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LEDs: the new revolution in lighting / Les LED : la nouvelle révolution de l'éclairage

LED lighting efficacy: Status and directions

Efficacité de l'éclairage LED : état de l'art et directions

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A B S T R A C T

A monumental shift from conventional lighting technologies (incandescent, fluorescent, high intensity discharge) to LED lighting is currently transpiring. The primary driver for this shift has been energy efficiency and associated cost savings. LED lighting is now more efficacious than any of the conventional lighting technologies with room to still improve. Near term, phosphor-converted LED packages have the potential for efficacy improvement between 160 lm/W (now) to 255 lm/W. Longer term, color-mixed LED packages have the potential for efficacy levels conceivably as high as 330 lm/W, though reaching these performance levels requires breakthroughs in green and amber LED efficiency. LED package efficacy sets the upper limit to luminaire efficacy, with the luminaire containing its own efficacy loss channels. In this paper, based on analyses performed through the U.S. Department of Energy Solid State Lighting Program, various LED and luminaire loss channels are elucidated, and critical areas for improvement identified. Beyond massive energy savings, LED technology enables a host of new applications and added value not possible or economical with previous lighting technologies. These include connected lighting, lighting tailored for human physiological responses, horticultural lighting, and ecologically conscious lighting. None of these new applications would be viable if not for the high efficacies that have been achieved, and are themselves just the beginning of what LED lighting can do.

R É S U M É

Un passage radical des techniques d'éclairage conventionnelles (incandescent, fluorescent, décharge de haute intensité) aux technologies LED est en train de s'opérer. La première raison de cette mutation est à rechercher dans l'efficacité énergétique de ces dernières et dans les économies associées. L'éclairage LED est maintenant plus efficace qu'aucune des technologies d'éclairage conventionnelles, mais il reste de l'espace pour des améliorations. À court terme, les ensembles à LED converties au phosphore peuvent encore voir leur efficacité améliorée de 160 lm/W à 255 lm/W. À long terme, il est concevable que les ensembles à LED à mélange de LED de différentes couleurs puissent atteindre des niveaux

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d'efficacité de 330 lm/W, quoiqu'atteindre de telles performances demande des avancées majeures du côté des LED de couleurs verte et ambre. L'efficacité des ensembles à LED détermine la limite supérieure du luminaire, ce dernier contenant ses propres canaux de perte d'efficacité. Dans cet article, sur la base d'analyses réalisées au *Department of Energy* au sein du *Solid State Lighting Program* américain, différents canaux de perte des LED et des luminaires ont été élucidés, et des domaines critiques permettant leur amélioration ont été identifiés. Au-delà d'économies d'énergie massives, la technologie LED permet de nouvelles applications et une valeur ajoutée non possible ou non économiquement faisable avec les anciennes technologies d'éclairage. Celles-ci incluent l'éclairage connecté, l'éclairage adapté aux réponses physiologiques humaines, l'éclairage horticole et l'éclairage respectueux de l'écologie. Aucune de ces nouvelles applications ne serait viable sans les hautes efficacités qui ont été atteintes, et qui ne sont elles-mêmes que les prémices de ce que l'éclairage LED peut faire.

1. Introduction

Light-emitting-diode (LED) lighting, has advanced to the point where it is the best option for almost every lighting application. Over the last 15 years, the efficacies of cool white LED packages have improved from around 25 lm/W (lumens per watt) to over 160 lm/W, depending on color quality and drive conditions. Simultaneously, the costs of LED packages have decreased to the point where LED lighting products can be competitive with conventional lighting products on a first cost basis, while offering significantly lower cost of ownership (initial cost plus cost of electricity cost) during its life cycle. Increasing efficacy and decreasing cost have allowed luminaire manufacturers to provide improved color performance, optical distribution, form factor, and advanced control of the LED lighting products.

Even with these advancements, considerable room for further improvements remains, not only in efficacy and cost, but also in a broader range of functionalities. In this article, drawing heavily on 2017 stakeholder inputs to the U.S. DOE SSL R&D Program [1], we give a status report on LED lighting, and discuss the opportunities and challenges associated with those further improvements. Our emphasis is on efficacy and the resulting energy savings, but we mention at the end some of the new directions in lighting for which new functionality enables additional value beyond efficacy. These include human physiological responses to light and its impact on human health and productivity; connected lighting and its impact on the Internet of Things and on sensing/control of the built environment; horticultural lighting and its impact on indoor farming; and ecologically conscious lighting and its impact on the environment.

2. Lighting product efficacies and energy savings

A comparison between the luminous efficacies (output of optical lumens/input of electrical watts, lm/W) and lifetimes of top-performing LED and conventional lighting products is shown in Table 1. The efficacies of LED products compare well to conventional products in every product category, and are now more efficacious than even the best performing conventional lighting products. The lifetimes also compare well, although, we note that the listed lifetimes for the LED products account only for the 70% lumen depreciation point, not for other possible failure mechanisms such as catastrophic failure and parametric color shift.

Taken together, the higher efficacy and extended lifetime of LED products give them a lower life cost of ownership compared to conventional lighting products. This is spurring adoption, which in turn results in significant energy savings at national and global scales; and as both efficacy and adoption of LED lighting continue to increase, these energy savings are projected to become even more significant.

Current annual primary energy savings for the U.S. from LED lighting are estimated at 0.3 Quads (quadrillion British thermal units), equivalent to approximately 30 TWh/yr and $3B/yr in energy and cost savings. Similar savings can be expected from the penetration of LEDs in Europe. As shown by the top line in Fig. 1 [2], total lighting energy consumption is expected to increase over the next two decades. However, as indicated by the light blue region of the figure, by 2035, if the U.S. Department of Energy (DOE) cost and performance targets are met, LED lighting could save 5.1 Quads of primary energy per year, equivalent to 500 TWh/yr and $50B/yr, and accounting for possibly 5% of the total U.S. energy budget. Worldwide, the savings would be 3–5$\times$ higher.

3. LED package efficacies

The heart of LED lighting and LED lighting products is the LED package, which both produces the various colors of light as well as mixes them to create white light. Here, we consider two LED package architectures whose spectra are illustrated in Fig. 2 [3]: the phosphor-converted (pc) architecture, which is dominant in today's products; and the color-mixed (cm) architecture, which has the most headroom for improvement.

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