Review

Rosaria Ciriminna, Lorenzo Albanese, Francesco Meneguzzo* and Mario Pagliaro*

LED Street Lighting: A Looking Ahead Perspective

DOI 10.1515/green-2015-0020
Received November 11, 2015; accepted December 15, 2015

Abstract: Provided that LED street lighting is guided by quality principles, outdoor illumination using light-emitting diodes will have a significant global impact helping to reduce carbon dioxide emissions, save relevant amounts of electricity and enhance the quality of life in cities as well as in remote areas. This study summarizes recent findings providing guidelines for further progress in this crucially important technology on the common pathway to sustainable development.

Keywords: LED lighting, light pollution, road lighting, energy management, lighting design, systems approach

1 Background

In 2014, the Nobel Prize in physics was awarded to the inventors of efficient blue light-emitting diodes (LED) Nakamura, Akasaki, and Amano "which has enabled bright and energy-saving white light sources" [1]. The new solid state lighting (SSL) sources are not only energy efficient (the most recently commercialized lights emitting 150 lm/W) but have an unprecedented lifetime, offering relevant savings through increased energy efficiency *and* decreased maintenance [2].

In 2006, the International Energy Agency estimated that artificial lighting accounted for 19 % of global electricity consumption [3]. Since then, the world's population has considerably grown and outdoor lighting has further increased, so much that the compound annual growth rate of the respective market is estimated to be 42 % in period 2011–2020 [4]. It is perhaps not surprising, then, that in the course of the past decade, street lighting with LED as integrated light sources has rapidly evolved to become one of the preferred technologies also thanks to enhanced visual performance for motorists [5].

The subsequent year, Torraca, a small Italian city, became the first entire urban agglomerate lit with LED lights [6], even though the resulting lighting performance was generally poor [7]. In 2013 Los Angeles started to install 140,000 LED lights replacing conventional light sources in one of the world's largest LED street light project [8]. In brief, the rapid progress in the reliability of LED street lighting fixtures along with rapid price fall and enhanced illumination explain why high-pressure sodium (HPS) and mercury vapor lamps can be considered legacy lighting technologies.

Excellent books [2] detail the new SSL technology, and its revolutionary impact due to entirely different nature of the point-like solid light sources that are assembled in either rigid or flexible 1-D, 2-D and 3-D geometries [9].

While until not long ago traditional luminaires were replaced by energy-efficient LED street lamps ("relamping") on the basis of simple financial metrics, new LED installations can take into account health, environmental, safety, light quality, financial and aesthetic aspects, as it is since long well understood that light does much more than just enable us to see, but rather has a direct effect on our wellbeing and health, meeting both physiological and psychological needs (Figure 1) [10, 11].

Following a brief review of this rapid illumination evolution with reference to the energetically relevant street lighting sector, we identify open opportunities and conclude adding recommendations that hopefully will be useful to energy managers, engineers, lighting designers, landscape planners and policy makers evaluating the LED technology for street illumination.

2 LED street lights

In general, most LED lights used for street lighting are integrated lighting fixtures comprised of multiple LED light sources sealed and assembled to a focus panel encompassing a lens, with a further crucially important

***Corresponding authors: Francesco Meneguzzo,** Istituto di Biometeorologia, CNR, via Caproni 8, 50145 Firenze, Italy, E-mail: francesco.meneguzzo@cnr.it
Mario Pagliaro, Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, Italy, E-mail: mario.pagliaro@cnr.it
Rosaria Ciriminna, Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, Italy
Lorenzo Albanese, Istituto di Biometeorologia, CNR, via Caproni 8, 50145 Firenze, Italy

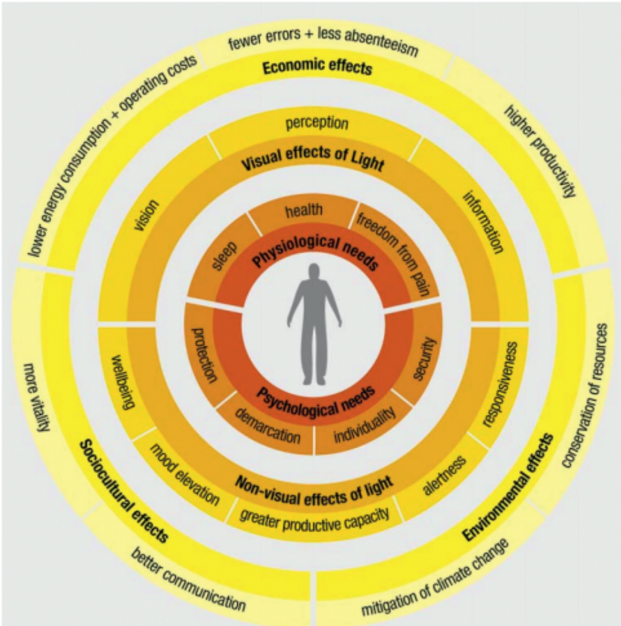


Figure 1: Model of the effects of light on human beings [Reproduced from Ref. [10], with kind permission].

heat sink to effectively dissipate heat as a flow of hot air to ensure long lifespan of the single LED lights [2]. Light fixtures of multiple shapes are available on the market, whereas the original lens on the LED panel casting light in a rectangular pattern to the road, and thus reducing light in the surrounding environment such as the footpaths, are increasingly being replaced by specialized lens designed to widen the light pattern.

The current trend is to use high power 1 W diodes. As mentioned above, the chip-on-board (COB) diode employed in commercial luminaires targeted at street and area lights have lately approached the 150 lm/W efficacy threshold. For example, one company announced in late 2015 the commercialization of a LED module based on COB diodes that delivers 15,000 lm, available over the range of 2,200–5,700 K color temperature which, compared to similar power high-intensity discharge (HID) lights, i. e. 100–150 W, would generate a far higher illumination.

We remind here that in 2014, the efficiency of the electrical and optical systems has already approached the technologically best possible values [2] so that the luminous efficacy of the luminaires will improve through the concomitant development of the *luminous efficacy* of the white LEDs and their *thermal management*.

For example, in 2014, cold white LEDs with a luminous efficacy of about 150 lm W^{-1} were used with modern LED electronics of 90–94 % electrical efficiency, primary optics of 92% optical efficiency and a transmittance of the protection glass of the luminaire of 92 % [2].

$$\eta_{\text{Luminaire}} = 0.92 \cdot 150\,\text{lmW}^{-1} \cdot 0.92 \cdot 0.92 = 116\,\text{lmW}^{-1} \quad (1)$$

From the above values, the overall luminous efficacy of the whole LED luminaire would be estimated from eq. (1) to be 116 lm W^{-1} rather than 150 lm W^{-1}.

3 LED street lighting: advantages

The advantages of LED lights when compared to conventional HID lamps, such as mercury vapor, metal halide and HPS vapor lamps are clear.

Contrary to HID street lights requiring a reflector (a glass cover) to capture the light emitted upwards from the lamp, which absorbs some of the light while requiring a careful design in order to avoid wasting some fraction up to the sky (light pollution), (*i*) LED street lights do not use reflectors because they emanate light only into a halfspherical space (a solid angle of 2 πsr, Figure 2), thereby preventing light pollution, i. e. achieving zero Upward Light Output Ratio (ULOR) without any special additional device.

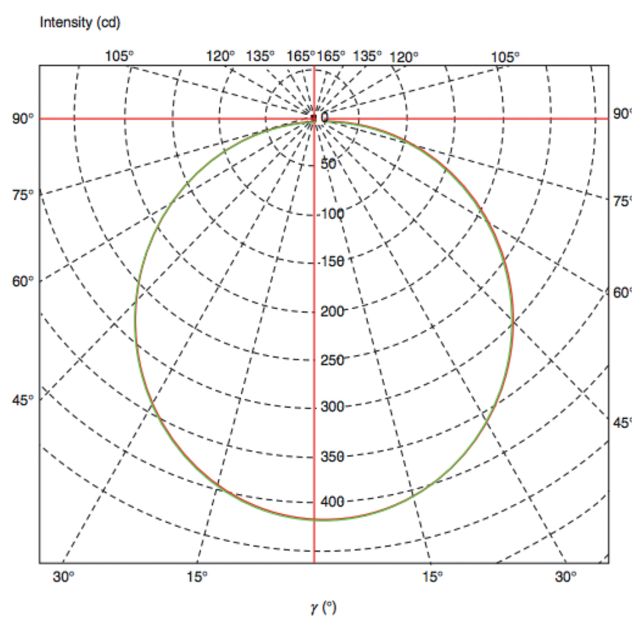


Figure 2: Luminous intensity of a diffusely emitting white LED [Image source: Technische Universität Darmstadt [Reproduced from Ref. [2], with kind permission].

In other words, LED lighting systems are much more efficient at directing light to desired areas, therefore reducing the amount of light escaping to nearby environments. Indeed, while only about 50 % of the light from traditional roadway luminaries reaches the roadway, as much as 85 % of LED lighting can do so [12].

We recall here that there are three main types of lighting effects that have the potential for varying degrees of intrusiveness to both vehicles and residents living near lighting installations. Displayed in Figure 3, these effects are:

- Spill light, which can also be backlight
- Glare
- Sky glow (upward light)

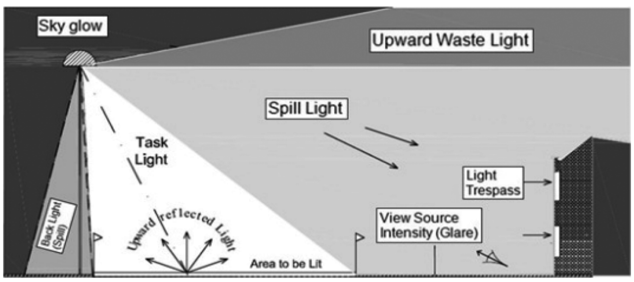


Figure 3: Types of obtrusive lights. [Reproduced from Ref. [13] with kind permission].

To help mitigate these adverse effects from new lighting schemes, luminaires need to be installed at either tilt angles of no more than five degrees.

In addition, opposite to HID lights which take significant (and hazardous) lapse of time to heat up once switched on (*ii*) LEDs emit light at full brightness instantly after switch on. Furthermore, LED lights do not suffer (*iii*) low winter temperatures offering high light output even at very low temperatures.

Compared to HID lamps, LED street lights have (*iv*) a longer projected average lifetime of any single unit (50,000–100,000 h), namely about double that of currently prevalent HPS [14]. This unique feature, coupled to the absence of the reactor used in HID lamps, leads to (*v*) lower maintenance cost due to less frequent need to service or replace the lights.

In comparison to HPS street light with their poor color rendering (color rendering index, CRI = 0.25–0.30), LED street lights (with CRI > 0.7 and now often > 0.8) [14] reproduce (*vi*) the colors of the lit objects far more accurately, making it easier for drivers to recognize potential hazards and improving the perception of the lit environment in general (Figure 4) [15].

The CRI is linked to the color temperature, and increasingly better control over the color temperature is allowing to illuminate roads with light of lower color temperature compared to 6,000 K lights used at the beginning of the LED lighting era (see below).

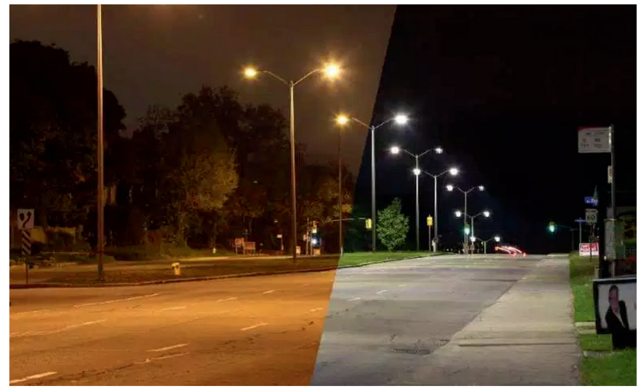
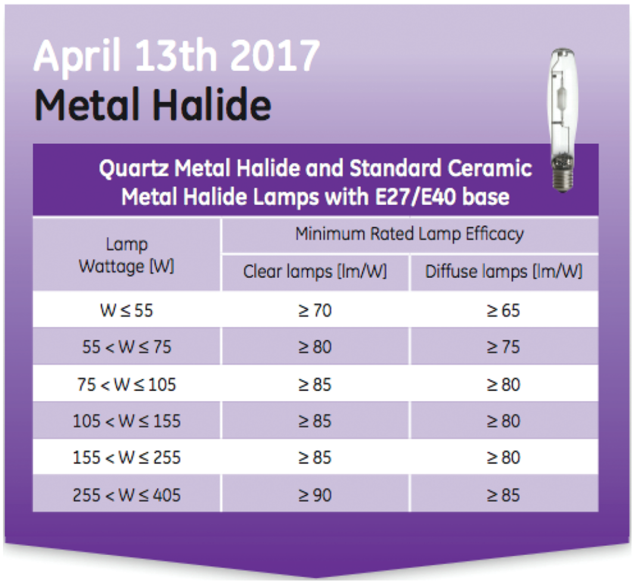


Figure 4: 2014 composite photo shows LED street lights on right on Carling Ave. and old style streetlights looking east, across the street from Civic Campus of The Ottawa Hospital [Reproduced from Ref. [16] with kind permission].

Another unique feature of LED lights when compared to HID lamps is that they (*vii*) do not contain poisonous mercury and sodium gases, nor toxic lead, lowering the environmental impact and the disposal cost for the owners of damaged street lights, provided that specific rules are established for disposal and more research is performed about the life cycle analysis (LCA) of LED lighting systems [10].

Mercury is a neurotoxin causing damage to the central nervous system, and when emitted in vapor form by broken lamps poses a serious danger to health and to the environment [17]. In 2015, with the coming into force of the second stage of the EU Directive 245/2009 (ErP = Energy-related products) and the specifications of the EU Directive 2011/65 (RoHS = Restriction of the use of certain hazardous substances), the EU has banned sales of all mercury vapor lamps, mercury hybrid lamps and many sodium vapor lamps (Figure 5).

To understand the market impact of this decision, it is enough to notice that 18 million of mercury vapor lamps for street lighting were still sold in Europe in 2007. Mercury-containing HID “metal halide” lamps (wherein “metal” is indeed mercury) can still be commercialized, likewise to Hg-containing compact fluorescent lamps (CFL), which exhibit at least 2.5 and 1.3 times higher human and eco-toxicity potentials than the LED lights [18]. For comparison a CFL may contain up to 15 mg of mercury, with 1 mg being enough to contaminate 10,000 L of water. Finally, contrary to conventional mercury light sources, the best LED street lights (*viii*) do not emit ultraviolet light which makes them less attractive to nocturnal.



Lamp Wattage [W]	Minimum Rated Lamp Efficacy	
	Clear lamps [lm/W]	Diffuse lamps [lm/W]
W ≤ 55	≥ 70	≥ 65
55 < W ≤ 75	≥ 80	≥ 75
75 < W ≤ 105	≥ 85	≥ 80
105 < W ≤ 155	≥ 85	≥ 80
155 < W ≤ 255	≥ 85	≥ 80
255 < W ≤ 405	≥ 90	≥ 85

Figure 5: Metal halide lamps will be phased out in the European Union market as of 13 April 2017 due to the EU Directive 245/2009 (ErP = Energy-related products) and the specifications of the EU Directive 2011/65 (RoHS) [Reproduced from Ref. [1] with kind permission].

4 LED street lighting: limits

Like any other technology, LED lighting has its own limits. The pronounced luminance from the point-like sources of LED lamps, and the abundancy of blue radiation in the white light spectrum worsen problems of glare on LED-lit streets. Furthermore, the very same spectral character of the white radiation emitted by LED lights poses new environmental and health problems. In 2010, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) was the first national regulatory authority to publish a 300 pages report [19] on the potential health problems caused by LED lighting. Among the recommendations to manufacturers and integrators of lighting systems using LED the report contained a call to use optics to diffuse the beams of light emitted by the diodes, thereby reducing glare and the photobiological risk.

Whereas HPS lamps emit orange light, the white light generated by the LED lamps with its significant blue component at wavelengths of 400–500 nm, significantly increases suppression in the production of melatonin in humans and animals at a rate more than five times greater than the HPS bulb (Table 1) [20].

Prolonged exposure affects the biological clock resulting in poor sleeping. To limit the impact of light pollution on human health and environment, Haim and co-workers concluded their 2011 study with three suggestions, all of which can be easily achieved with the LED technology, namely to adjust lampposts so that their light is not directed beyond the horizon; using only the amount of light needed for a task; and reducing or turning off lighting when not in use.

Table 1: 440–500 nm energy ratios (second column) and melatonin suppression efficiency (third column) for some common lamps [Reproduced from Ref. [20], with kind permission].

Lamp type	Energy relative to HPS, 440–500 nm band	Melatonin suppression effect (relative to HPS)
HPS	1	1
LPS	0.02	0.3
Metal Halide	2.7	3.4
Natural White LED	7.0	5.4
Incandescent 65 W	2.5	2.5

The team even suggested that industry should produce only warm light LEDs, with no blue emissions.

One reason for the use of conventional cool-white lights, which emit a far higher amount of blue light, has to do with the considerable higher efficiency of the former LED sources when compared to warm-white lights (Figure 6).

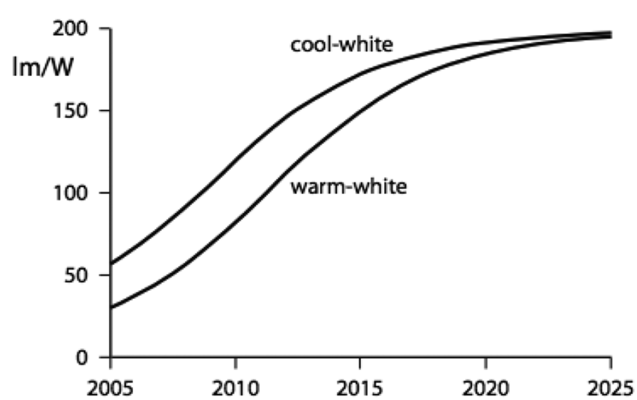


Figure 6: White-light efficiency projections for commercial LED packages. Warm-white: Tk between 2,600 K and 3,700 K with Ra > 80; cool to bluish white: Tk between 4,800 and 7,000 K with Ra > 70 [US Department of energy, 2013, Reproduced from Ref. [21] with kind permission].

However, as shown in Figure 6, the efficiency gap is closing and the growing industry activity in the field might even shorten the time to parity or so.

In a related work published two years later by researchers in Spain, the high level of short-wave, high-energy blue of LED lights was found linked to irreparable damage of the eye's retina upon long-term exposure [22]. To prevent serious health problems, the same team invoked adequate protection from the blue band of LED lights.

It is indeed the exposure to unnatural levels of light of short wavelength to cause eye strain and fatigue, as well as to suppress the hormone melatonin, disturbing our sleep-wake cycle, and the production of the protective pigment melanin.

For the first decade of massive LED commercialization (2003–2013), the most profitable way to make white LEDs has been to combine a blue-wavelength diode with a yellow luminophore affording LED lamps with high color temperature. The first LEDs emitting primarily blue light (wavelength 450–495 nm) at high color temperature, though, are currently being replaced by newer LED sources emitting warmer light, with considerably lower amounts of blue light (Figure 7) [23].

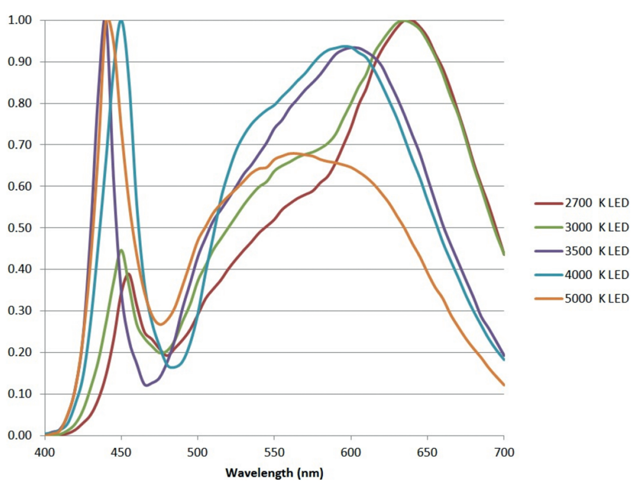


Figure 7: Typical LED spectral power distributions (normalized) of white LEDs [Reproduced from Ref. [23] with kind permission].

We remind here that in case of direct, repeated exposure at high power, blue light can harm the eyes (risks are especially significant for children because of their higher sensitivity to blue light).

The photochemical blue light hazard can be evaluated on the basis of the European EN 62471:2008 standard on the photobiological safety of lamps which provides a methodology for evaluating risk due to blue light emission, eventually classifying light sources into risk groups 0, 1, 2 and 3 (Table 2) from 0 = no risk through to 3 = high risk, that of the sun [2].

Safety-oriented companies ensure that their products comply with the photobiological safety standard, commercializing lights in the lower photobiological risk groups, manufacturers, thereby avoiding RG2 hazards in their products either by avoiding LEDs capable of producing an RG2 rating or by using appropriately designed optics to lower the source radiance of LEDs that are RG2 [24].

Table 2: Risk groups according to EN 62471:2008.

Risk group 0: no risk.
Risk group 1: low risk. The product presents no risk related to exposure limits under normal usage conditions.
Risk group 2: moderate risk. The reflex to look away from the lamp suffices to reduce the risk.
Risk group 3: high risk. The product can present a risk even with a momentary or short exposure.

Problems arising from LEDs emitting light of high color temperature, for example, were evident during the recent streetlight conversion project of the city of Portland in the United States from HPS to LED-based streetlights. The city received and accepted citizen requests to reduce brightness in the stages of installation, despite the fact that the lumen output of the LEDs was already significantly lower than the HPS products they replaced [25]. The higher color temperature in combination with a smaller area from which the light emanates leads to a common perception of LED lights as being "brighter."

To reduce glare on roadways, namely the amount of light that is directed into driver's eyes causing a serious threat to safety, a team of researchers in China and in the Netherlands recently developed a model predicting discomfort glare caused by LED road lights [26]. In detail, to investigate the effect of LED streetlights on the discomfort glare perceived by drivers, the researchers devised a laboratory set-up to mimic visual conditions on the road (Figure 8). Selected volunteers were asked to rate their level of discomfort with the glare on a standard rating scale, ranging from unnoticeable to unbearable.

The team found that the vertical illuminance (namely the interaction between the LED luminance and the solid angle) is the most significant factor affecting perceived discomfort glare. The team concluded that for a LED street uniformly emitting light, the discomfort glare is very much affected by the same main parameters of a traditional light source, with the foremost difference between the two types of light sources being not in *how* the key parameters affect perceived glare, but just in the *weighting* coefficients of these parameters.

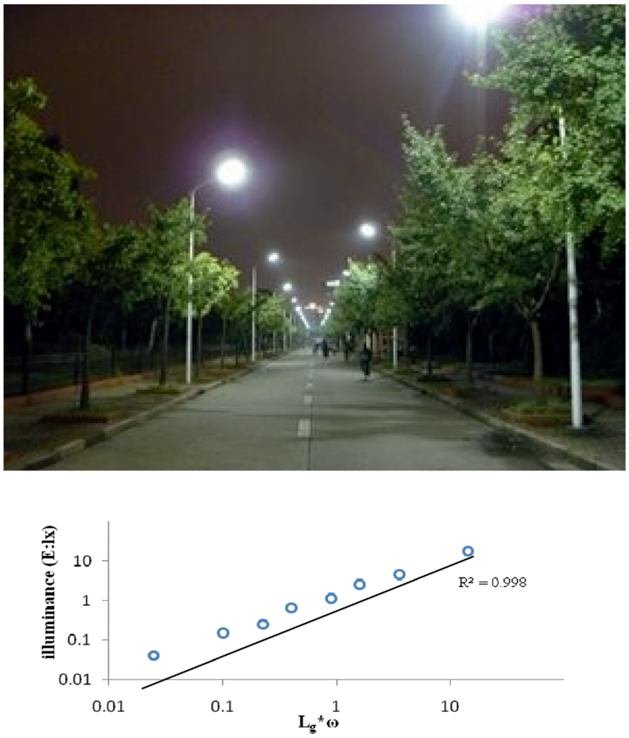


Figure 8: The road (*top*) with LED streetlamp glare where the researchers validated their laboratory findings; and the relation (*bottom*) between the vertical illuminance at the eye produced by the glare source and the product of the glare source luminance and its solid angle (for a viewing angle of 10°) [Reproduced from Ref. [26], with kind permission].

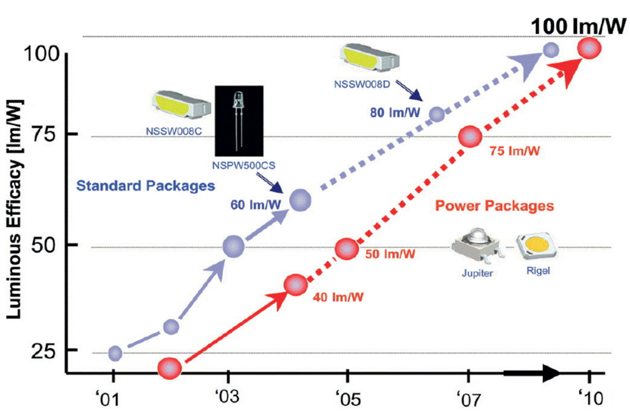


Figure 9: The internal roadmap of a leading Japanese manufacturer (Nichia) for luminous efficacy improvements in standard packages [Reproduced from Ref. [30] with kind permission].

Good optical design of the LED light unit and careful placement of each streetlight will minimize both the amount of light hitting the observer's eyes, and the luminance contrast between the streetlights and the background.

Finally, LED lighting increases the ecological impact of light pollution irrespective of color temperature [27]. White LEDs are more attractive and thus have greater ecological impacts than HPS due to the peak UV-green-blue visual sensitivity of nocturnal invertebrates. On average, LED light traps captured 48 % more insects than were captured with light traps fitted with HPS lamps, and this effect is greatly affected by air temperature.

Alas, the team found that the switch to white LEDs of significantly lower color temperature would not minimize the ecological impacts of the adoption of white LED lights, concluding with a call to ecologists and technologists to work together to focus future developments in lighting technology that balance the needs of illumination with reduced ecological impact.

Nevertheless, a further recent study investigating the attraction of nocturnal arthropods by white LEDs found that suitably adjusting spectral composition of white light allows minimizing such attraction, along with their disease potential to humans. Remarkably, in the same study was found that spectral characteristics that minimize insect attraction *probably* also reduce impacts on circadian rhythms, adding to the overall reduction of the health impact [28].

5 Performance and price progress of the technology

In 1999 Roland Haitz, a leading industry's practitioner at a large microelectronics company, postulated an empirical price/performance exponential trend of LED lighting technology according to which every 10 years there will be a tenfold drop in the cost of a lumen, and a twentyfold increase in efficacy (Figure 9) [29].

Subsequent analysis carried out fifteen years later by another industry's practitioner actually shows that on price, the Haitz prediction has been largely conservative. Indeed, driven by unprecedented competition, the price per lumen has decreased at a much faster rate than predicted with the cost per lumen having dropped by a factor at least 25 between early 2005 and early 2015, namely 2.5 times more than Haitz's law predicts [31].

On the other hand, the law is far from reproducing the efficacy performance trend, especially with regard to the last decade. For example, in 2005 the efficacy of state of the art commercial LED was about 40 lm/W for warm white (2,700 K) and 50 lm/W for cool white (5,000 K). Ten years later, the efficacy of standard LEDs commercialized

Table 3: Progress of the street LED lighting technology supplied to the City of Los Angeles (LED fixtures manufactured by Cree, Philips Hadco and Leotek).

2009	2010
Average price = $ 432 Efficiency = 42 lm/W Lifespan = 80,000 h Warranty = 5 years	Average price = $ 298 Efficiency = 61 lm/W Lifespan = 111,000 h Warranty = 6 years
2011	**2012**
Average price = $ 285 Efficiency = 72 lm/W Lifespan > 150,000 h Warranty = 6 years	Average price = $ 245 Efficiency = 81 lm/W Lifespan > 150,000 h Warranty = 7 years

by the same leading manufacturers was 110–130 lm/W for warm white and about 120–140 lm/W for cool white, namely up to three times better than in 2005, but far less from the 10:1 prediction of the Haitz law.

It is thus relevant to notice, as emphasized by Benya [32], that LEDs with a color temperature of 2,700 K are now only 10 % less efficient (such figure keeping on dropping) than LEDs emitting light with CCT of 4,000 K, so that today there is little impact on the projected energy savings when using a warmer (and ecologically more sound, see below) LED light.

Figures in Table 3 testify the rapid fall in price and increase in efficiency as being evaluated by administrators of the city of Los Angeles during the switch to LED street lights between 2009 and 2012 (Figure 10).

According to the program managers, the main lessons learned from the results (Table 4) of said massive switch to LED street lighting were two:

– The change from yellow sodium light to white light with the LEDs is being perceived as a significant increase in lighting levels, with white light having improved visibility as noticed by residents;

Table 4: Program goals and actual results of the Los Angeles switch to street LED lighting [Adapted from Ref. [1], with kind permission].

	Program goals	Actual goals
Total units installed	110,000	140,000
Energy savings	40 %	63 %
Performance	Uniformity a concern	Good uniformity, better than HPS
Community feedback	Anticipated negative	Mostly positive
Removed HID units	Recycle	Auction and recycle, > $1 million in revenue

– The energy savings are being realized and continue to increase, having reached the 63 % threshold (and costs savings of around $8.7 million in 2014) in place of the 40 % objective originally planned.

In January 2015, the City of Los Angeles Bureau of Street Lighting reported 157,000 units of LED lights, with energy savings of 63.1 % and annual savings of $8.3 million [33]. For comparison, in 2009 the city had spent around $15 million for the first round of the LED lighting project. Through sensors and digital connection technologies to provide light only on demand, the city was planning by the end of 2015 to aim at energy savings of up to 80 % [34].

Indeed, in contrast to traditional light sources, LED street lamps are adaptive lighting systems that can be instantaneously dimmed to 20 % or 10 % when light is not needed, with analogous instantaneous switch on when a car or a pedestrian is approaching the lamppost. As suggested by Kyba and Hölker after two decades of seminal studies aimed to provide guidelines for reducing light pollution [35], this *simple* solution will reduce costs, provide enhanced visibility and minimize adverse health effects.

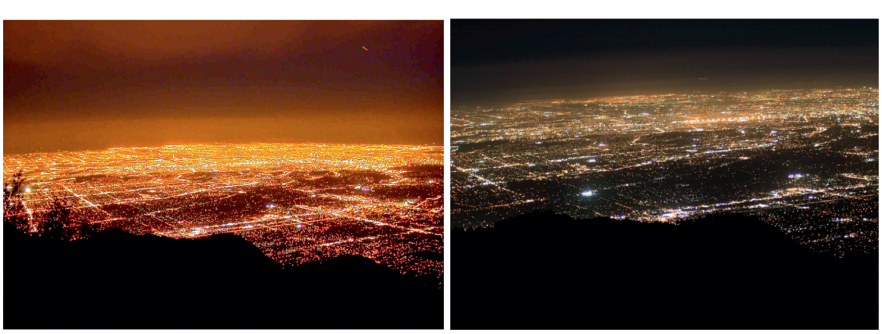


Figure 10: Los Angeles prior and after the switch to the LED public lighting [Reproduced from Ref. [8], with kind permission].

6 Quality management of LED street lighting

In a fully systemic approach to public lighting, contemporary and future road LED lighting will be guided by aesthetic, health, energy efficiency, reliability and environmental criteria. Much work was performed concerning both LCA of LED lighting systems, highlighting residual critical areas such as disposal [10], as well as recommendations were identified in order to prevent that more efficient lighting systems could lead to excess illumination and therefore vanish the effort to cut light pollution [36].

In other words, rather than narrowly focusing on improving luminous efficiency, namely the approach that has dominated the deployment of LED lamps in urban street lighting in the last decade, the goal of evolved LED lighting strategies will be providing the amount of light required for a given task, thereby preventing the rebound effects that without practical usage limits made possible by digital LED technology, will actually increase, rather than decrease, illumination costs due to enhanced utilization of artificial lighting [37].

Concerning lifetime and reliability, researchers summarizing the lessons learned up to 2013 rightly emphasize that LEDs are just one component out of many that can cause failure, with failure of the LED package met in only 10 % of the cases (Figure 11) [38].

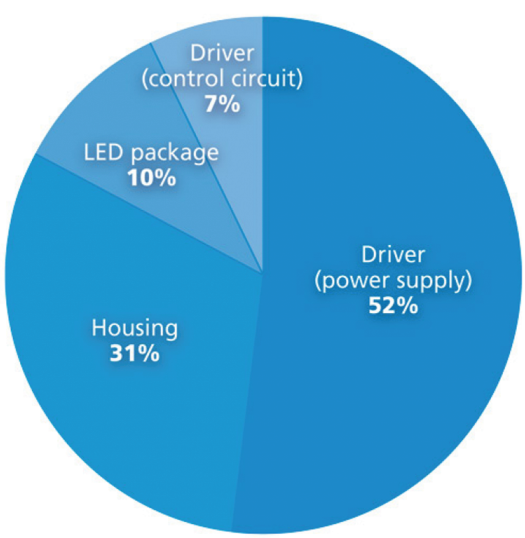


Figure 11: The chart depicts the distribution of 29 failures over 34 million operating hours for one manufacturer's family of LED outdoor luminaires [Source: Appalachian Lighting Systems, Reproduced from Ref. [39], with kind permission].

Pursuing the above mentioned systems approach, leading manufacturers of LED outdoor luminaires will focus on the driver (power supply and control circuit) technology, which accounts for >50 % of the failures, as well on poor housing which, causing overheating of the LEDs, was found responsible of more than 30 % of the failures.

Furthermore, users of LEDs in large-scale applications such as street lighting and traffic lights will actively utilize system health monitoring techniques providing early warning of failure, reducing unscheduled maintenance events and extending the time interval of maintenance cycles [40].

Getting to the aesthetic aspects, the unique nature of the solid state light sources allows to meet advanced aesthetic criteria. For example, in the case of Bastia Umbria, a small city in Italy, three different light color levels were used: one for the historic district (3.500 K), one for the first ring of roads around the historic district (4.300 K, Figure 12), and yet another one for the outer zones and suburban areas (6.000 K) [41].

Figure 12: LED street lighting downtown Bastia Umbra, an historical town in Italy [Reproduced from Ref. [41], with kind permission].

Concerning light pollution and energy savings, in the transition to LED-based street lighting, light emission above the horizontal and even near-horizontal will be entirely avoided, in order to minimize sky glow and glare [20].

Advanced optical lenses will help in the careful distribution increasing visibility, whereas the intrinsically adaptive nature of the semiconductor-based LED technology will allow in suburban and rural locations with very little activity after midnight, to dim the LED lights to a fraction (10 % or 20 %) of their flux [35]. In this respect, indeed, guidelines for road lighting design encompassing the LED technology already exist in several countries, from New Zealand [42] to Germany [43]. For example, in the indoor multi-storey and outdoor car park displayed in Figure 13 a control system dims lights to 20 % of full output when there is nobody using the area, leading to 80 % energy savings and a payback period of less than 3 years [44].

Figure 13: In the outdoor car park, 62 road luminaires installed at a height of 8 m and spaced at 8–9 m, each containing 40 LEDs consuming 94 W use microwave sensors for dimming. The average illumination in the car park is 100 lx, with a uniformity ratio of 0.57 [Reproduced from Ref. [40], with kind permission].

Moreover, recent studies have demonstrated that reducing street lighting at night, generally as a result of budget restraints or carbon reduction incentives, produces insignificant to very low impact on road accidents and casualties and crime [45], as well as on the overall human health, often going unnoticed apart from few psychologically motivated individuals [46]. On the other hand, past studies claiming the opposite have long since been rigorously demonstrated to have been poorly carried out [47].

With well-designed LED luminaire applications, today it is entirely feasible to adhere to the principles of the International Dark-Sky Association (IDA), with manufacturers getting the IDA fixture certification label based on prevention of upward light emission (approved fixtures must emit no light above 90 degrees as shown from photometric imagery from a certified testing laboratory) [48].

In 2011, a research team on behalf of the city of Pittsburgh planning to replace its existing 40,000 street lighting fixtures with LED fixtures investigated the technological potentials offered by LED lighting, best management practices and lessons learned from cities where LED lighting had been installed, as well as the placemaking and aesthetic impact of LED lighting and associated technologies [49].

The team concluded that simple retrofits of any of the existing luminaires with LED sources would provide *little* benefit when compared to simply selecting new luminaire heads designed appropriately, and that cities adopting LED street lighting technology were not using its unique and beneficial characteristics to its fullest potential, typically ignoring or overlooking additional applications such as dimming, variable color treatment, emergency communication functions and, above all, the aesthetic and placemaking potential of LEDs.

The same team recommending a 2,800–5,000 K color temperature range, and preferably 3,500 K if only a single color temperature is to be provided, with a color rendering index (CRI) of at least 80.

Light pollution depends also on the light source correlated color temperature (CCT). The IDA's Fixture Seal of Approval program mentioned above [42] provides third-party certification for luminaires that minimize glare, reduce light trespass, and do not pollute the night sky (Figure 14) has recently reduced the maximum allowable CCT from 4,100 K (neutral white) to 3,000 K (warm white).

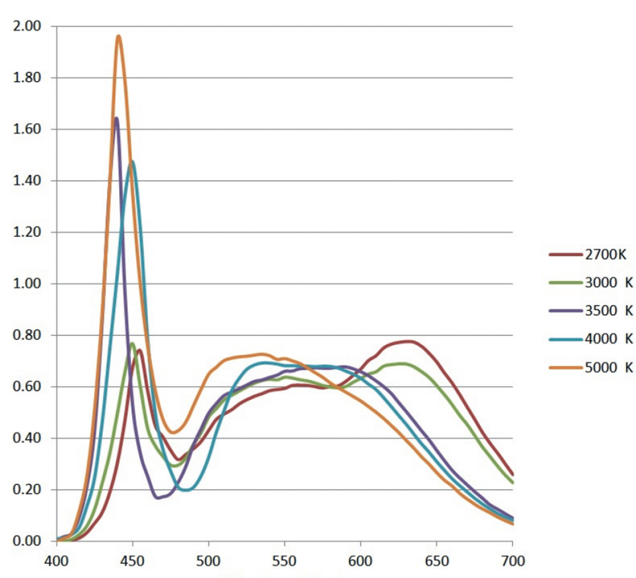


Figure 14: Overhead sky glow spectral power distribution at 80 km [Reproduced from Ref. [23], with kind permission].

Using recent research results based on a comprehensive light pollution model [50], Ashdown concluded that the concerns over high color temperature LEDs are well founded and concluded that requiring LED street lighting with correlated color temperatures of 3,000 K or less that indeed minimize glare and sky glow is completely justifiable [23].

The fact that many people prefer low-CCT outdoor lighting, especially in residential areas is reflected, for example, by the recent decision of the city of Davis (California) to replace the 650 LED street lights emitting light at 4,800 K with 2,700 K luminaires a few months after they were installed, following residents' complaints [51].

7 Outlook and conclusions

Mostly located in cities, there are around 300 million street lights around the world, out of which about 10 % are already LEDs (with less than 1% being currently connected) [52]. In Europe only, 75 % of streetlights are at least 25 years old. At the current conversion rate of 3 % per year, a complete shift to the LED lighting technology would take around 30 years.

Major cities around the world are either upgrading or plan to upgrade soon to LED street lighting, as it is now evident from a decade of trials across the world that cities that have adopted LED street lighting have achieved energy savings of between 50 % and 70 %. The technical and financial barriers for switching to LED have been overcome. The fall in price of LED lights allows rapid (3–5 years) return on investment. It is enough, for municipalities, to allocate resources currently used to pay their electricity lighting bill to access credit and finance and switch to light-emitting diodes.

The cutting effect in carbon dioxide emissions can be very important insofar LED lighting reduces the primary energy demand. Hence, the policy outcomes of the UN conference on climate change (COP21), which is going on at the time of writing, could create more support from governments around the world to boost the transition of outdoor lighting to the LED technology.

This study summarizes in a single report the major opportunities for improvement in LED outdoor and street lighting, with the aim to assist city planners, energy managers and policy makers to take into account not only the economic advantages due to reduced energy requirements but also those health, environmental and aesthetic aspects that will allow them to exploit the full potential of LED lighting.

In order to assess the social and environmental impacts of LED lights before their installation, city planners will require lighting designers to effectively (and creatively) apply lighting design guidelines such as, for example, those formulated in the German standard DIN SPEC 67600 [43], supporting the design of biologically effective lighting installation. Modeling programs such as the Outdoor Site-Lighting Performance [53], developed by researchers in the US, are also available, allowing to analyze a variety of design options in the context of existing site conditions and identify the best possible lighting scheme to minimize sky glow, light trespass, and glare.

In conclusion, the undergoing global lighting revolution taking place at accelerated pace requires a full understanding of the advantages and limitations of the new SSL technology to effectively design and use it for street lighting. The relevance of this sector is a single segment of the energy scenario is self-evident: 304 million street lamps scattered worldwide (likely to reach 350 million by 2025), accounting for more than 10 % of the global power demand (i. e. more than half of the worldwide energy demand for artificial lighting).

This work will hopefully contribute toward this crucially important sector of contemporary sustainability efforts to improve energy utilization while protecting the environment.

Acknowledgments: This article is dedicated to Dr Ian Ashdown, eminent lighting scientist currently at Lighting Analysts, for all he has done to advance the practice of LED lighting. An anonymous reviewer is gratefully acknowledged for careful consideration and very valuable suggestions.

References

1. The official web site of the Nobel Prize, Press Release, 7 October 2014. Available at: http://www.nobelprize.org/nobel_prizes/physics/laureates/2014/press.html.
2. Khanh TQ, Bodrogi P, Vinh QT, Winkler H, editors. LED lighting: technology and perception. Weinheim: Wiley-VCH, 2014.
3. International Energy Agency. Lights labour's lost: policies for energy-efficient lighting. Paris: OECD/IEA, 2006.
4. Farahat A, Florea A, Martinez Lastra JL, Branas C, Azcondo Sanchez FJ. Energy efficiency considerations for LED-based lighting of multipurpose outdoor environments. IEEE J Emerg Sel Top Power Electron 2015;3:599–608.
5. Khanh TQ, Trinh Vinh Q, Ganev H. Optimization and characterization of LED luminaires for outdoor lighting. In: Led Lighting: Technology and Perception, Khanh TQ, Bodrogi P, Vinh QT, Winkler H, editors. Weinheim: Wiley-VCH, 2014: Chapter 7, 443–71.

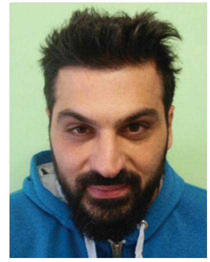
6. Biello D, LED There Be Light, Scientific American, March 18, 2009. Available at: http://www.scientificamerican.com/article/led-there-be-light/.
7. Loguercio C, Illuminazione a LED: Chimera o realtà? Napoli 13 March 2009. Available at: http://www.led-lighting.it/DOCUMENTI-pdf/attidelconvegno/loguercio.pdf. Accessed: 11 Nov 2015.
8. Ebrahimian Ed, Los Angeles Bureau of Street Lighting, City of Los Angeles "Changing our Glow for Efficiency," U. S. Embassy in Helsinki, 6 June 2013. Available at: http://photos.state.gov/libraries/finland/788/pdfs/LED_Presentation_Final_June_2013.pdf. Accessed: 11 Nov 2015.
9. Lenk R, Lenk C. Practical lighting design with LEDs. Piscataway, NJ: IEEE Press, 2011.
10. Jägerbrand AK. New framework of sustainable indicators for outdoor LED (light emitting diodes) lighting and SSL (solid state lighting). Sustainability 2015;7:1028–63.
11. Licht.de, Impact of Light on Human Beings, licht.wissen 19, September 2014. Available at: http://humancentriclight.com/wp-content/uploads/2014/09/1403_LW19_e_Impact-of-Light-on-Human-Beings_web.pdf. Accessed: 11 Nov 2015.
12. Wu MS, Huang HH, Huang BJ, Tang CW, Cheng CW. Economic feasibility of solar-powered LED roadway lighting. Renew Energ 2009;34:1934–8.
13. van Bommel W. Road lighting. Switzerland: Springer International Publishing, 2015.
14. Pinto MF, Mendonça TR, Coelho F, Braga HA. Economic analysis of a controllable device with smart grid features applied to LED street lighting system. IEEE 24th International Symposium on Industrial Electronics (ISIE), 2015;1184–9.
15. Jin H, Jin S, Chen L, Cen S, Yuan K. Research on the lighting performance of LED street lights with different color temperatures. IEEE Photonics J 2015;7:1–9.
16. Pearson M. City seeks to convert all street lights to LED by 2020, Ottawa Citizen. Available at: http://ottawacitizen.com/news/local-news/city-seeks-to-convert-all-street-lights-to-led-by-2020. Accessed: 30 Sep 2015.
17. World Health Organization, Mercury and health, September 2013. Available at: www.who.int/mediacentre/factsheets/fs361/en/.
18. Lim SR, Kang D, Ogunseitan OA, Schoenung JM. Potential environmental impacts from the metals in incandescent, compact fluorescent lamp (CFL), and light-emitting diode (LED) bulbs. Environ Sci Technol 2013;47:1040–7.
19. ANSES. Effets sanitaires des systèmes d'éclairage utilisant des diodes électroluminescentes (LED). Paris: ANSES, Oct 2010.
20. Falchi F, Cinzano P, Elvidge CD, Keith DM, Haim A. Limiting the impact of light pollution on human health, environment and stellar visibility. J Environ Manage 2011;92:2714–22.
21. Department of Energy. Solid-state lighting research and development: multi-year program plan. Prepared for lighting research and development, building technologies office, office of energy efficiency and renewable energy. Washington, DC: Department of Energy, 2013.
22. Chamorro E, Bonnin-Arias C, Pérez-Carrasco MJ, Muñoz J, de Luna D, Sánchez-Ramos V.C. Effects of light-emitting diode radiations on human retinal pigment epithelial cells in vitro. Photochem Photobiol 2013;89:468–73.
23. Ashdown I, Temperature C, Lighting O. All Things Lighting. 2 Jul 2015. Available at: http://agi32.com/blog/2015/07/07/color-temperature-and-outdoor-lighting/. Accessed: 11 Nov 2015.
24. Lighting Global. LED Lights and Eye Safety Part *II: *Blue *light *hazards, Issue 5, May 2015. Available at: https://www.lightingglobal.org/wp-content/uploads/2013/12/Issue_5_EyeSafety2_EcoNotes.pdf.
25. DOE Gateway Report Reveals Lessons Learned in Midst of Portland Street Lighting Project. Available at: http://www.solidstatelightingdesign.com/doe-gateway-report-reveals-lessons-learned-in-midst-of-portland-street-lighting-project/. Accessed: 11 Nov 2015.
26. Lin Y, Liu Y, Sun Y, Zhu X, Lai J, Heynderickx I. Model predicting discomfort glare caused by LED road lights. Opt Express 2014;22:18056–71.
27. Pawson SM, Bader MK. LED lighting increases the ecological impact of light pollution irrespective of color temperature. Ecol Appl 2014;24:1561–8.
28. Longcore T, Aldern HL, Eggers JF, Flores S, Franco L, Hirshfield-Yamanishi E, et al. Tuning the white light spectrum of light emitting diode lamps to reduce attraction of nocturnal arthropods. Philos Trans R Soc London, B Biol Sci 2015;370:20140125.
29. Haitz R, Tsao JY. Solid-state lighting: 'The case' 10 years after and future prospects. Phys Status Solidi A 2011;208:17–29.
30. Mills A. LED 2005 illuminates. III-Vs Rev 2005;18:30–5.
31. Rodriguez E, Haitz's Law: Fact or Fiction? 4 February 2015. Available at: www.allledlighting.com/author.asp?section_id=455&doc_id=563857. Accessed: 11 Nov 2015.
32. Benya JR. Nights in Davis. LD + A 2015;45:32–4.
33. Available at: http://bsl.lacity.org/led.html. Accessed: 11 Nov 2015.
34. Bien W. LED street lighting: an untapped opportunity in driving energy efficiency. Energy Manager Today. 28 September 2015. Available at: http://www.energymanagertoday.com/led-street-lighting-an-untapped-opportunity-in-driving-energy-efficiency-0116174/. Accessed: 11 Nov 2015.
35. Kyba CCM, Hänel A, Hölker F. Redefining efficiency for outdoor lighting. Energy Environ Sci 2014;7:1806–9.
36. Lyytimäki J. Avoiding overly bright future: the systems intelligence perspective on the management of light pollution. Environ Dev 2015;16:4–14.
37. Jenkins J, Nordhaus T, Shellenberger M. Energy emergence: rebound and backfire as emergent phenomena. Oakland: Breakthrough Institute, 2011.
38. Pacific Northwest National Laboratory. Solid-state lighting: Early lessons learned on the way to market. Solid-State Lighting Program, Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U. S. Department of Energy, Jan 2014.
39. Available at: http://www.ledsmagazine.com/articles/print/volume-11/issue-3/features/programs/led-lighting-progresses-driven-by-lessons-learned.html. Accessed: 11 Dec 2015.
40. Chang M-H, Sandborn P, Pecht M, Yung WK, Wang W. A return on investment analysis of applying health monitoring to LED lighting systems. Microelectron Reliab 2015;55:527–37.
41. Available at: http://www.cree-europe.com/en/progetti-dwn.php?idProgetto=23. Accessed: 11 Nov 2015.

42. Available at: http://www.nzta.govt.nz/assets/resources/specification-and-guidelines-for-road-lighting-design/docs/m30-road-lighting-design.pdf. Accessed: 11 Nov 2015.
43. DIN SPEC 67600 Biologically effective illumination – Design guidelines, April 2013.
44. Bain R. Lux Magazine. 22–3 Mar 2013. Available at: https://goo.gl/GSd6Tm. Accessed: 11 Dec 2015.
45. Steinbach R, Perkins C, Tompson L, Johnson S, Armstrong B, Green J, et al. The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis. J Epidemiol Community Health 2015;69:1118–24.
46. Green J, Perkins C, Steinbach R, Edwards P. Reduced street lighting at night and health: a rapid appraisal of public views in England and Wales. Health Place 2015;34:171–80.
47. Marchant P. What is the contribution of street lighting to keeping us safe? An investigation into a policy. Radical Stat 2010;102:32–42.
48. IDA. Greenroads Manual v1.5. Available at: https://www.greenroads.org/files/227.pdf
49. Remaking Cities Institute, Carnegie Mellon University, LED Street Light Research Project, Pittsburgh: 2011. Available at: http://www.cmu.edu/rci/documents/led-updated-web-report.pdf. Accessed: 11 Nov 2015.
50. Aubé M. Physical Behaviour of Anthropogenic Light Propagation into the Nocturnal Environment. Philos T Roy Soc B 2015;370:20140117.
51. Janes N. Davis Will Spend $350,000 To Replace LED Lights After Neighbor Complaints, CBS Sacramento 21 Oct 2014.
52. The Climate Group, The Big Switch: Why it's time to scale up LED street lighting, New York: 24 Sept 2015. Available at: http://www.theclimategroup.org/_assets/files/LED-September.pdf. Accessed: 11 Nov 2015.
53. Brons JA, Bullough JD, Rea MS. Outdoor site-lighting performance: a comprehensive and quantitative framework for assessing light pollution. Light Res Technol 2008;40:201–24.

The Authors

Rosaria Ciriminna
Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, Italy

Rosaria Ciriminna is a chemistry scholar in the top 1% of most cited chemists based at Palermo's Institute of Nanostructured Materials of Italy's Research Council. Her widely published research in the field of green, nano- and photochemistry is developed in cooperation with several research Groups worldwide. Her interest in solar energy is reflected in books, articles and educational activates besides the graduate and undergraduate students mentored every year.



Lorenzo Albanese
Istituto di Biometeorologia, CNR, via Caproni 8, 50145 Firenze, Italy

Lorenzo Albanese is a researcher at National Research Council's Institute of Biometeorology based in Florence, where he works along with Dr Meneguzzo at several research projects aimed to reduce the energy input, and improve the outcomes, of new food processing technology. His recent articles on the great solar boom detailing the progress and impact of solar PV technology has been widely covered by the press.

Francesco Meneguzzo
Istituto di Biometeorologia, CNR, via Caproni 8, 50145 Firenze, Italy, **francesco.meneguzzo@cnr.it**

Francesco Meneguzzo is a physicist based at Florence's Institute of Biometeorology of Italy's CNR where he coordinates a research Group active in a vast field of research domains, including energy, propulsion, agri-food processes and geophysics. His recent achievements include the development of an entirely clean production and sanification process applicable to liquid foods based on the hydrodynamic cavitation technology. As weather forecaster he has established Tusacany's Regional Met Service Tuscany (1996-2002), later to become the well-known LAMMA weather forecast center. Currently, he chairs the organization committee of SuNEC 2016 conference on solar energy.

Mario Pagliaro
Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, Italy, **mario.pagliaro@cnr.it**

Mario Pagliaro, co-founder of Sicily's Solar Pole, is a chemistry and solar energy scholar based at Italy's CNR. His research Group achievements include 150 research articles, 20 books, and numerous book chapters. A Fellow of the Royal Society of Chemistry, Mario's research interests are in the broad areas of nanochemistry, solar energy, sustainability and management. Between 2011 and 2015, he has chaired the "SuNEC-Sun New Energy Energy Conference" and the "FineCat-Symposium on heterogeneous catalysis for fine chemicals" held every year in Sicily. Since late 2015 he is the president of Palermo's municipality energy company AMG Energia.