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

Historical perspective on the physics of artificial lighting

Perspective historique sur la physique de l'éclairage

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ABSTRACT

We describe the evolution of lighting technologies used throughout the ages, and how the need for improvements was such that any new technology giving better and cheaper lighting was immediately implemented. Thus, every revolution in energy sources – gas, petrol electricity – was first put to large-scale use in lighting. We describe in some detail several "ancient" techniques of scientific interest, along with their physical limitations. Electroluminescence – the phenomenon by which LEDs directly convert electricity into light – was long thought to only be of use for indicators or flat panel displays supposed to replace the bulky cathode-ray tubes. The more recent uses of LEDs were mainly for street traffic lights, car indicators, small phone displays, followed by backlighting of TV screens. LED lamps for general lighting only emerged recently as the dominant application of LEDs thanks to dramatic decrease in cost, and continuous improvements of color quality and energy conversion efficiency.

RÉSUMÉ

Nous décrivons l'évolution des technologies d'éclairage utilisées à travers les âges, et comment le besoin d'améliorations était tel que toute nouvelle technologie donnant un éclairage meilleur et moins cher a été immédiatement mise en œuvre. Ainsi, chaque révolution en matière de sources d'énergie – gaz, pétrole, électricité – a été dans un premier temps utilisée à grande échelle dans l'éclairage. Nous décrivons en détail plusieurs techniques anciennes présentant un intérêt scientifique, ainsi que leurs limites physiques. L'électroluminescence – le phénomène par lequel les LED convertissent directement l'électricité en lumière – a longtemps été considérée comme étant uniquement utile pour les indicateurs ou les écrans plats censés remplacer les tubes cathodiques volumineux. Les utilisations les plus récentes des LED concernaient principalement les feux de signalisation, les indicateurs pour voitures, les écrans de téléphone, suivies par le rétroéclairage des écrans de télévision. Les lampes LED pour l'éclairage général ne sont apparues que récemment, comme leur application dominante grâce à une réduction spectaculaire des

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coûts et à des améliorations continues de la qualité des couleurs et de l'efficacité de la conversion d'énergie.

1. Historical perspective up to the 20th century – Lighting through ages: a major human need and energy use

Artificial lighting has always been a fundamental human need that has continuously mobilized a significant share of resources, right now 15 to 20% of electricity in developed countries. This may sound like a lot, but it reflects the need for lighting. Despite numerous improvements through new emerging technologies, lighting has always exercised and is still exerting a major drain on energy resources. Any progress in chemical resources, physical phenomena has been put to good use throughout centuries to increase efficiency, improve light quality and decrease costs.

1.1. Early lighting systems [1,2]

Lighting methods have changed from burning wood in fireplaces or torches to oil lamps (vegetable or animal, which includes whale oil from the 16th to 19th century, which almost led to extinction) with wicks, and then to candles (based on oil, tallow, or wax) from 1200 onwards. There were continuous improvements: for instance, beeswax-based candles were producing less smoke and smell, and better light, but were more expensive. Depending on technological advances, availability and cost, sources for candles material evolved from animal to plant to whales to paraffin (extracted from minerals like coal or petrol), and often coexisted. Oil lamps also evolved from wicks placed directly in the oil reservoir to advanced designs where the wick is fed with air through a chimney to ensure a fuller oil combustion (Argand lamp, 1783, equivalent to 6–8 candles), much resembling the later petrol/kerosene lamps that displaced the oil lamps from the 1850s on.

Lighting remained a luxury for a long time: between 1 and 2% of the average income was spent until 1950 in Europe (1% in the UK) with a very limited individual lighting consumption until 1800, which then increased by a factor of 1500 between 1800 and 1950 (Fig. 1b, c). For a long time, until 1800, the cost of lighting hardly decreased, but between 1800 and 1950 it decreased by 600 times. Between 1950 and 2000, the cost further decreased by a factor of 6, consumption increased by 5X times as well as GDP per capita, reducing the cost of lighting to 0.17% of income [3].

As of today, there were at all times many different needs (or markets) for lighting: private individual house, palaces or temples, streets, lighthouses, which required different solutions.

As an example of the development of one key need, public lighting was a critical demand for safe walking in streets at night. Before its implementation, the only way to find one's way was to have a lantern or rent the service. For a very long time, the public service was minimal: ancient Romans used oil lamps filled with vegetable oil in front of their houses and had special slaves whose only duty was to take care of those lamps, to light them, extinguish them, and make sure that they always had oil. First organized public lighting was done on 1417 in London with the mayor ordering owners to hang lanterns in the early night hours during the winter months. Paris followed in 1524 with an order to put lights in windows facing streets [4].

As is evident from Fig. 1b, while lighting generation remained stagnant during many centuries, things changed dramatically in the 19th century, with three revolutions in lighting, successively due to gas, kerosene, and electricity. The main factor for the jump in individual light consumption are the increase in light source efficiency (Fig. 1a) and the decrease in lighting fuel cost by a factor of 10 between 1700 and 2000, as GDP per capita "only" increases by a factor 20 between 1700 and 2000 [3].[1] At the appearance of each new source of energy capable of producing light, most of that new energy production was consumed by lighting, so critical was the demand for better light (Fig. 1d).

1.2. Gas lighting

Efficient lightning only started with the demonstration of gas lighting fueled with coal gas (produced by the distillation of coal, a by-product of coke fabrication for the steel industry, up to then rejected in the atmosphere). Efficient gas production appeared at the beginning of the 19th century. The cost of gas lighting was only 25% that of oil lighting, and thus it grew rapidly [2]. Local gas production and distribution companies quickly developed: in 1860, there were more than 400 gas companies in the US, 900 in Britain, and 266 in Germany [2]. London got its first gas streetlight in 1807. Other cities followed, with Paris starting gas lighting in 1820. Gas was supplied to lantern poles through pipes running in the cities.

The light-emitting species in gas flames is due to de-excitation of the heated carbon species originating in hydrocarbons ("illuminants") dissolved in coal gas, producing a bright yellow color, but also soot. The initial coke production process produced such illumination gas by partial pyrolysis of coal in air, but it produced poor coke for metallurgy. The process was refined in the 1850s by coal burning in air and steam cycles, producing gas containing only H_2 and CO after elimination of

[1] For a discussion of the relation between GDP and lighting consumption, see [7].