Factors Involved in Choosing LEDs for General Lighting Applications: a Critical Review

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Abstract — **Electric lighting accounts for 19% of electricity consumption worldwide and generates remarkable concern to get energy savings. As a modern source of light, LEDs open up a multitude of innovative lighting solutions. LEDs lighting is already widely used in many niche areas like traffic lights, car lights, lighting displays, TVs etc. Now, based on lowered manufacturing costs, they penetrate into the general lighting market. But for specialists, LEDs are not yet the end solution in any lighting application. There are a lot of factors that can influence their adoption decision. Among them, the most favorable and promising one is the high efficiency, with values in permanent increasing. The paper discusses various aspects of LEDs efficiency and demonstrates that luminous efficiency is not a relevant criteria for a decision, a better understanding being got with an indicator like the Lighting Power Density, in W/m^2. And beyond the efficiency, the paper makes a critical analysis of other parameters that matters in the lighting decision-making process, like lifetime, color rendering and chromatic shift, health and environmental impact. Finally, the paper point out that the calculation of cost and return of investment represent a very technical effort, based on accuracy of the entry data, often unknown by the investor itself, like different confidential costs, daily average time of functioning, temperature hazards and lifetime in condition of poor quality of electricity.**

Keywords: *LEDs lighting, luminous efficiency, operation temperature, color rendering, health impact, investment return.*

I. INTRODUCTION

The history of LEDs started one hundred years ago with the experimentation of electroluminescence by the British physicist H. J. Round (1907). But only many decades after, in the '50s, they began to be produced. An important moment represents the appearance of blue LEDs in the '90s, achievement that favored the creation of the first white LEDs, by coating blue LEDs with phosphor.

Remarkable advances have been made in LEDs technology in recent years, leading to a dramatic increase in their use. LEDs present advantages that make them a great solution for certain lighting scenarios. Their luminous efficiency is one of the best among the light sources. They have excellent lamp life that lowers the maintenance costs, but also makes them a great choice for locations where changing the lamp can be very difficult or expensive. Because they do not have a filament, LEDs are a great choice for high vibration locations. Also they represent an excellent choice for lighting in coolers and freezers because perform very well in cold environments. They can be built into a low profile or small package making them great for under-cabinet lighting or lighting in any confined area. They are an almost instant on light source making them a good choice for low frequency strobe lights. They can be built to output a very narrow light wavelength making them a great option for when you want colored light. They have a very directional output making them great for accent/spot lighting, flashlights, etc. LEDs are particularly advantageous in the street and roadway lighting domain because they are excellent directional light sources, durable, and exhibit long lifetimes [1].

Apart from color lighting and a few high-volume markets that meet niche requirements, all of today's high volume components are used to provide the consumer with a wide selection of new, more efficient and presumably more desirable products.

But LEDs are not yet the end solution in any lighting application. They didn't conquered yet the sector of residential, commercial and industrial buildings. The paper goal is to review the state-of-the-art in LEDs lighting and to do a critical comparison with other solutions for general lighting applications.

II. LED TECHNOLOGY DEVELOPMENT

The most claimed reason for adopting LEDs remains their higher luminous efficiency. But, for a long period, the biggest barrier to widespread adoption of LED lighting was its price. It seems that beginning 2012, the lower production costs resulted in improved return on investment. As the payback periods fall now below 2–4 years in more and more applications, people involved in lighting decision-making are not only tempted but also forced to consider this comparatively new technology.

Few years ago, LEDs efficiency was not enough high for general lighting applications [2]. Beside this, other impediments to LEDs adoption have been associated with different rules and application technologies. Among these are standards, changes in regulations or imposed conditions for drivers, control of lighting systems, luminaires etc. Maybe the biggest problem with LED lights was - and still concerns - the shortened life due to overheating in standard fixtures.

Nowadays these barriers are almost overpassed. New standards and regulations have been adopted, as DIM2, a European eco-design regulation released in September 2013, which sets minimum performance requirements for avoiding low-quality lamps from the market. In the same time, new higher quality products are released, and based on the technological development of each LED or luminaire component, the manufacturing costs rapidly decrease (Fig.1). However, this evolution could suffer important changes, relevant for long term estimation.

According to Navigant Research, global unit shipments of LED lamps and modules are expected to grow at a compound annual growth rate of 19.0% between 2015 and 2024 [4].

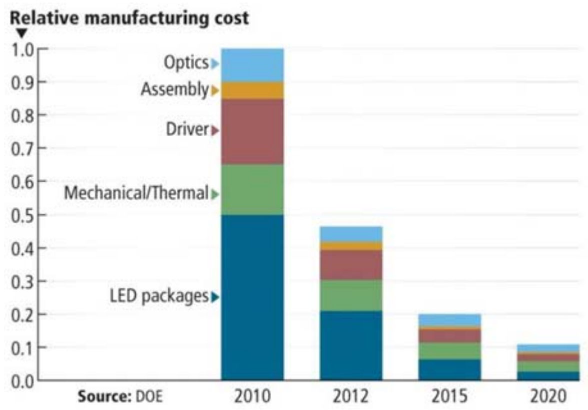
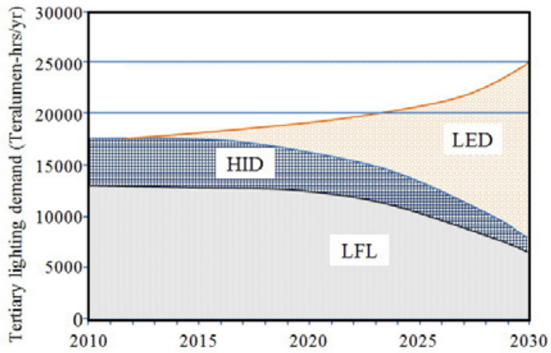


Fig. 1. Relative manufacturing cost evolution for LEDs [3].

The development of LEDs systems just started, and the expansion is not necessary followed by the extinction of high intensity discharge (HID) or linear fluorescent (LFL) lighting solutions (Fig.2).



Courtesy Navigant Consulting

Fig. 2. Tertiary lighting demand (Teralumens-hrs/year).

Interchangeability of LED lighting products will be important in the years ahead and it should be define standards and published over the next few years [5].

While LEDs will become the most used solution in lighting, the next generation of solid state lighting technology represented by the organic LEDs is already creating interest. Even these are already being used in TVs and phones, because of the lower performances, the mass-market adoption is not expected to occur very soon.

III. LED Luminous Efficiency

When speaking about the energy efficiency of lighting it refers to the luminous efficiency, measured in lumens per watt, as the ratio between the luminous flux and the electricity consumption. Some authors make a distinction between efficiency and efficacy, the last one being expressed as a unitless figure (percentage). Other authors, like Murphy (2013) prefer to use extensively the term efficacy. He identifies two components of the total luminous efficacy, namely the spectral η_S and η_E electrical components [6]:

$$\eta_L = \eta_S \cdot \eta_E \qquad (1)$$

The electrical part, η_E is unitless, representing the ratio of (luminous) radiated power output to electrical power input and express the lamp capability to produce photons from the input power source. The spectral part, η_S carries units of lm/W, and express how efficient are distributed the photons inside of the visible spectrum.

The incandescent lights are excellent in generating photons from the input electrical source (high η_E), but these photons are generated mostly in the near-infrared wavelengths domain, so invisible for the human eye (low η_S). A blackbody at the temperature of the Sun results in a luminous efficacy of η_S = 93 lm/W (only 37% of its light falls within the visible band 380-760 nm), peaking at 6640 K and 96.1 lm/W. On the contrary, LEDs have lowest η_E, but a much better η_S.

There are two common ways to get white LEDs. The first one combine the light output of red, green, and blue LEDs. The second one, most widely used, called phosphor converted blue (PCB), get white by transforming part of a blue LED by means of phosphoric coatings on the interior of protecting lens. By a proper phosphors combination, the visible wavelengths can be optimal covered, resulting in a higher spectral luminous efficacy (Fig.3).

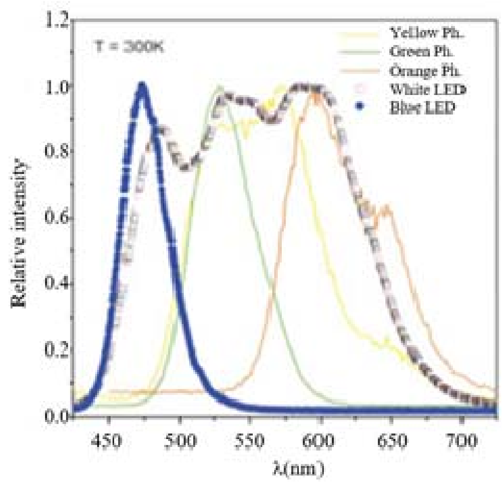


Fig. 3. Three phosphorus white LED spectrum.
Yellow Phosphor: $Y_3Al_5O_{12}$: Ce
Green Phosphor: $SrGa_2S_4$: Eu
Orange Phosphor: SrS : Eu

The theoretical limits to spectral luminous efficacy for lights that could be perceived as white, is in the range of η_S = 250–370 lm/W [5]. This emphasizes that improvements in the efficacy of current solid-state lighting technology must primarily involve advances in photon generation efficiency rather than spectral conditioning.

At present, most LEDs present on the market offer an average of η_L =115 lm/W. In author's opinion, this parameter must be presented not for the lamps, but only for the luminaires. A huge discrepancy, in present, is the fact that the LED manufacturers include the driver efficiency in the global efficiency of the luminaire (but not in every case, be careful !!!), but when on compare luminous efficiency for T5 tubes or HID lamps, the additional losses are neglected, one must search the technical data to find them, separately.

Starting from this observation, the effect of the optical system of luminaire has an important contribution to the global luminous efficiency, due to reflectance and transmittance of the materials. Supplementary, today the performance of the lens are in continuous progress, going to the custom made lenses, if necessary [3].

After all this, one consider that the LEDs luminous efficiency is not a sufficient criteria for a decision (a small increase in efficiency will not justify an important increase of the luminaire price). A better understanding we obtain using Lighting Power Density, in W/m^2. Without comments, even a better criteria is the Normalized Lighting Power Density in $W/m^2/100$ lux, due the illuminance level correction.

To demonstrate that the luminous efficiency is not a relevant criteria, on present a technical comparison of a global lighting system, Fig.4 (one pole, with alternative solution, based on two different lighting sources, obtained from a Romanian manufacturer). Luminaire A is based on LED, 35W, 3956 lm. Luminaire B is using a High-pressure Sodium Tubular (HST) lamp, 50 W (total consuming 60W), 4400 lm. From the starting point, we have 113 lm/W (A) against 73 lm/W (B).

We impose three calculating surfaces, $S1=15x5m^2$, $S2=12x3m^2$, $S3=8x2m^2$. For every hypothesis, we calculate the Normalized Lighting Power Density (NLPD), in Table I. Even the proportion between luminous efficiency of our luminaire was 0,64 (=73/113 lm/W), this number is not found in the final illuminance, for ours surfaces. Supplementary, the S3 configuration illustrated the situation when an important luminous flux is lost in the exterior of the working plane.

TABLE I.
COMPARISON FOR NLPD FOR TWO LUMINAIRES AND THREE DIFFERENT LIGHTING SYSTEMS

No	Surface	Luminaire A ($W/m^2/100lx$)	Luminaire B ($W/m^2/100lx$)	NLPD A/B
1	S1	3.88	7,27	0,53
2	S2	3,5	6,84	0,51
3	S3	13,25	23,58	0,56

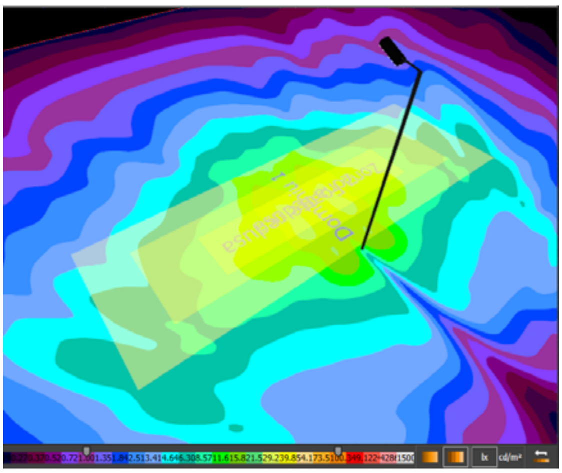


Fig. 4. The lighting system for the three NLPD calculation

LEDs require a “driver” that usually converts line (AC) power to the appropriate DC voltage, but may also include supplementary electronics for dimming and/or color correction control. To conversion energy loses are about 15%, so the currently available LED drivers are typically about 85% efficient [7]

However, to judge a lighting solution it is not enough to consider only the lumens per watts ratio. Among others, key equivalency criteria to consider includes color attributes, spatial distribution of light, electrical and mechanical compatibility, rated lifetime, warranty, and cost [8].

IV. LIFETIME

For incandescent, fluorescent and HID lamps the rated lamp life is the time until 50% of lamps is expected to have failed. For LED based lamps the rated (lumen maintenance) life represents the period after which the luminaire emits only a certain percentage of its original output. In most cases is the time to 70% light output, also known as „time to L70”, because 30% reduction in light output represents the threshold for detecting gradual reductions in light output. The standards state that during these times, the LED should not exhibit any major shifts in chromaticity. Where light output is not critical, the time to L50 may be more suited.

Good-quality white LEDs in well-designed fixtures are expected to have a useful life of 30,000 to 50,000 hours or even longer, comparing to the best linear fluorescent lamps lifetime of 30,000 hours, compact fluorescent lamps lifetime 8,000 to 10,000 hours, or the modest incandescent lamp lifetime of about 1,000 hours [9]. But LED lamps consist of many components. The LED drivers incorporate more than 50 components, and among them electrolytic capacitors are considered the weakest link.

Heat is produced both in the driver and the processes of light emission from the semiconductor itself. This heat will affect the luminaire output (Figs.5 and 6). LEDs in a well-designed luminaire with adequate heat sinking will produce 10%-15% less light than indicated by the “typical luminous flux” rating [7].

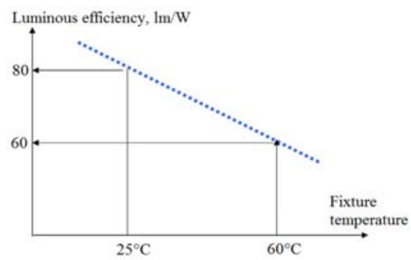


Fig. 5. Luminous efficiency vs. fixture temperature.

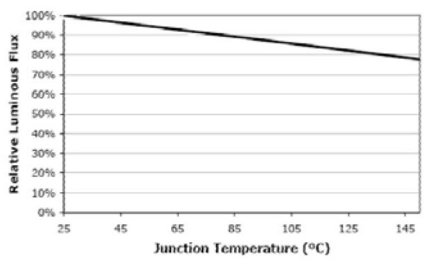


Fig. 6. Relative luminous flux vs. junction temperature.

V. Color Rendering

Another factor to consider before replacing a current lighting fixture is the color quality. The common assessment is based on the Color Rendering Index (CRI) of that maximum value of 100 is reached by the Sun or incandescent lamps. Few years ago, at least one report has demonstrated that T5 fluorescents lights have a significantly higher CRI rating of 85 than a single LED CRI rating of 70 [10]. Other studies have shown that higher quality light yields numerous benefits, including increased worker productivity [2].

Regarding the correlated color temperatures (CCTs), there are three categories in LEDs lighting technology. Because of lower losses when phosphor converting, cool-white LEDs offer higher efficacy at low cost, but have very high correlated color temperatures (bluish in appearance). This is why it is not acceptable in interior lighting applications. On the other side, warm-white (2700K to 3000K) and in some cases neutral-white (3500K to 4000K) light is appropriate in interior lighting applications, having a CRI of phosphor-converted warm-white devices of 80 or higher. In general, a minimum CRI of 80 is recommended for interior lighting, with CRIs of 90 or higher indicating excellent color rendering [11].

Color stability is a key characteristic in many lighting applications (stores, medical examination rooms, museums etc.), regardless of the source type, and some lighting technologies tend to maintain their color over time better than others. In the LEDs case, color shift can be caused by physical changes of the package or by modifications in the forward voltage, changes that reconfigure the ratio of blue pump to phosphor emission. Most white LEDs use a blue LED "photon pump" allied to an yttrium aluminum garnet (YAG) phosphor. Some of the photons from the blue LED pass through the phosphor unaffected, while others are absorbed by the material and re-emitted in the yellow part of the spectrum. The eye perceives the combination of blue and yellow light as white. At low current, the light looks 'warmer' (more yellow). However, at high current, the phosphor becomes less efficient and the blue emission becomes more dominant, making the light 'cooler' or bluish. LED manufacturers specify that their devices will produce the nominal CCT at a particular forward voltage [12]. However, cooling conditions are important too, because junction temperature alters the chromaticity because the LED's band gap (which determines the wavelength of emitted photons) narrows as the temperature rises.

Dimming is an essential feature in many lighting applications and, when necessary to change the light color, it is applied in case of lamps based on RGB LED combination. Color is controlled by adjusting the relative intensities of primary LEDs in the luminaire [13]. To notice that the chromaticity shift for the RGB systems are more marked than for the white LEDs, primarily due to the significant change in wavelength suffered by the red device.

Because the correlated color temperature (CCT) of LEDs changes with voltage, have to be used different dimming techniques than the simple and cheap analog methods used for traditional lighting. The most popular methods used in the industry are: pulse width modulation (PWM) and amplitude modulation (AM, also named "continuous current reduction"). But, at lower current concentrations LED's efficacy tends to increase and therefore the AM dimming is not linear. At very low forward current, significant chromaticity shifts occur. Under pulse width modulation the diode is turned on and off with fixed frequency and variable duty cycle, different combinations of peak current and duty cycle can produce the same value of average current. So it seems that PWM technique could be better and is mostly preferred. But, as experimental data show, the junction temperature can be influenced by the PWM duty cycle, resulting in chromaticity shift [12].

More, different dimming schemes will have different effects on diodes spectral properties e.g. AlGaInP diodes will experience spectrum shifts towards shorter wavelengths with both AM and PWM while InGaN diodes experience opposite shifts under these methods [13].

More recently a hybrid PWM/AM dimming method was proposed, in order to control two parameters. This feature is especially useful for white phosphor-converted LED based luminaires where luminous flux can be kept constant and the color shifts due to temperature change can be minimized.

The color stability of LEDs varies from product to product, and a non-well-designed LED may suffer a shift in color so much that they need replacing after only several thousand hours. There are certainly many products with excellent color stability, but it may be difficult for consumers or specifiers to identify them.

VI. Possible Side-Effects of Using LEDs

The use of LEDs can generate two kind of effects: environmental and health effects.

The environmental impact, like for many other electronic goods, concern mainly the LEDs' rare earth content. Raw material like lead, copper, nickel, silver, gold and arsenic are considered either toxic or deficient, generating increase pressure on natural resources. But in contrast with the discharge lamps, LEDs are mercury-free source of lighting. So, to avoid the negative environmental impact, similar to other electronic waste, a fundamental importance will have the management at end-of-life.

A second issue related to the environmental impact is the EMI one. LED technology can lead to the emission of electromagnetic fields insofar as such systems are combined with a driver. The need of a universal LED driver, flexible enough to be applied to different wiring configurations, has to overcome the difficulties related to EMI that depends on environmental and parasitic components. LEDs, as a special diode, follow the Shockley exponential I–V law and so, for a very small fluctuation on the voltage across them, a very high variation on their current can be generated. This involve not only lighting disturbs, but also affects both efficiency and life time, as proved in [14]. When the LEDs are not properly driven and supplementary are separated by the driver with long connections the wiring parasitics can generate ringing and EMI.

But the main discussions and concerns are related to LEDs' health impact. At a high enough intensity, all light sources have the potential to be harmful to both the skin and the eyes through ultraviolet (UV), blue light (400-480 nm) and/or infrared (IR) emissions. Unfortunately, there is currently quite little information on human exposure to lighting with regard to the many identified potential health effects (photochemical effect, glare, etc.)

As a result of the increasingly widespread use of LEDs, of greatest concern are, due to both the severity of the corresponding dangers and the probability of their occurring, the photochemical effects of blue light on the eye and the glare phenomenon. There are two causes: the LEDs spectral imbalance (because white LEDs are usual a combination of blue LED with a yellow luminophore, they will emit a portion of their total output as blue light; mostly in cool white LED versions, which typically have a higher percentage of blue light emissions) and the very high luminance (LEDs are highly concentrated point sources characterized by high brightness density per surface unit).

The photochemical risk that is associated with blue light depends on the accumulated dose to which the person has been exposed, which is generally the result of low intensity exposure repeated over long periods. Based on converging observations on experimental studies, blue light is recognized as being harmful and dangerous to the retina, as a result of cellular oxidative stress. There is a strong suspicion that blue light aggravates age-related macular degeneration (ARMD).

The results of the analysis and testing done by a group of experts coordinated by the French agency for food, environmental and occupational health & safety [15], or by an important LED producer company [16] show significant health risks from some visible light LED lamps when viewed without diffusers or secondary optical devices. As consequence, the users are advised to not look directly at any operating LED lamp. Especially sensitive to the risk or highly exposed to blue light are children (because of the transparency of their crystalline lens), light-sensitive patients (sufferers of eye and skin diseases, or treated with photosensitising substances) and workers or professionals (theatre and film industry etc.) subjected to high-intensity lighting.

On the opposite, representatives of the lighting industry argued that the photobiological risk of using LEDs is, similar with the other lighting technologies, well within the uncritical range [17]. The portion of blue in LED is not different from the portion of blue in lamps using other technologies at the same color temperature. More, the blue light exposure is considered important to human beings because it regulates the biological clock. As consequence, people that spend the most part of the time indoor, without the natural daylight exposure, need daily portion of blue light to keep their physiology in good parameters.

Beside the blue light, some concern regard also the ultraviolet (UV) and infrared (IR) radiation. Comparing to other lighting technologies, LEDs sources do not emit any UV radiation (unless specifically designed for that particular purpose) or hardly emit IR light (unless specifically designed to emit a certain type of IR). So, from the normal uses of LEDs, there is very little potential risk to harm people with a specific UV sensitivity or to produce thermal effects, associated with burns to the retina and generally resulting from short-term exposure to very intense light.

In lighting, another harmful potential on health consists in the flicker generated by the voltage variations. The flicker, a repetitive change in a visual stimulus within the frequency range 3 Hz to 70 Hz, presents the greatest potential of seizures for the frequencies range 15 Hz to 20 Hz. LEDs are driven usual by a power supply in direct current (rectified and filtered), when the frequency of fluctuation is 100 Hz, or by a Pulse Width Modulation (PWM) power supply, when the frequency is of the order of tens of kilo-Hertz. So, there are no health risk associated to the biological effects of flicker in the various LED lamps [11].

VII. Cost and Return of Investment

LED product price is not always a clear indicator of performance, but relatively low prices are often associated with some form of compromise. In comparing lamps that produce an equivalent quantity and quality of illumination, current prices for LED products are substantially higher than for more established technologies [7].

TABLE II.
LED PACKAGE: PRICE, PERFORMANCE AND PROJECTIONS [1]

Metric	2011	2013	2015	2020	Goal
Cool white efficacy (lm/W)	135	164	190	235	266
Cool white price ($/klm)	9	4	2	0.7	0.5
Warm white efficacy (lm/W)	98	129	162	224	266
Warm white price ($/klm)	12.5	5.1	2.3	0.7	0.5

These analysis are considered in general a linear calculus, with no special difficulties. After some experience, we have a different approach. As we will demonstrate, some gaps are hidden, and solving them are not easy. The entry data are the most interesting to discuss:

- Energy price: For the first step, data are available. But for the bigger company, the price is periodically negotiate, and thus, *confidential!* Another problem, if the energy metering is on medium voltage, the losses of power station must be estimate, in the daily and annual global regime;
- Annual energy price index: could be found in statistical data, but when we are forced to realize estimation for ten years, a high level of incertitude occurred;
- Power lossless in lighting systems (old or modernized): detailed of electrical network must be available;
- Maintenance cost and program for lighting system (old and modernized). This activity is neglected, without documents or cost analysis;
- Equipment and installation works: also confidential, difficult to be estimated;
- Lamps and ballast price: surprising, not very easy to find these information, because the acquisition prices are different from catalog prices;
- Maintenance costs for LEDs luminaire, especially by the electronic driver livelong. The average of this parameter is not well documented, and special proofs must be obtained. As mentioned before, the life of a good-quality LED luminaire shall be 50,000 hours, compared with T5 fluorescent lamps that have a life of approximately 20,000 hours. With an average of

250 working days per year with 9 hours, the annual operating time is approximately 2250 hours. In this case, the LED bulbs will last about 25 years and the fluorescent tube about 10 years. Theoretically you can plan today that your LED lights will run for 25 years, but you rather then would probably need two bulbs. Because of the series connections, the failure of an LED often can lead to partial replacement or submitting to the manufacturer;

- Daily average time of functioning: very important, especially when we try to compare with the old situation (with NO light or maximum economy);
- Life period of classical lamps: difficult to accept the catalog data, due the temperature, or on/off cycle, quality of electricity;
- Elevator cost, when necessary: this is an additional cost, also with supplementary labor cost, for the safety.

All these comments illustrates that the Cost and Return on Investment represent a very technical effort, based on accuracy of the entry data, often unknown by the investor, itself.

VIII. CONCLUSIONS

Although performance varies widely among available general service LED lamps, the technology continues to improve even as the price per lumen decreases.

The return on investment argument for using LEDs involves a number of considerations including energy, maintenance, life, color quality, color consistency and using best available technology. It depends on the lighting project nature: it is a new or a retrofit one. However, LED lighting is in attention of everybody, from big corporations and companies up to individual homeowners.

Among the different factors to be considered, a special importance is accorded to the environmental and health impacts. If in the first case, the situation is similar with any other mass produced electronic goods and force to an improved management at the end-of-life. The health impact of LEDs large-scale use is yet not enough studied. However, to avoid harmful effects of blue light or glare, diffusers or secondary optical devices are recommended. These are necessary for a better lighting quality, even that their use means a loose of global efficiency (any reflection or transmission of light involve a minimal light flux loss).

Beyond doubt, due to the permanent and dramatic increase of their efficiency, in the next few years, LED will become the most energy-efficient and versatile technology for general lighting and will provide high-quality light and visual performance together with new architectural and design options for enhanced comfort and well-being.

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REFERENCES

[1] U.S. Department of Energy, *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*, August 2014.

[2] S. Sanchez and S. Sweeny, “LED vs. T5 Technology: the Advantages and Disadvantages.” *Lumiversal* (2010). http://lumiversal.net/upload/T5%20v.%20LED.pdf.

[3] http://www.navigantresearch.com/research/led-lighting-global-outlook .

[4] M. Brodin, „Why the future is bright for LEDs”, *LuxReview*, August 2015, on http://luxreview.com/article/2015/08/the-future-is-bright-for-leds .

[5] T.W. Murphy, „Maximum Spectral Luminous Efficacy of White Light”, *Journal of Applied Physics*, arXiv:1309.7039 [physics.optics], 2013.

[6] U.S. Department of Energy, *Adoption of Light-Emitting Diodes in Common Lighting Applications*, July 2015.

[7] U.S. Department of energy, energy efficiency and renewable energy, *Building Technologies Program*: “Document of Energy Efficiency of White LEDs” June 2009.

[8] U.S. Department of Energy, General Service LED Lamps, *Building Technologies Program*: Solid-State Lighting Technology Fact Sheet, PNNL-SA 87502, April 2012.

[9] http://www1.eere.energy.gov/buildings/ssl/sslbasics_ledbasics.htm

[10] M. Burmen, F. Pernus and B. Likar, “LED light sources: as survey of quality-affecting factors and methods for their assessment” *Measurement Science and Technology* 19.122002 (2008): pp.1-15.

[11] S. Albani, Assessment of evolution in LEDs lighting as energy-saving, *2nd International Conference on Energy Systems and Technologies*, 18 – 21 Feb. 2013, Cairo, Egypt

[12] http://www.digikey.com/en/articles/techzone/2014/feb/led-color-shift-under-pwm-dimming

[13] S. Beczkowski, and S. Munk-Nielsen. “LED spectral and power characteristics under hybrid PWM/AM dimming strategy”, *IEEE Energy Conversion Congress and Exposition*, 2010, pp. 731 – 735.

[14] G. Sauerlander, D. Hente, H. Radermacher, E. Waffenschmidt, and J. Jacobs, “Driver electronics for LEDs,” in *Proc. IEEE Ind. Applicat. Society* (*IAS*), Oct. 2006, vol. 5, pp. 2621–2626.

[15] ANSES, Opinion of the French agency for food, environmental and occupational health & safety. in response to the internally-solicited request entitled “Health effects of lighting systems using light-emitting diodes (LEDs)”, 94701 Maisons-Alfort, Oct. 2010.

[16] CREE, “LED Eye Safety”, Technical article, CLD-AP34 rev 2, © Cree, Inc. 2009-2012.

[17] The European Lighting Industry represented by ELC & CELMA “Optical safety of LED lighting”, 1st Edition, July 2011.