International Solid-State Lighting Alliance

SSL Industry Quarterly Report 2023-4

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1. Introduction:

It was good that the ISA was able to hold its Annual General Assembly (AGA) in person in Xiamen after a break of three years. The staff gave their time and talents generously to ensure that the business was carried out expeditiously and that the members were able to renew friendships and make new ones.

The meetings were part of the 20th Anniversary celebrations of the China International Forum on Solid State Lighting. These celebrations provide an opportunity to review the progress that solid-state lighting has made towards the revitalization of the lighting industry and the provision of high-quality artificial lighting at affordable cost across the globe.

The gathering took place at the same time as COP28 in Saudi Arabia. At each meeting of that body, it becomes ever clearer that the world is falling behind in the endeavour to slow down global warming and to protect many of the most valuable assets of our environment. The remarkable technical advances made possible by SSL have provided an opportunity for the lighting industry to demonstrate leadership in constraining the demand for non-renewable resources and minimizing pollution of all forms.

Light is one of the most basic necessities of life and the supplementation of daylight has become crucial in the development of human lifestyles, cultures and well-being. Recent scientific discoveries have shown that light contributes to our health in many ways, in addition to providing food and enabling us to carry out our daily activities.

Although most of the benefits of light come from daylight, the preponderance of time spent indoors has greatly increased the importance of artificial light. Before the advent of SSL, the distribution of high-quality artificial light across the globe was very uneven and the increasing cost of energy could have significantly exacerbated these inequities. It is therefore important to consider the balance between the positive and negative effects of the provision of more light that have resulted from SSL.

The evolution of SSL is far from complete and so it is worthwhile to update the roadmap for the industry, from both the technical and social perspectives. This report is intended to stimulate discussion of future trends and to encourage ISA members to continue to offer leadership to the industry. An outline of this report was presented by the editor at the Annual General Assembly.

Since the major goal of SSL is to provide more high-quality light across the global without increasing the consumption of energy or causing undesirable side effects, it is extremely important to use the light effectively and avoid waste, as stressed by Robert Karlicek and Georges Zissis at the AGA. Chapter 3 includes a brief assessment of the progress that has been made in the development of controls.

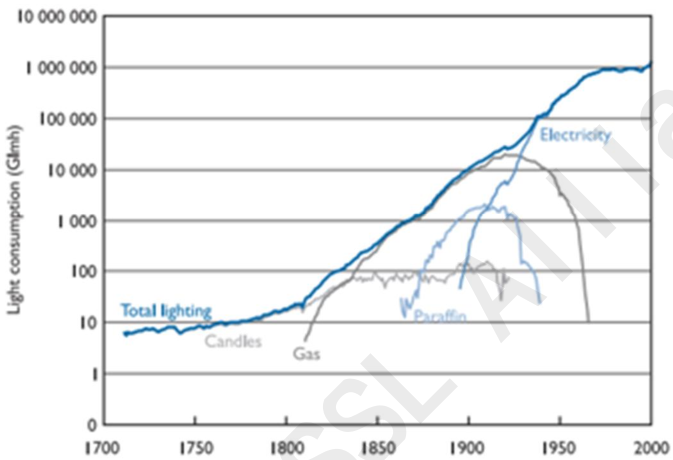
This analysis suggests that the major impact of SSL so far has been to provide more artificial light and reduce some of the inequity in the global distribution, but with a small increase in total electricity consumption. Much more progress in efficiency and controls will be needed to achieve the reduction in energy use that seemed possible twenty years ago.

2. The Challenge of SSL

2.1 Lighting before SSL

The status of artificial lighting before the introduction of SSL to general lighting was reviewed in great detail in the document "Light's Labour's Lost (LLL)[1]", published by the International Energy Agency (IEA) on the basis of research by a large team headed by Paul Waide and Satoshi Tanishima. The long-term historical perspective was perhaps best illustrated by the following figure, which was first published at a conference in 2003 by Roger Fouquet and J.G. Pearson in 2003.

Consumption of lighting by candles, gas, paraffin and electricity in the United Kingdom between 1700 and 2000



Source: Fouquet and Pearson, 2003 (reproduced with permission).
Abbreviation: Glmh = gigalumen-hours.

The increase in production by five orders of magnitude was driven by new energy sources and subsequent cost reduction, as estimated in this table.

Price (constant year-2000 GBP) of 1 Mlmh of light in the United Kingdom from 1300 to 2000

Year	Technology				
	Tallow candles	Whale oil	Gas light	Paraffin light	Electric light
1300	40 000				
1600	12 598	24 567			
1700	11 024	15 748			
1825	2 835		1 938		
1860	2 047		310	1 550	
1883	1 417		194	326	930
1900	1 260		119	171	341
1950			41	186	8
2000			12	209	2

Source: Fouquet and Pearson, 2003.
Abbreviation: Mlmh = megalumen-hour.

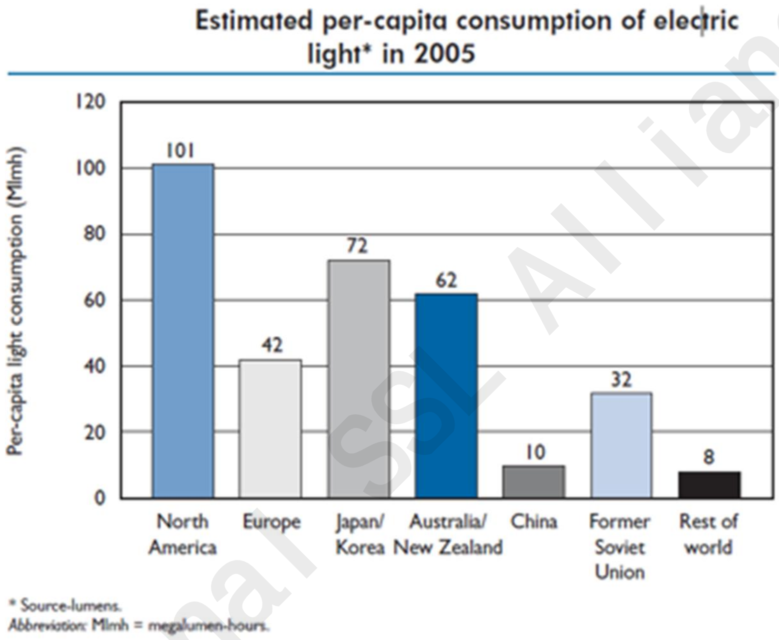
The LLL report estimated that the global average cost of electric light in 2005 was about US$2.80 per megalumen-hour (Mlmh), of which two-thirds was the energy cost and one-

[1] https://www.iea.org/reports/lights-labours-lost

third was the cost of the equipment (lamps, luminaires and control gear) and labour needed to install and maintain the lighting systems.

The figure above confirms that the progress created by the development of incandescent, fluorescent and high-intensity discharge (HID) lights stalled around 1975, suggesting that there was pent-up demand in even the most industrialized economies. The global lighting industry was dominated by three companies and little innovation was passing from R&D laboratories to high-volume production.

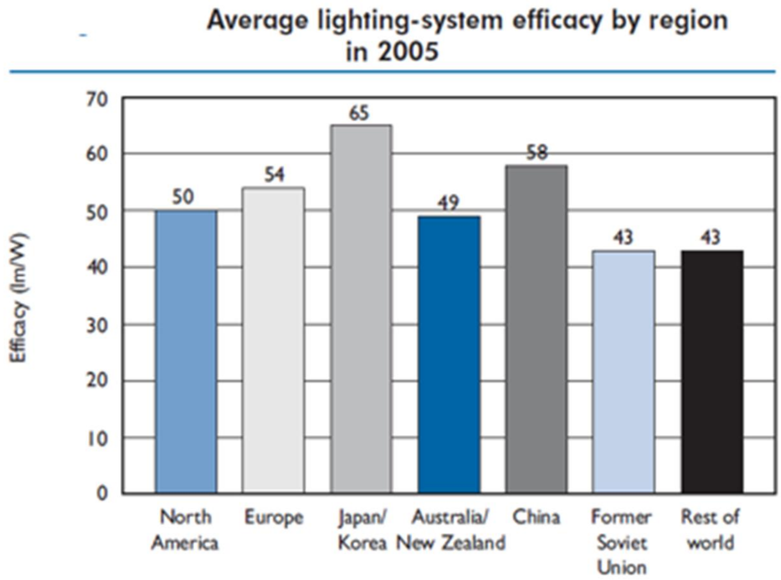
The global situation was more serious. The amount of light created per person in various regions is shown in the next chart. The value ranged from 101Mlmh in North America to 3Mlmh in India.



Based upon these data, it can be argued that the most important goal for a new technology would be to provide access to high-quality artificial light at a cost that would be affordable to all. Of course, this would have to be accomplished without significantly increased demand on global energy resources.

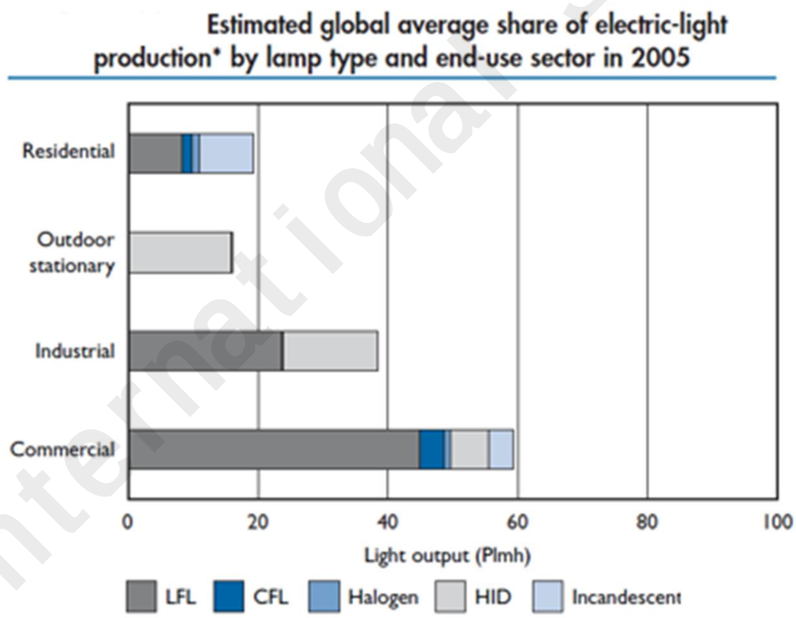
The total annual production of artificial light in 2005 was estimated to be 135 petalumen-hours (Plmh), which was equivalent to 20Mlmh per capita. The significance of these huge numbers can be difficult to comprehend. The personal ration of 20Mlmh is enough to illuminate an area of about 10 m^2 at 300 lux for our each of our awaken hours. The adequacy of such an allocation is a matter for ongoing debate, but it seems clear that the global inequities should be reduced substantially.

It is perhaps surprising that efficiency of light production varied less across the globe, as shown in the next chart.



The major factor seemed to be the relative popularity of incandescent and fluorescent lamps, with the latter being more favoured in Asia. The global average was 48lm/W, resulting in an electricity consumption of 2650 teralumen-hours (Tlmh), which contributed about 19% to the total global use of electricity.

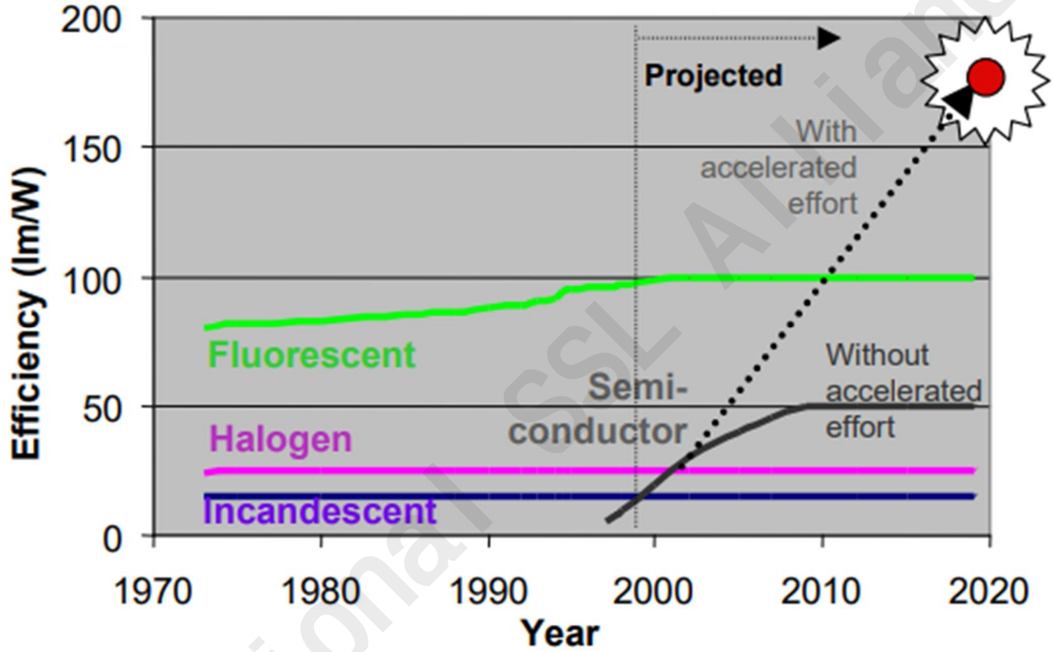
The next chart shows the breakdown of light production by technology and use sector.



In assessing the overall impact of SSL on total energy use, it is important to remember that the low efficiency of incandescent and halogen lamps was only important in the residential sector. Most of the light was created in other sectors, in which more efficient technologies were dominant.

2.2 The Promise of SSL

Although research on SSL had been underway for several decades, the potential impact on general lighting was unclear until the discovery in Japan of efficient blue LEDs. The opportunities were recognized around 2000 by a few prophets on at least three continents, although the major producers maintained their faith in the traditional technologies. Interest in the US was stimulated by a report from Roland Haitz and Fred Kish (Hewlett-Packard Company, and Jeff Tsao and Jeff Nelson (Sandia National Laboratories)[2]. They predicted that the efficacy of LEDs could reach upwards of 200 lm/W but doubted that this would happen unless additional resources could be provided to supplement the meagre R&D budgets of the existing industry. *"This new white light source would change the way we live, and the way we consume energy. The worldwide amount of electricity consumed by lighting would decrease by more than 50%".*



The potential impact of SSL was developed further in 2002 by the Opto-Electronics Industry Development Association (OIDA) in a roadmap[3] that helped to guide the formation of the SSL R&D program at the U.S. Department of Energy. A similar program was launched in China, supported by the China Solid-State Lighting Alliance[4]. Each of these programs lasted over 15 years and made significant contributions to the development of SSL technology. More limited national projects were initiated in other Asian countries and Europe.

The potential of SSL as foreseen by OIDA is summarized in the next table.

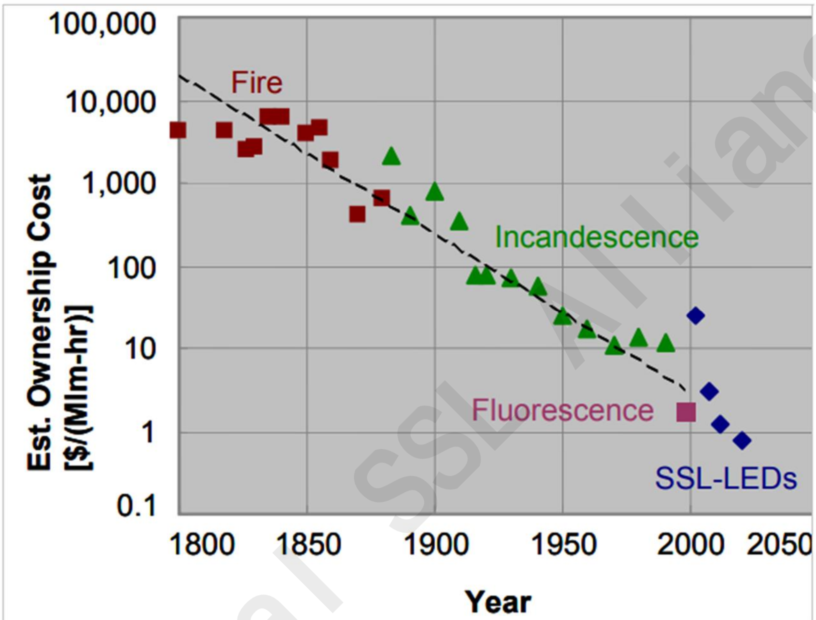
[2] The Case for a National Research Program on Semiconductor Lighting, https://www.researchgate.net/publication/237013116

[3] https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/report_led_november_2002a_1.pdf

[4] http://china-led.net/

Year	2002	2007	2012	2020
Luminous efficacy (lm/W)	25	75	150	200
Lifetime (khr)	20	>20	>100	>100
Flux (lm/lamp)	25	200	1000	1500
Lumen cost ($/klm)	200	20	<5	<2
Color rendering index	75	80	>80	>80
Lighting markets penetrated	low-flux	incandescent	fluorescent	all

Perhaps the boldest forecast was that SSL could lead to further reductions in the cost of light production, as shown in the next figure.



If the cost of light could be reduced well below that of the traditional technology, much of the pent-up demand could be met. This would have most effect in developing countries.

The increased demand could well offset the gains in efficiency and reduce the possibility of substantial savings in the use of electricity for lighting. If the global average per-capita use reached that of Europe in 2005 (42 Mlmh per year) and population increased to 8 billion, the demand for light would grow from 135 Mlmh to over 330 Mlmh. To offset that growth, the average efficacy of lighting would need to rise to 117 lm/W.

3. Progress in the First 20 Years

This chapter discusses the extent to which SSL packages and products have met the expectations of the early roadmaps, focusing on efficiency, cost and smartness.

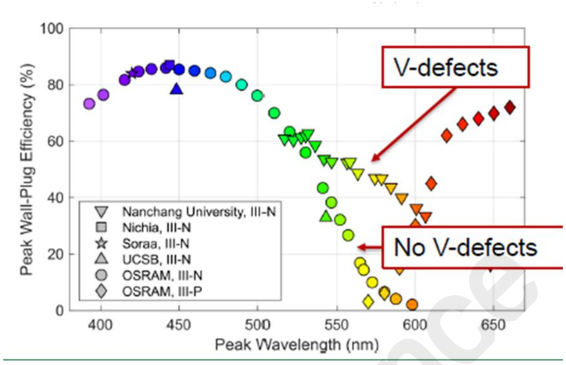
3.1 Progress on Efficacy

3.1.1 LED chips

The huge growth of the SSL market has been enabled by the development of highly efficient blue III-nitride LEDs at wavelength around 450nm, together with phosphors to provide light at higher wavelengths. Significant progress has been made in recent years on red LEDs around 660nm, but the 'green gap' has not yet been filled. The next table below comes from a valuable review focused mainly on agricultural applications[5] and shows the best performance in wall-plug efficiency (WPE of W W^{-1}) or in µmol/J, which is the unit most appropriate for horticulture.

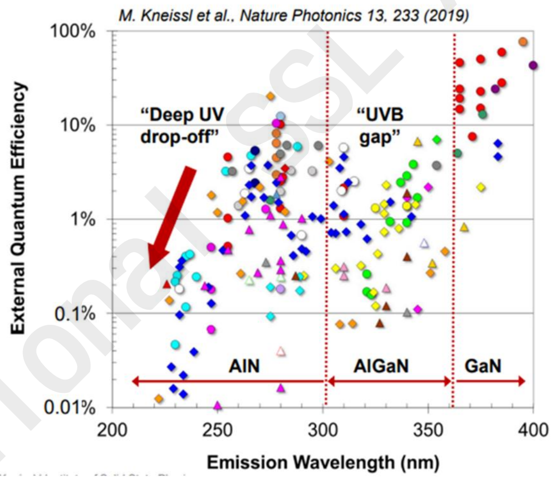
Table 1 **Efficiency and efficacy of some common LEDs at 100 mA per mm^2 (near-optimal efficacy) and a 25 °C junction temperature**

LED	Peak wavelength or correlated color temperature	Efficiency (W W^{-1})	Photon efficacy (μmol J^{-1})
Blue	450 nm	0.93	3.5
Green	530 nm	0.42	1.9
Red	660 nm	0.81	4.5
Far-red	730 nm	0.77	4.7



The accompanying chart from the University of California at Santa Barbara (UCSB)[6] shows the status of the green gap. Significant progress has been at Nanchang University and UCSB through the creation of V-defects, but this approach has not yet been implemented in high-volume production.

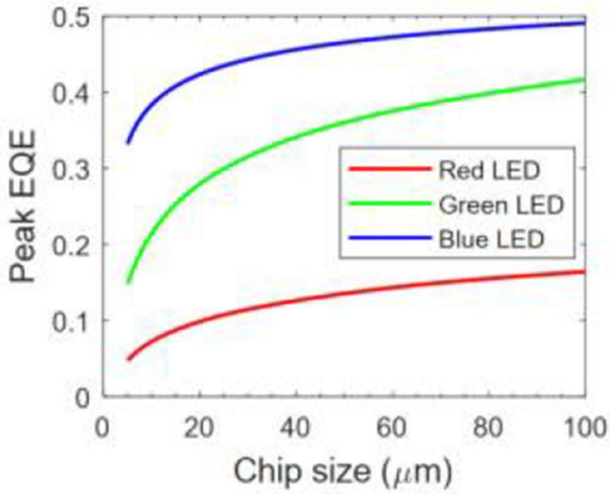
The efficiency of chips falls substantially in the UVB range and even more at UVC wavelengths below 285nm, as illustrated in the next chart.



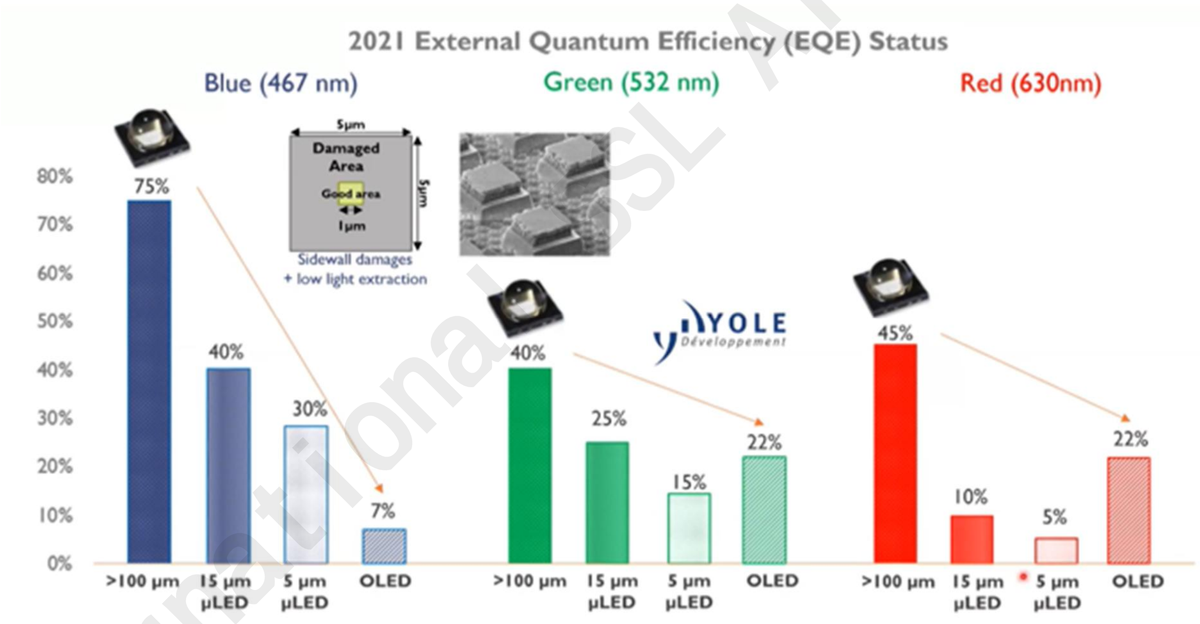
A useful database on UV LEDs is maintained by Kopp Glass[7]. The current product list has 167 LEDs at wavelengths of 285nm or less. The maximum WPE is 4% and the median value is only 1.2%. Both Nichia and Bolb offer LEDs with over 5% WPE, but much more progress will be needed to maintain the surge of interest in UV LEDs for disinfection that arose during the pandemic.

Low efficiency is also one of the challenges facing the development of micro-LED displays. Damage near the edge that results during processing of very small chips reduces the efficacy. This is especially serious for red chips, as shown in the first chart below[8].

[5] https://www.nature.com/articles/s41438-020-0283-7
[6] https://www.energy.gov/eere/ssl/articles/solutions-droop-and-green-gap-novel-carrier-injection
[7] https://www.koppglass.com/knowledge-center?topic=ultraviolet-glass
[8] https://www.microled-info.com/discussion-microled-efficiency-microled-chip-efficiency



Most display analysts forecast that microLED displays will compete with OLEDs at the high end of the display market. The next chart[9] shows the importance of the size effect in this competition. Although the efficiency of current OLED displays is low, this is expected to change with the introduction of phosphorescent blue OLEDs in 2024.



To solve this problem, some research teams are developing new manufacturing techniques to minimize sidewall damage, while others are exploring the use of different GaN crystal structures[10]. Others believe that very different designs and manufacturing methods may be needed. For example, NSNanotech has reported record performance using nanowires[11].

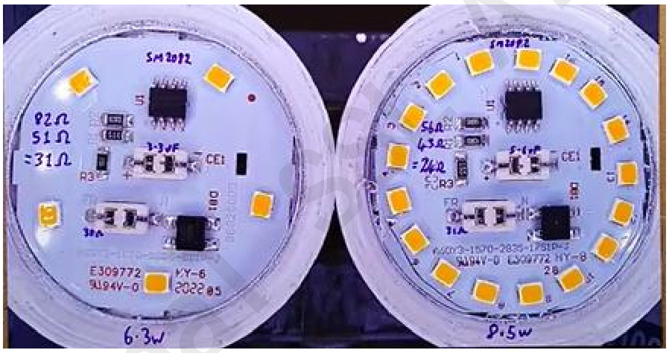
3.1.2 LED packages

LED packages that provide white light at over 220 lm/W are offered by most of the leading manufacturers. Although these have been incorporated in some lamps and fixtures, the

[9] Eric Virey in Master Class for TechBlick; https://www.techblick.com/masterclasses
[10] https://www.eetimes.eu/microleds-the-race-for-red/
[11] https://www.semiconductor-today.com/news_items/2023/may/nsnanotech-190523.shtml

efficacy of the packages in most products remains well below this level. For example, the number of 2835 packages from Samsung with CCT of 4000K and CRI 80 in Digikey's catalogue[12] on December 21st, 2023 was 243. The list includes only 8 packages with efficacy over 200 lm/W and 22 over 180lm/W. The median efficacy is 142 lm/W.

One factor that leads to less efficient operation is the dependence on current density. Most mid- size packages, such as 2835 or 3030, are designed to be driven around 200 mW. This would mean that an 8 Watt lamp would require 40 LEDs to run most efficiently. It is tempting for lamp designers to reduce the bill of materials by running the LEDs at a higher current. The next photos are taken from an interesting video by "BigClivedotcom" showing a teardown of two general service lamps bought at high-volume retailers in the UK[13]. The LEDs and circuit designs appear to be very similar, but the 6W lamp on the left uses only 5 LEDs, each driven at 1.2W while the 8.5W lamp on the right uses 17 LEDs, driven at 5W. This Digikey data set suggests that the penalty in efficacy for running at 0.5W is close to 10%, increasing to 20-25% at 1W. Driving LEDs at more than the optimal current raises the junction temperature and leads to a substantial reduction in operating life. Of course, this may not be of great concern to some manufacturers who look forward to replacement sales and offer limited warranties.



Greater efficacy at high powers can be obtained by using larger LEDs, such as a 5050 package. For example, the JR5050C 6-V E Class LEDs from Cree produce 480lm at up to 213 lm/W operating at 400mA and 5.6V. However, these packages are far more expensive than the mid-power packages that are produced in very high volumes.

The provision of higher quality light also reduces LED efficacy, although the penalty has decreased in recent years due to the development of better phosphors. The next table shows the dependence of efficacy of two LEDs from leading manufacturers on CCT and CRI. Note that the Samsung data includes the minimum and maximum values for each choice, whereas the Lumileds data gives the minimum and typical values.

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[12] https://www.digikey.com

[13] https://www.youtube.com/watch?v=5HTa2jVi_rc

Samsung LM301B

CCT	min lm/W			max lm/W		
	CRI			CRI		
	70	80	90	70	80	90
3000	187	187	192	227	227	209
4000	204	204	204	238	238	221
5000	204	204	207	238	238	224
5700	204	204	204	238	238	221

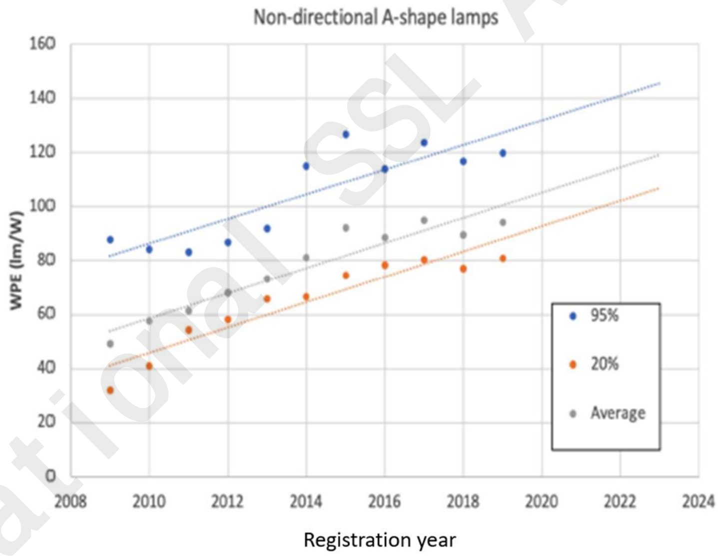
Lumileds Luxeon HE plus

CCT	min lm/W			typical lm/W		
	CRI			CRI		
	70	80	90	70	80	90
3000	193	181	153	210	199	171
4000	204	193	162	221	210	180
5000	204	193	162	221	210	184
5700	199	190	162	216	207	184

Perhaps the major factor is price. Binning is still essential and the vendors can charge a premium for the top bins. LEDs made on older equipment tend to be of lower quality and are sold at a lower price.

3.1.3 Lamps and luminaires

For almost all applications, the efficacy of lamps and fixtures now exceeds that of traditional technologies, even within a specific application area. The 4E-SSL Annex2 of the IEA gathered data from numerous international databases totalling about 90,000 lamps and 150,000 luminaires for the 10-year period between 2009 and 2019 in order to track the wall-plug efficiency evolution of various LED-lamps and LED-fixtures[14]. The next chart shows the result for general service lamps (GSL).



The data show that the efficacy is now much higher than that of incandescent and CFL lamps. More recent data is available from the EPREL database that tracks lamps in Europe using information provided for the mandatory energy-efficiency label. The next table shows the distribution between the seven efficiency classes.

[14] A Review of Advances in Lighting Systems' Technology—The Way Toward Lighting 4.0 Era
Georges and Paolo Bertholdi - https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10087336

Class	Mains Efficacy	Product Distribution (%)	
	lm/W	Apr-22	Dec-23
A	over 210	0.07	0.5
B	185-210	0.34	1.3
C	160-185	3.6	6.5
D	135-160	9.9	13.2
E	110-135	23.3	23.5
F	85-110	43	35.8
G	below 85	19.7	19.7

Although the introduction of the new labelling system encouraged some manufacturers to offer lamps that qualify for the top grade, the majority of the bulbs still fall below 110 lm/W.

Providing a substantial improvement in the efficacy of LED replacements for fluorescent tubes has been more challenging. The Clean Lighting Coalition[15], coordinated by CLASP, has performed comprehensive studies of the impact of these replacements on many developing countries. They gathered price and performance information on over 1200 lightbulbs, including both mercury-containing fluorescent and LED retrofits from those markets.

The next chart plots the efficacy of lamps as a function of the output flux, for both the Asia-Pacific region and for Central and South America. LEDs show a clear advantage for fluxes up to about 2000 lumen, but the distinction is not so obvious for the more powerful lamps. More details can be found in three regional reports[16,17,18].

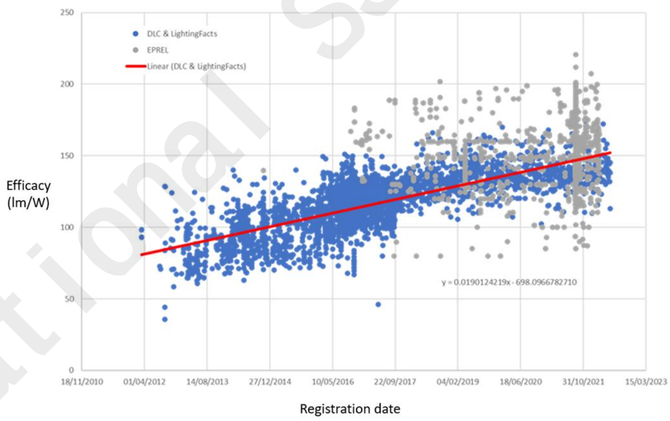
[15] https://cleanlightingcoalition.org/
[16] https://cleanlightingcoalition.org/wp-content/uploads/sites/96/Africa-Regional-Profile.pdf
[17] https://cleanlightingcoalition.org/wp-content/uploads/sites/96/Asia-Pacific-Regional-Profile.pdf
[18] https://cleanlightingcoalition.org/wp-content/uploads/sites/96/LAC-Regional-Profile.pdf

Another perspective on LED replacements for fluorescent tubes is provided by the database of the Design Lights Consortium (DLC), which provides information on products that are offered for sale in North America and meet their performance criteria. This list is designed for use by utilities and others who offer rebates for energy-saving products. It of course excludes many lights that are sold on price rather than performance. The next table shows the efficacy of LED LFLs that were certified in each year between 2017 and 2013. Values are given for lamps at the 75%, 50% and 25% quartile when ranked in efficacy.

Rank	2017	2018	2019	2020	2021	2022	2023
75%	135	135	138	141	143	145	146
50%	129	129	129	131	132	134	135
25%	122	125	125	127	126	127	127

Although these data confirm that LEDs offer higher performance than fluorescent tubes, they suggest that manufacturers have become complacent with their efficiency. The median efficacy has risen by less than 1% per year over this period.

Perhaps the greatest benefit of LED technology in energy savings has come in outdoor lights for streets, roads and area lighting, most of which are chosen by professionals who take life-cycle costs into account as well as the initial purchase price. The next chart was prepared by Michael Scholand by combining data from the US Lighting Facts Program, DLC and EPREL.



The distribution of lights that qualify for DLC certification is shown in the next table.

Rank	2018	2019	2020	2021	2022	2023
75%	145	146	143	142	145	147
50%	130	134	135	133	135	136
25%	122	126	127	126	127	128

Once again, the improvement over the past few years has been modest.

In summary, although LED lamps and luminaires clearly are more efficient than the traditional lights, the data confirms that the priority of vendors has moved away from efficacy towards other factors, such as price and light quality.

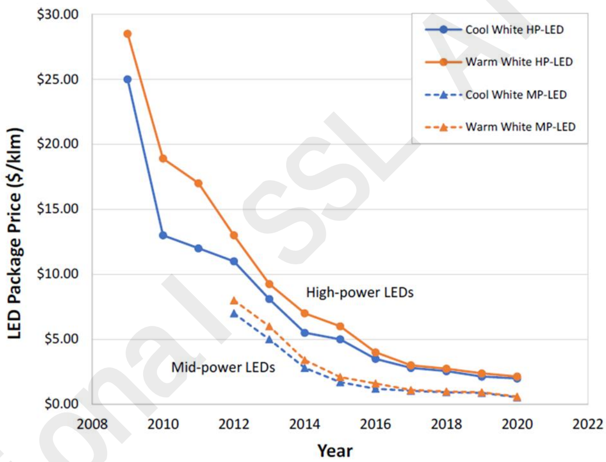
3.2 Progress on Cost

This section discusses the cost of LEDs and SSL systems, both in terms of purchase price and operating costs. Insufficient evidence has yet been gathered regarding disposal costs. There is increasing concern about the disposal of all electrical equipment, although the extended lifetime of SSL products should help to ameliorate the total effect.

3.2.1 Chips and packages

The LED packages and products that were introduced in the first few years came at a substantial premium in initial price and customers had to be persuaded to consider lifetime costs as well as purchase price. This section shows that prices have fallen sufficiently that LEDs can be easily justified on economic grounds.

The rate at which LED prices declined over time can be seen in the following chart form the US Department of Energy[19].



The price is scaled by the light output, showing that the cost of high-power LEDs to produce any desired output is still much higher than using a larger number of mid-power packages.

The current price of LEDs varies widely, even from a single supplier. As an example of a mid-power 2835 package, LM281 LEDs from Samsung that produce 24lm from 0.2W are available from Digikey at 0.43 cents (US), when bought in quantities of 40,000. More efficient LEDs from the same family that give 36lm cost 1.3 cents. These prices correspond to $0.18/klm and $0.37/klm. High power 5050 packages from the same manufacturer and distributor that produce around 500 lumens cost between 23 and 33 cents, corresponding to $0.40 and $0.65 per klm.

3.2.2 Lamps and luminaires

Price reduction in LEDs has led to much lower prices for most general lighting service (GLS). 9W bulbs that produce around 800 lumens can be bought at retail in China for less than

[19] https://www.energy.gov/sites/default/files/2022-02/2022-ssl-rd-opportunities.pdf

US$1 and in North America and Europe for under $1.50. The light produced by these bulbs is not necessarily of low quality although their efficacy is relatively low. Lamps that provide CRI of 90 and can be switched between 5 values of CCT are available in California for less than $2.

The advertised operating life of these bulbs is typically 10-15 thousand hours (kh) so that they will consume 90-135 kWh of electricity over their lifetime. This might cost 600-900 rupees (US$7.20-10.80) in India, where the average cost of electricity is 6.3 rupees per kWh, or $27-$40 in California where the average cost is $0.30/kWh. So, the total cost of operating these lamps depends much more on the efficacy and the cost of electricity than it does on the purchase price.

As noted above, GLS bulbs with efficacy of around 210 lm/W have been introduced in Europe by several vendors to quality to qualify for Class A status with EPREL. 800 lumens can be delivered using only 4W. The current retail cost of these bulbs is around US$10 or higher, which will deter many consumers. However, since the lifetime is around 50,000 hours, buyers can justify investing in these bulbs if they are used for many hours each day.

As part of their analysis of the benefits and cost of eliminating fluorescent lamps, the Clean Lighting Coalition compared the cost of CFL and LFL lamps with equivalent LED replacements by purchasing lights at retail outlets. The following three tables show the results in the three regions.

Asia-Pacific:

COUNTRY	CFL PRICE	LED PRICE
Bangladesh	BDT 280 (US$ 3.36)	BDT 330 (US$ 3.96)
India	INR 160 (US$ 2.08)	INR 155 (US$ 2.02)
Philippines	PHP 120 (US$ 2.40)	PHP 180 (US$ 3.60)
Sri Lanka	LKR 375 (US$ 1.84)	LKR 495 (US$ 2.43)
Pakistan	PKR 130 (US$ 0.74)	PKR 100 (US$ 0.57)
Vietnam	VND 15,000 (US$ 0.66)	VND 30,000 (US$ 1.33)
Indonesia	IDR 31,950 (US$ 2.24)	IDR 21,600 (US$ 1.51)

COUNTRY	LFL PRICE	TLED PRICE
Bangladesh	BDT 320 (US$ 3.84)	BDT 580 (US$ 6.96)
India	INR 58 (US$ 0.75)	INR 346 (US$ 4.50)
Philippines	PHP 84 (US$ 1.68)	PHP 170 (US$ 3.40)
Pakistan	PKR 210 (US$ 1.20)	PKR 650 (US$ 3.71)
Vietnam	VND 20,000 (US$ 0.88)	VND 40,000 (US$ 1.76)
Indonesia	IDR 36,000 (US$ 2.52)	IDR 75,100 (US$ 5.26)
Japan	JPY 583 (US$ 5.07)	JPY 980 (US$ 8.53)

Even when the LED lamps cost more than the traditional ones, the excess is recovered quickly in reduced electricity costs and the payback period is almost always less one year.

Central and South America:

COUNTRY	CFL PRICE	LED PRICE
Antigua & Barbuda	XCD 19.95 (US$ 7.38)	XCD 18.95 (US$ 7.01)
Belize	BZD 9.75 (US$ 4.82)	BZD 6.41 (US$ 3.17)
Brazil	BRL 10.9 (US$ 2.15)	BRL 7.99 (US$ 1.58)
Peru	PEN 9.9 (US$ 2.64)	PEN 9.9 (US$ 2.64)
Guyana	GYD 700 (US$ 3.34)	GYD 550 (US$ 2.64)
Mexico	MXN 40 (US$ 1.88)	MXN 42 (US$ 1.97)
Argentina	CFL not available	ARS 249 (US$ 2.29)
Chile	CLP 3,490 (US$ 4.33)	CLP 2,190 (US$ 2.72)
Uruguay	UYU 70 (US$ 1.63)	UYU 77 (US$ 1.76)
Colombia	COP 7,900 (US$ 1.98)	COP 3,690 (US$ 0.92)
Jamaica	JMD 393 (US$ 2.55)	JMD 560 (US$ 3.61)
Trinidad & Tobago	TTD 41.65 (US$ 6.11)	TTD 33.75 (US$ 4.95)
Panama	PAB 1.99 (US$ 1.99)	PAB 2.99 (US$ 2.99)

COUNTRY	LFL PRICE	TLED PRICE
Antigua & Barbuda	XCD 16.48 (US$ 6.10)	XD 55 (US$ 20.35)
Belize	BZD 4.50 (US$ 2.25)	BZD 18 (US$ 9)
Brazil	BRL 14.90 (US$ 2.94)	BRL 29.99 (US$ 5.92)
Peru	PEN 6.90 (US$ 1.64)	PEN 14.90 (US$ 3.98)
Guyana	LFL not available	GYD 1,000 (US$ 4.80)
Mexico	LFL not available	MXN 174 (US$ 8.31)
Argentina	LFL not available	ARS 399 (US$ 3.68)
Chile	CLP 1,790 (US$ 2.15)	CLP 2,390 (US$ 2.96)
Uruguay	LFL not available	UYU 199 (US$ 4.60)
Colombia	COP 2,200 (US$ 0.55)	COP 7,900 (US$ 1.98)
Jamaica	JMD 488 (US$3.15)	JMD 718.75 (US$ 4.60)
Trinidad & Tobago	TTD 70 (US$ 10.50)	TTD 45 (US$ 6.60)
Panama	PAB 1.59 (US$ 1.59)	PAB 3.99 (US$ 3.99)

An example of the replacement costs in Brazil can be found in the case study of two hospitals in Brazil[20]. 2200 LFLs were replaced by TLEDs. Although the cost of the TLEDs, at 30 real (US$5.60) was twice that of the LFLs, the premium was recovered in less than six months. The cost of electricity assumed in the study was 0.72 real/kWh (US$0.148/kWh).

[20] https://cleanlightingcoalition.org/wp-content/uploads/sites/96/Brazil_MTPilot_2Pager-1.pdf

Africa:

COUNTRY	CFL PRICE	LED PRICE
Burkina Faso	XOF 2,500 (US$ 4.50)	XOF 2,200 (US$ 3.96)
Cameroon	XAF 1,650 (US$ 2.92)	XAF 1,200 (US$ 2.12)
Ethiopia	EBT 75 (US$ 1.58)	EBT 75 (US$ 1.58)
Gabon	XAF 1,000 (US$ 1.80)	XAF 1,500 (US$ 2.70)
Ghana	GHS 17 (US$ 2.72)	GHS 22 (US$ 3.52)
Kenya	KES 140 (US$ 1.26)	KES 100 (US$ 0.90)
Nigeria	NGN 400 (US$ 0.96)	NGN 340 (US$ 0.82)
South Africa	ZAR 49.99 (US$ 3.25)	ZAR 27.50 (US$ 1.79)
Togo	XOF 800 (US$ 1.44)	XOF 500 (US$ 0.90)
Uganda	UGX 14,000 (US$ 3.92)	UGX 8,000 (US$ 2.24)
Zambia	ZMW 35 (US$ 2.03)	ZMW 30 (US$ 2.84)

COUNTRY	LFL PRICE	TLED PRICE
Burkina Faso	XOF 2,200 (US$ 3.96)	XOF 4,000 (US$ 7.20)
Cameroon	XAF 2,500 (US$ 4.42)	XAF 3,500 (US$ 6.19)
Ethiopia	EBT 95 (US$ 2.00)	EBT 170 (US$ 3.57)
Gabon	XAF 650 (US$ 1.17)	XAF 2,500 (US$ 4.50)
Ghana	GHS 7 (US$ 1.12)	GHS 10 (US$ 1.60)
Kenya	KES 125 (US$ 1.13)	KES 400 (US$ 3.60)
Nigeria	NGN 500 (US$ 1.20)	NGN 1,500 (US$ 3.60)
South Africa	ZAR 39.99 (US$ 2.60)	ZAR 39 (US$ 2.54)
Uganda	UGX 14,500 (US$ 4.06)	UGX 8,600 (US$ 2.41)

Moving on to outdoor lights, the cost of LED streetlights varies widely, especially in countries like India. Among the lamps manufactured by ELCOMA members, the 70W Nexo lamp from Bajaj produces 8400 lumens with an advertised lifetime of 50,000 hours and is available for 2350 INR (US$28). Lights from other manufacturers that are approved by the Bureau of Indian Standards include a 120W streetlight from Forus that gives 18000 lm for 3995 INR (US$48) with a 54,000 hours 10-year warranty. These prices correspond to $3.33/klm and $2.67/klm. Less efficient lamps of uncertain quality can be obtained at much lower prices.

A brief review of on-line vendors of streetlights in Australia reveals prices per kilolumen between AUS$7 and AUS$22[21]. The efficacy is in the range 119-160 lm/W. For example, a 140W light from Philips that produces 17.5klm is available at AUS$379. The warranties vary from 2 to 5 years. Even if the lights are used for 12 hours each day, these warranty periods seem to be much shorter than is implied by the promised operating lifetime.

[21] As of December 27,2023, 1 AUS$ was equivalent to US$0.68.

Clearly, the wholesale price must be considerably less than these retail prices. The cost of an LED upgrade project also varies widely, depending upon how much work needs to be done in addition to the purchase of the lamp. The cost per light of some recent upgrade projects has ranged between AUS$249 and AUS$1765.

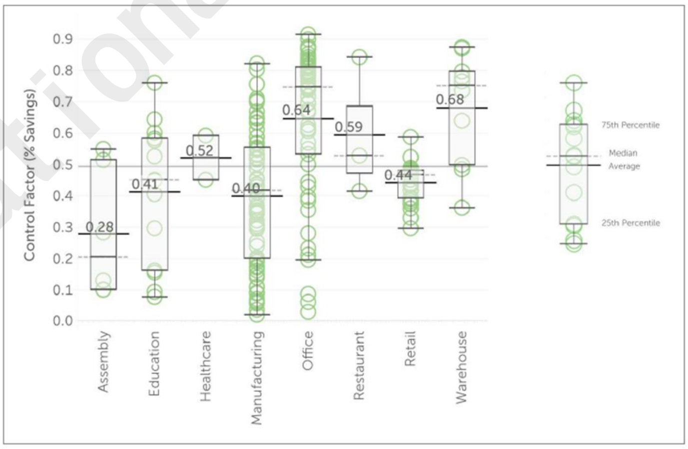
3.3 Progress on Smart Lighting

The digital nature of SSL enables new ways to control the intensity and colour of the light that is created and to connect to networks as part of the Internet of Things (IoT). Smartness can be interpreted in several ways. The first is reduce energy use by emitting light only when and where it is needed and avoiding over-lighting. Another is to optimize the characteristics of the light to the purpose of the illumination and the needs of the beneficiaries. Examples of this are seen in human-centric lighting (HCL), agricultural lighting and dynamic car headlights.

A comprehensive discussion of the status and potential of smart and connected lighting that has just been published by Georges Zissis and Paolo Bertoldi on behalf of the Joint Research Centre for the European Commission[22]. This newsletter will just include highlights from that publication and other recent documents that are available on the internet. Georges has just joined the ISA Advisory Board and we look forward to more guidance from him on this topic.

3.3.1 Potential energy savings of controls

An interesting study of Energy Savings from Networked Lighting Control (NLC) Systems in the US was published in 2020 by the Northwest Energy Efficiency Alliance (NEAA) and the DLC[23]. They present their findings in terms of a control factor (CF), which is the fraction of savings that accrue from the implementation of controls rather than the increased efficacy of LED lighting. The next chart shows that the CF is highest in office and warehouse applications and averages 49%.



[22] https://publications.jrc.ec.europa.eu/repository/handle/JRC135597

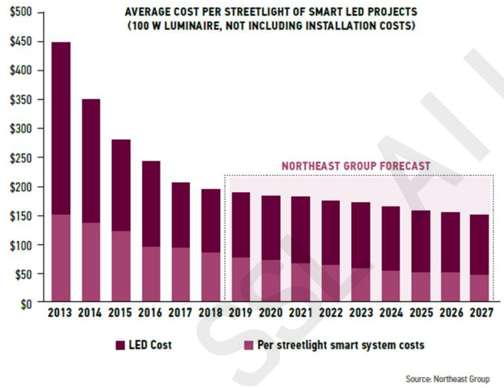
[23] https://www.energy.gov/sites/default/files/2021-09/ssl-connected-lighting-systems-stakeholders-research-study-sept21.pdf

In a companion report, NEEA studied the incremental cost of smart lighting in offices[24]. They distinguished between three levels of smartness and found that the average cost per fixture was between $49 and $90 on top of the $90-100 cost of the basic light.

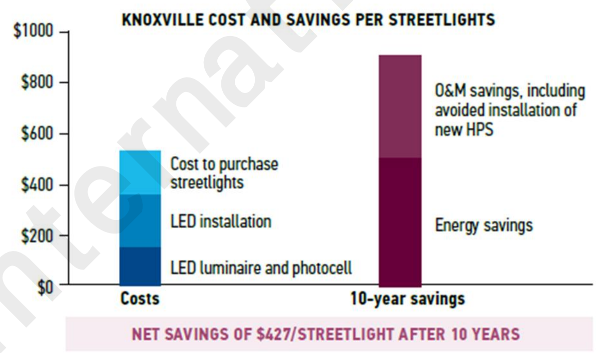
Vendors sometimes offer a more promising analysis. For example, a white paper from Acuity Brands and Itron[25] suggested that adding network control to streetlights may only increase the cost by 20% and reduce the payback period by 25%.

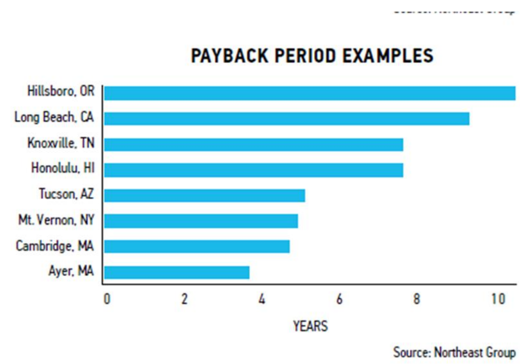
A detailed study of the costs and benefits of smart streetlights was published in 2022 by the Northeast Group and Citylab[26]. They found that the total savings from the use of LEDs and controls varied from 47% to 80% with an average of 66%. The contribution from controls was typically 10-20%.

The next chart shows that the average cost per streetlight has come down significantly since 2013.



These figures do not include the cost of installation or administrative costs in designing and purchasing the lights. The total costs for one project in Knoxville are shown in the next chart, in comparison to the anticipated savings over a 10-year period. The payback period is about 8-years which is within the range of 4-10 years found in the studied projects.

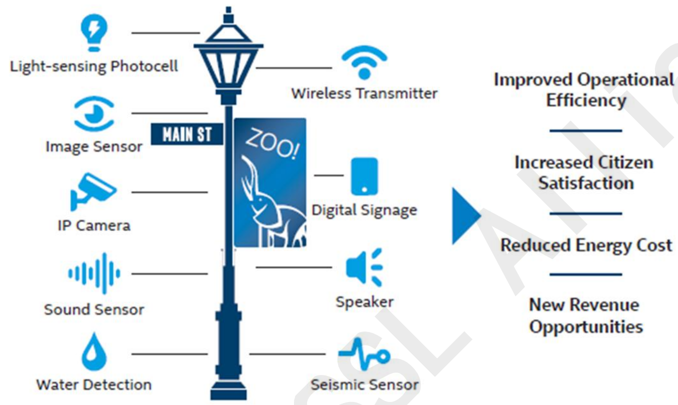




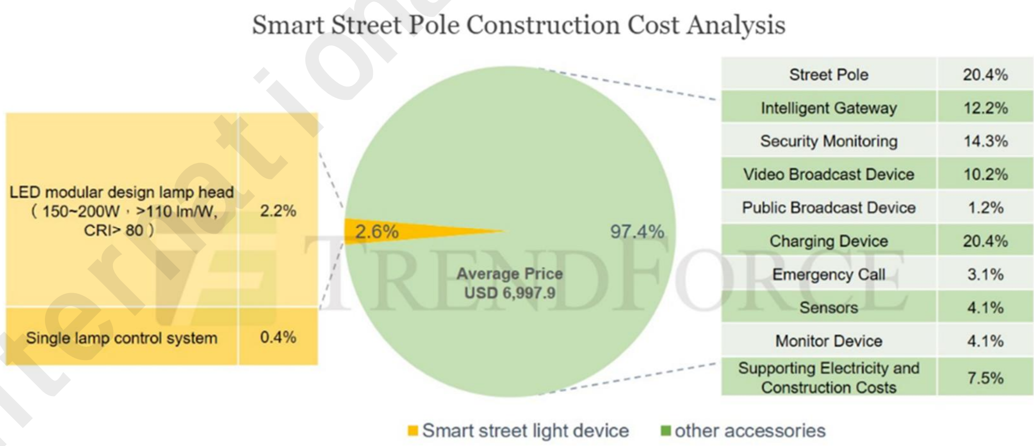
[24] https://neea.org/resources/2020-luminaire-level-lighting-controls-incremental-cost-study
[25] https://img.acuitybrands.com/public-assets/catalog/767140/dtl-dsn---the-business-case-for-smart-street-lights.pdf?abl_version=05%2F02%2F2019+06:44:46&DOC_Type=White_Paper
[26] https://northeast-group.com/wp-content/uploads/2022/01/CityLab-Northeast-Group-the-benefits-of-led-and-smart-street-lighting.pdf

The most recent analysis of connected lighting by the Design Lights Consortium is focused upon two US states, Connecticut and Arizona but studies the wider economic impact on utilities and the community[27]. They conclude that significant energy savings are achieved for large offices, retail, healthcare, and other high energy use buildings when NLCs are paired with HVAC systems. In the most optimistic scenario, the study found reductions of the commercial building electric energy consumption in 2030 by nearly 10 percent in Connecticut and 5 percent in Arizona.

The installation of smart streetlights offers opportunities for further services that use the same poles and communication networks. This prospect has attracted many leading companies from outside the lighting industry. For example, Intel published a white paper with the following illustration[28].



Such a system can cost far more than that of the lamp. In the analysis published by TrendForce in 2020, the lamp head contributed less than 3% of the total cost of a pole designed for many functions.



Adding functionality can bring risks as well as rewards. In 2017 San Diego began installing 3,200 smart streetlights, with stated goals around cost and energy savings and using data to

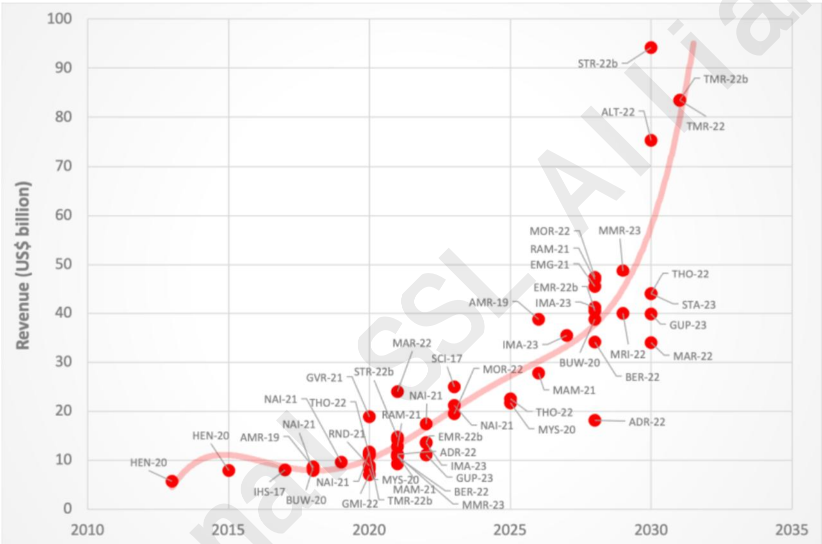
[27] https://www.designlights.org/resources/reports/future-proofing-energy-efficiency-with-networked-lighting-controls/

[28] https://www.intel.com/content/dam/www/public/us/en/documents/solution-briefs/smart-street-lights-for-brighter-savings-solutionbrief.pdf

improve parking and traffic management. However, the US$30 million project drew controversy over transparency and police access to camera data. In September 2020 the mayor ordered the streetlight sensors and cameras to be deactivated until an ordinance was in place governing their use. This did not occur until August 2023, when guidelines were adopted and the addition of automatic vehicle license plate readers was approved. The system is expected to be reactivated in January 2024. It is notable that the cost of the whole system far exceeded that of the lights alone and much of the added value has yet to be realized.

3.3.2 Adoption of connected network controls

Market researchers and reporters have become very excited about smart lighting and sometimes describe it as a revolution in lighting. Forecasts of the market for smart lighting by various analysts are shown in the following chart which was taken from the review by Zissis and Bertoldi.



This data suggests that global sales growth between 2013 and 2021 was only modest and that rapid growth is still in the future. Aggressive vendors have often experienced reluctance on the part of potential customers to try untested systems.

Much of the success in sales of smart lighting has occurred in China. with lots of publicity about smart homes and smart cities. Statista reports that the market there rose with a CAGR of 25% between 2015 and 2019, reaching 37B yuan (US$5.2B) in 2021.

Zissis and Bertoldi estimate that 33,800 patents relating to smart/connected lighting and lighting controls were granted between 2000 and 2022, with the majority coming since 2015. However, the proliferation of proprietary systems protected by patents is part of the problem that is hindering adoption.

Smart and connected lamps still form a very small fraction of the installed lighting base, although reliable recent data is hard to fine. The following table summarises the penetration of lighting controls in the installed stock of lights in the U.S. in 2017[29].

Installed Stock Penetration (%)	Commercial	Residential	Industrial	Outdoor
None	66%	86%	93%	13%
Dimmer	3%	11%	4%	4%
Daylighting	<1%	<1%	<1%	53%
Occupancy Sensor	6%	<1%	2%	17%
Timer	4%	<1%	<1%	12%
Multi	4%	<1%	<1%	<1%
EMS	16%	<1%	<1%	<1%
Connected	<1%	<1%	<1%	<1%

The only common applications were daylight sensors for use with outdoor lights and energy management systems in commercial buildings.

A study by DNV in 2020 found that lighting controls were deployed on less than 1% of the lights in Massachusetts and that more than 80% of these were operated manually.

3.3.3 Complexity of systems and components

Control systems can be very simple, with one lamp connected to a dimmer switch or single sensor, or can be part of a network involving multiple sensors, many lights and other services. However, the more capabilities a connected lighting system (CLS) has, the more complex it is, leading to potential complications and challenges.

A very comprehensive study of the design, installation and operation of connected lighting systems in the US has been made by Guidehouse[30]. The following excerpt illustrates some of the lessons learned from their study.

<u>Consumer Lack of Perceived Value</u>: Many CLS stakeholders cited a lack of perceived value as the greatest barrier to adoption. Building owners generally do not see the need for advanced features and tend to want simpler, consistent, low-cost, minimum code level lighting systems. Tech-savvy building owners, tech companies, or businesses that create a unique user experience (museums, entertainment, hospitality, etc.) see more value in CLS. Also, the longer and uncertain payback periods of CLS present a challenge as energy savings can be highly variable.

<u>Embedded Sensors & Controls</u>: In general they have low adoption, and their complexity can be intimidating. However, luminaire level lighting controls have the potential to enhance control/sensor granularity, accuracy, and efficiency of systems and simplify installation and configuration. These capabilities offer a better lighting experience and enhanced energy savings, as well as expand business applications and other non-energy benefits.

[29] https://www.energy.gov/sites/default/files/2020/02/f72/2019_ssl-energy-savings-forecast.pdf. U.S. DOE 2019b. U.S. DOE. December 2019.
[30] https://www.energy.gov/sites/default/files/2021-09/ssl-connected-lighting-systems-stakeholders-research-study-sept21.pdf

<u>Cost Transparency:</u> Cost transparency is one of the largest challenges facing for CLS and commercial lighting in general. First, many building owners assume CLS will cost more than it actually does and shy away from adoption. Also, cost transparency becomes an issue during the value engineering process, if the system ends up being higher than expected and the design/specification process must be repeated. With lighting being the last piece of construction, it can also be difficult to stay on budget with initial designs. Cost of CLS can also be highly variable, depending on the project.

<u>Interoperability:</u> Manufacturers often develop proprietary products that don't easily integrate with other systems/products made by other manufacturers. Lack of interoperability between CLS and other building systems (and standardization in communication protocols) can make integrating CLS with other systems challenging.

Occupation sensors often contribute to the challenges in an effective control system. For example, passive infra-red (PIR) sensor systems often turn off unless there is movement in their field of view. A valuable review of the performance and testing methods for occupation sensors has been given by the Pacific Northwest National Laboratory[31].

4 Impact on Global Energy Use

Although the introduction of SSL has led to significant energy savings, the demand for artificial light has indeed increased and global consumption of electricity for lighting has changed little over the last twenty years, according to data collected by the International Energy Agency (IEA)and United Nations Environmental Protection Agency (UNEP). In 2005, 2650 terawatt hours (TWh) of electricity was used to create 135 petalumen hours (Plmh) of artificial light at average efficacy of 48 lm/W. By 2017/8 the demand had risen to 220 Plmh. with almost all the increase coming from economically developing countries. The growth in demand was slowed temporarily in 2020 by the COVID pandemic and our best estimate of current demand is 230 Plmh with an average efficacy of 80lm/W, giving a total consumption of electricity around 2900 TWh. More accurate data is needed to enable a more accurate estimate to be made.

An independent analysis of the current status has been provided in a recent report by Georges Zissis for the Joint Research Centre of the European Commission[32]. His analysis is based more than 175 recent (2018 and after) freely accessible documents and data harvested by open access databases for more than 150 countries. He concludes that the current annual production is 215 Plmh and will rise to almost 285 Plmh in 2040. He estimates the average efficacy to be 74 lm/W and the global annual consumption of electricity at 2900 TWh.

Unfortunately, there appears to be little accurate data on the use of electricity for lighting in the OECD countries during the last decade. Some data was available until recently on the energy savings due to the adoption of SSL in the US and Europe, but we are not aware of any authoritative data on the change in demand for lighting. It seems likely that electricity

[31] https://www.osti.gov/servlets/purl/1669040
[32] https://publications.jrc.ec.europa.eu/repository/handle/JRC135597

consumption for lighting has decreased, but not sufficiently to offset increases in the rest of the world. The situation in China is of special interest as China should now be regarded as having a developed economy.

4.1 China

The impact of SSL had been seen most dramatically in China. In a plenary address to the 2023 SSLChina Conference Dr. Cao Jianlin, President of ISA, stated that in 2022 lighting contributed about 14% of the national consumption electricity. This would imply the use of 1200 TWh, up from around 600 TWh in 2010[33]. Assuming an average efficacy of 70 lm/W would lead to a light production of 84 Plmh and a per-capita level of 60 Mlmh. This is higher than the level reported for Europe in 2005.

The demand for electricity tracks closely with GDP, which in China has risen three-fold since 2010. The doubling of use for lighting is consistent with the GDP growth moderated by a 50% increase in efficacy.

Local governments have continued to drive the demand for more light in 2023, especially for outdoor applications. Night lighting has become an important part of "cultural tourism". The Guangzhou International Light Festival resumed after a three-year absence and has attracted almost 100M visitors. Over 800M domestic tourism trips were recorded across the country in the Autumn Festival period. In the 3rd quarter of 2023, over 1.5B yuan was invested in 25 regions to boost night lighting shows. Two new lake-side projects are illustrated below[34].


In addition, smart street lighting projects were announced by more than 20 regions in the first three quarters of 2023, with the investment of close to 2.5B yuan. The purpose of the smart light poles goes well beyond energy savings in lighting. For example, one project in Fuzhou city will provide 3304 poles to integrate system, public charging equipment, light control and other service functions[35]. Traffic management and parking control are important features of many systems. A wide range of sensors are being deployed, including facial recognition systems that might prove to be controversial in other countries. Relatively little information is available about the energy savings in lighting. One earlier project in Chongzhou City, initiated in 2016, led to savings of 57%. The lights were dimmed to 10-30% of peak brightness when the sensors indicated that no one was present on the streets. The

[33] UNEP en.lighten Program Country Assessment 2012
[34] https://www.alighting.cn/news/20231023/175294.htm
[35] https://www.alighting.cn/news/20231213/175618.htm

residents commented that “the street lights were effective and sensitive, lighting up their way home and warming their hearts”[36].

Local governments have also been encouraging residents of major cities to spend more time out of their homes in the evenings. Outdoor lighting is being improved to make the streets safer and more attractive. Public buildings, such as museums, are being encouraged to stay open in the evening, once again increasing the demand for artificial light.

Much of the installation of improved indoor lighting systems has been motivated by health reasons. Recent concern about myopia among school children has led to the development of new standards for classroom lighting and greater support by local governments. According to data collected nationwide by the Educational Equipment Procurement Network, 25 projects were launched in October 2023[37] and 61 projects in November[38].

Lighting designers in China are also concerned about the weakening of vision systems among the elderly, recommending higher levels of illumination in certain settings. An interesting set of guidelines has been published by the Sichuan Fine Arts Institute School of Architecture and Environmental Art[39].

Hospital lighting is also a major responsibility of local governments. From January to November 2023, at least 28 regions across the country released projects related to hospital building lighting, with a total of 127 completed projects, at a total cost of 344M yuan.

4.2 Developing Economies

According to estimates by the United Nations, India overtook China in 2023 as the country with most people. The population has risen from 1.15B in 2005 and 1.24B in 2010 to 1.43B in FY2023. Although the GDP has more than doubled since 2010, reaching US$3.4 trillion in 2022, this is still only 20% of that of China. The per capita consumption of electricity has tracked the GDP, rising from 640kWh in 2010 to 1330 kWh in 2022.

The changes in electricity use and GDP in BRICS countries is shown in the next table.

Country	TWh			GDP per capita		
	2010	2020	Ratio	2010	2020	Ratio
Brazil	72.7	65	0.89	10710	8921	0.83
China	550	1000	1.82	4428	9771	2.21
India	114	128	1.12	1475	2016	1.37
Russia	115	133	1.15	10442	11289	1.08
South Africa	24.7	34.5	1.4	7279	6340	0.87

In a 2019 report prepared for the UNEP, the demand for artificial light from 156 developing economies was predicted to rise by a further 50% from 134 Plmh in 2018 to 200 Plmh in 2040, requiring electricity use to rise from 1480 TWh to 1600 TWh.

[36] https://www.alighting.cn/news/20231110/175421.htm
[37] https://www.alighting.cn/news/20231117/175478.htm
[38] https://www.alighting.cn/news/20231213/175622.htm
[39] https://www.alighting.cn/news/20231120/175483.htm

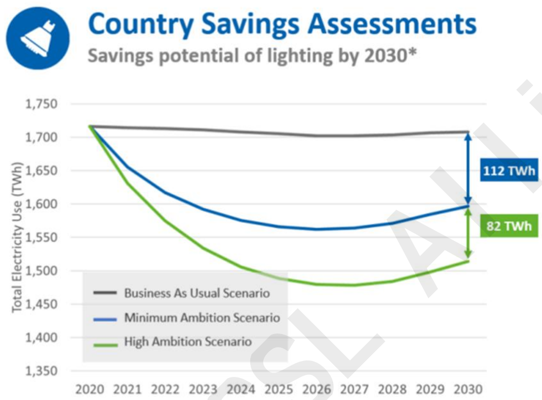
The U4E country assessments for lighting and several other applications were updated in 2022 and can be seen at

https://united4efficiency.org/countries/country-assessments/

More recently in July 2022, the UNEP United for Efficiency (U4E) program presented a technical brief based on its 156 Country Savings Assessments,

https://www.un.org/sites/un2.un.org/files/technical_brief_unep_u4e_efficient_lighting_and_appliances_in_asia_synergies_conference.pdf

In this report, U4E raised their estimate of global electricity use in developing countries to over 1700 TWh, but suggested that savings of about 15% could be made by 2027 before demand starts to rise again.



U4E and the CLiC have published some valuable studies of individual countries, and more are planned. The 2020 U4E study of Pakistan shows that the penetration of LEDs has been larger in the residential sector than in commerce and industry[40].

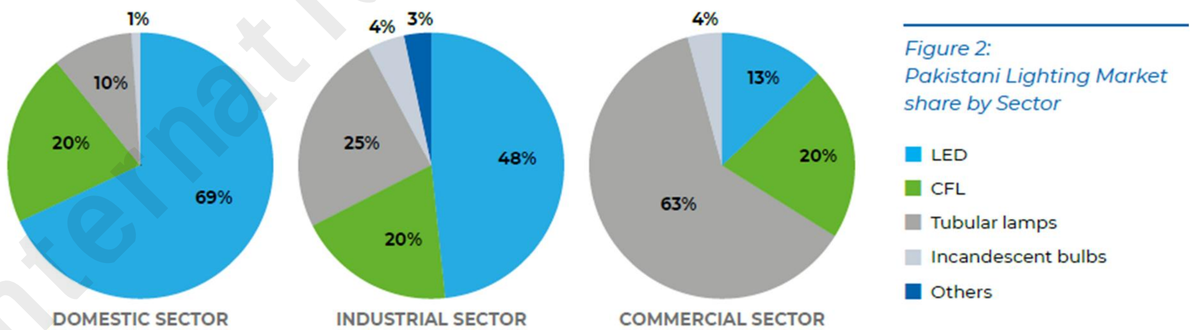


Figure 2: Pakistani Lighting Market share by Sector

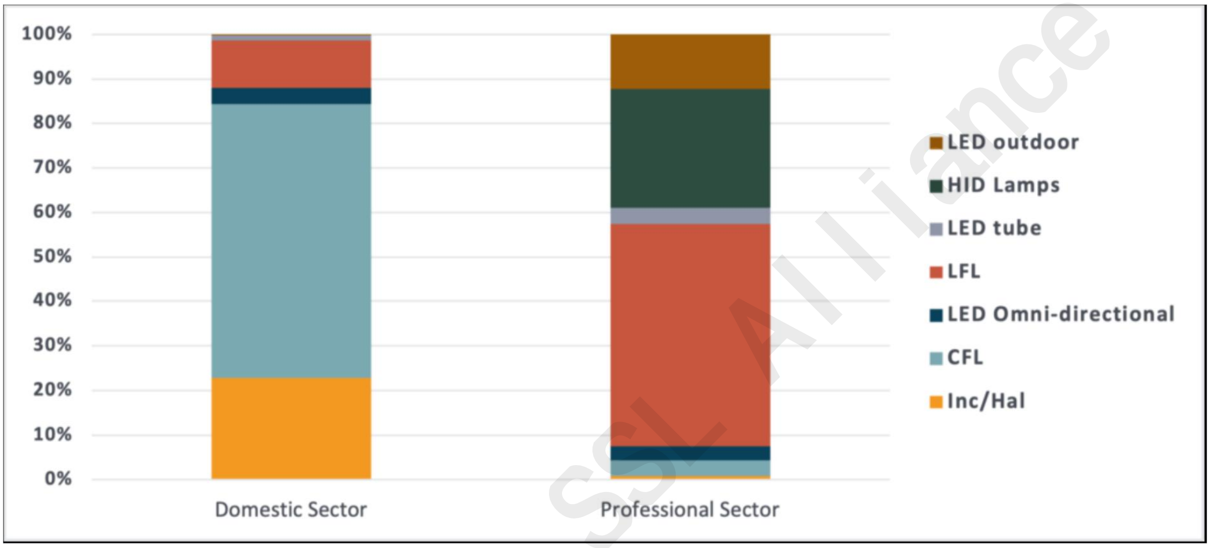
The U4E assessment results indicated that domestic LED product durability is less than four years – a lifetime four times shorter than average LED bulbs. In the case of commercial LED lights, the weighted average life is of 2.25 years, around 3,200 operation hours, and in the industrial sector, lifetime is 2.5 years, around 3,500 operation hours. These lifetimes are even shorter than for the domestic sector and are not aligned with high quality LED

[40] https://united4efficiency.org/successful-implementation-of-first-minimum-energy-performance-standards-meps-and-labels-for-energy-efficient-led-lighting-in-pakistan/

products in other countries that can reach 25,000 hours. Tests carried out by the Pakistan Council of Scientific and Industrial Research (PCSIR) found that the average CCT of the bulbs and tubes was extremely high (around 7500K) and that the light output often varied significantly from the advertised value.

To combat the problems with imports of LED products, Pakistan introduced new mandatory minimum energy performance standards (MEPS) in December 2020, supported by a 5-star energy labelling scheme.

A more recent survey carried out by the CLC in Mozambique[41] showed the following distribution.



However other estimates suggest that there may be far more incandescent lamps than is indicated by this chart.

A study by CLASP in 2020[42] of residential use in Indonesia reported a distribution of 6% for incandescent and halogen, 41% for CFL and 52% for LED.

Although these few in-depth studies do not provide a comprehensive picture, they do suggest that most lamps with very low efficiency have already been replaced. It therefore may be difficult for the reduction in electricity use from further upgrades to compensate for the increased demand for light.

4.3 IEA Annual Report for 2023

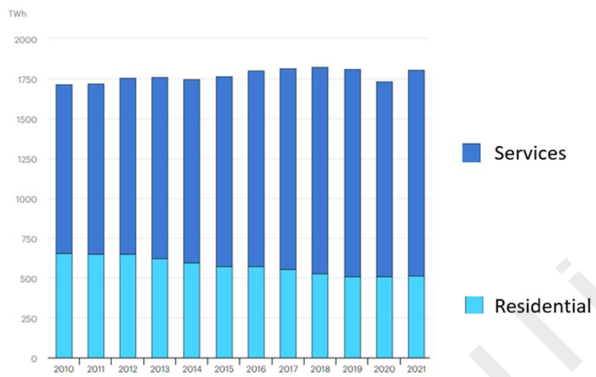
In conjunction with its annual report for 2023, the IEA updated its tracking report on the electricity consumption for the residential and services sectors. The text in italics in this section is taken from their report at

[41] https://www.clasp.ngo/updates/understanding-the-mozambique-lighting-market/#:~:text=In%20Mozambique%2C%20CLASP%20conducted%20a,to%20more%20energy%2Defficient%20options.&text=CLASP%20is%20working%20to%20ensure,to%20high%2Dquality%20lighting%20options.

[42] https://www.clasp.ngo/research/all/indonesia-residential-end-use-survey-2/#:~:text=CLASP%20and%20Ipsos%20conducted%20a,for%20household%20consumers%2C%20manufacturers%2C%20and

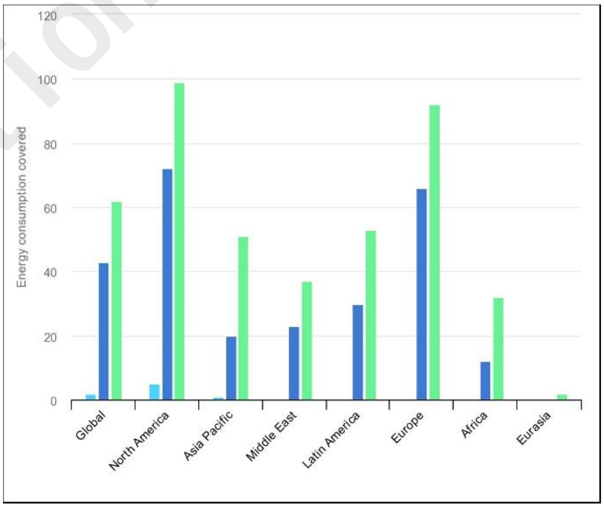
https://www.iea.org/reports/lighting

In its overall assessment, IEA concludes that *electricity consumption for lighting increased in 2022, with greater efficiency not offsetting increased use of lighting. Despite the falling carbon intensity of electricity, CO_2 emissions from lighting rose slightly in 2022. Increased energy demand for service lighting more than offset a drop in residential lighting in 2022. Although electricity consumption for residential use fell from 655 TWh to 512 TWh between 2010 and 2021, that for services grew from 1057 TWh to 1293 TWh.*



2022 saw continued progress both in the deployment of light-emitting diodes (LEDs) and in lighting efficiency. While numerous countries began to phase out incandescent lamps more than ten years ago, many are now beginning to eliminate fluorescent lighting as well to make LEDs the dominant lighting technology. About 50% of global residential lighting sales use LED technology.

The adoption of more efficient lamps has been driven partially by the enforcement of minimum energy performance standards (MEPS). The next chart shows the proportion of lighting electricity use covered by MEPS since 2000.



Looking forward, IEA recognizes that the demand for lighting will continue to rise.

With wealth increasing and the cost of lighting products falling, householders can afford more lighting services – especially in emerging economies. This increased demand for lighting services is also being driven by rising populations and a growing number of *households and especially floorspace. Building floor area has grown by about 60% in the past two decades and is set to increase by another 20% this decade, adding a total floor surface area of nearly 45 billion m^2, equivalent to about five times the floor area in Indonesia today. These pressures are pushing up demand for lighting, highlighting the importance of deploying LED lamps in all markets to limit overall energy consumption.*

Since 2010 the average efficacy of LEDs has improved by around 4 lm/W each year. The best-in-class technologies now achieve over 200 lm/W, but they are currently more expensive. The efficacy of new LEDs continues to rise, though needs to reach about 140 lm/W by 2030 to align with the Net Zero Scenario, which would be around 30% higher than the 2022 average.

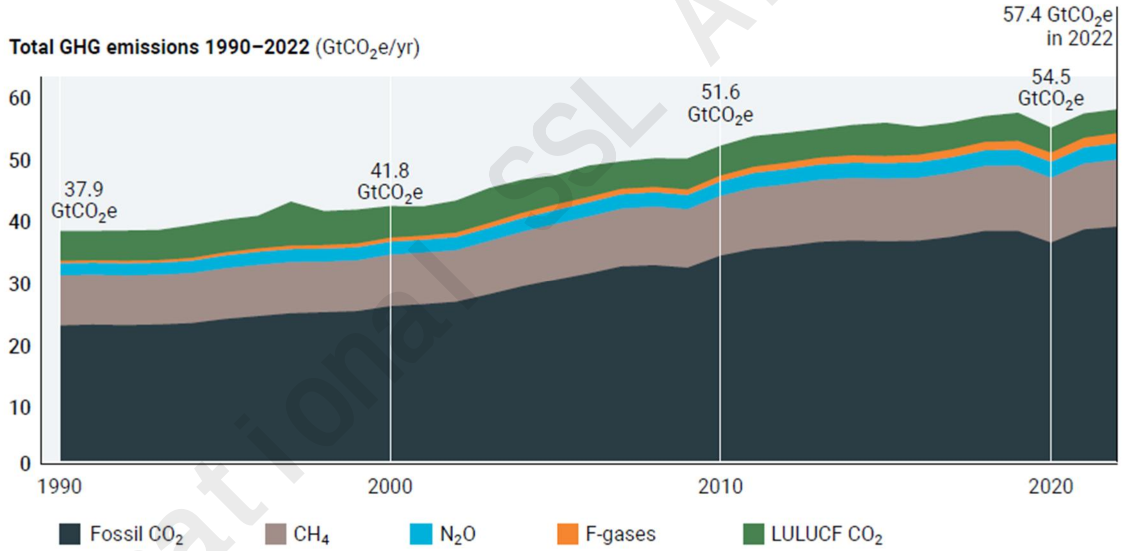
While the trends described in this IEA report are consistent with those from other analysts, the magnitude of the total annual electricity use, at around 1700 TWh is puzzling. It is unclear whether the designation of “service” applications includes all uses outside homes. One of our goals in 2024 will be to resolve this difference between the IEA and other estimates of global electricity use for lighting.

5 Looking to the Future

It seems certain that the global demand for artificial light will continue to grow, perhaps beyond the 285Plmh forecast by Zissis and Bertoldi. Based on our estimate of 230Plmh for 23 and the historic CAGR of 2.5%, the demand could reach 350Plmh by 2040 and 450Plmh by 2050. The latter figure would be enough to supply each of the anticipated global population of 10B people with 45Mlmh, which is still less than that supplied across the economically developed world in 2005.

Growth in the demand for more artificial light may not be confined to developing economies. Some in the lighting community, such as the Good Lighting Group, are pressing for substantial increases in the intensity of indoor lights in the morning, offsetting any reductions that may be possible in the late afternoon and evening. The changing weather patterns may necessitate the widespread adoption of indoor farming to feed the ever-increasing population.

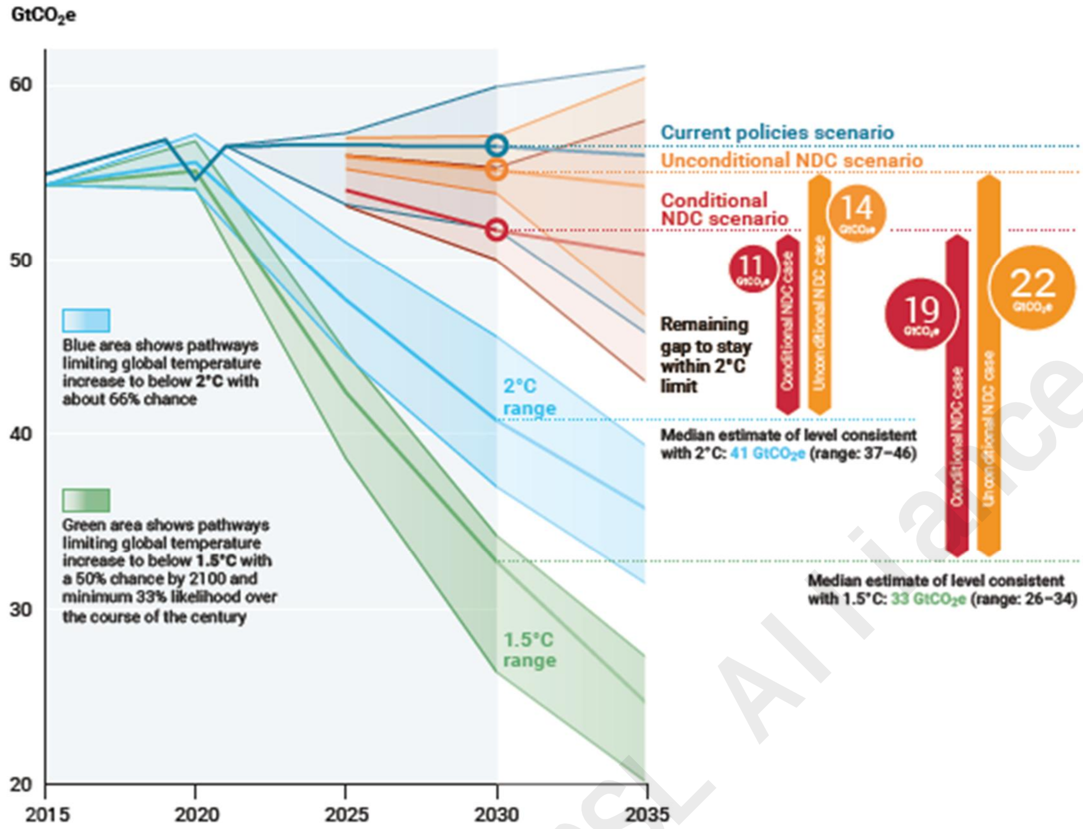
In its Emissions Gap Report 2023[43], the UNEP reports that the total emissions of greenhouse gases (GHG) due to human activity reached record levels in 2022, more than compensating for the slight fall in 2020.



Over 75% of the emissions come from the countries of the G20 group, in which the emission-per-capita is almost four times that in the least developed economies.

The following chart compares the anticipated GHG emissions over the next 12 years if current policies are followed and compares these with what would be needed to set the world on a path to limit the increase in average global temperature to either 2% or 1.5%. It is clear keeping emissions at their present level and preventing further increases does not represent sufficient progress.

[43] https://wedocs.unep.org/bitstream/handle/20.500.11822/43922/EGR2023.pdf?sequence=3&isAllowed=y



Given this context, we believe that providing 70% more light with only 10% increase in the consumption of electricity, although being a substantial technical achievement over the past 20 years, does not yet represent the major contribution to solving the climate crisis that some reporters and members of our community claim.

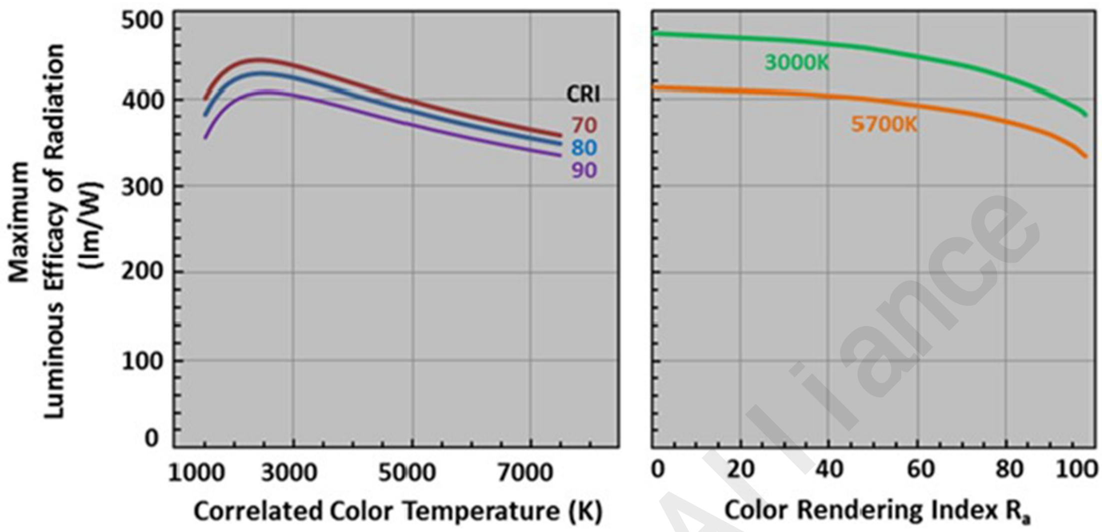
There is not a single solution to extending our contribution and multiple routes need to be taken. These might include:

- A renewed commitment to R&D on source efficacy and more efficient delivery of the light that is created.
- Improved manufacturing techniques that will tighten processing variations and reduce the cost of high-quality products.
- Continued efforts by governments and NGO's to facilitate the acquisition and use of SSL products across the globe.
- Greater emphasis on testing of product performance and lifetimes.
- More local manufacturing, especially of luminaires, to reduce the cost and environmental effects of transportation.

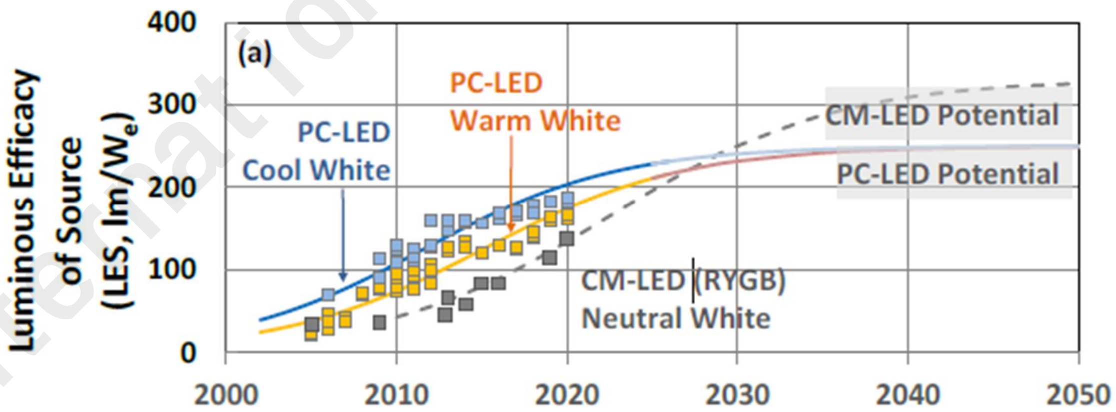
It is not possible to discuss each of these in depth in this issue. The remaining section includes brief observations on the need for further R&D.

5.1 Renewed Commitment to Research and Development.

The results summarized in section 2.3 show that significant progress has been made on LED efficiency over the past twenty years. But much more can be done, going even beyond the limitations described in that section. The following charts show the theoretical limits of the efficacy of white LED packages as a function of CRI and CCT[44].



Perhaps the most interesting feature of these charts is that they show that white LEDs should be more efficient at low CCT, which is preferred for many applications. These results suggest that a target of 300 lm/W at all CCT and CRI might be an achievable target for 2040, as recommended in the SSL program of the US DOE[45]. This would require the closing of the green gap and the mixing of light from multiple primaries (CM-LED), rather than phosphor conversion of blue light (PC-LED). Such a transition would be good for other applications, since it would enable the efficient production of any desired spectrum.



The progress that has been made over the past twenty years would have not occurred without coordination by governments, academia and industry to accelerate the

[44]https://www.researchgate.net/publication/237013051_Maximum_White_Luminous_Efficacy_of_Radiation_Versus_Color_Rendering_Index_and_Color_Temperature_Exact_Results_and_a_Useful_Analytic_Expression

[45] https://www.energy.gov/sites/default/files/2022-02/2022-ssl-rd-opportunities.pdf

development of SSL. These efforts have been reduced substantially in the past five years, particularly in respect to R&D. The SSL program within the US DOE has shrunk significantly and the focus has evolved into the integration of lighting with other building systems and national infrastructure.

Collaborative research programs funded by the European Commission (EC) now include almost no projects involved with the core challenges in SSL lighting. The following table summarizes the results of a query to the CORDIS database of EC-sponsored projects with both 'LED' and 'lighting' as search terms.

Programme	Dates	Projects
Framework 4	1994-7	61
Framework 5	1998-2002	109
Framework 6	2002-6	185
Framework 7	2007-13	2904
Horizon 2020	2014-20	5384
Horizon Europe	2021-7	71

The results span five stages of EC funding of science and technology projects and suggest a precipitous change in priorities since 2020.

The leading showcase for SSL R&D in China has been the annual China International Forum on Solid State Lighting, which celebrated its 20th year in 2023. The event is now combined with the International Forum on Wide Bandgap Semiconductors (WBS), now in its 9th year. The balance in the program seems to be trending towards other applications of WBS. Only one of the nine plenary talks was focused upon SSL. Nevertheless, there were over 80 talks on lighting applications and so R&D on SSL still seems to be healthy in China. One notable change from the pre-pandemic meetings was that very few of the talks or attendees came from outside China and translations were not provided for most of the talks.

In most of the world, lighting companies are not well placed to compensate for the reductions in government funding and academic collaborations. Revenues are recovering only slowly from the pandemic and profit margins are slim or non-existent. The next tables show changes in sales and profits reports in recent company reports, with LED suppliers on the left and lighting companies on the rights. Almost all the manufacturers of LED chips or packages experienced a reduction in profits or a loss. Shenzhen Mason was profitable in this period after a year-earlier loss. The situation is not much better for the companies that sell SSL products.

Company	Period	% change	
		Sales	Profit
AMS-Osram	2023Q3	-25	-40
Cree	2023Q4	-20	?
Ennostar	2023Q1-3	-34	loss
Foshan Nationstar	2023Q1-3	0	-34
HC Semitek	2023Q1-3	12	loss
MLS	2023Q1-3	4.5	-11
Sanan	2023Q1-3	1.4	-83
Seoul Semiconductor	2023Q3	-0.6	loss
Seoul Viosys	2023Q3	20.9	loss
Shenzhen Mason	2023Q1-3	53	profit

Company	Period	% change	
		Sales	Profit
Fagerhult	2023Q1-3	7.5	18.4
Signify	2023Q3	-14	-18
Zumtobel	2024Q1	-9	-10
Acuity Brands	2023	-1	2
Foshan Electrical	2023Q3	8.2	2.5
Opple	2023Q1-3	5.9	30
Zhejiang Yankon	2023Q3	-14	-88
Crompton Greaves	2024H1	-12	17
Havells	2024H1	-0.6	-6.8
Surya Roshni	2024H1	4.6	39

The next table shows the R&D spending of some of these companies, both in local currencies and as a fraction of sales revenues. It is encouraging that both AMS-Osram and Seoul Semiconductor remain committed to maintaining a long-term view.

Company	Report	R&D	Sales	%
Acuity	22AR	95.1	4006	2.37
AMS-Osram	23H1	265	1778	14.9
Glamox	22AR	32.8	3704	0.89
MLS	23H1	182	8261	2.2
Sanan	23Q2	179	3562	5.03
SSC	23H1	45	480	9.38
Signify	23H1	145	3322	4.36
Zumtobel	FY23AR	67.8	1209	5.61

The data was taken from quarterly, half-year or annual financial reports, as indicated in the second column. The R&D expenditures and sales are given in the local currency.

In conclusion, given the financial state of the industry and the priorities of most company boards and investors to favour short-term profits over longer-term returns broader social benefits, we believe that is time for all governments to renew their commitment to more efficient lighting. Increased support for local industry and academia is especially needed outside of China to create new jobs and prevent further consolidation of the industry in that country.