DOE, have made rapid progress along both the efficacy and cost trajectories. Critical milestones have included overcoming challenges in materials and processes, as well as addressing fundamentals of LED lighting performance, such as the ability to attain acceptable lumen output and product longevity.

Currently, the highest-performing LED technologies are more than halfway to the technically achievable efficacy goals established by the program. DOE analysis has shown that with aggressive and strategically focused R&D, LED lighting efficacy can still be substantially increased. Today's highest-performing LED devices can produce 160 to 170 lumens per watt; DOE projects that a target of 255 lumens per watt can be reached using phosphor-converted (pc-LED) architectures. LED luminaires (complete lighting fixtures) using pc-LEDs achieve 125 to 135 lumens per watt; DOE believes a target of above 200 lumens per watt is achievable. With greater breakthroughs in LED performance, the phosphor can be removed from the system, enabling 350 lumens per watt performance with resulting luminaire performance levels of 280 lumens per watt.

Prospects would be markedly different if DOE were to stop investing in LED technology. While incremental gains in efficacy still would be likely, market pressures to decrease costs and fill existing sockets would likely trump industry investment in technology progress and design innovation, locking in current-performance-level products for decades.

In short, although LED technology could now be considered "good enough" to work in most lighting applications, the upside potential for improving efficacy remains impressive. Reaching the technically achievable efficacy goals for LED lighting can benefit the United States in five key ways, as profiled below.

Top five benefits Americans will realize by meeting DOE goals for LED efficacy

1. Enormous energy savings of 5.1 quads annually by 2035, cutting U.S. business and homeowner electricity bills by $50 billion a year and enhancing energy security.
2. Scientific progress and technological advances on semiconductors, phosphor materials, quantum dots, power supplies, and optical materials with crossovers into other technology.
3. Better LED products that deliver improved lighting quality, longevity, and reliability, as well as enhanced services.
4. Lower first costs for LED lighting products, which, in turn, will encourage change-out of the existing lighting stock to more efficient devices.
5. Stronger positioning of domestic LED manufacturers who produce high-value, high-brightness LEDs.

1 While this paper focuses on inorganic light-emitting diodes (LEDs), DOE also works in partnership with industry and research communities in advancing organic LEDs (OLEDs). OLED technology offers potential for significant energy savings but is at an earlier stage of technology development than LEDs.

2 1,000 lumens, approximately the output of a 75-watt incandescent bulb.

Benefit 1: Enormous Energy Savings

First and foremost, DOE has invested in solid-state lighting to realize energy savings, which are potentially enormous. As market acceptance of LED lighting continues to grow, and as industry and government team up on the bold new approaches needed to reach DOE targets, Americans can realize annual savings on the order of 5.1 quads of primary energy by 2035. This reduction of 490 terawatt hours of electricity consumption will yield $50 billion in annual cost savings in today's dollars for businesses and consumers.

To put those savings in perspective, 5.1 quads is nearly twice the amount of electricity the Energy Information Administration predicts will be produced by solar power in 2035. Energy efficiency on this scale will go a long way toward making the United States more energy secure, slowing demand for power generation. Efficient LED lighting also will go hand in hand with making renewable energy more competitive. For example, by decreasing electricity use for lighting, LED technologies will make it far more affordable and practical to construct zero-energy buildings—buildings so energy efficient that, on an annual source energy basis, they can use on-site renewable technologies to provide at least as much energy as they acquire from the grid.

Benefit 2: Far-Reaching Scientific and Technological Advances

In advancing LED efficacy, researchers will continue to realize scientific and technological progress on multiple fronts. Research into improved LED efficiency already has yielded valuable insights into materials science, semiconductor physics, phosphor materials, quantum dots, power supply components, and optical materials. This research is likely to have significant crossover into other clean technology, consumer, and communications applications.

One example is the progress on gallium nitride (GaN) electronic devices that has emerged from efforts related to LED manufacturing. Now making headway as high-efficiency power converters for large-scale photovoltaic and wind power generation facilities, GaN power electronics also will likely be used in most hybrid and electric vehicles due to their thermal stability and power conversion efficiency.

Even seemingly intractable challenges in LED R&D are spinning off scientific innovations. Today, the operating performance of LED lighting products is limited by "droop," an efficiency fall-off that occurs with increasing current density in LEDs. In exploring droop in indium gallium nitride (InGaN), researchers in the DOE program have developed new semiconductor physical models and experimental methods that are proving valuable in other fields. Similarly, researchers are tackling the mystery of the "green gap," in which LEDs become less efficient as their emission is pushed from blue to green wavelengths. Investigations in this area are very likely to yield fundamental insights that open new directions for advancing semiconductor technology.

Other advances in SSL power supplies, thermal components, optical materials, phosphors, and quantum dots will likely play a role in enhancing lighting efficiency and will almost certainly be used in other applications. For example, quantum dots (nano-scale semiconductor optical converters) found their first commercial application with SSL and still hold promise for improving LED efficacy. In addition, they are now being used to boost energy and color quality performance in televisions and displays and they have possible application in solar cells.

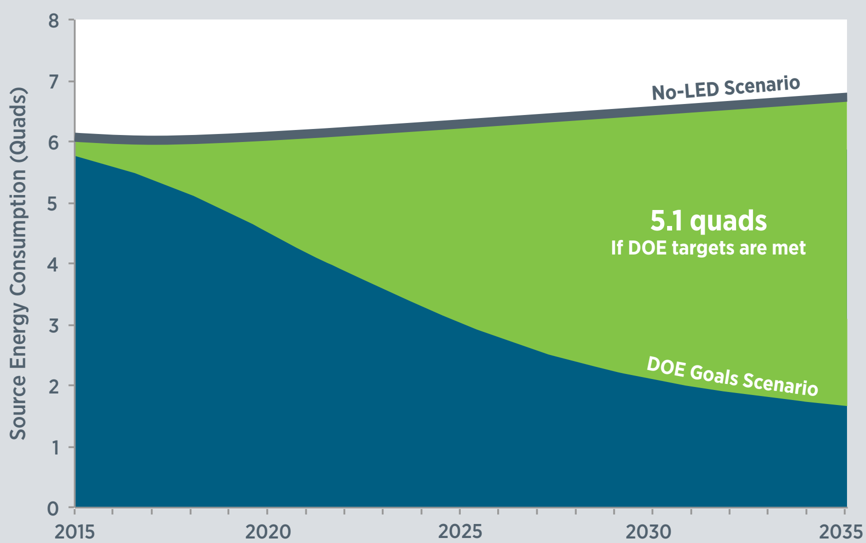
Benefit 3: Better Lighting Products with Improved Lighting Quality

Greater LED efficacy enables more light to be produced with less electrical power at lower operating temperatures. As a result, lighting manufacturers and designers can choose to reduce the light source size, decrease the number of LEDs, increase light output for a given source size, reduce electrical power input, reduce the amount of generated heat, or many combinations of the above.

In short, increased efficacy creates headroom for improving quality, performance, longevity, and reliability; lowering costs; and adding new services that can be delivered through integration with controls and intelligence. Where each company goes with that headroom in creating competitive advantage is determined by its unique market strategy. The competitive opportunities cross a host of interrelated dimensions, including:

- **Optical control**: Greater efficacy allows manufacturers to produce more light from a smaller source, which provides more precise optical control, enabling the tighter light beams and higher center beam intensities valued in directional lamps such as PAR38s and MR16s. The current generation of LED MR16s cannot compete with the high center beam intensities of conventional halogen narrow beam, high power MR16s, such as 75W models.
- **Glare mitigation**: Higher efficacy provides lamp and luminaire designers more freedom to mitigate potential glare, allowing, for example, the use of reflectors and diffusing optical elements that might otherwise cause unacceptable light loss. Many manufacturers have designed products to yield as many lumens as possible, in order to compete with high-efficiency conventional light sources such as fluorescent and HID sources. However, in some cases, the resulting products have been considered too glary. Higher-efficacy LEDs allow manufacturers to mitigate glare while still offering substantial potential energy savings over conventional light sources.
- **Color stability**: High operating temperatures are a known contributor to color shift. All other things held equal, improving the efficacy of phosphor conversion LED packages lowers their operating temperature per lumen of output. Lower temperature slows thermal degradation of phosphors, LED package encapsulants, and other optical elements, allowing for longer-term color stability.

DOE Targets Bold Energy Savings from LED Lighting



To date, our nation has realized only a fraction of the potential energy savings possible from LED lighting. Moving forward, enormous energy savings can be realized as industry and government continue to focus R&D efforts on achieving the DOE efficacy targets. Meeting these ambitious goals for LED lighting can yield a total of 5.1 quads in annual energy savings by 2035, lowering U.S. electricity bills by $50 billion and enhancing energy security.

- **Lumen maintenance**: Lower operating temperatures from greater efficacy can be exploited to enhance lumen maintenance. Good thermal design is critical to good lumen maintenance, and can result in very stable light output over long periods of operation.
- **New features**: A related benefit of reducing thermal handling and heatsinking requirements is the ability to diminish the material stream and create space within the volume of the lighting product to improve functionality or add features. This space can be used for better optics, additional LEDs, sensors, controls, or communications. The expanded range of LED light output levels, reduction in thermal handling, better optical control, and additional functionality enable LED lighting products to address more extreme lighting applications and provide dramatically more flexibility in LED lighting product design.

Across all these dimensions, better lighting quality from LED products will speed the transition to efficient LEDs, shortening the time that users will hold onto older inefficient technology.

Benefit 4: Lower First Costs for LED Lighting

In a growing number of market niches, LED products are becoming increasingly competitive against incumbent lighting technologies on a lifecycle cost basis, factoring in their energy savings, longer lifespans, and lower operating costs. Nevertheless, most remain at a notable disadvantage on a first cost basis. A competitive first cost is necessary to achieve the broadest possible market acceptance of LED lighting products.

With continued R&D, LED products not only can compete head to head on first cost, they have the potential to be less expensive than many incumbent lighting technologies. Greater efficacy is the key to these cost improvements.

Already, LED manufacturers estimate that one-third of the cost reductions accomplished to date in LED lamps and luminaires can be attributed to efficiency improvements. Moving forward, further decreasing the number of LED packages needed to deliver a given light output level enables lower input power, cutting the cost of the power supply. It also minimizes the amount of thermal handling materials and heatsinking needed for a luminaire, and enables the optical system to be simplified and desired optical performance to be achieved at a lower cost. All these factors can dramatically reduce costs, and, in turn, can accelerate change-out of the existing lighting stock.

Benefit 5: Stronger Positioning of Domestic Manufacturing

Efficacy-driven research can specifically benefit the competitive position of domestic LED manufacturers. Domestic manufacturers have focused on producing high-value, high-brightness LEDs, while Asian manufacturers have focused on lower-cost, mid-power LED products. Currently, many LED lighting product integrators are finding it cost effective to use the mid-power LED packages as a light source. These products can have very good efficacy at low current densities, but suffer from droop at higher current densities, requiring a large number of smaller LEDs to reach typical lighting levels.

If droop efficiency losses can be mitigated, high-brightness LED packages can be run at even higher flux levels per package, reducing their effective cost per lumen. This would alter the cost-performance trade-offs between mid-power and high-brightness LEDs, to the clear benefit of domestic LED manufacturers.

Opportunity	Research Challenges
Improve phosphor conversion processes	Creating LED products with 'warmer' white light and enhanced color quality involves phosphor conversion processes that cut into efficacy. Blue LED chip efficiency must continue to advance so manufacturers have headroom to achieve desired color temperature and color quality while still delivering good efficacy. Optical downconverting materials—phosphors and quantum dots—can be improved to be more efficient and stable.
Replace phosphor conversion processes	Using direct-emitting LEDs (RGB or RGB+ sources) would remove phosphor conversion losses and enable ultimate LED lighting efficacy. Direct emitters can also enhance dynamic spectral tunability, providing just the right spectrum of light for an application. Tunability offers a new value in lighting products that can increase adoption. Dramatic gains in the efficiency of green and amber LED sources are necessary, as well as more modest improvements to red LED emitters.
Mitigate droop	Droop describes the phenomenon of reduced LED efficacy at higher applied current density. Understanding and mitigating droop will result in LEDs that can emit more light per package, which cuts the cost per lumen of LEDs and enables more compact emitters with lower material costs.
Address the green gap	Green-emitting LEDs suffer from relatively low efficiency. Higher green LED efficiency will enable removal of the green phosphor and the associated phosphor loss mechanisms, leading to the ultimate possible efficiency of LED light sources. Better green LEDs also will increase the feasibility of full color-tunable LED lighting products.
Improve encapsulants	The encapsulant is a high-value optical material that protects the LED, increases light output, and acts as the optical matrix for the phosphor. Increasing the optical index of refraction of the encapsulant (while maintaining transparency and stability) can raise the efficiency of LEDs. In addition, improving the temperature stability of these materials can enable higher temperature operation of LEDs, resulting in increased light output from an LED package.
Develop novel luminaires	New SSL lighting products can be designed to fully optimize LED and lighting application performance. Current LED luminaires and lamps typically operate LEDs below their peak efficiency due to cost and form factor constraints. Rethinking LED lighting products beyond conventional lighting form factors (which are based on previous technologies) will result in dramatically better source efficiency as well as the opportunity to more effectively use the generated light in the specific application.
Enable connected lighting	Connected lighting refers to lighting systems that are connected to data networks to facilitate such functions as lighting control, improved HVAC control, and building security. To realize the deep potential energy savings possible with connected lighting, several important developments are needed, including enhanced interoperability among system devices, accurate luminaire self-energy measurement and reporting, and reduced system configuration complexity.

Seizing the Opportunity

Forward progress on LED lighting efficacy has been extraordinarily rapid in the past ten years, and has yielded an attractive 12-fold return[3] on the Federal investment in SSL in terms of energy cost savings alone. While future gains will likely be somewhat more incremental due to decreased headroom for improvement in the technology, the impacts of the advancements will be larger given the proliferation of SSL technology.

If the United States is to realize the full energy savings benefits from LED lighting, a continued focus on LED efficacy will be essential, along with the rapid translation of that progress into high-quality, cost-competitive products that achieve broad market acceptance.

Fast progress on efficacy is equally important to DOE's industry partners. The marketplace has been receptive to LED lighting products in sectors where they provide performance and lifecycle cost advantages over incumbents. Now, in addition to continuing to displace incumbent products, manufacturers need a compelling value proposition that gets those early-adopter customers to upgrade from 2010-era products to future, much better-performing products. With more efficacious LEDs, manufacturers and designers can create the high-value products and applications that will keep buyers coming back for more.

Collaborative teamwork by leading organizations in the nation's private, public, and academic sectors has been essential to progress in LED efficacy. Looking forward, DOE intends to continue focusing outstanding scientific, engineering, and product development capabilities from these sectors on the goal of increasing lighting efficiency while simultaneously improving quality and lowering costs. ■

For more information on solid-state lighting research and development, subscribe to the SSL Updates mailing list by contacting DOE.SSL.Updates@ee.doe.gov.

3 The almost 290 solid-state lighting R&D projects DOE has funded since 2000 have resulted in more than 270 patents applied for or awarded and a huge industry footprint. Literally millions of SSL products currently on the market are based on at least some DOE-funded R&D. Those products have contributed to more than $4.7 billion in energy savings so far—a remarkable return on the total DOE SSL program investment of about $400 million over that same period.

U.S. DEPARTMENT OF ENERGY
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For more information on solid-state lighting research and development, visit energy.gov/eere/ssl/.

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