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A Review of Advances in Lighting Systems' Technology—The Way Toward Lighting 4.0 Era

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(Invited Paper)

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ABSTRACT Research and development over the last century have historically concentrated on improving one specific aspect of energy efficiency. The market penetration rate for systems using solid-state light sources is currently between 40 and 45 percent, and it is rising. This article provides an update on the state of lighting technology based on the compilation of more than 160 recent documents. The only widespread use of solid-state lighting sources over the next years might help reduce greenhouse gas emissions by up to 500 Mtn per year and decrease electrical energy utilization for illumination by up to 4% by 2030. But this forecast could be severely affected by the "rebound effect." Switching to the SSL^2 concept, which consists of sustainable smart lighting systems based on solid-state lighting devices, might be one way to stop that harmful effect. Smart, human-centered lighting that incorporates light quality is driven by "appliance efficiency." This merely suggests that the "Right Light" should be provided by next-generation lighting systems with the best levels of quality and efficiency when and where it is needed.

INDEX TERMS Lighting systems technology, smart lighting, solid-state lighting (SSL), white light emitting diodes (LEDs), white organic light emitting devices.

I. INTRODUCTION

In 2019, around 2900 TWh ($\sim 3 \times 10^{15}$ Wh), or 13,5% of the world's yearly electricity generation, has been used for artificial light production. Even though this amount is still pretty large, it should be noted that until the beginning of 2010, electrical light sources were thought to have consumed about 2651 TWh of electricity, or about 19% of the world's total electrical production. The improvement in light system efficiency, while maintaining a constant service level (measured in quantity of light), can be used to explain this tendency, which points to the beginning of harnessing of consumption. Further, the use of "legacy" lighting technology is declining rapidly since the mid of last decade.

The last ten years have seen a challenge to legacy lighting technologies from solid-state lighting (SSL) systems and equipment based on light emitting diodes (LEDs), OLEDs, and laser diodes (LDs). In particular, LED has changed the game, outperforming legacy technologies in every way. Therefore, it is projected that all electric lighting would soon be based on SSLs.

Currently, SSLs move toward the anticipated result: replacing all legacy technologies. This is a significant shift in the lighting industry that is seen as a revolution (the third in the domain of artificial lighting since the dawn of humanity). Although the technology for creating white light from phosphor-converted LEDs (pcw-LEDs) is now fully developed, the luminous efficacy (LE) of the package is still being improved. The predicted maximum output for packaged pcw-LEDs is 255 lm/W. The luminous efficacies of LED-filament bulbs, available for domestic use in many industrialized countries, exceeded presently 200 lm/W, and they overcome the 160 lm/W target set by the US Department of Energy (DOE) for 2030 [1].

This work provides a comprehensive review on SSL technology advancements that can be the foundation for environmentally friendly smart lighting systems. It is based on the collection of more than 160 current documents.

TABLE 1. Potential Improvements in Research and Development at the Component or Device Level

Domain	R&D efforts and Improvement domains	Concerned Objective
White-light Light Emitting Diodes	Improving basic understanding of LED material-device-synthesis relationships [1]	Objective 1, Objective 2
	Understanding and Improving quantum dot down converters for on-chip LED usage [1]	Objective 1, Objective 3
	High Luminance Emitters: Improving efficiency at high luminance to enhance optical control, including device structures and phosphors. [1]	Objective 1, Objective 3
White-light Large Area Diffuse emitters	Advancing the efficiency and lifetime of emitter materials and device architectures for low profile, diffuse, and direct emitters [1]	Objective 1
	Improve light extraction efficiency and optical control for low profile, diffuse, and direct emitters [1]	Objective 1
White-light Laser Systems emitters	Developing phosphors that converts the laser light to eye-safe, broad-spectrum, and incoherent white light [2]	Objective 3
	Developing phosphors that can support temperature elevation due to Stokes shift losses [3] and support better long-term effects of intense radiation exposures [4]	Objective 1
	Developing efficient supercontinuum white laser sources coupled with optical fibers [5]	Objective 1

The objective's number refers to the list provided in the preceding paragraph.

TABLE 2. Potential Improvements in Research and Development at System Level

Domain	R&D efforts and Improvement domains	Concerned Objective
Lighting System	Developing the Lighting Application Efficiency (LAE) Framework: Understanding relationships between and energy impacts of light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness. [1]	Objective 3
	Improve power supply efficiency, functionality, and/or form factors. [1] Reduce light flicker	Objective 1, Objective 3
Human-centric lighting	Understanding and Demonstrating Human Physiological Impacts of Light: Translate lab-scale human physiological responses to light understanding to practical guidance and understanding of impacts in realistic lighting situations. [1]	Objective 3, Objective 4
Smart Lighting systems	Develop Connected lighting inserted in IoT global systems.	Objective 4
	Develop Visible Light Communications protocols.	Objective 4
	Develop light as a service concept.	Objective 4

The objective's number refers to the list provided in the preceding paragraph.

II. RECENT ADVANCES IN THE DOMAIN OF SSL AND THE WAY FORWARD

Based on the review of the literature, this section provides an update on solid-state lighting technology performances. It offers a fresh perspective on how SSL technology and lighting systems are developing, as well as, a summary of how the global market has changed over time by geographical region and end-use industry. It should be noted that since the middle of 2010, we have seen a net increase in planned technical advancements at system level, while those at the component/device level are becoming less common. The technological advancements from a few previous years concern both lighting systems and components.

All of these developments work toward at least one of the following goals.

- Objective 1: Increasing the efficiency and reliability at all levels from the component to the global system.
- Objective 2: Using more environmentally friendly materials and lowering the cost of individual bulbs and component parts.
- Objective 3: Enhancing the comfort-related aspects of light and putting a greater emphasis on the effectiveness of lighting applications.
- Objective 4: Adding extra features and services beyond just basic lighting for visibility and illumination.

As indicated in Table 1, this allows us to pinpoint a number of areas that still have room for improvement at the component or device level. According to Table 2, there is still a lot of development to be made in the area of lighting systems.

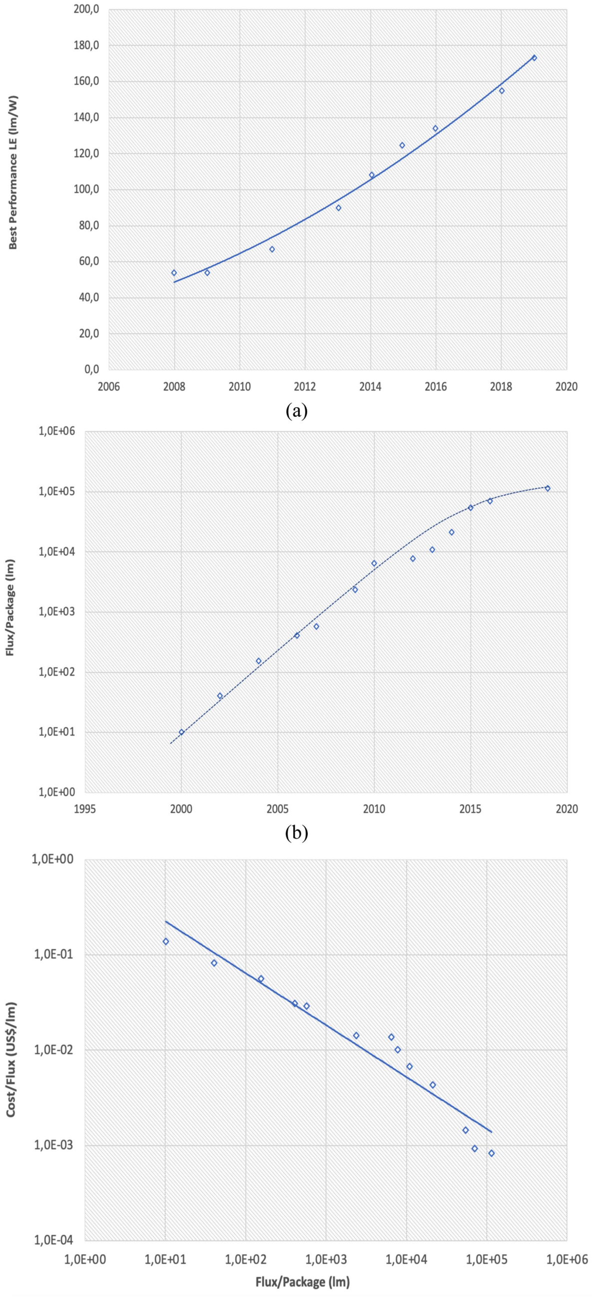
A. *WHITE-LIGHT EMITTING DIODES*

Even though some indicators of saturation are beginning to show, packaged white LED's performance is continuously improving every year. The improvements relate to light flux, LE, white light quality, and color rendering (as expressed classically by color rendering index – CRI), among other properties. Additionally, packaged LEDs continue to provide light quantity (expressed in lumens) at a lower cost. The question is whether LED manufacturers would be interested in promoting innovation to achieve even better efficacy levels considering that LED efficacy is presently the highest in the market and that improvements in this area only recently started to slow down [6], [27], [28].

The aforementioned improvements are clearly shown in Fig. 1(a). In addition, Fig. 1(b) demonstrates that the Haitz-law will continue to be applicable for at least a few more years. While Fig. 1(c) indicates the economic path expressed by the cost per emitted lumen by the package.

Fig. 2 highlights two widely recognized facts: 1) LE falls with increasing CRI, and 2) over 2500 K, LE also decreases with increasing color correlated temperature (CCT). At first glance, this latter fact could seem to contradict the saying "cool-white LEDs are more efficient than warm-white ones." This paradox can be understood by the fact that modern high-light quality cool-white LEDs at high CCTs have more energy losses than the preceding generation did. We should take note of the most recent announcement in LpR journal regarding Luxeon HL2X's record-breaking luminous flux, which is more than 318 lm at 700 mA and 85 °C junction temperature corresponding to a LE more than 310 lm/W [7].

The ability to produce white light from pcw-LEDs is now a fully developed technology, but as Fig. 3 shows, there is still room for improvement. Based on forecasts made using

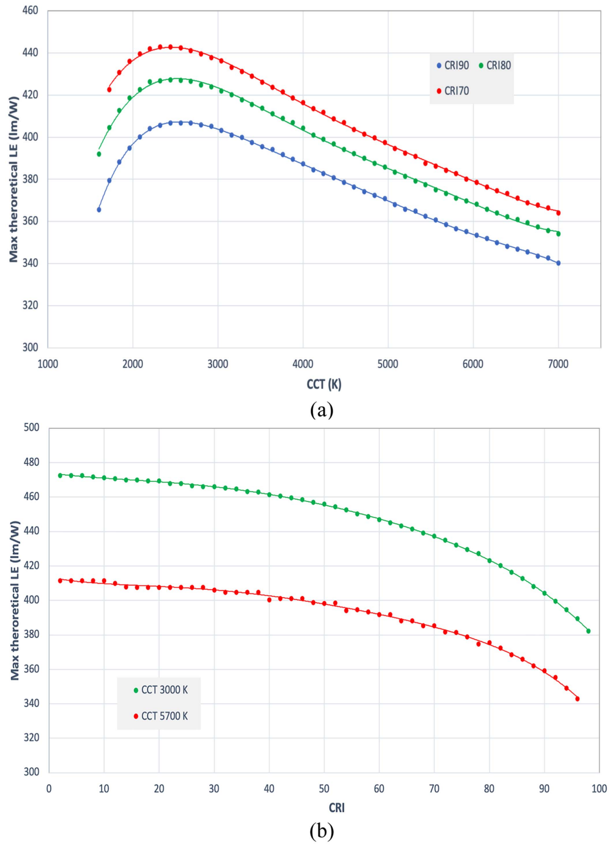


(a)

(b)

(c)

FIGURE 1. **(a) Best performing pcw-LED for LE. (b) Luminous flux per package. (c) Cost per emitted lumen per package.**



(a)

(b)

FIGURE 2. **Theoretical maximum LE of pcw-LEDs as a function of (a) correlated color temperature and (b) CRI. Data from [8].**

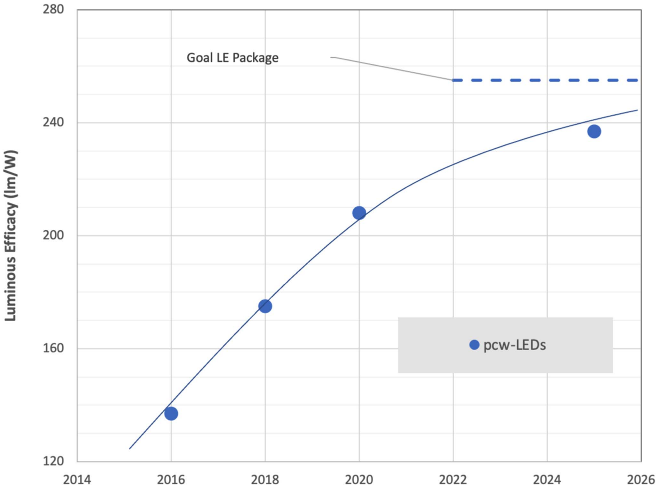


FIGURE 3. **LE evolution projections for 3000 K pwc-LEDs CCT pcw-LEDs and DOE goal (for a current density of 35 A/cm^2 and junction temperature 25 °C). Data from [8].**

historical LE measured values up until 2016, the DOE set a target of 255 lm/W for packaged pcw-LEDs [8].

At the elementary manufacturing level, blue die efficiency has significantly increased since [8], but it is still at its greatest at low current densities. LED packages have exceeded 80% efficiency according to the "best" research currently available, but only at modest current densities. The LED efficiency declines with the higher current densities desired for low-cost lighting to promote greater market penetration. This alleged "efficiency droop" is estimated to be 10% from 10 to 35 A/cm^2, and 15% from 100 A/cm^2. It will be difficult to avoid Auger recombination, the main physical process that causes efficiency droop [9].

Even though pcw-LED is the dominating technology at the moment, two additional architectures have recently demonstrated their viability and are increasingly being regarded as viable alternatives to the current standard:

In order to provide white light, the hybrid LED (Hy-LED) architecture combines a blue LED, a yellow-green phosphor, and a red LED. This white light architecture is novel yet developing. For instance, in the Cree TrueWhite and OSRAM Brilliant Mix technologies, greenish-white light from a pcw-LED is blended with a pure red component from a red die. The original goal of the technology was to boost the R9 (the ninth component for CRI calculation) value by increasing the red concentration in the spectrum. This architecture has a significant efficiency gain over the more typical pcw-LED architecture because the red die doesn't face Stokes losses when producing red light.

According to DOEs predictions [8], the upper potential for HY-LEDs is thought to be around 280 lm/W, or an efficiency of roughly 68%, while the efficiencies and CRIs can be better. This architecture's primary drawback is the inclusion of two different technology chips in the package: AlInGaP for the red and AlInGaN for the blue. This induces different thermal and electrical behaviors, more complicated drivers, as well as various aging mechanisms and light emission drifts, they have to be taken into account for system management. The opposite is also true; by using HY-LEDs, CCT-tunable light sources that perfectly suit the requirements of the human-centric lighting concept can be obtained.

Mixing colors (at least primaries: red, green, and blue) to obtain a white light source is another method that can be used. This concept has been around for a while, but up until a few years ago, it was impossible to implement due to a number of color-LED technology-related restrictions. The concept is particularly appealing since it makes it possible to create fully color-tunable light sources without the usage of phosphors, as well as naturally CCT-tunable white light (this discards all stoke losses that suffer pcw-LED and HY-LED). The concept might now become appealing again thanks to the development of color-LED technology. The name "color mixing white LEDs" refers to this new technology (cmw-LED).

When phosphor down-conversion losses are overcome, DOE predicts that the technology's maximum potential will be around 330 lm/W. The main issues are the following:

1) a low CRI, which can be improved by adding more mixed colors, like amber;
2) a sophisticated color stability management system; and
3) as in the past, a lack of efficient green and amber dies.

To meet the ambitious DOE objective set at 327 lm/W, R&D initiatives must be intensified in that direction (this includes optical and driver loss enhancements).

The forecasts and objectives for the LE of the three competing technologies mentioned above are summarized in Fig. 4.

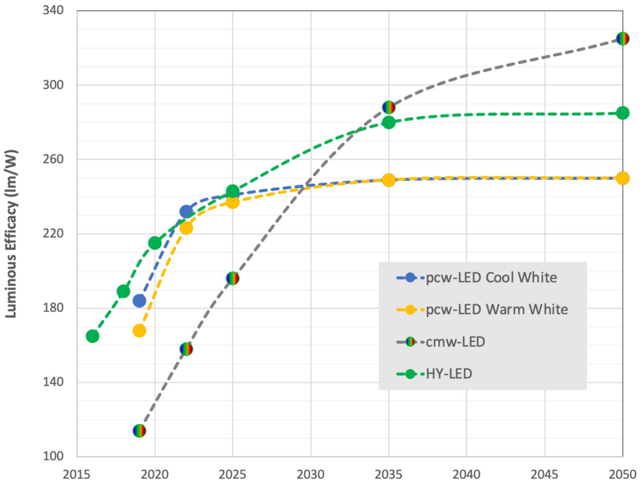


FIGURE 4. **Projection for the evolution of LE for pcw-LEDs (cool and warm white), HY-LEDs, and cmw-LEDs (warm white only) and goals fixed by DOE. Drive current density (35 A/cm^2) and junction temperature 25 °C. Data from [1] and [8].**

Further, GaN-based nanowire (NW) heterostructures have attracted attention recently due to their potential to produce emissions with wavelengths ranging from ultraviolet to near-infrared regions, providing the lighting industry with additional flexibility to create white-LEDs without phosphor. The technology for NW LEDs is now still developing. Due to their exceptional qualities, such as drastically reduced polarization fields, dislocation densities, and the associated quantum confined Stark effect because of their efficient strain relaxation, III-nitride based NW light-emitting diodes have drawn a lot of attention as a potential candidate for SSL for making cmw-LEDs. More specifically, AlGaN shell in InGaN/(Al)GaN core-shell LEDs improves carrier confinement and decreases non-radiative surface recombination that occurred in bottom-up NW heterostructures, such as dot/disk/well-in-a-wire or core-shell structures, that are axially or radially aligned. Although III-nitride NW LEDs are typically produced on Si substrates, NW LEDs on copper (Cu) have recently been shown to be feasible. They have a number of benefits, including improved light extraction efficiency and more effective thermal management as a result of the use of extremely high thermal conductivity metallic substrate. These outstanding qualities are opening the door for a brand-new generation of optoelectronic devices for wearable electronics, flexible displays, and SSL in the future.

Furthermore, since they are sought for use in numerous applications, flexible LEDs are currently the subject of significant research. This is made possible through the usage of NWs. By combining the high efficiency and long lives of inorganic semiconductor materials with the high flexibility of polymers, Guan et al. [11] showed that polymer-embedded nitride Nano-Wires offer a beautiful solution for making flexible optoelectronic devices. Due to the extreme flexibility of the individual NWs used in these prototype devices, the NW arrays—which are encased in a flexible film and may be lifted off of their native substrate—can survive significant deformations. In addition, individual NW footprints are much smaller than the average curvature radius of LEDs (i.e., on the order of a few millimeters or more).

TABLE 3. LE Data Collected by IEA 4E-SSL Annex to Track the Evolution During the Last Decade

	Dataset Source	Number of lamps	Entry Years	Number of luminaires	Entry Years
Market Data	US Lighting Facts database	63 691	2009–2016	73 814	2010–2019
	Australian Market Survey	3196	2017–2018		
Register data	Energy Star database	9,671	2009–2019	19 200	2009–2020
	Japan energy-saving product database	433	2017		
	Thailand Label No. 5 product database	95	2019		
	Korea high-efficiency certification system database	3487	2017–2019	29 255	2017–2019
	Design Lights Consortium (DLC) Quality Product Listing	9 204	2016–2020	27 578	2016–2020
	Total listing	**89 777**	**2009–2019**	**149 847**	**2009–2019**

Increased lighting efficiency at the component level is evidently converted into wall-plug efficacy (WPE) efficient lighting fixtures. The International Energy Agency 4E-SSL Annex[1] gathered data from numerous international databases totaling about 90 000 lamps and 150 000 luminaires for the 10-year period between 2009 and 2019 in order to track the WPE evolution of various LED-lamps and LED fixtures, as shown in Table 3 [12].

From that impressive database, Annex's experts could deduce trends looking at the average WPE values as well as the number of products lying in the 20- and 95-percentils of the registered products. A few of the results, extrapolated to 2024, are shown in Fig. 5. It is evident that higher percentile products have advanced significantly during the previous ten years in all categories.

Even if the advancement is remarkable, there is still room for improvement. According to DOE, by 2035, WPE efficacy, which includes thermal droop, driver efficacy, and light extraction from the luminaire, could reach an 86% level, up from 2019's values of 75% for LED luminaires and 64% for A-shape LED lamps. In this scenario, the WPE will go along the path depicted in Fig. 6.

B. WHITE-LIGHT LARGE AREA DIFFUSE EMITTERS (W-LAD)

In today's consumer electronics, organic light-emitting diodes (OLEDs) have become a standard technology for display applications. Even if it is more difficult, it is still possible to infiltrate the lighting domain. Due to their superior and healthy white light, OLEDs are actually regarded as a viable technology for SSL sources.

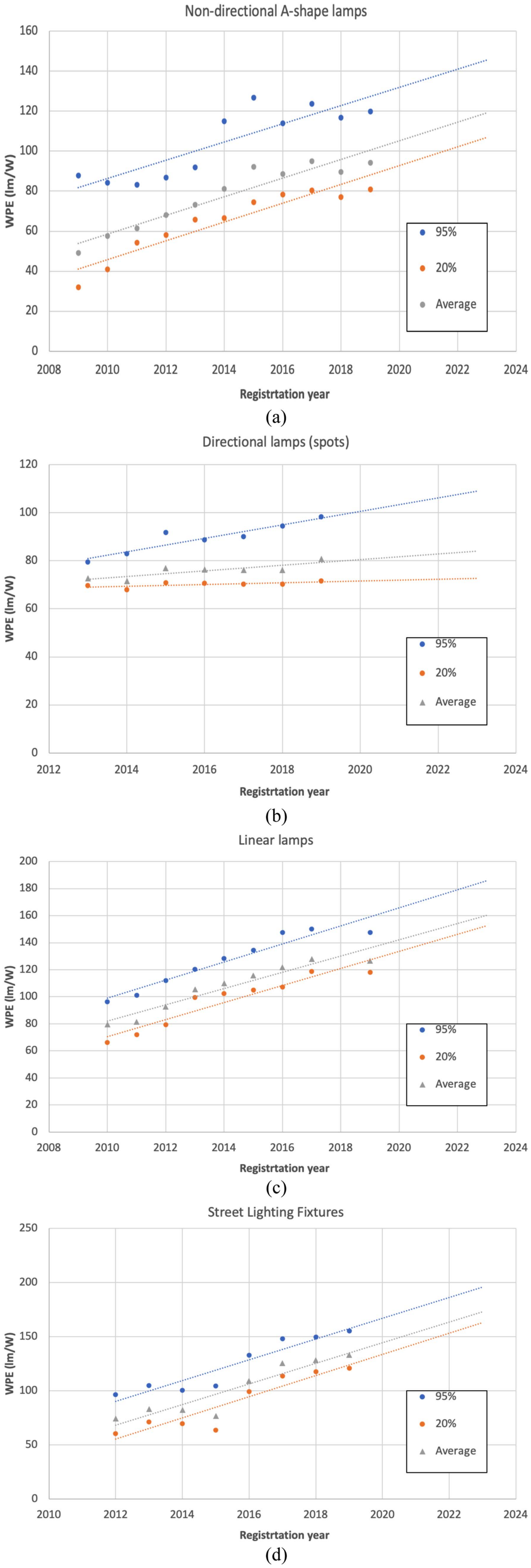


FIGURE 5. LE efficacy evolution observed using international databases. (a) Non-directional LED lamps (A-shape). (b) Directional LED-lamps (spots). (c) Linear LED tubes. (d) Street lighting LED-luminaires. Data from [12].

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[1] Online Available: https://www.iea-4e.org/ssl/

FIGURE 6. **Evolution of the average WPE of LED any-type and DOE goal set by 2035. Data from [8].**

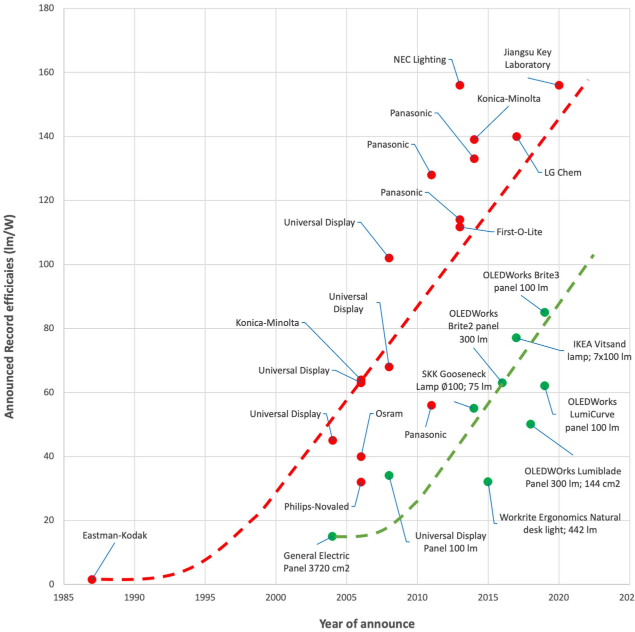


FIGURE 7. **Record luminous efficacies announced since the demonstration of the first white OLED (Eastman-Kodak, 1987). The green dots correspond to OLED lighting panels and lamps (commercially available).**

OLEDs are diffuse "lambertian" type emitters by definition; therefore, they may be seen directly without the use of diffusers that are needed to tame the intense brightness of LEDs. OLEDs can also be integrated on any suitable surface, such as glass, plastic, or metal foil. We believe that, because of their superior mechanical qualities, flexibility and transparency, and cost-effective production in large quantities, particularly when using roll-to-roll techniques this technology will earn more and more parts in the general lighting market. The technology responds also to customers who are with higher aesthetic expectations for lighting that integrate high quality of life and art nowadays.

According to Fig. 7, between 2004 and 2020, the year-on-year LE yield is excellent, increasing by 33% for lighting manufacturers and 28% for laboratory prototypes (across all technologies) (commercial or demonstrators).

On the other hand, the theoretical upper limit LE for white OLEDs is around 240 lm/W for a device without any outcoupling enhancements [14], which is 65% lower than the absolute record value of 156 lm/W obtained independently, within a 7-year interval, by NEC Corporation (Japan) and Jiangsu (China) [13].

On the other side, current commercial OLED panels have an effectiveness that lags behind LED panels by about 90 lm/W [1]. However, according to US DOE projections, for OLEDs to be competitive and have the best chance of capturing a share of the lighting industry by 2035, the device's LE and longevity must both grow by a factor of 2 and a factor of 3, respectively, in comparison to 2018 values. At the same time, OLED luminaire WPE must reach more than 150 lm/W; this calculation is based on the assumption that the device efficacy is 180 lm/W and that the entire efficiency from the device to the luminaire is 88%. In Fig. 8(a) and (b), the DOE goals are displayed.

Furthermore, continuing scientific progress in the fields of emitter materials and device designs will be necessary for OLED device advances [1]. The following are the main R&D obstacles that DOE has identified as affecting the price and efficiency of OLEDs in lighting:

- performant materials for stable, efficient devices;
- light extraction from the device;
- advanced mass fabrication technology;
- luminaire design—including optical control and driver's efficiency;

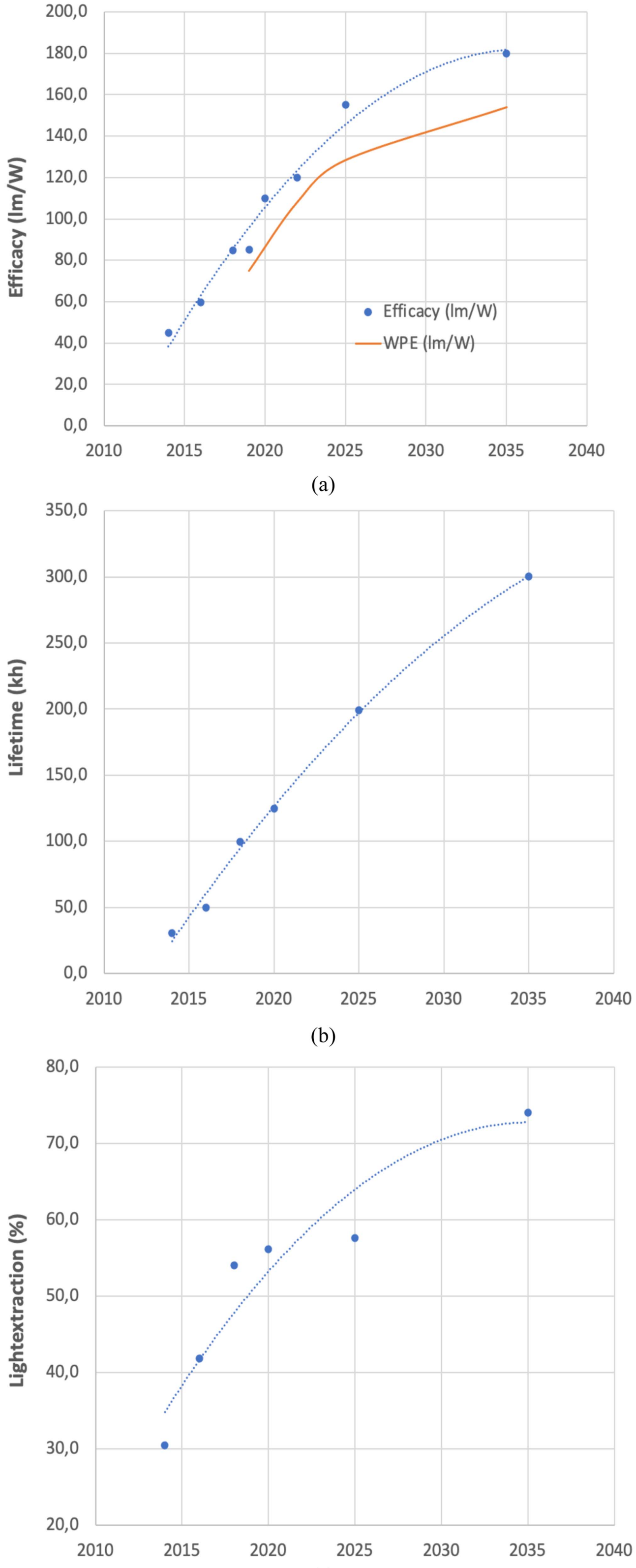
For transparent white bottom-emitting OLEDs, the transparent electrode, for example, must have excellent optical transparency (i.e., >90% in the visible range), strong electrical conductivity (i.e., a sheet resistance of 20 Ω/□), and mechanical flexibility.

Fig. 8(c) shows the DOE fixed target (x1,4 compared to 2018) for light extraction efficiency from a competitive OLED device by 2035.

C. WHITE-LIGHT LASER SYSTEMS EMITTERS

Blue LDs have been used to replace blue LEDs since the early 2000s, according to Narukawa et al. [15].

This technology's first commercial focus was on the automotive industry. BMW attempts to develop effective white light for vehicle headlights by fusing blue-emitting laser-diode light with a phosphor at least since 2011 [25].



(a)

(b)

(c)

FIGURE 8. US DOE's roadmap for improving OLEDs based on three parameters. (a) LE for devices (blue), and luminaire WPE. (orange). (b) Device lifespan L70B50. (c) Light extraction from the OLED devices. Data from [1].

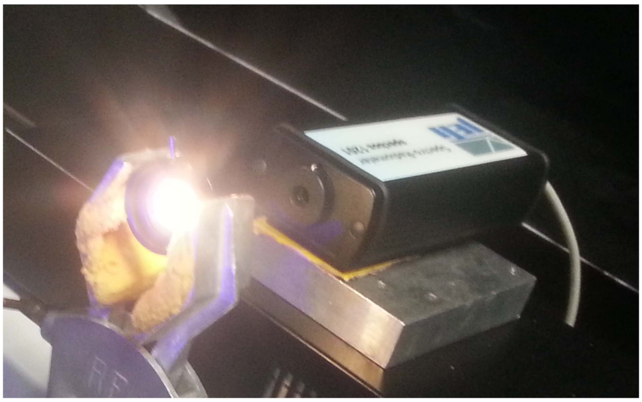


FIGURE 9. White light obtained by exciting remote phosphor by blue light from LD (40 lm/W; 4000 K; CRI: 94). Photo credits: LAPLACE laboratory [16].

Since then, the technology and its potential application to lighting have piqued the curiosity of numerous academic research centers and business development divisions around the globe. Narukawa demonstrated 26 lm/W for a flux of 5 lm, a CCT of 5800 K, and a CRI of 85. A laser-activated remote phosphor (LARP) white source with a 40 lm/W CCT and 94 CRI was created by Ledru et al. [16] in 2014 (see Fig. 9).

Since then, the use of violet lasers has been investigated, and SoraaLaser has developed white-light surface-mount devices that have an emitting area of 300 μm^2 and can provide up to 500 lm of output [2].

It is well known that efficiency droop in LED technology results in a progressive drop in light emission efficiency as the operating current density of the device rises. There are two problems with this unwanted effect: 1) the maximum efficiency is limited with higher currents, 2) the maximum light density an LED chip can output is significantly impacted. The droop effect is eliminated in a solid-state LD by the stimulated emission, which enables instantaneous recombination of injected charges into the emission area.

In reality, although if the WPE of LD is lower than that of LEDs (which is 70% of the electrical power passing through them into light at a power density of 3 W/cm^2), the LDs can nevertheless be more efficient than LEDs at higher currents due to the suppression of the droop effect (see Fig. 10).

Due to the significant blue light component in the spectrum, as shown in Fig. 11, using blue, violet, or even near-UV lasers to generate white light may be dangerous for human vision. However, the blue light component can be decreased by modifying the phosphor shape [19] as depicted in Fig. 12.

Beyond the abilities of LARP devices to 1) achieve high CRIs using custom phosphors; 2) reduce the harmful blue-component of the spectrum by optimizing the shape of the spectrum; and (3) reduce aging effects due to long-term exposure in intense radiation by choosing the right ligands and substrates, researchers anticipate achieving, in the mid-term,

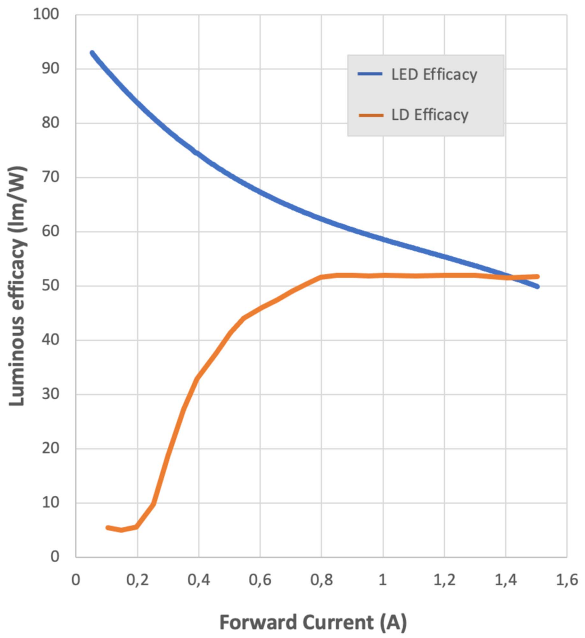


FIGURE 10. **Comparison of the forward current-dependent luminous efficacies of LDs and LEDs. From original data [18].**

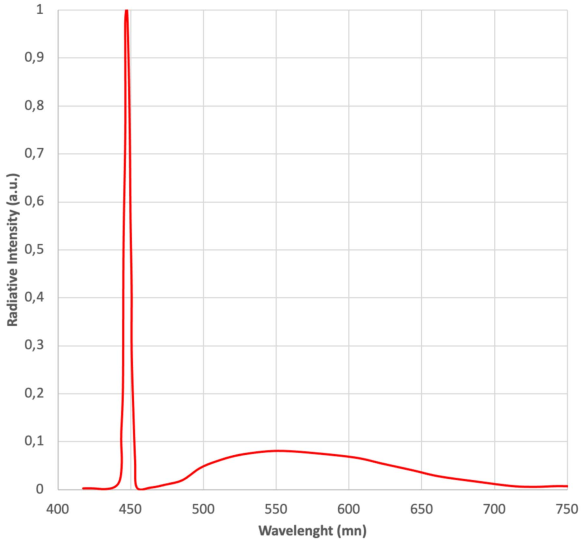


FIGURE 11. **Spectrum obtained from an experimental high CRI LARP in LAPLACE Laboratory [20].**

efficacies as high as 200 lm/W as reported by Laser Focus World [21], and even higher, at high currents. Nevertheless, this technology has the potential to capture a sizable portion of the market in industries where high fluxes are required.

III. TOWARDS “LIGHTING 4.0 ERA”—THE “SSL^2” CONCEPT

LED lighting has contributed to saving almost a half billion tons of CO_2 from entering our atmosphere each year because of this exponential increase in LE. Based on market shares, the analyst wished to distribute these savings among the major packaged LED manufacturers in response to an IHS report (see Fig. 13) [22]. However, this model doesn't take into account the behavior of the end-user and excludes the action of the “rebound effect” or “Jevons' Paradox”[2] that tends to offset the beneficial effects of the new technology or other measures taken. For instance, the energy savings could be eroded as people find new uses for inexpensive lights. As related by the Pulitzer Prize-winning Phil McKenna, Thomas Theis director of the Institute for Environmental Science and Policy said “I am doubtful that we will save any energy by going to LED

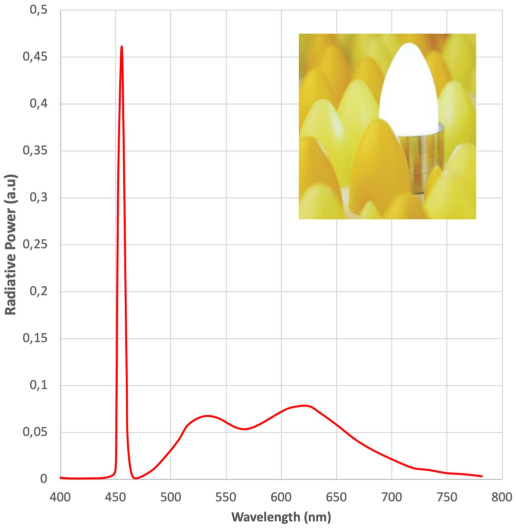


FIGURE 12. **It is possible to reduce the blue light component by shaping the phosphor [19] (photo credits: LAPLACE Laboratory).**

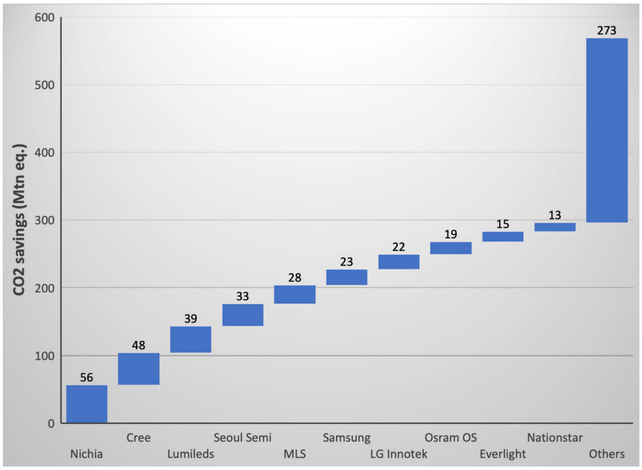


FIGURE 13. **Greenhouse emission savings thanks to LED lighting reattributed to packaged-LED manufacturers. Data from [22].**

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[2] In energy economics, the rebound effect is the reduction in expected gains from new technologies that increase the efficiency of resource use, because of behavioral or other systemic responses. This paradox has been formulated by William Stanley Jevons in his book published in 1865.

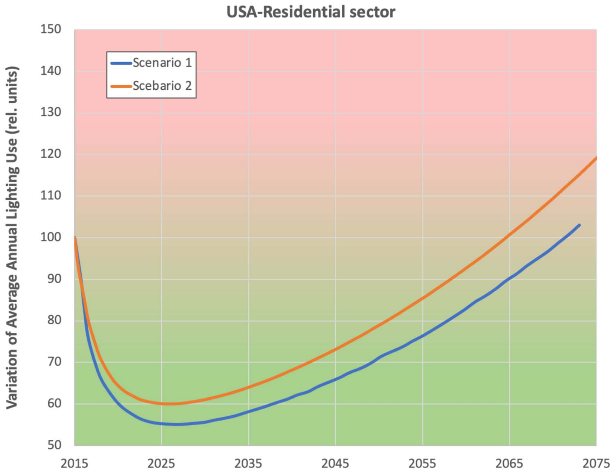

FIGURE 14. **Results of rebound effect on the average US-household annual electricity use for lighting. Original data from [24] modified by G. Zissis.**

lights" [23]. Hicks et al. [24] elaborated various scenarios to illustrate the rebound effect on the average annual US household consumption. Fig. 14 shows the impact of rebound effect under two scenarios—Scenario 1: Individual households do not use more light as the cost of lighting decreases but population growth and increase in housing size over time result in the increase of energy demand for lighting; Scenario 2: Energy use increases over time because individual households demand more light as the cost of lighting decreases and lit areas increase as a result of population and housing area growths.

Both scenarios show that the LED "effect" will vanish somewhere in between 2065 and 2070. Even if this seems to be far beyond in the future, this is not acceptable; solutions are then necessary to solve the issue. One potential solution consists of switching to smart human-centric lighting driven by both "application efficiency" and quality of light. This is usually abbreviated as "smart lighting" concept. This fourth generation of lighting systems (Lighting 4.0) is imminent. However, the definition of a smart lighting system is still diffuse. To compensate for this deficit, Zissis et al. [26] came up with the following definition.

"A smart lighting system has a principal function which is to produce, at any moment, the right light: where it is needed and when it is necessary. It should adapt the quantity and quality of light to enhance visual performance in agreement with the type of executed tasks. It must guarantee well-being, health and safety of the end-users. It should not squander passively the resources of our planet and limit actively the effects of light pollution on the biotope, or, any other impacts on the environment. Ideally, the system could offer additional services (geo-localization, data connectivity …) to the end-users preferably through Visible Light Communication protocols."

Smart lighting systems are part of the solution because they allow to "Light-up smart," to a sustainable and affordable way, where it is needed, when it is necessary, and as best as possible! This leads us to the following proposed "Sustainable Smart Lighting – SSL^2 Concept":

A SSL (the first "SSL") system uses and optimizes in an intelligent way the best existing technology, aka, solid state lighting (the second "SSL") to best fulfill, in an affordable way, the present needs for artificial light and reduce undesirable side-effects, without compromising the ability of future generations to innovate.

That way SSL^2 concept (solid state lighting coupled to SSL) will allow an efficient and robust retaliation to Jevon's paradox effects. To include all these aspects, analysts/scientists/engineers think that LE is no more the best metrics to account for quality. A proposal consists to replace (or to supplement) LE and WPE with a new metric called "Lighting Appliance Efficacy" (LAE).

This LAE metric should include at least the following aspects:

1) energy efficacy;
2) spectral efficiency following the application;
3) environmental impacts;
4) end-uses acceptability and satisfaction;
5) economic affordability.

LEA should be the new frontier in improving the next generation of lighting systems. LEA can enable optimization of the various factors of lighting application efficiency according to understood tradeoffs between the various "efficiency" parameters listed in the above lines. It opens clearly the way to the characterization of SSL systems.

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