C. R. Physique 19 (2018) 159–168

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

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

LED lighting, ultra-low-power lighting schemes for new lighting applications

L'éclairage LED, concepts d'éclairage à ultra-basse consommation d'énergie pour de nouvelles applications

Marc Fontoynont

Danish Building Research Institute, Aalborg University, Copenhagen, Denmark

ARTICLE INFO

Article history:
Available online 28 December 2017

Keywords:
Efficient lighting
Daylighting
Colour rendering
Total Cost of Ownership
Virtual Reality

Mots-clés :
Eclairage efficace
Éclairage naturel
Rendu de couleurs
Coût total de possession
Réalité virtuelle

ABSTRACT

In 2018, Solid-State Lighting (SSL) can totally outperform, if properly designed, most of other lighting products used for general lighting applications. This concerns various attributes such as luminous efficacy, life, spectral qualities, dimming potential, and more and more total cost of ownership. SSL can also mimic a large variety of reference light sources from candlelight to sunlight. The absence of international standards concerning LED modules remains the major difficulty for luminaire manufacturers and their clients, since perfectly matching replacement of ever-changing LED modules is not guaranteed over time. But extraordinarily innovative lighting schemes can be developed, bridging the gap between the world of entertainment and the world of general lighting, and leading to new lighting schemes with more powerful emotional content. LED sources, mostly DC driven, also can benefit from progress in photovoltaics and batteries, as well as wireless control to offer integrated solutions. This could radically change the operation of lighting in the next 10 years.

RÉSUMÉ

En 2018, les dispositifs luminescents solides (SSL) peuvent surpasser, s'ils sont correctement conçus, la plupart des autres systèmes d'éclairage couramment utilisés. Ceci concerne différentes caractéristiques telles que l'efficacité lumineuse, la durée de vie, les qualités spectrales, le potentiel de gradation et, de plus en plus, le coût total de possession. Les SSL peuvent aussi imiter une large variété de sources lumineuses de référence, de la chandelle au soleil. L'absence de standards internationaux concernant les modules LED reste la difficulté majeure pour les fabricants de luminaires et leurs clients, puisque la possibilité de remplacement à l'identique de modules LED qui changent régulièrement n'est pas garantie dans le temps. Mais des schémas d'éclairage extraordinairement innovants peuvent être développés, jetant une passerelle entre le monde des loisirs et celui de l'éclairage généraliste, conduisant à de nouveaux modes d'éclairage avec un contenu émotionnel encore plus puissant. Les sources LED, pour la plupart alimentées en courant continu, peuvent aussi tirer bénéfice des progrès dans les domaines de l'énergie photovoltaïque

---

E-mail address: mfo@sbi.aau.dk.

https://doi.org/10.1016/j.crhy.2017.10.014

et des batteries, aussi bien que dans celui du contrôle sans fil pour offrir des solutions intégrées. Cela pourrait changer radicalement la mise en œuvre de l'éclairage dans les dix prochaines années.

0. Introduction

Light-emitting diodes (LEDs) were first used as luminous devices associated with electronic equipment (displays, dashboards, control panels, etc.) where their ability to run on low voltage and to provide energy-efficient source with saturated colour and high versatility were the main drivers. We had to wait until 2010 to see that such technology could massively be deployed for general lighting, in competition with technologies such as halogen, fluorescent, metal halide, or sodium. Reduction in costs, improvement in colour rendering (CRI), adjustment of attributes as a function of applications made the LED sources more attractive, beyond their energetic performance (Fig. 1).

Today LED-based luminaires become standard solutions in buildings for recessed circular spotlights, or 60 × 60 ceiling flat luminaires. LED luminaires are also becoming a standard in street lighting, although the High-Pressure Sodium lamps they replace have a high efficiency. The reason stands in the optical precision of the LED luminaires, which leads to an improvement of the ability of the luminaires to better distribute fluxes over and around streets, with less flux toward the sky (but this is however often obtained at the cost of increased glare). LEDs also offer improved spectral properties leading to possible improvement of visibility and higher satisfaction of the users in urban environments. Due to the significant improvement of the luminous efficacy of Solid-State Lighting (which is the ratio of delivered luminous flux (lm) to the electric power (W) of the source – unit lm/W), SSL is expected to represent 88% of the quantities of light delivered (lumen·hours: luminous flux in lumens times duration in hours) produced in the USA by 2030 [1]. The luminous efficacy of LEDS for general lighting will stabilize in the range of 150 lm/W to 200 lm/W, which is well above all other light sources of white light.

It is clear that beyond energy efficiency, which is the major driver for the deployment of SSL today, there are many other reasons for the development of SSL: this technology can offer significant benefits for users and facility managers, with sometime radical change in the way lighting installations can be designed and maintained.

1. Improved spectral performances for colour rendering

The continuous spectra of LEDs, the absence of emission of UV and IR radiations, make them potentially attractive sources to illumination of light-sensitive objects in good conditions. However, the emission of blue radiation can be significant if LEDs are not selected with care. Typical light-sensitive materials are clothing, oil and water-colour paintings, organic materials, photographic prints, etc. The improvement of Colour-Rendering Indices (CRI) [15] has been a high priority on SSL. Solutions first dealt with development of clusters of LEDs (mixing warm white, cold white, and Red-Green-Blue-Amber (RGBA) LEDs. Progressively, the spectral quality of individual white LEDs (from warm white to cold white) was significantly improved, with visual aspects closer to halogen lamps (for sources with Correlated Colour Temperatures (CCT) of 3000 K, ("warm" light)), and significantly better than fluorescent or metal halide for higher CCTs ("cold" light).

LEDs can offer superior colour rendering to most arc sources (metal halide, sodium, and fluorescent sources) if they are selected correctly: they can provide vivid colours, with good saturation, and colour temperatures (CCT) in accordance with the products that should be illuminated Figs. 2 and 3). But there are many low-quality LEDs entering the lighting market, which are not at all appropriate for stores and museums, for instance. It is important to ask for quality insurance and stability of performance to suppliers concerning colour rendering. Beyond the typical Colour-Rendering Index (CRI, ILV) – use at least 90 if possible –, and the colour temperature (between 2700 K and 5000 K, depending on the desired luminous atmosphere), the present trend [16] is to qualify light sources with two indexes: R_f for rating the Colour Fidelity (Colour Fidelity Index), and R_g (Colour Gamut Measure) to rate colour distortion. This was developed because some lamps with high CRI (the previous definition of colour quality) were found to create some unacceptable colour distortion for demanding uses. It is therefore important to select products with a clear rating (R_f and R_g).

Once the lighting quality is obtained, the next objective is the reduction of the Total Cost of Ownership (TCO), in comparison with the solutions SSL is supposed to replace. The Total Cost of Ownership includes the initial cost (investment and installation) as well as the operating costs (maintenance, electricity consumption, replacement of light sources). The cost of professional equipment can be sometimes lower with LEDs, but most often they are 10 to 30% higher when equipped with SSL. Most gains in the TCO can be obtained through the reduction of electricity use and maintenance, and in relation with the dimming potential of LED lamps. Typical return on investment (ROI) in case of replacement of fluorescent installations by SSL is less than 4 years for installations used at least 4000 hours a year [2], which is typical of office spaces. Most SSL solutions are expected to last at least 40,000 hours (state-of-the-art rated life), and sometimes more. But the flux decreases progressively over time, reducing the interest of SSL solutions beyond the rated life.

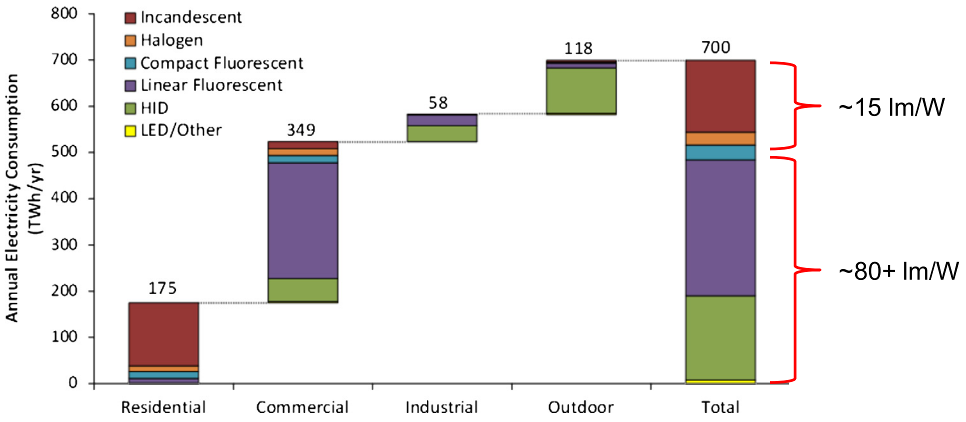

Fig. 1. Distribution of electricity consumption for light production (TWh/year) between the different markets and lighting sources. Note that most of consumption is concentrated in lamps with high luminous efficacy in the commercial, industrial, and outdoors markets, meaning that by far most of lighting production (lm·hours) is produced today by high-efficiency sources. To contribute significantly to energy savings, LED lamps aim at 150+ lm/W luminous efficacy (after 2012 DOE Solid-State Lighting Multi-year Program Plan).

LED luminaires can operate without maintenance, except a slight cleaning in case of dirt deposits. In LED luminaires, it is rare to change the light sources (called LED modules, due to the absence of international standards). Anyway, progress in LED module development is so rapid that there is a high probability that it will not be possible to replace a failing product by one that is identical, after a period of use of more than 5 years. In consequence, for professional lighting (commercial in particular), it is recommended to purchase products from well-established companies offering warranties (many companies offer 3–5-year warranties). It is also recommended to purchase a few extra luminaires for safety (typically 5–10% of the stock) to allow replacement in case of failure before the end of life.

The flux of LEDs decreases continuously during operation, and LEDs do not collapse abruptly. The human eye hardly notices a decrease less than 30% of the power over operating hours. This gives a margin of acceptance for the decrease of flux and a resulting extension of lamp lifetime.

The rating of life of LED products uses a nomenclature related to the statistical testing of product [3].

There is always a risk that one light module may not perform as expected. LED modules are rated as follows:

- life time L_x.
- failure fraction B_y.

An attribute such as $[B_{50}, L_{70}]$ means that at least 50% of the products have at least 70% lumen maintenance for the projected number of operating hours (typically 40,000 or 60,000 h). A 70% maintenance value is common. B_y can be selected at high values B_{60}, B_{80}. The issue of life should be part of any contract with a supplier, attached with warranties.

For example, in museums, where lights on paintings are used about 10 hours a day (about 3000 hours a year, the LED projectors have typically a life of 13 to 20 years. In shops, lighting tends to be used about 5000 hours/year, leading to a life of products of 8 to 12 years, which is in line with the frequency of refurbishment of stores.

Today, the whole industry of light projectors is integrating LED modules (with a large range of powers, from a few watts to over 100 watts). These projectors successfully replace projectors with metal halide or high-pressure sodium lamps used in commercial centres, or even in sport facilities. At low power, they now offer zooming and framing possibilities, as well as colour adjustment, which are very attractive in museums. For closed environment, they can also diminish the thermal load in comparison with inefficient installations, leading to a reduction in air-conditioning loads.

Finally, what may be even the most attractive attribute of LED light sources is the ability to vary (or dim) the luminous power on the entire range of power (0 to 100%) without any modification of the spectrum of the LED, which can be either white, red, green, blue, or amber, typically. This can lead to extremely attractive solutions:

1) to adjust, on site, the luminous power to reach the expected effect;
2) to dim, during operation, very progressively the power, sometimes in a way that cannot be perceived;
3) to vary (softly or rapidly) colours when using multi-coloured chips or clusters of LEDs.

Such features are of great interest in the world of entertainment (shows, commercial spaces). They are also quite attractive in city beautification of dynamic façade designs. Here we can clearly see the merging of display technologies (screens and video projectors, using RGB, RGBA or any other combinations of LEDs (see also Figs. 4, 5).

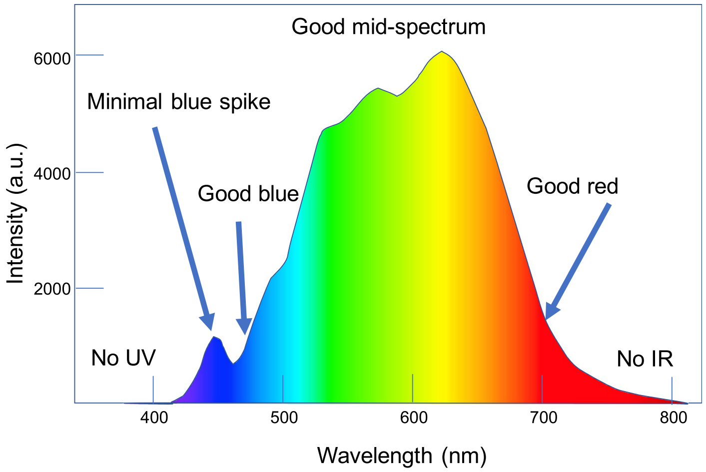

Fig. 2. Improvement of the spectra of LEDs showing interest for the quality of rendering of objects in museums and presentation of objects in shops (source Xicato).

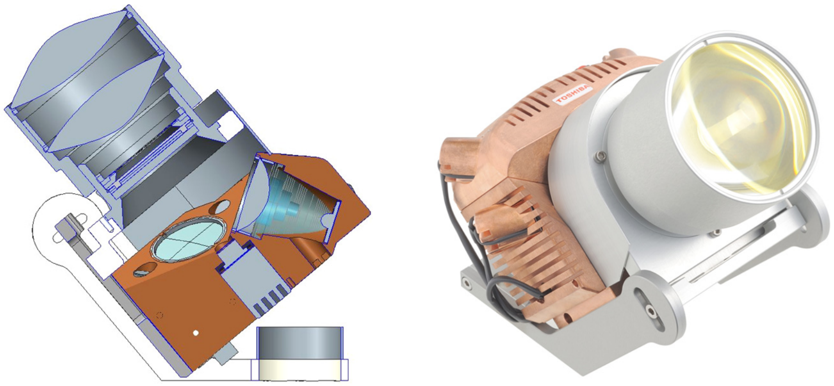

Fig. 3. LED luminaire developed to light the “Mona Lisa” painting in The Louvre museum, Paris. It uses multichip solutions to improve the mixing of cool white, warm white, red, blue, green, and amber LEDs. This allows for spectral corrections due to protective glass and ambient lighting, and attenuates shifts of colours on the painting over time [4] (source Sklaer Lighting).

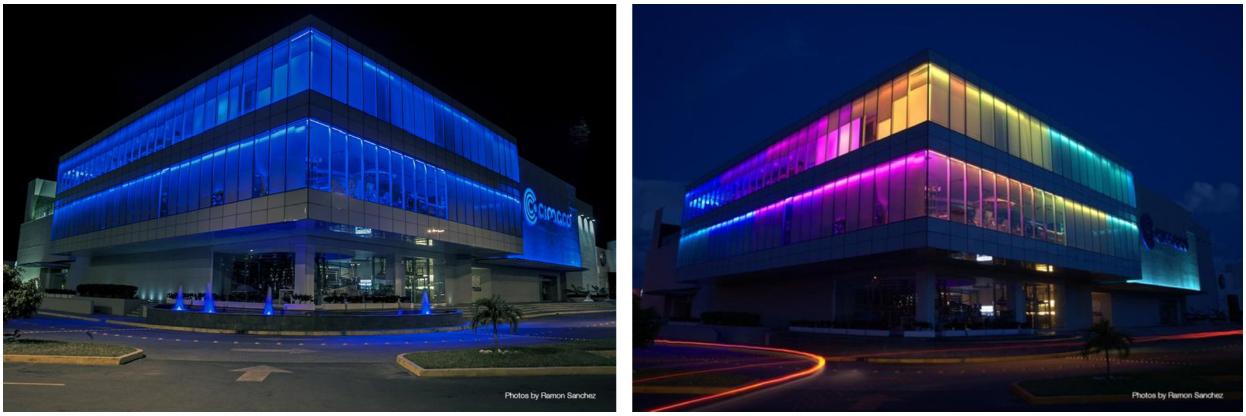

Fig. 4. Examples of dynamic façades using variations of power and colour of light sources on a given façade (CIMACO Department store, Mexico, Traxon/LEDInside, Design, Luisa Medel, 2013.

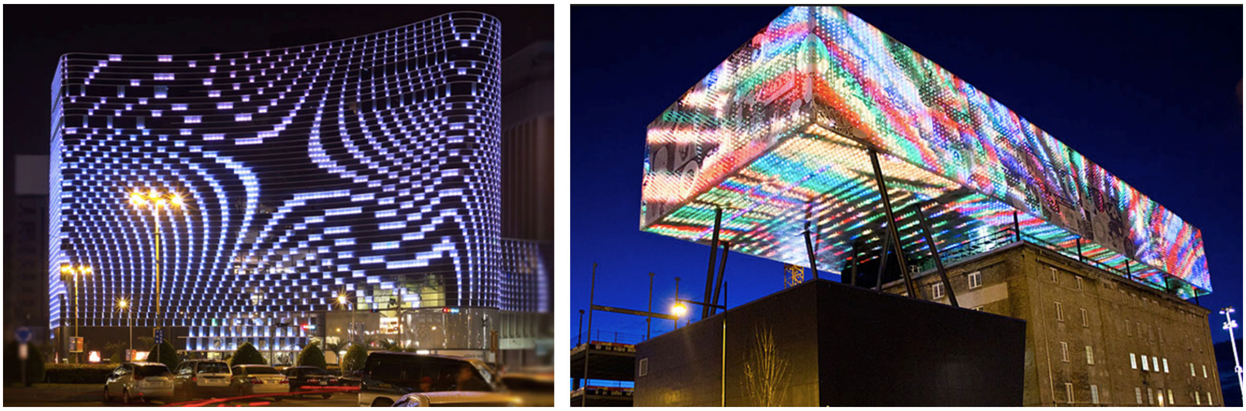

Fig. 5. Using building façades as large screens, with RGB pixels networks. Left: by Xtrememedia; right: Rockheim, Trondheim Museum by Marious Waltz.

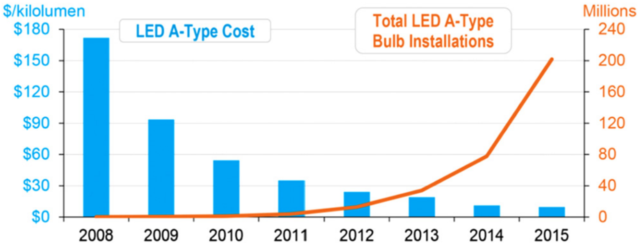

Fig. 6. Evolution of the costs of LED A-type (light bulbs) in $/klm and lamp bulb installations [US Department of Energy, Revolution … now, 2016].

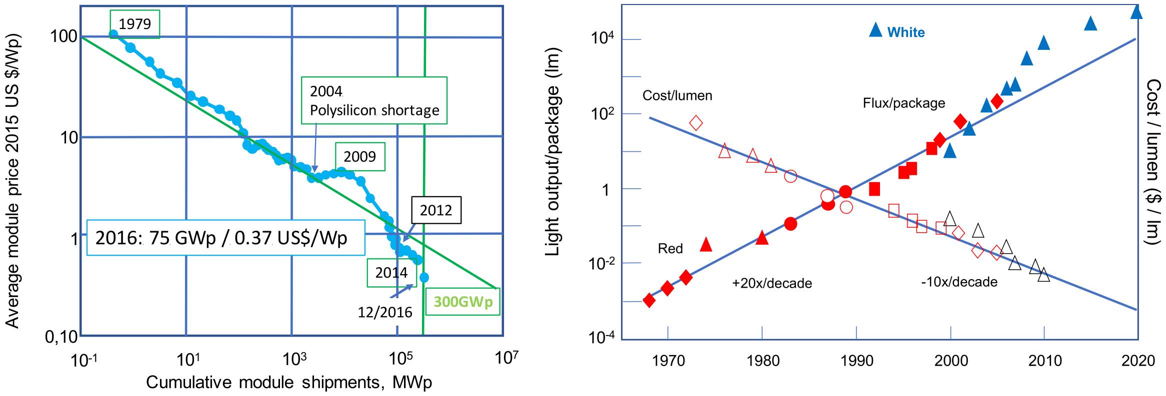

Fig. 7. Cost reduction in photovoltaic modules ($/Watt, left, so-called Swanson's law) and in LEDs ($/lm, so-called Haitz' law).

2. LED and photovoltaics, an alternative to daylighting solutions in windowless environments

It is interesting to link two technologies related to semiconductors: LEDs and photovoltaics. Both technologies present high development rates, and significant perspective regarding cost reduction (see Fig. 6). These two technologies work in DC modes with compatible voltage range (usually 12 V–48 V) and are compatible with requirements in buildings (safety issues, constraints on the length of cables).

Looking at combined efficiency, it is interesting to note that

- photovoltaics converts solar energy into electricity at a cost of less than 1 $/W (installed power, 2017) and prices of PV modules fall by about 10% per year [5] (see also Fig. 7);
- the cost of LED modules fell below 10 $/klm in 2017, with the standard Luminous efficacy of systems exceeding today 130 lm/W [1].

Most PV power lighting installations use battery storage or are connected to the electrical grid to allow access to electrical power during night time. We propose here a specific system where the battery is absent, and no inverter is needed to convert DC to AC. The light sources use the power supply of the photovoltaic panels directly, using a voltage and intensity

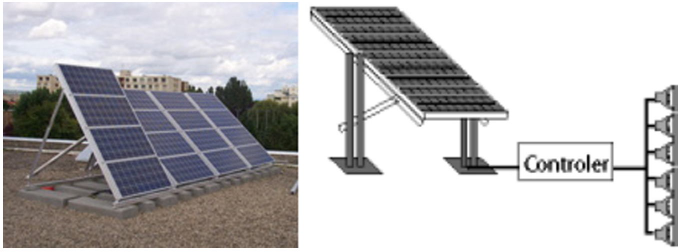

Fig. 8. Description of a PV-lighting system.

Table 1
Value of the parameters for performance assessment (LEDs powered by PV, synchronized).

Photovoltaic and LED installation	
Surface	1 m^2
Solar irradiation, per year (in Lyon, tilt 30°, facing south)	1488 kWh/yr·m^2
Electrical production (in Lyon, tilt 30°, south facing, average efficiency: 0.095) per m^2	141,4 kWh/yr·m^2
Life of the PV panel	40 yr
Investment costs PV only, including installation (1 €/PkW × 136 W) per m^2	= 136 €
Investment cost for control system, installation, wiring, no battery, no inverter, per m^2	100 €
Total investment cost for installed PV, per m^2	236 €
Total investment cost for PV, per m^2, per year (life: 40 years)	5.9 €/yr
Cost of production of electricity: the system is off grid, does not have batteries or AC–DC converter	4 cents/kWh
Investment cost for LEDs (base 2017, 10 €/klm, 130 lm/W, 10 €/7W, 1.42 €/W) For 136 W:	193 €
Life of LEDs (40 000 h, LED on during daylight hours 4000 h/yr	10 years
Investment cost, in LEDs, per year	19.3 €/yr
Total system cost, PV and LEDs, per year	25.2 €/yr
Annual illumination delivered by the system (average LED luminous efficacy 130 lm/W 141 Kwh/year leads to 18 Mlm/yr	18 Mlm·h/yr
Cost of the light delivered by PV LED (2017 price)	1.4 € per Mlm·h per year
Cost of the light delivered by industrial roof tops [7]	0.35 €/Mlm·h per year
Cost of the light delivered by north-facing windows [7]	1 €/Mlm·h per year
Cost of the light delivered by tubular daylight guidance systems [7]	5 €/Mlm·h per year
Cost of the light delivered by standard fluorescent luminaires [7]	6 €/Mlm·h per year

adaptor to allow them to benefit from a regulated DC power supply. Light is therefore produced by the LED modules in a *synchronized* way with the amount of solar irradiation incident on the PV panel located outside.

The PV–LEDs lighting option can be considered as an interesting complement to daylighting systems, able to provide off-grid light deeply into building interiors (5–30 meters from the roof). It can also be seen as a competitor of tubular daylighting systems, often called light tubes [6], which aim at providing daylight deep in a building interior, as a function of the available daylight on the roof. At night time, the PV–LED system does not provide any light. But under sunny conditions, daylight provided to windowless spaces could be abundant, without any electricity from the grid. Typically, these systems should be sized for average sky conditions, or for below average sky lighting conditions, to avoid the situations when the light produced would be overabundant (as it is the case with regular windows). This means that extra light and heat would be generated, making the system unsuitable for hot climates.

We show below an estimation of the costs and performance of such a system, based on an earlier publication [7], but with adjustment of hypothesis to consider the evolutions of the equipment costs (see Fig. 8 and Table 1).

From our analysis and using the hypothesis that should correspond to the market prices in 2017 (white LEDs with luminous efficacy of 150 lm/W at a cost of 10 €/klm, installed PV at 236 €/m^2), the TCO of the delivered illumination, 1.4 € per Mlm·h per year, appears four times lower than the one obtained with Daylight Guidance Systems, and almost five times lower than the TCO of a fluorescent lighting system (if used only during daylight hours). It is also interesting to note that 4/5 of the TCO are related to the LED system. A future reduction in SSL costs will have a significant impact on the interest of the PV–LEDs approach.

From the comparison above, we see that there is already a potential for producing light in synchronous mode from PV–LED systems, for daytime applications. Although it cannot compete with regular windows or standard roof tops, it is definitely the best economical solution to bring light during daytime in all areas that are windowless, or that are located far away from windows.

To be successful, the PV–LED system is expected to provide vivid lighting, with variations in a synchronous way with the external daylight, and with no maintenance costs. The variable light that is produced would be targeted to areas that would be suited to such variations, as indoor areas containing plants (Fig. 9). In this case, the spectrum should be carefully adjusted to match daylight, which is an objective easily reachable by clusters of LEDs (see the following section).

Fig. 9. Various indoor plants can benefit from the lighting provided in a synchronous mode with daylight and make windowless spaces more attractive for their occupants.

3. Simulation of daylight with clusters of LEDs

The spectrum of light produced by LED is continuous, and does not present any emission peak as it is the case with arc lamps (fluorescent, metal halide or sodium lamps for instance). Furthermore, producing full-spectrum light with high CCT (above 5000 K) is rather easy with white LEDs, and this makes LEDs quite attractive to simulate daylight.

Some studies showed the benefit of exposing humans to the daylight spectrum during daylight hours in building interiors. Peter Boyce [8] identified various benefits, through the visual system and through the circadian system. Among them are improvement of sleep quality, reduction of the Seasonal Affective Disorder (SAD), or reduction of stress. Today, manufacturers are carefully investigating the possible benefits associated with using blue-rich spectra during daytime, and lamps with low blue emission in the evening to facilitate sleep [9].

There is therefore a potential interest in developing light sources that provide spectra that are close to the one of natural light, with a full colour spectrum and values of CCT that are close to the ones obtained with daylight.

But what is the spectrum of daylight entering buildings? It is, in fact, a combination of various spectra:

- sunlight (when available),
- skylight (clear sky, clouds, and possible fully overcast skies),
- light reflected by the environment (building facades, ground, vegetation).

It is essential to note that spectra from the direct and indirect light sources are quite different and vary over time (Fig. 10). This means that daylight is, in fact, a combination of various light sources with different spectra, varying over time. This suggests that not only the resulting spectrum is changing, but that the spatial distribution of the incoming light flux is also changing, creating subtle colour effects that are sometimes hardly noticeable, but essential to the natural rendering of the perceived light. Studies were conducted at ENTPE, Lyon France [10] to explore the possible interest of using clusters of LEDs that mimic the variations of daylight spectra to windowless spaces. Among the major findings, it was found:

- that daylight spectral variations were found to be attractive as long as the lighting system mimics a daylight aperture (such as a roof top or a window);
- that there was no need to tune the spectrum and the power in relation to the outdoor conditions. On the contrary, the user was happy to benefit from sunlight conditions when the weather outside was overcast, for instance.

These “human centric” results demonstrate the interest of developing simulations of daylight spectra that are controlled as a function of the desires of the users, to maximise the benefits. Detailed investigations have been conducted worldwide to investigate the possible benefits for health of using light sources with spectra as close as possible to daylight, but the results seem to be rather inconclusive [11].

Presently, LEDs allow an historical opportunity to link the daylight reference with the light being produced by electricity. Solid-state lighting can mimic almost all possible lighting effects generated naturally. This does not mean that it should be done at a large scale, since humans also enjoy other types of light (candle, fire, coloured light, etc.). But mankind has today a universal light source able to meet almost all their demands.

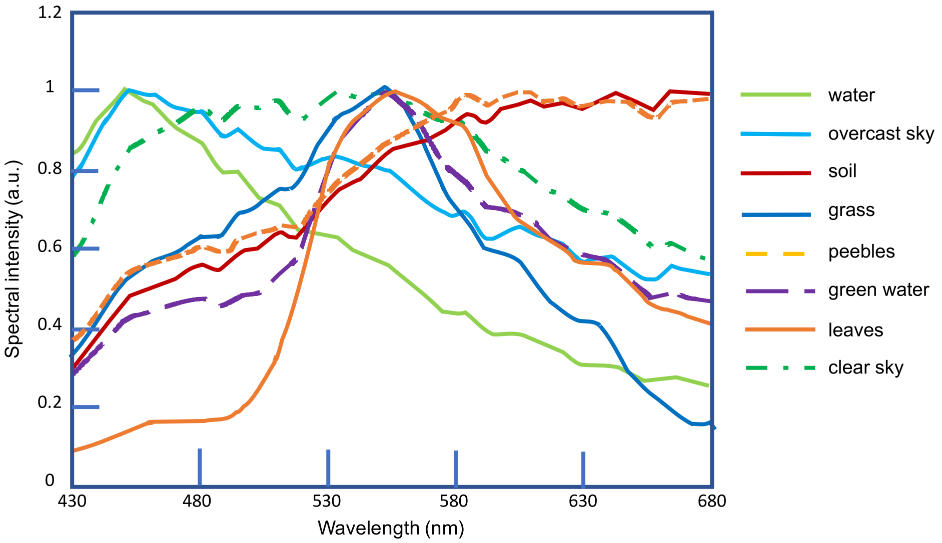

Fig. 10. Examples of spectra of the daylight components measured on a vertical plane, showing the large variety of spectra of light incident on a window from the sky and the outdoor environment [12].

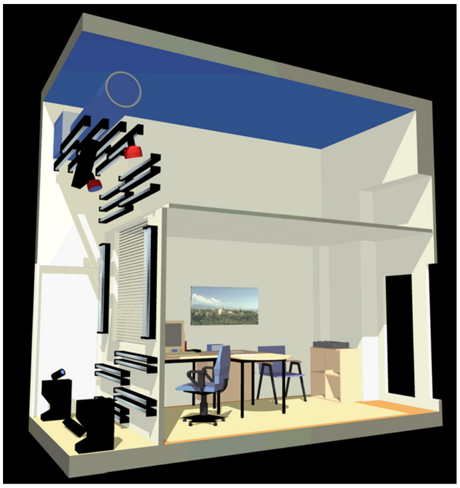

Fig. 11. Experimentation of the simulation of daylight with the multiple light sources used between 1999 and 2011 for a windowless workplace at ENTPE, Lyon, France.

4. Exploring human demand with respect to lighting: the road to SSL

With such a versatility, Solid-State Lighting lamps offers almost unlimited possibilities to meet the human expectations concerning light: their continuous spectrum can be freely adjusted in colour and intensity at any time. But how much do we know about these expectations? We have seen that lighting can be rated in relation to visual and non-visual effects. But what do we know about aesthetics, effects on mood, or more generally the desire of the humans? This is definitely a question linked to culture and experience.

For this reason, various campaigns of exploration have been launched in France (ENTPE, Lyon) and in Denmark (SBI-AAU, Copenhagen) to explore, test, and validate various lighting schemes with the involvement of panels of observers (Fig. 11). These campaigns used various type of experimental procedures:

- (A) installing occupants in test rooms with variable lighting schemes;
- (B) presenting to observers sets of calibrated realistic images of various lighting schemes;
- (C) inviting observers to judge photorealistic schemes using Virtual Reality (see Figs. 12 and 13).

Fig. 12. Presentation of calibrated photorealistic lighting scenes to panels of observers to identify the most attractive lighting schemes (source: SBI, AAU, Denmark).

Fig. 13. Exploring innovative lighting schemes through shared Virtual Reality sessions (source: SBI, AAU, Denmark).

The experimental procedures B and C allow total freedom in lighting design, with easy (and low-cost) possibilities of comparisons of lighting schemes. As an example, the technique B was used to explore what type of energy efficient lighting could be desired, and preferred, by panels of occupants. In [13], various energy effective solutions were preferred:

- thin LED arrays used as wall washers,
- multiple low-glare ceiling-mounted LED sources,
- discrete and efficient task lights,
- Multiple CCT light sources, etc.

This shows the large potential of LED developments to better meet the expectations of users.

5. Conclusion

Such experiments demonstrate that today Solid-State Lighting is a technology with a huge potential of development, because it allows us to control power and spectra very freely, with very reasonable electricity consumption. But is this desirable?

Lighting is first a necessity related to human development. Mankind needs “affordable light quantities” in homes, streets, work places, education buildings, hospitals, etc. Through globalisation, Solid-State Lighting contributes to making electric lighting a commodity, in lowering the Total Cost of Ownership of lighting. Reducing electric power facilitates the use of renewable electricity sources. But most of all, the value chain is changing, with new possible actors moving in.

We have seen that the value of LED engines is constantly being reduced (about 10% per year), as suggested by the Haitz Law. This means that the core value of lighting is progressively shifting from light sources (the led modules) to the other components, mostly the controls and the design.

More globally, the “value proposition” associated with lighting may benefit from the new capability of SSL to better meet the demand, to provide the right light (spectrum, power, effect) at the right time, for the right functionality, or to create the most attractive effects.

In this approach, the key aspect appears from providing the best possible benefits at a given cost of the products. Since the lighting market is dominated by retrofit activities, it is essential to better understand the financial models and the barriers associated with the deployment of SSL in cities and in buildings. Today, SSL can lower the TCO of lighting below 5€/Mlm·h).

Retrofitting existing fluorescent installations by SSL could lead to payback time below five years (including all costs of uninstallation and reinstallation) for energy intensive buildings such as commercial centres and open-space offices [13,14] Beyond this period, SSL offers five to ten years of a cheap lighting, at reduced costs. Lighting retrofit becomes a business, offering typically a 5–10% yearly return on investment. Hence the progressive shift of value from the lighting industry to the service to the client, selling lighting instead of lighting equipment, with an even greater pressure on the prices of products. This is already happening in street lighting, and in large size buildings with facility managers integrating this approach in their global business.

References

[1] DOE, Solid-State Lighting R&D Plan, Department of Energy, USA, June 2016, https://energy.gov/sites/prod/files/2016/06/f32/ssl_rd-plan_%20jun2016_2.pdf.
[2] M. Fontoynont, et al., Global Economic Models, section A.1, Technical Report of IEA SHC Task 50, Advanced Lighting Solutions for Retrofitting Buildings, International Energy Agency, 2016.
[3] International Electro-Technical Commission, IEC 62717, LED Modules for General Lighting, Performance requirements, Vienna, 2014.
[4] Fontoynont, et al., Lighting Mona Lisa with LEDS: details concerning innovating techniques, http://sklaer.com/cms/upload/pdf/Publication-Joconde-en.pdf, 2013.
[5] G. Carr, Sunny Uplands: alternative energy will no longer be alternative. Introducing Swansons’ Law, Economist (28 December 2012).
[6] Light Tubes, Wikipedia, https://en.wikipedia.org/wiki/Light_tube.
[7] M. Fontoynont, Long term assessment of costs associated with lighting and daylighting techniques, Light Eng. 16 (2) (2008).
[8] P. Boyce, C. Hunter, O. Howlett, The Benefits of Daylight through Windows Lighting Research Center, Rensselaer Polytechnic Institute Troy, New York, 2003, pp. 12180–13352.
[9] C. Vetter, M. Juda, D. Lang, A. Wojtysiak, T. Roenneberg, Blue-enriched office light competes with natural light as a zeitgeber, Scand. J. Work Environ. Health 37 (5) (2011) 437–445.
[10] C. Enrech-Xena, Simulation de la lumière naturelle par des sources artificielles : enjeux architecturaux, PhD Thesis, ENTPE, Lyon, France, 1999.
[11] S.L. McColl, J.A. Veitch, Full-spectrum fluorescent lighting: a review of its effects on physiology and health, Psychol. Med. 31 (6) (2001) 949–964.
[12] M. Fontoynont, Campaign of Spectral Measurements of Daylight Received on a VERTICAL Window Plane, Internal Document, ENTPE, Lyon, France, 1999.
[13] M. Fontoynont, et al., Energy Efficient Lighting Through Photorealistic Visualization, PSO contract, Final report, SBI-AAU, Copenhagen, 2016.
[14] M. Fontoynont, Financial Models to Justify Lighting Retrofit: Where Are the Benefits? Industry Workshop, Lund, Sweden, 20 March 2013.
[15] ILV, International Lighting Vocabulary, Electronic version, CIE, International Lighting Commission, Vienna.
[16] TM30-15, IES Method for Evaluating Light Source Color Rendition, IESNA, New York, 2015.