What's Next for LED Lighting?

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The development of electric light in the 19th century improved efficiency, made lighting safer, reduced costs, and enabled unforeseen additional benefits. Today we are undergoing another major lighting revolution, similar in scale, thanks to LED technology. LED lighting not only saves energy but also expands the frontiers of lighting in new directions to create whole new value propositions. With LEDs, lighting can do far more than it could before—not just in terms of saving energy but also adding benefits related to health, productivity, and learning; enabling more efficient indoor plant growth; improving safety; and protecting the night sky and minimizing the environmental impacts of outdoor light at night. However, while we know these benefits are possible, our understanding of how to achieve them remains dim. We have a lot to learn before we can use LED lighting to its full potential.

For general illumination, LED performance has been steadily improving while prices have declined. LED lighting products are now competitive for nearly every application and can outperform their conventional counterparts in most aspects of lighting performance, including color quality, lifetime, beam control, and cost of ownership. LED products can also offer new lighting features, such as dynamic color control, including dim-to-warm color temperature, and even dynamic beam control. And even with these improvements, there is still considerable room for improvement in LED technology, which will enable even more efficient products with better performance and additional features.

Redefining Lighting

One feature of LED lighting is improved optical control. LEDs deliver light with more precision than ever before and direct light where it's needed to effectively illuminate objects or tasks in a space, reducing wasted light. Similarly, LED technology enables precise control of lighting intensity over large areas, bringing the opportunity to get light intensity "just right" for the application—not overlighting and wasting energy when unnecessary, yet not underlighting, which could reduce the effectiveness of activity in a space or cause safety or health concerns.

These advantages are amplified by integration with connected technologies and compatibility with controls (see "Lighting Control for Lighting Quality" on page 8).

Another feature of LED lighting is control over color quality and spectrum. Unlike conventional lighting, which has limited color options, LED technology delivers any combination of colors, opening a whole new dimension for lighting. The exact best color of light can match the activities taking place in the lighted space. LED lighting offers color-rendering features such as high color fidelity and gamut, and the spectrum can be dynamically engineered to optimize human health and productivity as well as safety.

With LED outdoor lighting, these advantages can be combined to reduce light pollution and sky glow (a brightening of the night sky due to terrestrial light sources). The 2017 U.S. Department of Energy (DOE) study *An Investigation of LED Street Lighting's Impact on Sky Glow* found that a light source's contribution to sky glow typically includes, in order of importance:

- uplight from the source (LEDs eliminate this)
- luminaire output (LEDs minimize this, while still meeting illumination requirements)
- spectral content (shorter-wavelength "blue" light scatters in the Earth's atmosphere more readily than longer-wavelength light, but manufacturers can easily engineer spectral content of LEDs)

Making Tradeoffs

As LED lighting provides new capabilities and we learn how to apply these capabilities in lighting applications, we learn more about some of the necessary tradeoffs with the technology in specific applications. For example, with roadway lighting, reducing the blue content of the light may decrease sky glow (although less effectively than dimming and eliminating uplight), but early studies indicate that increased blue content also improves visibility and thus driving safety. However, we don't yet know what the optimal lighting is for roadway safety. Roadway lighting is one example of where ongoing research enables better-informed decisions and optimizes technology for safety and ecological considerations.

The spectral content of indoor lighting has also been receiving a lot of attention, thanks to LEDs. Physiological studies confirm that nonvisual receptors in the eye linked to melatonin secretion are more responsive to blue light and that higher intensity and

Tunable LED lighting in a classroom in the Carrollton-Farmers Branch Independent School District in Carrollton, Texas. The four spectral power distribution settings are shown in clockwise order, beginning with the upper left photo: 3000 K (Reading), 3500 K (Testing), 4200 K (General), and 5000 K (Energy). All luminaires were on at full light output when the photographs were taken.

Photos courtesy of Acuity Brands Lighting blue content in lighting promote alertness. But again, the scientific understanding of these physiological responses to light remains at a relatively early stage. Researchers are working on a variety of fronts to increase the scientific understanding of the nonvisual effects of light on human physiology and the related energy impacts. As we learn more, it is likely that lighting designers will need to consider both occupant visual needs and occupant health when designing lighting systems.

Adding to Our Understanding

Two current DOE-funded research projects will increase our understanding of the physiological effects of light. The Virginia Tech Transportation Institute's study[1] measures the impact of different types of roadway lighting on levels of melatonin in drivers, pedestrians, and nearby sleepers. And researchers at the University of California San Diego are studying the circadian health effects of light on night workers in a hospital setting. DOE also funds GATEWAY studies that assess the performance of lighting systems designed to engage physiological responses in a variety of real-world settings—in senior care, classroom, and healthcare facilities—where, in addition to the energy savings, the potential nonenergy benefits are of considerable interest.

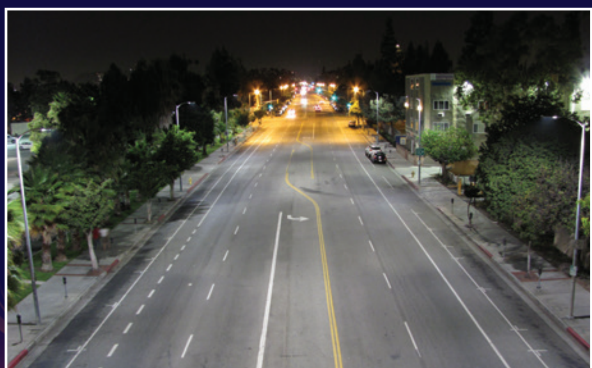
LED lighting also attracts interest in horticulture. Energy savings are a big part of the lure, but so is the benefit of tailoring the spectrum and intensity to specific crops to increase yield and control such parameters as growth, color, and nutritional content. But once again, scientific knowledge of the exact relationship of those parameters to plant growth is still in its relative infancy.

There is no doubt that LEDs are the future. DOE forecasts that by 2035, LED lamps and luminaires will be in most lighting installations and will result in annual energy savings of an astounding 5.1 quads in the U.S.—representing a 75% reduction in lighting energy consumption, compared to a scenario without LED lighting.[2] While LED lighting products can exhibit very good efficacy, energy savings, and lighting performance, there are still large variations in product performance, which is typical with a young technology. And LED technology is still changing—ongoing research will change and further improve LED efficacy and performance. LED technology still has a long way to go to fulfill its energy-saving potential and is only at the halfway point.

Beyond improvements to lighting technology, research to better understand the requirements of lighting applications can enable further energy savings, better lighting performance, and new value. LEDs offer precise control of the color quality, intensity, and optical distribution of the light. We need to connect the new capabilities of lighting technology with what is best for the application, and this requires new research in all aspects of lighting science—including human physiological responses to light, roadway safety, vision and visibility, horticultural lighting, and even old lighting science topics such as glare and flicker. LED lighting can give us the light we need—once we know what we need. In the meantime, there are very good, efficient products out there, but choose well. Get help if necessary. Not all LED lighting products are created equal.

1 *Investigating the Health Impacts of Outdoor Lighting*, Virginia Tech Transportation Institute and Thomas Jefferson University, https://www.energy.gov/sites/prod/files/2018/02/f48/gibbons_impacts_nashville18.pdf

2 *SSL Forecast Report*, Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/ssl/ssl-forecast-report



Left: Visible non-uniformities characterize illumination from high-pressure sodium and other bulb-based products. Right: The capability for improved optical control and more uniform distribution is visible after conversion to LED. Notice how the LED lights on the right do not emit light upward or directly into the camera. Photos courtesy of the Los Angeles Bureau of Street Lighting