International Solid-State Lighting Alliance

SSL Industry Report 2024-1

Editor: J. Norman Bardsley

Contents

1. Introduction

In this edition we will complete our review of the impact of LEDs on lighting over the past twenty years with an assessment of the contribution made by the lighting industry to reducing greenhouse gas (GHG) emissions to mitigate the rise in global temperatures. We also will identify some of the challenges in the design and deployment of smart lighting systems in preparation for our collaboration with the IEEE Smart Lighting project. We begin by assessing the state of the industry at the beginning of 2024 from summaries of reports from companies and market analysts.

One of the sad developments over the past few years has been the reduction in the number of sources for objective news and analysis of the lighting industry. On March 27th, LEDs Magazine announced that the March/April edition will be its last, after 20 years of excellent service to the industry. It is to be hoped that the team will continue to provide reliable information through its new on-line format. The editor-in-Chief, Carrie Matthews, indicates that they "have plans underway to integrate new partnerships into our content; to deliver continuing education and thought leadership across several channels, both live and on demand; to cultivate more regional and demographic insights on trends and opportunities; and to develop leading multimedia content that sparks discussion while entertaining and informing our audience.

One remaining resource is LED Professional Review. Although their annual in-person symposium has been discontinued, the magazine provides valuable information in both printed and on-line formats. The March/April edition contains the second of three articles submitted by the ISA Chief Analyst as well as a lengthy summary of the offerings at the 2024 Light + Building show in Frankfurt.

2 Market Reports

This chapter discusses recent trends in the LED lighting market as viewed from various sources.

2.1 Market Research Forecasts

Since Strategies Unlimited discontinued the publication of their LED and Lighting market reports in 2020, market coverage has been left to companies that cover many different industries. The depth of experience of their analysts in lighting technology and markets is far from clear. The level of uncertainty is illustrated in the following table, which compares the predictions for global LED lighting revenues by twenty market research companies.

Source	Base Year	Value $B	CAGR %	2030 $B		Source	Base Year	Value $B	CAGR %	2030 $B
Brainy Insights	2022	72.1	12.3	183		Maximize	2023	62.56	10.9	129
Emergen	2022	73.8	10.6	165		Mordor Intelligence	2024	46.54	5.8	65.1
Expert MR	2023	76.7	9.1	141		Polaris	2023	81.64	10.2	158
FMI	2022	76.1	16.1	253		Report Linker	2023	100.2	11.4	213
Fortune BI	2022	78.2	19.2	298		Research&Markets	2023	65.3	10.1	128
Grandview Research	2023	81.5	11	169		Skyquest	2021	63.8	11	169
imarc	2023	83.2	8.6	151		Statista	2023	79.61	4.5	109
Inf&Comm Tech	2023	34	5.1	48.2		Technavio	2022	78.5	7.4	140
Market Reseach Future	2021	57.9	11.2	135		Verified	2021	11.96	10.3	26.1
Markets&Markets	2024	78.9	8.5	129		Zion	2022	70.49	11.3	165

The first two data columns give the base year and the reported revenues in US $B. The estimates of recent revenues vary by more than a factor of 3, but the consensus seems to be between $75B and $80B. Some of the variation can be attributed to different definitions of the market scope, but if one cannot rely on estimates of past sales revenues, what confidence can one have in future guestimates. The predictions for the Compound Annual Growth Rate vary from 4.5% to a very optimistic 19%, leading to a six-fold range in the forecasts for revenues in 2030.

TrendForce has maintained good contact with the LED lighting industry in Asia, through its subsidiary LEDInside. The remaining part of this section presents excerpts from some of their most recent analyses.

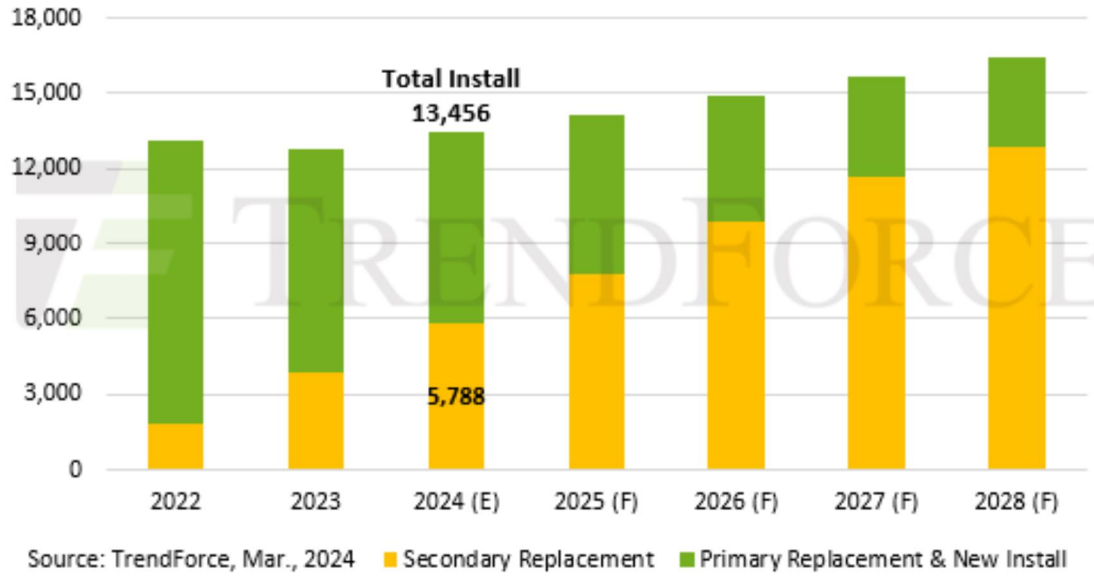
According to the report "TrendForce 2024 Global LED Lighting Market Analysis-1H24", the market value of LED sources shrunk to USD 12.6 billion in 2023 due to multiple negative factors such as sluggish end-market demand, slow inventory depletion for LEDs, and fierce price wars. The LED market value is forecast to grow to USD 13.0 billion in 2024 (+3% YoY). TrendForce also revised down the LED lighting market value for 2023 to USD 58.5 billion (-5% YoY). They estimate that the market value in 2024 will reach USD 60.9 billion (+4% YoY).

TrendForce's reports indicate a significant turning point for the LED lighting market in 2024, as an estimated quantity of 5.8 billion LED lamps and luminaires reach the end of their lifespan. This milestone is set to trigger a substantial wave of secondary replacements, breathing new life into the market and boosting total LED lighting demand to an impressive 13.4 billion units.

Currently, LED lamps and luminaires account for about 70% of all lighting solutions in use worldwide, narrowing the scope for replacing traditional fixtures with LED alternatives. Only specific, unique applications continue to rely on non-LED lighting, making the cost of transition increasingly

expensive and suggesting that the first wave of replacement may have largely concluded. Despite a dip in shipments of LED lighting products in 2023, the decline hasn't been drastic, thanks to the rising tide of secondary replacement demand, which has now become the LED market's key driver.

Global LED Lighting Installation and Replacement Forecast, 2022–2028
(Unit: Million Units)



LEDs are generally designed to last between 25,000 to 40,000 hours, translating to a real-world service life of 7 to 10 years. TrendForce suggests that LED lamps and luminaires installed between 2014 and 2016 have begun to hit their lifespan limit, propelling demand for secondary replacement year after year. This trend is expected to fuel the lighting market's growth over the next five years, making secondary replacement the dominant force by 2025, and they are projected to account for a whopping 78% of LED lighting demand by 2028,.

However, the road to realizing the potential of secondary replacement demand is fraught with challenges. Many households lack awareness about the need for replacements, with concepts like health-conscious lighting and environmental considerations not yet mainstream. Some potential users are hesitant, adopting a wait-and-see approach. Additionally, a general lack of understanding about the science of lighting and its commercial and artistic value persists in some regions, preventing full appreciation of what modern lighting technology can offer.

Last, but not least, product quality varies in the market, and presently, consumers often prioritize price over quality. Down the road, the LED lighting market will progressively step into a more stable, cyclically developing period. In this evolving landscape, brand significance is increasingly highlighted as a key factor in attracting consumer interest in repeat purchases.

TrendForce regularly compiles tables comparing the revenues of the leading lighting companies. They estimate that the global market for LED chips and packages in 2023 was $11.8B, with Nichia taking a 16% share, followed by AMS-Osram (13%), Seoul Semiconductors (7%), Samsung LED (6%) and Lumileds (5%). Their estimates for lighting companies in 2023Q2 and 2023Q3 are shown in the next table:

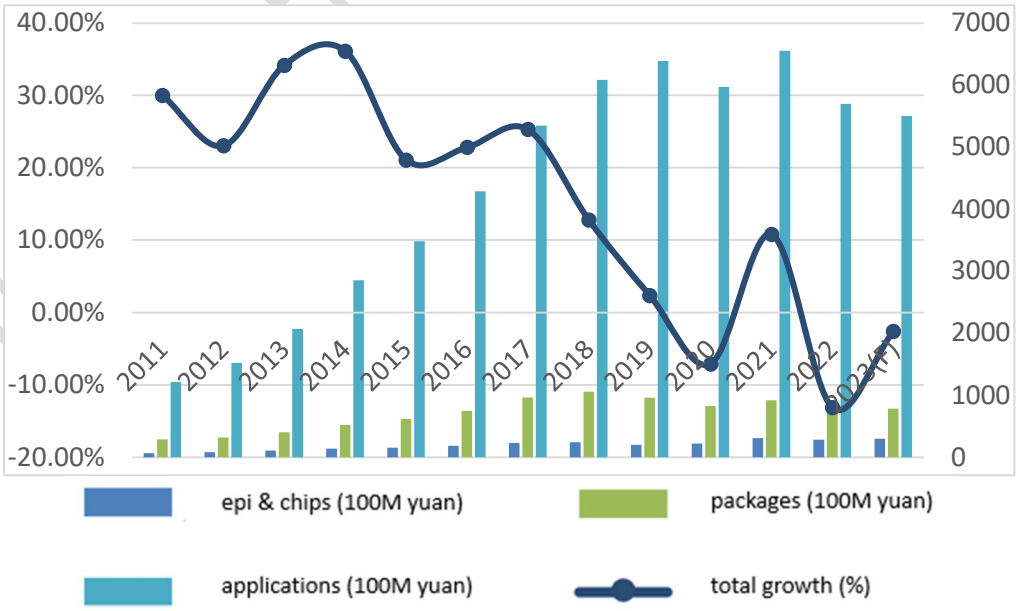
3Q23 Revenue Rankings of Top Ten Lighting Manufacturers (Unit: Million USD)

Rank	Company	Revenue			Market Share	
		3Q23	2Q23	QoQ	3Q23	2Q23
1	Signify	1,745	1,789	-2.5%	33.6%	34.1%
2	Acuity Brands	1,000	1,010	-1.0%	19.2%	19.3%
3	Panasonic	477	458	4.1%	10.2%	9.7%
4	LEDVANCE (Incl. MLS Lighting)	448	438	2.3%	9.6%	9.3%
5	Zumtobel	314	320	-1.9%	6.0%	6.1%
6	Current (Incl. Hubbell C&I)	283	281	0.7%	5.4%	5.4%
7	Opple	274	292	-6.2%	5.3%	5.6%
8	Savant Systems (GE Lighting Segment)	258	254	1.6%	5.0%	4.8%
9	Toshiba	210	198	6.1%	4.0%	3.8%
10	Fagerhult	190	199	-4.5%	3.7%	3.8%
	Top 10 Lighting Total Revenue	5,199	5,239	-0.8%	100%	100%

2.2 China Solid-State Lighting Annual Report

Each year the China Solid State Lighting Alliance (CSA) prepares an annual report on the status of the LED lighting market. This document, which is often referred to as the "Blue Book", is published right at the beginning of the year and so does not give final values for the annual data for the most recent calendar year. Nevertheless, it provides a valuable summary of the state of the LED lighting industry in China.

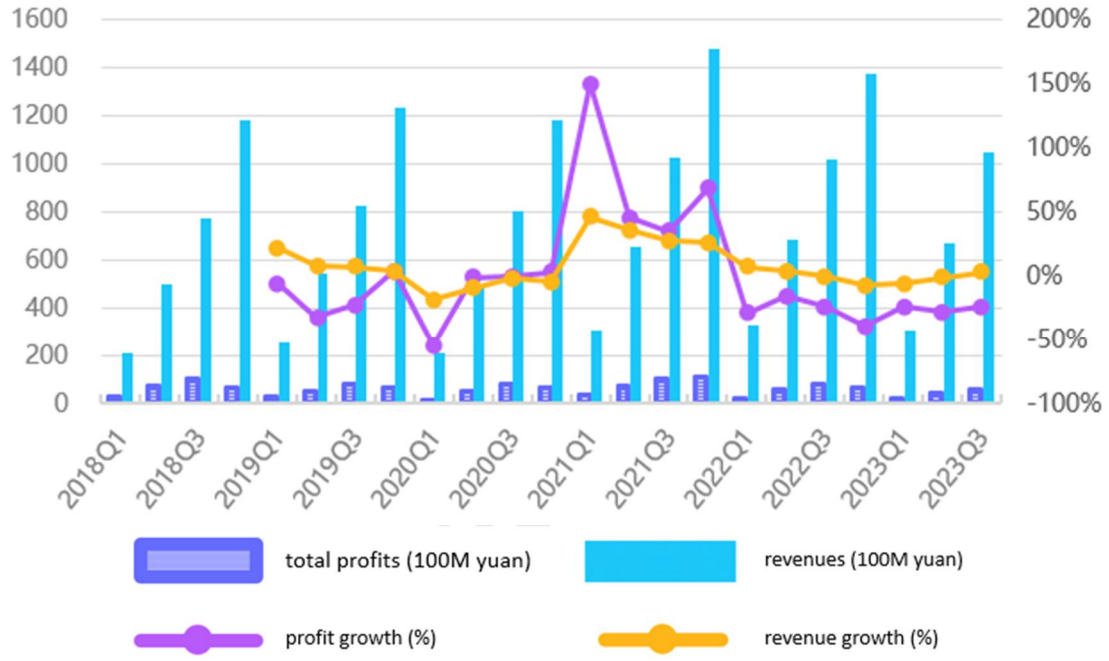
The overall demand in 2023 was weak, with high inventory and insufficient capacity utilization. The total output value in 2023 was approximately 658B yuan, down 2.6% from 2022, of which the upstream epitaxial chip scale was 29.5 billion yuan, the midstream packaging scale was 78.2 billion yuan, and the downstream application scale was 550B yuan. The following chart shows that sales have fallen below the pre-pandemic levels of 2018 and 2019.



Industrial scale and growth rate of each link in the SSL industry in China from 2011 to 2023

On the corporate side, affected by factors such as insufficient demand and complex situations at home and abroad, the overall operating quality of the industry has been slow to recover. In the first 9 months of 2023, the total operating income of 52 listed companies mainly engaged in LED was 105B yuan, a slight increase of 2.6% year-on-year. This small gain was only possible through price reductions. The total profit was 5.8B yuan, a year-on-year decrease of 24%. Market demand is weak, operating costs are increasing, product prices are declining, and corporate profit margins are being squeezed to varying degrees. It is still difficult for small and medium-sized enterprises to survive. Enterprises with the advantages of scale and differentiation have demonstrated their development resilience.

The next chart shows the quarterly revenues and profits of these 52 listed companies over the past 5 years.



The total revenue and profit of 52 listed companies mainly engaged in LED in 2018-2023

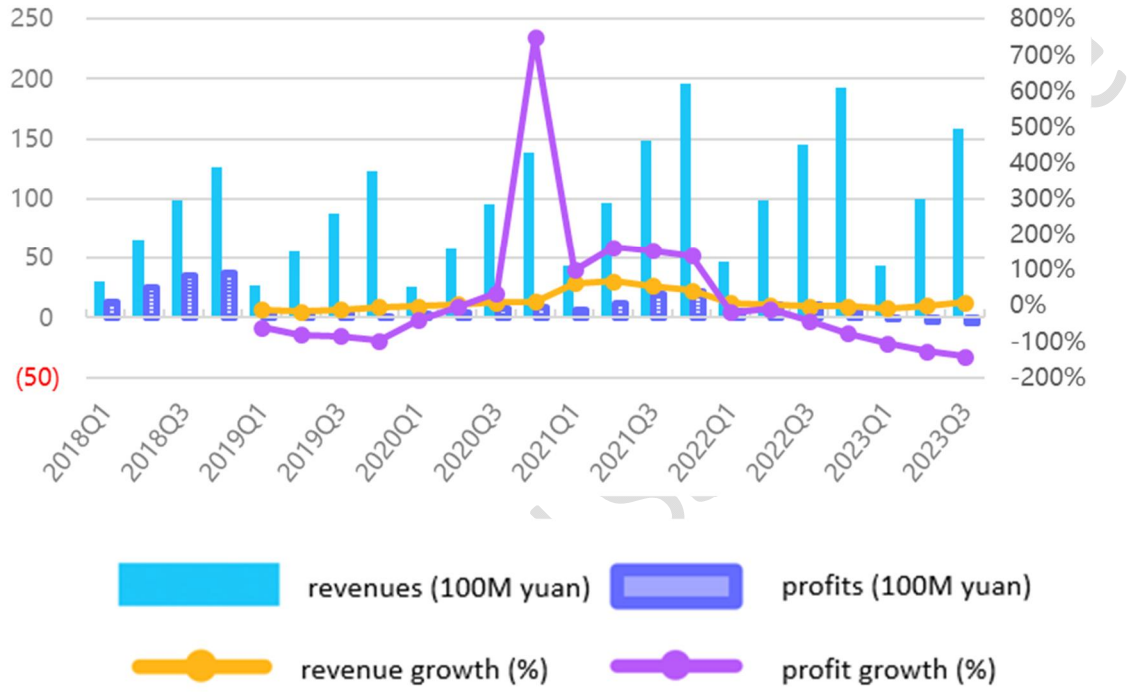
Some parts of the industry fared better than others. The year-on-year growth rate of each segment's revenue, from high to low, was:

supporting materials 12.2%
downstream engineering 9.6%
upstream chips 8.7%
midstream packaging 4.6%
downstream display 4.2%
downstream lighting -6.1%.

The total profit growth rate of each segment, from high to low, was:

downstream engineering 72.1%
midstream packaging 7.2%
supporting materials 3.2%
downstream display -7.2%
downstream lighting -14.4%
upstream chips -142.4%.

In the chip sector, due to lower-than-expected market demand, price competition has intensified, costs have continued to rise, and operating costs have grown at a high rate. Here also total revenue has increased slightly but the overall profitability has declined. Leading companies have laid out high-end product lines and increased investment in lighting application fields such as automotive lighting, vehicle-mounted displays, industrial and commercial lighting, agricultural lighting, and new displays to maintain continued technological leadership. In the third quarter of 2023, the operating income of the main LED chip companies was 15.807B yuan, an increase of 8.7% compared with the same period last year. Total profits fell off a cliff, and the segment as a whole was in a state of loss. The total profits of the main LED chip companies in the first three quarters were -474M yuan. The following chart shows that this segment has struggled to make profits since the end of 2018.

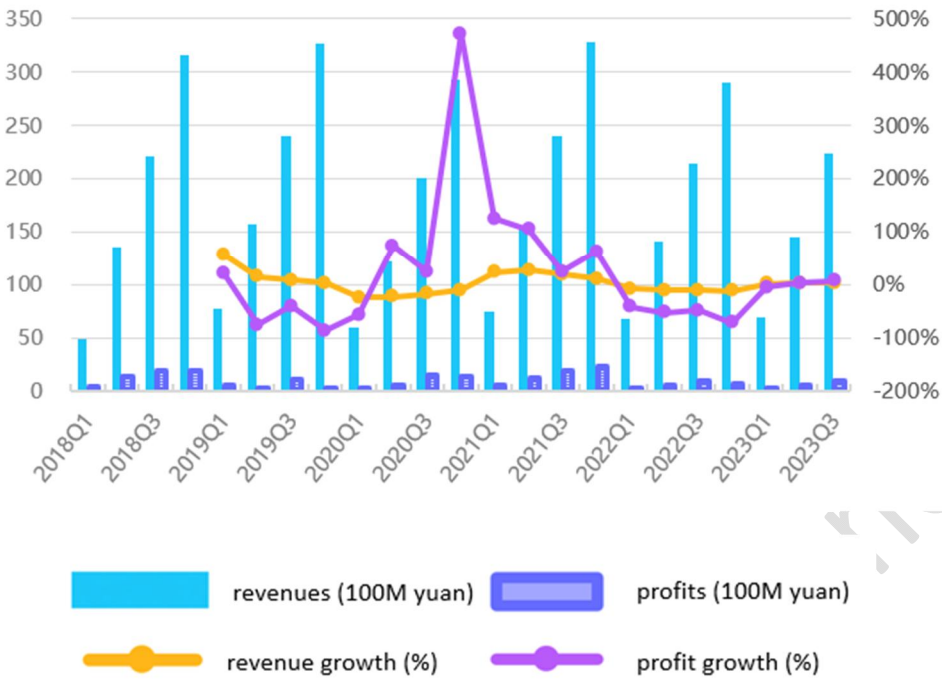


Revenue and profits of listed companies mainly engaged in the chip segment from 2018 to 2023

Faced with these challenges, the leading chip makers have formed partnerships with display panel manufacturers. For example, Huacan Optoelectronics and Qianzhao Optoelectronics are controlled by BOE and Hisense Video respectively, and will rely on the industrial chain advantages to further accelerate the research and development and product promotion of new technologies such as mini/micro-LED; Sanan Optoelectronics has a joint venture with TCL. Other chip manufacturers such as Jucan Optoelectronics , Azure Lithium Core , and Zhaochi Semiconductor also regard mini/micro-LED as one of the main growth points in the future, but profits in that area could be just as elusive.

Revenues in the packaging segment have improved compared with last year, but the price and cost inversion in the first half of the year has caused profit margins to continue to decline. In 2023, affected by rising upstream chip costs and downstream demand, traditional general lighting device packaging companies have had high inventories and insufficient capacity utilization. Display devices are also facing a slow recovery in demand. During this process, the industry structure has undergone major changes. More than a thousand small and medium-sized packaging companies have withdrawn from the market. The number of companies engaged in LED packaging nationwide has concentrated from more than 1,400 to just over 200 currently.

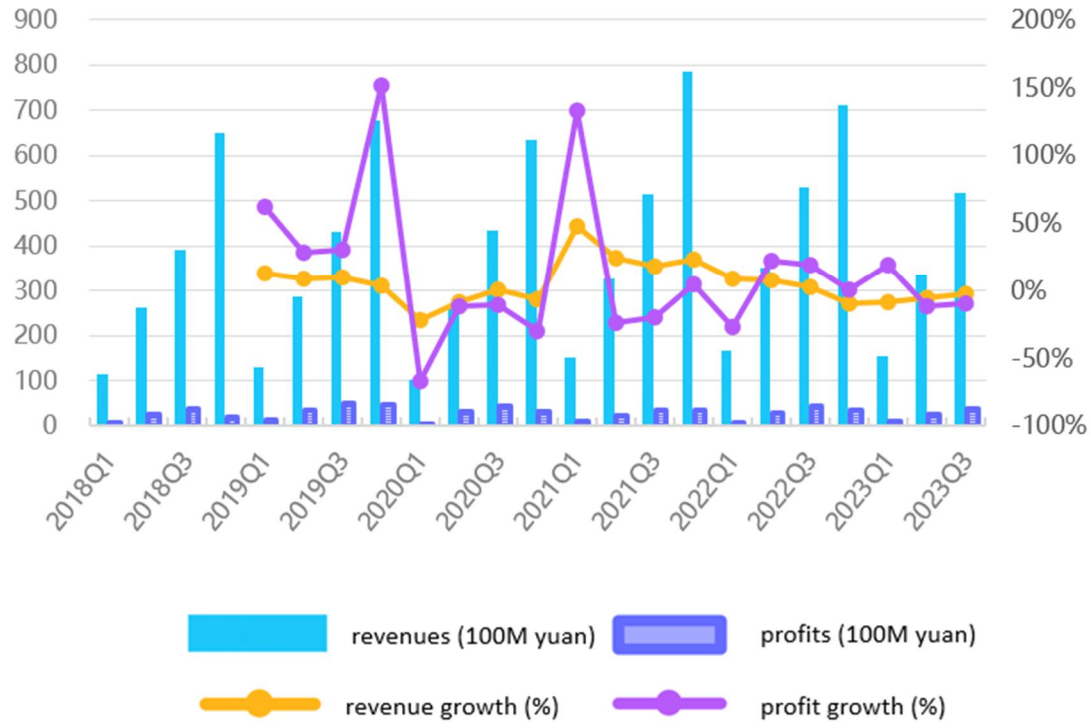
The five-year chart for the packaging segment shows that business is highly dependent on the season and that profits have been steady but small.



Revenue and profits of listed companies mainly engaged in packaging in 2018-2023

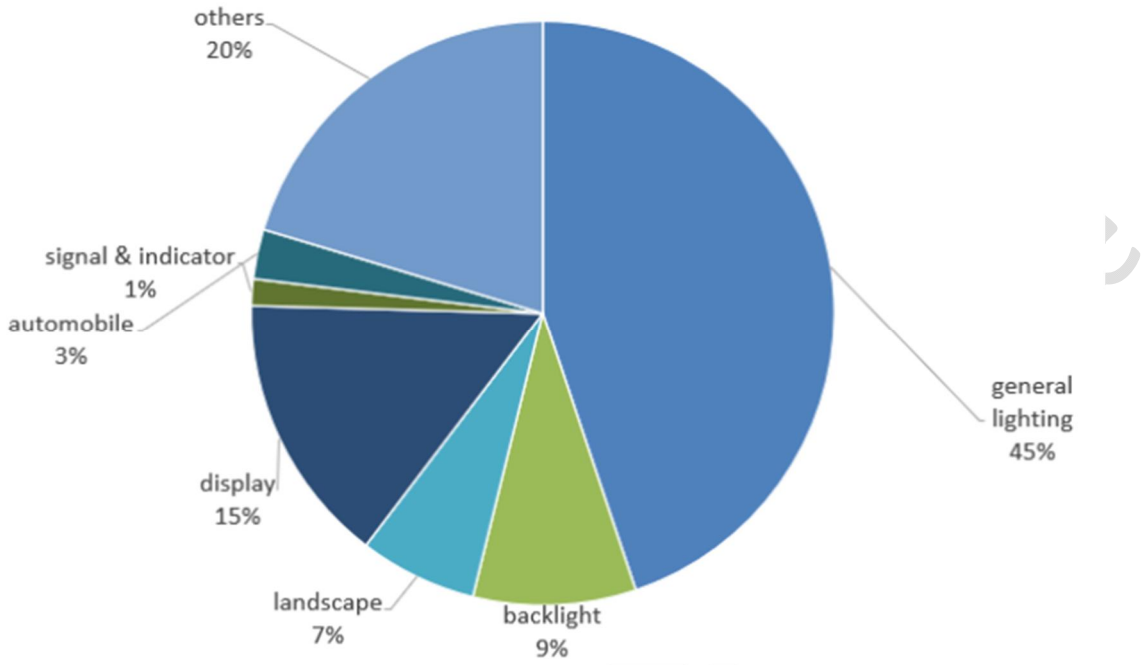
Many packaging companies are also accumulating technology and expanding production capacity around mini/micro-LED displays, especially for automotive applications.

In 2023, due to weak domestic and foreign market demand, the recovery of downstream application links has been less than anticipated. China's downstream application output value is expected to be 550.1B yuan, down 3.4% year-on-year. The next chart shows the revenues and profits of the applications segment over the past five-years.



Revenue and profits of companies mainly operating in the application segment from 2018 to 2023

Among applications, the decline in the general lighting market is the most obvious. The operating income and profit of the sector fell by 6.1% and 14.4% year-on-year respectively. But, with 2023 sales of around 247B yuan, general lighting remains the dominant application, as shown in the next chart.

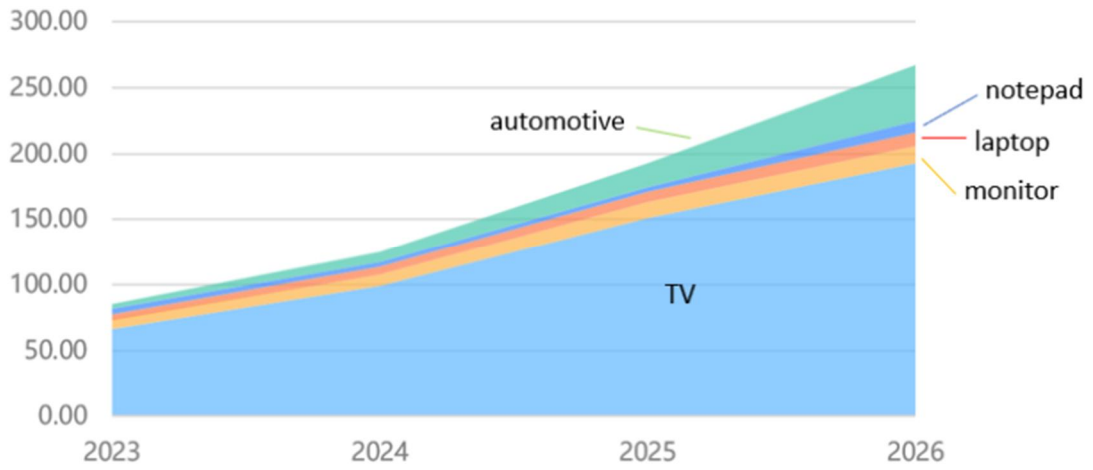


Distribution of semiconductor lighting application fields in China in 2023

Two emerging applications have shown major growth, mini-LEDs and UV-LEDs.

According to data from Aowei Cloud Network, domestic sales of mini-LED backlight TVs in the first half of 2023 were 380,000 units, a year-on-year increase of 188%. The sales share was 8.7%, a y-o-y increase of 6.1%. With the continuous cost reduction and efficiency improvement in all aspects of the mini-LED backlight industry chain, such as reducing the amount of PCB substrates, the price of mini-LED chips has dropped by more than 50% year-on-year, and the price of driver IC has dropped significantly, driven by the maturity of technology and the continuous improvement of yield rates. The cost of mini-LED backlight modules continues to fall, which in turn promotes the rapid increase in the penetration rate of mini-LED backlights.

At the same time, leading TV brands have vigorously strengthened the market promotion of sets with mini-LED backlights, driving the mini-LED backlight market to rapid growth. In 2023, the sales volume of mini-LED backlight TVs exceeded that of OLED TVs. It is expected that by 2026, the global sales penetration rate of mini-LED video displays will increase from 3% in 2023 to 16 %, and global shipments will increase from about 6M units to about 30M. The adoption of mini-LED automotive backlights is also accelerating. As a result, the total mini-LED backlight module market is expected to grow from 8.5B yuan in 2023 to 26.8B yuan in 2026.



Mini-LED backlight module market size (100M yuan)

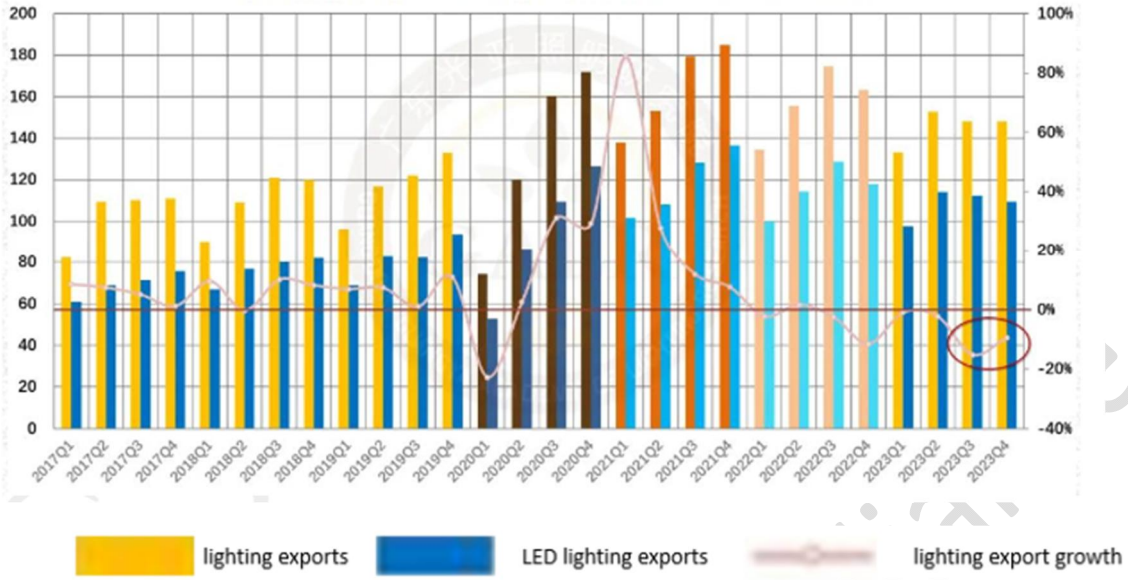
In 2023, UV LED companies continued to make efforts in technological innovation, market channels, product research and development, cost-effectiveness, etc., and so UV LED applications are advancing. According to CSA Research market research, the market size of UV LED chips, devices and modules in 2023 was approximately 2.28B yuan, a year-on-year increase of 16.2%.

A new round of price wars is intensifying, so that UV LED is becoming more cost-effective for customers. The expansion of production scale, continuous improvement of technology, new products emerging one after another, and the accumulation of various factors such as inventory backlog of some products have led to a sharp drop in prices. The price of UV LED chips dropped significantly in 2023. The industry generally believes that the annual decline in UV LED sales was around 10%, even though the price reduction of some products exceeded 50%. Nevertheless, in this post-epidemic era, UV LED is still a key area of concern for the industry. New companies continue to pour in. The UV LED segment track is becoming increasingly crowded, and "homogenization" has intensified the competitive pressure on enterprises. At the same time, the decline in upstream and midstream prices has further accelerated the expansion of the application market. With the continuous innovation of UV LED technology and the continuous reduction of costs, the performance and price ratio of UV LED products have become more competitive, which will accelerate their application in medical, food processing, public health, home appliances and other fields.

Exports

Part of the reason for pressure on manufacturers in all sectors has been weakness in the export market. In 2023, China's exports of lighting products was expected to be about US$58.2B, a year-on-year decrease of ~7.2%. Among them, the export value of LED lighting products was close to US$43.3B, accounting for 74% of the overall export value, down 6.2% year-on-year.

From the perspective of export products, the proportion of light source products continues to decline, while the export value and export volume of LED modules, lamps, photovoltaic lighting, and automotive lighting products have increased. Exports to European and American markets continue to be sluggish, and orders from Vietnam, South Korea, and Japan have also declined in varying proportions. However, exports to emerging economies such as ASEAN, Africa, and India have increased, and the foreign trade of “Belt and Road” countries has risen. The following chart shows that although the value of exports has fallen since 2021, it is still above pre-pandemic levels.



China's export volume of lighting products and LED lighting products (2017-2023) (100M USD)

2.3 News from the Aladdin Network

The Aladdin Lighting Network was formed in 2007 and is supported by the China Illuminating Society and many partners from the lighting community in China. It provides a comprehensive source of news on the industry through its website at

https://www.alighting.cn/news/

This section is designed to illustrate the type of information that is available from this source.

Unit Production and Cost Pressures

At least 25 of the leading lighting companies in China announced new construction projects in 2023. Opple Lighting plans to spend 3B yuan on its Headquarters complex in South China, but construction had not begun by the end of the year. Most attention has been paid to Signify's investment of 2.8B to build the world's largest LED lighting production base in Jiujiang City, Jiangxi Province, through its joint venture company Zhejiang Klite Lighting Holdings Co., Ltd. Fully operational by the end 2023 with 192 production lines, the 200,000-square meter facility uses world-class manufacturing technology, advanced process control, and intelligent logistics to produce LED lighting sources and luminaires for both professional and consumer markets.

Other companies planning investments of over 1B yuan include Unilumin Technology, Yiguang Technology, Qianzhao Optoelectronics, China Micro and Youweixin. All of the 25 projects are located in cities in the Pearl River Delta and the Guangdong-Hong Kong-Macao Greater Bay Area. Among them, the city of Zhongshan has 9 projects.

Many of the smaller projects are aimed at specific market sectors. These include

- the solar streetlights and educational lighting fixtures of Langxing Technology's LED optoelectronic equipment manufacturing base,
- the 4.5th generation OLED production line of Yiguang Technology,

- Huaibei OLED car lighting modules,
- UV LED chips and devices from Youweixin UV LED Industrial Base,
- stage lighting fixtures and supporting products from Haoyang Entertainment Lighting Equipment Production Base.

Many of these projects reflect the new era of smart technology for lighting companies across the country. These include projects by companies such as Liyang Optoelectronics, Langxing Technology, Yiguang Technology, Zhiyan Technology, Songyan Lighting, Jianlang Lighting, LTECHTechnology, Huapu Sunlife, Wuku Lighting, Songwei Lighting, Unilumin Technology, and Balin

A promising feature is that many projects by small and medium size companies have the purpose of integrating research and production. The companies include Lite Technology, Liyang Optoelectronics, Zhiyan Technology, Songyan Lighting, China Microelectronics, and Songwei Lighting, showing that innovation is not confined to the large companies that are known on a global scale.

Exports:

In the first quarter of 2024, China's lighting product exports totaled US$13.05B, a slight decrease of 2.0% year-on-year[1]. Among them, the export value of LED lighting products was US$9.62B, accounting for 74% of the overall export value, a slight decrease of 1.3% year-on-year. Exports to North America declined by 10% to $US3.1B and those to Europe fell by 6% to $US2.7B. These two regions now account for less than 50% of exports. On the other hand, exports to emerging economies such as Southeast Asia, South Asia, Central Asia, the Middle East, Russia, and Africa recorded growth.

The average export price of most lighting products has continued the downward trend since last year. The total number of exports of light source products was 1.87B, a y-o-y increase of 12%, including 1.54B LED light source products, a y-o-y increase of 20%. The number of traditional light source products decreased by 17% to 330M.

Outdoor markets:

With about 65% of the population of China now living in urban areas, the need for outdoor lighting is growing steadily.

According to data from the Ministry of Housing and Urban-Rural Development, the length of roads with installed streetlights in 2022 was about 433,000 km, up from 344,000 km in 2018. The number of lights rose from 27.4M in 2018 to 34.5M in 2022. With an average lifetime of 8 years for existing lights and a growth of 2M lights per year, the total annual demand for new lights should be over 6M units. Based upon an average price of 12,800 for each set of lights, China Business Industry Research Institute (CBIR) predicts that the market size of urban road lighting industry will reach 79.1B yuan in 2024, up from 72.5B yuan in 2023 and 66.2B yuan in 2022[2].

The landscape lighting market is also showing steady growth with anticipated revenues of 36.6B yuan in 2024, up from 34B yuan in 2023 and 20.5B yuan in 2018.

In addition to these investments by government agencies, the contribution of commercial and industrial companies to the outdoor market size rose to 66.3B yuan in 2022 from 39B yuan in 2018, according to data compiled by the Guanyantianxia Data Center.

[1] https://www.alighting.cn/news/20240422/176087.htm

[2] This price estimate seems high but reflects the increasing adoption of smart lights.

The CBIR estimates that the total outdoor lighting market size will reach 193B yuan in 2024, up from 178B yuan in 2023 and 98B yuan in 2018. These values seem to be much higher than those implied by the data in the CSA blue book.

Night-time tourism:

In order to boost revenues following the pandemic, many local authorities have promoted night-time tourism. Total investments in 2023 were in excess of 5B yuan, including at least 20 projects costing over 100M yuan. Among the most ambitious were the Lianyungang Monkey King Legend Paradise Project, with investment of 2B yuan, and the Fujian Culture Fantasy Drama Town "Da Ming Qianxing Port", costing 1.7B yuan.

Source: China Central Radio and Television International Online

Shanghai Yuyuan Lantern Festival

Fujian Culture Fantasy Drama Town "Da Ming Qianxing Port"

Taihang Mythical Night City,

These projects clearly involve the purchase of powerful LED lights but are raising concern about energy consumption and light pollution. Comprehensive new regulations regarding outdoor lighting are being developed in Hebei province, Beijing and elsewhere.

Classroom lighting:

Concern about children's eyesight and new regulations has led many local governments in China to upgrade classroom lighting in their schools. The Educational Equipment Procurement Network identified 139 projects in the 3-month period from September to November 2023 with a total expenditure of over 418M yuan. The investment per school appears to be over 1M yuan, so that the total renovation cost for all 500,000 schools in the country could be as high as $500B yuan.

The national requirements for classroom lighting were updated in standard GB/T 36876-2018. The recommendations include "Maintain an average illuminance of not less than 300lx and an illuminance uniformity of not less than 0.7. The average illumination on the blackboard surface shall not be less than 500lx, and the uniformity of illumination shall not be less than 0.8. The unified glare

value (UGR) should not be greater than 19. The colour temperature should be 3300K-5500K, and the Colour Index should not be less than 80."

The document included recommendations of how these requirements should be met using fluorescent lamps. It is interesting that the illumination levels were less than those recommended for daylighting systems in 2012, in which the minimum horizontal illumination level was 450lx. Since that date, new recommendations have been made to take into account the availability of LED sources. With LEDs the recommended values for the Colour Index are 90 for R_a and 50 for R_9. Some regional governments, such as Guangdong and Fujian Province, have developed local regulations to complement the national standards.

Increasing the lighting levels in all the schools could add substantially to the electricity load. So, school administrators are again stressing the importance of outdoor exercise for students as part of myopia control.

Displays:

The display market was the prime driver for the commercial success of LEDs and still provides the motivation for many technological advances. The market peaked in 2018 and is still trying to recover from the loss of sales during the pandemic. According to data compiled by GGII and China Business Industry Research Institute, the LED display market size should rise to 63.4B yuan from 53.7B yuan in 2023 and 49.3B yuan in 2022, but still below the record level of 65.9B in 2018. It should be noted that these values are about 50% higher than the estimates of CSA, perhaps due to difference in the definition of the market.

Prices at the low end of the display market have fallen so rapidly that many companies are striving for profits by focusing on the high end, with high resolution, large dynamic range, vivid colours and large screens. The next figure shows a TV exhibited by TCL at the 2024 China Home Appliances and Consumer Electronics Expo.

High-end TV shown by TCL in March 2024

Excitement about the ultra-high-definition video display industry has been particularly strong in Shenzhen. Local revenues from the sector were around 200B yuan in 2022 and are expected to exceed 450B yuan in 2025. Breakthroughs have been made in key links such as ultra-high-definition video display transmission, basic software, and new displays. The completeness of the infrastructure is propelling Shenzhen to world leadership in the ultra-high-definition video display industry.

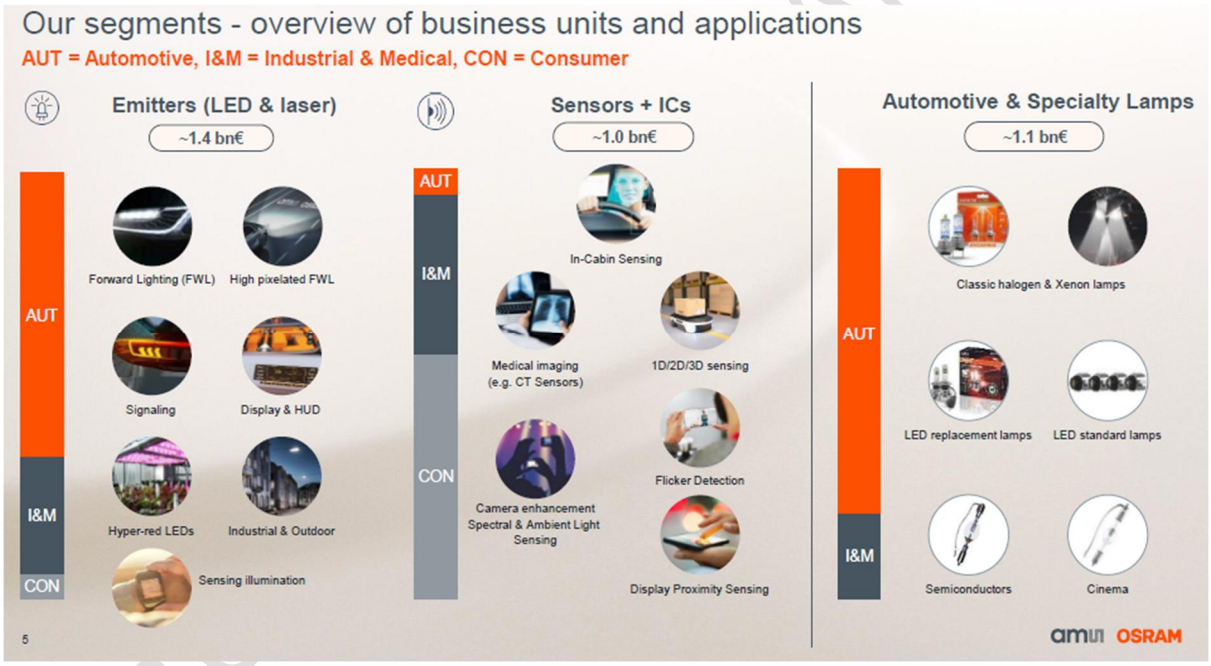
2.4 Company Reports

LED Packages:

According to TrendForce, the global market for LED packages in 2023 was about $11.8B. The revenues of the top 5 leading manufacturers were Nichia (US$1934M, down 13% from 2022), Osram ($1580M down 10%), Seoul Semiconductors ($784M down 8%), Samsung LED ($713M down 13%) and Lumileds ($589M down 18%). An earlier report listed MLS as in 5th place, with estimated package sales of about $660M, but MLS has not yet released its annual report. Following the purchase of LEDVANCE a few years ago, MLS announced that it would focus on LED products rather than packaging.

As a private company, Nichia does not publish annual financial reports. Omdia estimated that their revenues fell from $2.2B in 2021 to $1.8B in 2022. The 2022 estimate is about 10% lower than that cited above. The data from Trendforce suggest that the decline continued in 2023.

Osram is now part of AMS-Osram. Their annual report for 2023 shows that the three business units each have revenues exceeding $1B. Osram sold most of its general lighting units and its lamp business is now focused on automotive applications, as shown below:



Total revenues in 2023 were 3590M euros, down from 4819M euros in 2022. Profits from operations fell to 233M euros from 407M.

AMS-Osram took a major gamble on micro-LEDs through an investment of almost US$1B in a modern factory in Kulim, Malaysia, with hopes of manufacturing micro-LEDs in an economically efficient manner using 8-inch wafers. However, in February 2024 the company announced that it would reevaluate the use of this factory and write off most of the associated assets, following a major strategy revision by their leading potential customer.

The 2023 revenues of Seoul Semiconductor (SSC) were KrW1033B, down from KrW1109B in 2022. The company continued to struggle with profitability and the operating loss increased to KrW638B from KrW597B in 2022. The situation improved in 2023Q4, with sales rising by 11% y-o-y and they expect a similar rise in 2024Q1. In order to reduce costs, SSC plans to increase its activities in

Vietnam by building a second factory and transferring some development work. Its first factory there was built in 2017 at a cost of around US$350M.

Samsung's LED business unit was merged into Samsung Electronics in 2012 and has not published separate financial data since that time. Although most of its LED manufacturing is still done in Korea, a factory was established in Tianjin, China, in 2009. In 2020, Samsung announced that it would close some of its less profitable factories in Tianjin and focus on high-end products such as micro-LEDs. This strategy was reaffirmed in November 2023. It will be interesting to see whether Samsung follows the lead of Apple in reassessing its enthusiasm for micro-LED displays.

Among the manufacturers of UV LEDs, Seoul Viosys increased its sales to KrW 505M from KrW 480M in 2022, but also experienced a rise in its operating losses, to KrW 73M from KrW 62M.

The financial reports from the chip manufacturers in China confirm the summary given in the CSA blue book discussed above. Revenues increased at most companies, with only Jiangsu Azure (Jiangsu Aucksan) suffering a substantial decline. The pressure on profits has been particularly severe at Sanan, HC Semitek and Jiangsu Azure.

Jucan Optoelectronics has changed its name to Focus Lightings Tech Co., Ltd. It offers LED epitaxial wafers and chips used for display backlighting, general lighting, and medical beauty applications. The company also provides lighting, display, and optoelectronic devices. In addition, it offers contract energy management services and leases non-resident real estate properties. The good performance may have been at least partially due to its other business units.

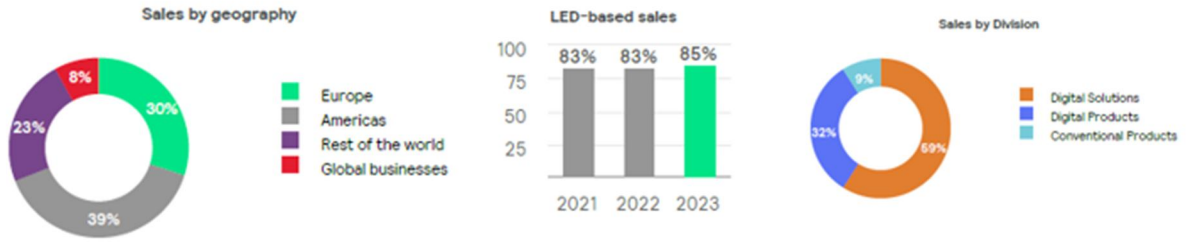
The following table summarizes the reports of these companies for 2023.

Company	Months	Units	Sales			Profits		
			2023	2022	Change	2023	2022	Change
AMS Osram	12	M euros	3590	4819	-25%	233	407	-43%
Ennostar	12	B NT$	22.31	28.88	-23%	-6.78	-0.04	
HC Semitek	12	M yuan	2903	2355	33%	-846	-147	
Jiangsu Azure	12	M Yuan	5222	6285	-17%	141	378	-63%
Jucan Opto	12	M Yuan	2481	2029	22%	41	-48	
Jufei Opto	12	M yuan	2512	2262	11%	210	154	36%
Sanan	9	M yuan	10156	10012	1.5%	173	987	-82%
Seoul Semi	12	B KrW	1033	1109	-6.8%	-482	-334	
Seoul Viosys	12	M KrW	505	439	15%	-73	-62	

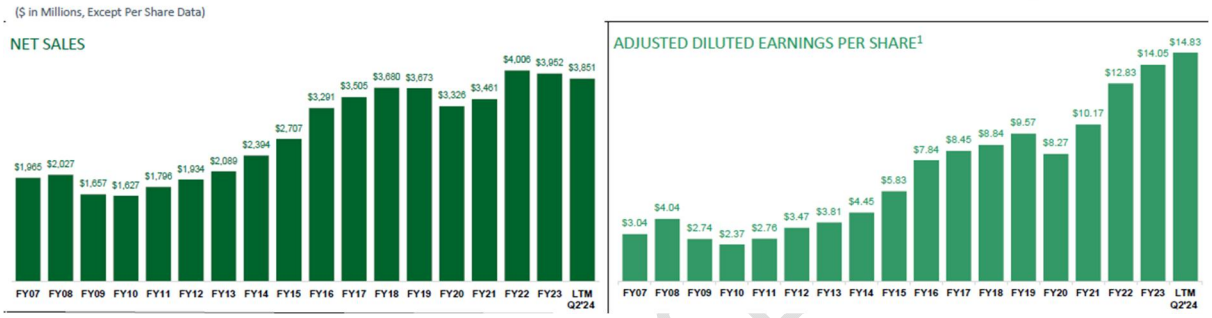
LED Lighting Products:

Let us first see what the latest company reports tell us about the leading lighting companies listed above in section 2.1.

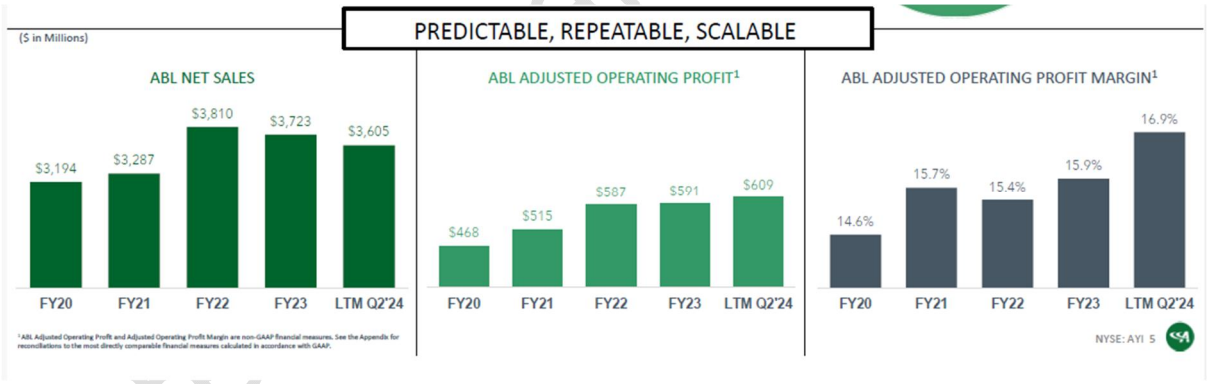
Signify remains by far the largest global company, despite shedding many of the businesses that it inherited from Philips Lighting. It is continuing to reorganize, focusing on lighting systems and solutions, rather than individual products. Revenues declined by 8% in 2023 to 6704M euros, representing about 10% of the global market, which is well under half the share held by Philips in the pre-LED era. Operating profits declined more substantially, weighed down by restructuring expenses of 167M euros. Three breakdowns of revenues are shown in the next chart. It is disappointing that the share coming from products and systems using LED sources is still only 85%.



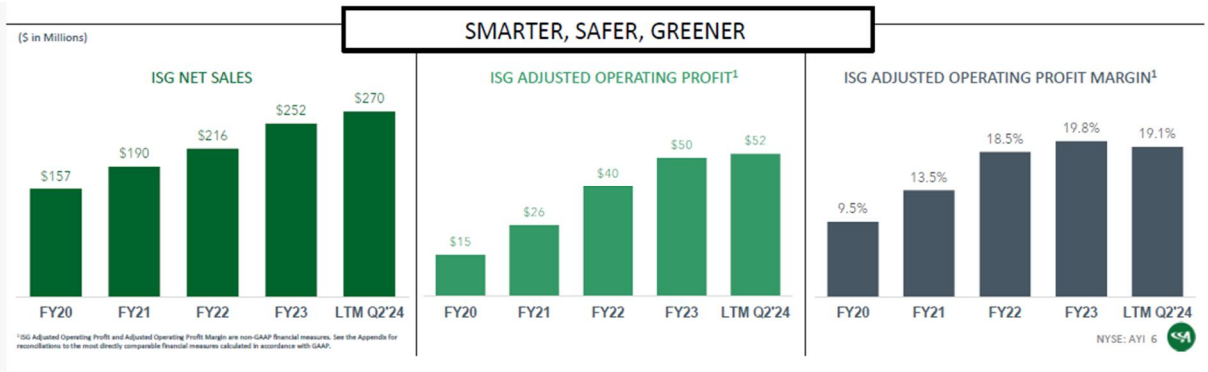
Over the past fifteen years Acuity Brands has grown substantially to become the largest lighting company in the US. Although revenues have changed little since 2018, profits have surged, as shown in the next chart.



The company has now separated into two business units, Acuity Brands Lighting and Lighting Controls (ABL) and Intelligent Spaces Group (ISG). Despite small declines in sales, ABL has continued to increase profitability over the past two years.



ISG offers building management solutions and building management software. The building management solutions include products for controlling heating, ventilation, air conditioning ("HVAC"); lighting; shades; refrigeration; and building access that deliver end-to-end optimization of those building systems. Both sales and profits have continued to grow in this unit.



The revenues of Acuity Brands come primarily from the US, but international sales are growing.

	2023	2022	2021
Net sales[1]:			
Domestic[2]	$ 3,412.9	$ 3,486.4	$ 2,982.4
International	539.3	519.7	478.6
Total	$ 3,952.2	$ 4,006.1	$ 3,461.0
Operating profit:			
Domestic[2]	$ 382.6	$ 428.3	$ 369.9
International	90.8	81.4	57.7
Total	$ 473.4	$ 509.7	$ 427.6

The dependence of ABL on imports from Asia is relatively low, as shown in the table below. The company manufacturers most of its products at eighteen manufacturing facilities, including six facilities in the United States, seven facilities in Mexico, two facilities in Europe, and three in Canada.

	Manufactured	Purchased	Total
United States	15 %	7 %	22 %
Mexico	57 %	— %	57 %
Asia	— %	15 %	15 %
Others	6 %	— %	6 %
Total	78 %	22 %	100 %

Although Panasonic and Toshiba remain among the top global lighting companies, they do not publish separate financial data for lighting business.

The continued growth of LEDVANCE means that MLS may have gained 3rd position in the top ten list. 2023 seems to have been a good year for MLS, with revenues rising to 17.5B yuan from 16.6B yuan in 2022. Operating profits recovered from a meagre 316M yuan in 2022 to 836M yuan in 2023 but are still below the 1784M yuan gained in 2021.

The next table summarizes the sales and profits of publicly-owned companies across the globe in 2023. The data on profits refers to operating income in most cases, rather than net income.

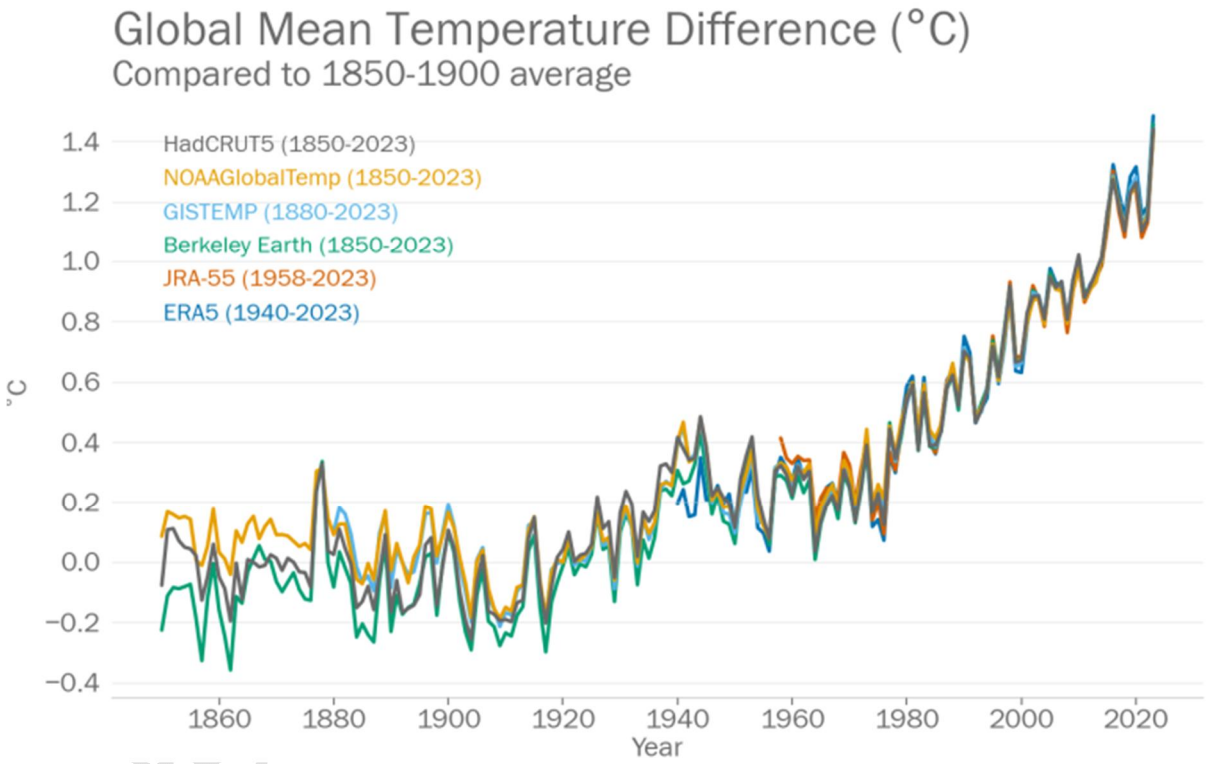
			2023	2022	Change	2023	2022	Change
Acuity	12	M US$	3851	3952	-2.6%	619	597	4%
Bajaj Elec	9	M Rs	7664	8196	-7%	565	651	-14%
Crompton Greaves	9	M Rs	7160	7660	-7%	800	700	14%
Dixon	9	M Rs	5900	7850	-25%	450	640	-30%
Fingerhult	12	M SEK	8435	8243	2%	901	833	8%
Foshan Elec	12	M yuan	9057	8760	3%	259	360	-29%
Havells	9	M Rs	11934	11882	0	1710	1714	0
MLS	12	M yuan	17536	16517	6%	836	316	165%
Nationstar	12	M yuan	3542	3580	-1%	17	46	17
Opple	9	M yuan	5514	5206	6%	614	417	47%
Signify	12	M euros	6704	7514	-8%	369	718	-49%
Surya Roshni	9	M Rs	11537	11135	3.6%	844	596	42%
Zhejiang Yankon	12	M yuan	3075	3731	-18%	215	184	17%
Zumtobel	6	M euros	574	628	-8.5%	40	50.8	-21%

3. Impact of Lighting on Greenhouse Gas Emissions

Through the adoption of LEDs, the lighting industry has made a substantial contribution to the mitigation of global warming. But more needs to be done.

3.1 Global Warming and Greenhouse Gas Emissions

Stocktaking made in 2023 by the United Nations Environmental Program (UNEP) showed that the total global effort to reduce emissions of greenhouse gases (GHG) is falling far short of what is needed to achieve the targets set in the Paris Agreement of 2015. The World Meteorological Organization (WMO) judged that 2023 was the hottest year on record and there seems to be no slowing in the rate of increase in the global mean temperature. The purpose of this section is to assess the contribution of lighting in reaching these goals and to urge the industry to maintain its concern about this important issue.



Global temperature rise persists (Source: WMO)

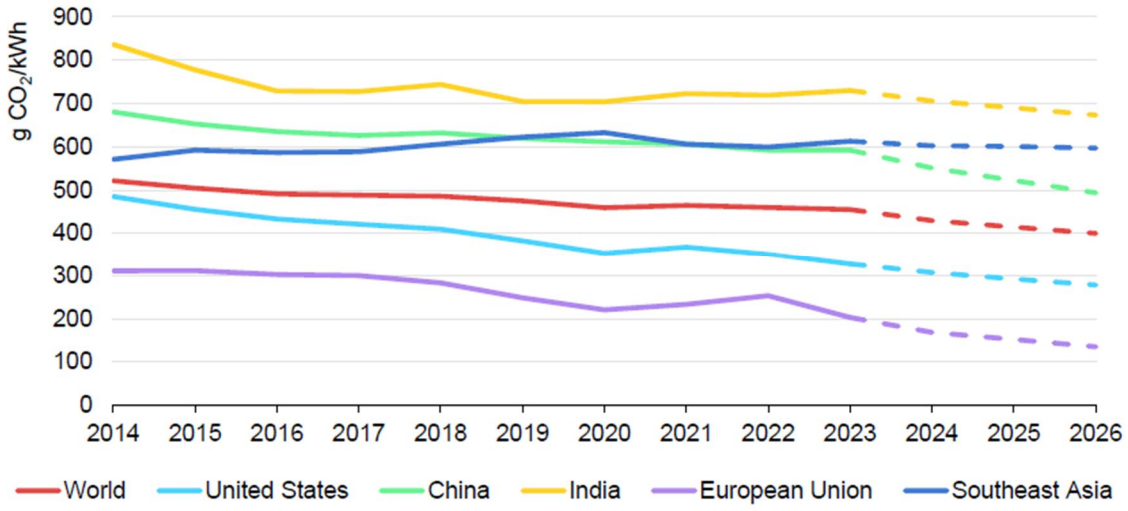
It is generally accepted that higher emission of greenhouse gases is the major cause of global warming. Total global GHG emissions rose from 47 gigatonnes (Gt) in 2005 to 57 Gt in 2022, with about two-thirds coming from energy production. According to UNEP, the total emissions need to be reduced to below 40 Gt by 2030 to meet the minimal goal of restricting mean temperature rise to less than 2%[3] .

The key to meeting the goals seems to be to increase the role of electricity in power generation and to reduce the burning of fossil fuels in electricity production. Through greater reliance on renewable energy sources, the electricity generation industry in North America and Europe has achieved

[3] https://www.unep.org/resources/emissions-gap-report-2023

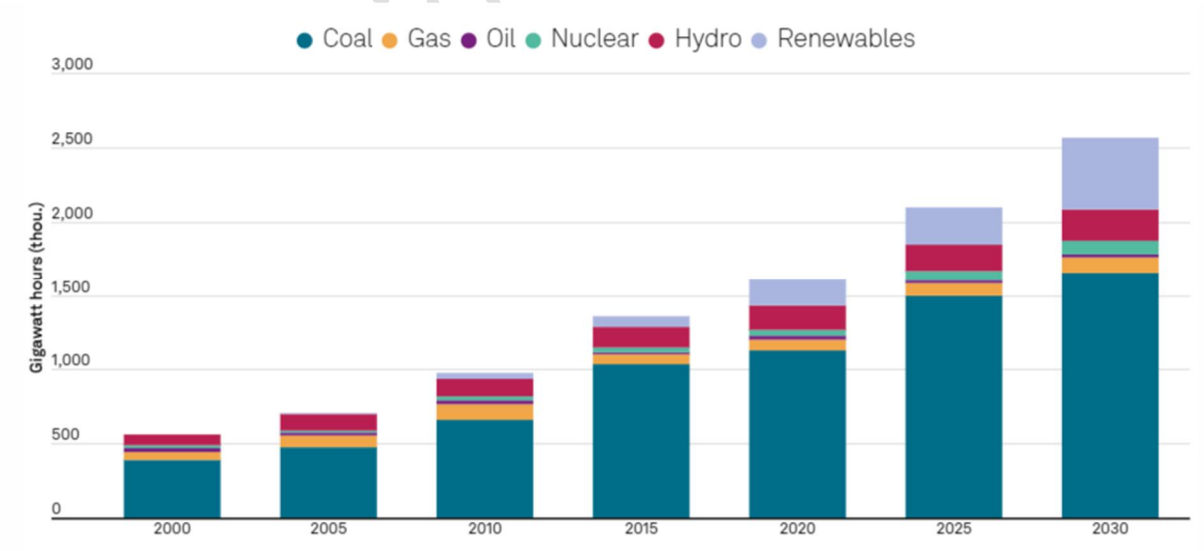
substantial reduction in GHG emissions. However, these gains have been offset by greater emissions in many countries within Asia.

The adoption of renewable sources of energy has led to a reduction in the average global emission of GHG for each kWh of electricity to less than 500 grams of CO_2. However, the value remains high for most developing countries, especially in Asia[4] .



CO_2 emission intensity from electricity generation (Source: IEA)

Coal-fired power remains the major source of supply in the Asia-Pacific region, accounting for 57% of electricity generation in 2023. This leads to other environmental concerns, in addition to global warming. The figure shows that the consumption of coal in India is expected to rise significantly in the next decade.



Electricity generation is driving the burning of coal in India (Source: S&P Global Commodity Insights)

[4] https://www.iea.org/reports/electricity-2024

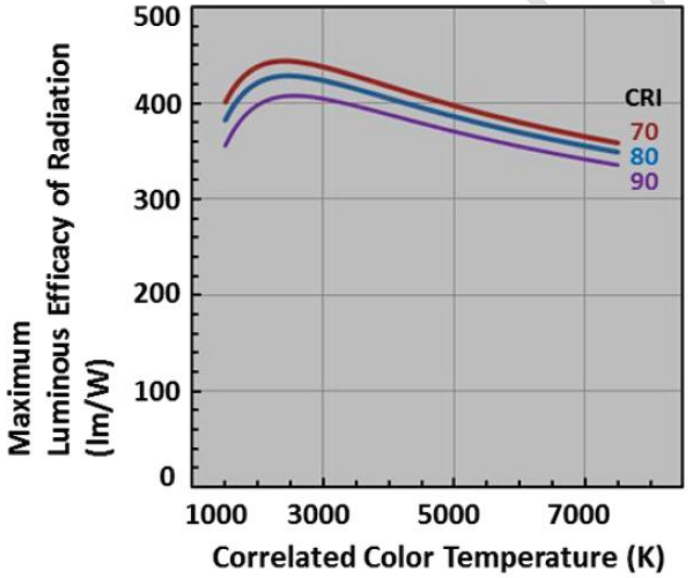
3.2 Lighting Contribution to GHG Emissions

The contribution of lighting to greenhouse gas emissions in 2005 was about 1900 megatons (Mt) of CO_2 per year[5]. The ISA estimates that this contribution is now around 1350 Mt, with 250 Mt in OECD countries, 600 Mt from China and 500 Mt from other developing economies The reduction has been enabled by the adoption of LEDs but has been achieved mainly by the greater use of renewable sources in electricity generation.

The data from the WMO shows that radical actions are needed to constrain the rise in mean global temperature to less than 2^0C. The lighting industry can continue to provide leadership by reducing electricity consumption to well below the 2005 level of 2650 lm/W. The remainder of this chapter summarises some of the ways that this can be done.

3.3 Lighting Efficacy

Although LEDs now offer efficiency far superior to that of traditional sources, much more can be achieved. The theoretical limit for the production of while light is around 400lm/W for a wide range of Colour Rendering Index (CRI) and Correlated Colour Temperature (CCT). Some losses are unavoidable and the target of the US DOE for 2050 is 320lm/W. Reaching this goal will require the mixing of LEDs of different colours, rather than phosphor-converted blue LEDs.



Maximum efficacy for white light (Source: Jeff Tsao)

3.4 Lamp Manufacture and Distribution

In order to reduce costs, most lamps on the market today use LEDs that are far from the best available. For example, recent data from the European Product Registry for Energy Labelling (EPREL) shows that around two-thirds of the General Service Lamps (GSL) now on sale have efficacy less than 110lm/W.

Although the bans on □uorescent lamps will eliminate many inefficient lights, the industry is missing an opportunity to enable a significant rise in the average efficacy of the installed base. The EPREL data confirms that LED tubes are available with efficacy greater than 160lm/W and the on-line vendor 1000 Bulbs shows that these can be purchased in the U.S. at prices less than $2 per klm. But

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

65% of the LED tubes listed in the EPREL database in March 2024 and almost all tubes offered by major hardware stores in the US have efficacy less than 135 lm/W. Most of these products have operating lifetimes of 35,000 hours or more and so may remain in operation for decades. Innovative manufacturing methods are needed to reduce the cost of producing good quality lamps and lighting systems. In addition, distributors and retailers need to pay more attention to the efficacy of the products they offer and to promoting the benefits of lower energy consumption for both the user and the environment.

3.5 Incentives and Regulations

A wide range of means have been devised across the globe to encourage the use of more efficient lights. For example, the DesignLights Consortium (DLC) provides guidelines and a product database for U. S. utilities that offer rebates for purchases that will help to reduce electricity demand. The EPREL labelling system clearly induced manufacturers to introduce products that meet the highest standards, although some of these products are relatively expensive. The overall effect of the EPREL program is illustrated in the table below. The distribution (%) between the seven efficiency classes is shown for products on the market in April 2022 and February 2024. The last column shows those added since October 2023. Although the recent entries show a substantial increase in the top three classes, most products on the market are still in the bottom two.

Class	Mains Efficacy	Product Distribution (%)		
	lm/W	April 2022	February 2024	Last 5 months
A	over 210	0.07	0.6	2.4
B	185-210	0.51	1.4	4
C	160-185	3.2	5.9	8.3
D	135-160	8.9	13.1	13.2
E	110-135	23.1	23.6	26.4
F	85-110	43.2	35.6	30.4
G	below 85	19.7	19.5	15.7

There is an urgent need for a comprehensive labelling system for the efficiency of lights in the US. Certification by the Energy Star program is almost meaningless, since more than 93% of the approved lamps have efficacy below 110lm/W and so would fall in the lowest two classes of the EPREL scale. The program is not used for suppliers of LED tubes and specification of the electricity consumption or the light output is missing from some packages on store shelves.

3.6 LED Adoption in Developing Countries

Valuable support for the adoption of LEDs in developing countries has been provided by international organizations such as CLASP, the IEA 4E SSL Annex, UNEP and the ISA. This support should be continued, perhaps together with additional help from the Global Lighting Alliance and the IEEE Smart Lighting initiative. However, much of the responsibility lies with the national and local governments, who could follow the example of the authorities in China.

Much of the early adoption has been enabled by the availability of affordable LED products from China, which have been heavily subsidized by the Chinese governments. However, countries such as India, Indonesia and Thailand are building the facilities and infrastructure needed for substantial local manufacturing. For example, India has launched a production-linked incentive (PLI) initiative to boost the value of local addition to imported chips and packages from 25% to 85% by 2028.

4 Smart Lighting

Smart lighting has become a mantra for many in the lighting community. There are many ways to improve the efficiency with which the light produced by LEDs is delivered. Greater control over light distribution can enable the desired illumination levels to be met with less total light. This is especially true for outdoor lighting. Schemes to adapt to daylighting, room occupancy, circadian rhythms and personal preferences have been promoted for years, but successful implementation has proved to be challenging. The problems are most severe for connected lighting with networked controls.

The Institute of Electrical and Electronics Engineers (IEEE) has recently initiated a Smart Lighting program, led by Professor Georges Zissis of the University of Toulouse. Georges has been appointed to the ISA Board of Advisors and is helping to plan joint activities between the two organizations.

The IEA SSL Annex has issued two reports on Smart Lighting through its Task 7 Working Group, which was formed to address new features enabled by LEDs,. The second report, issued in November 2022, begins with a short history of the concept.

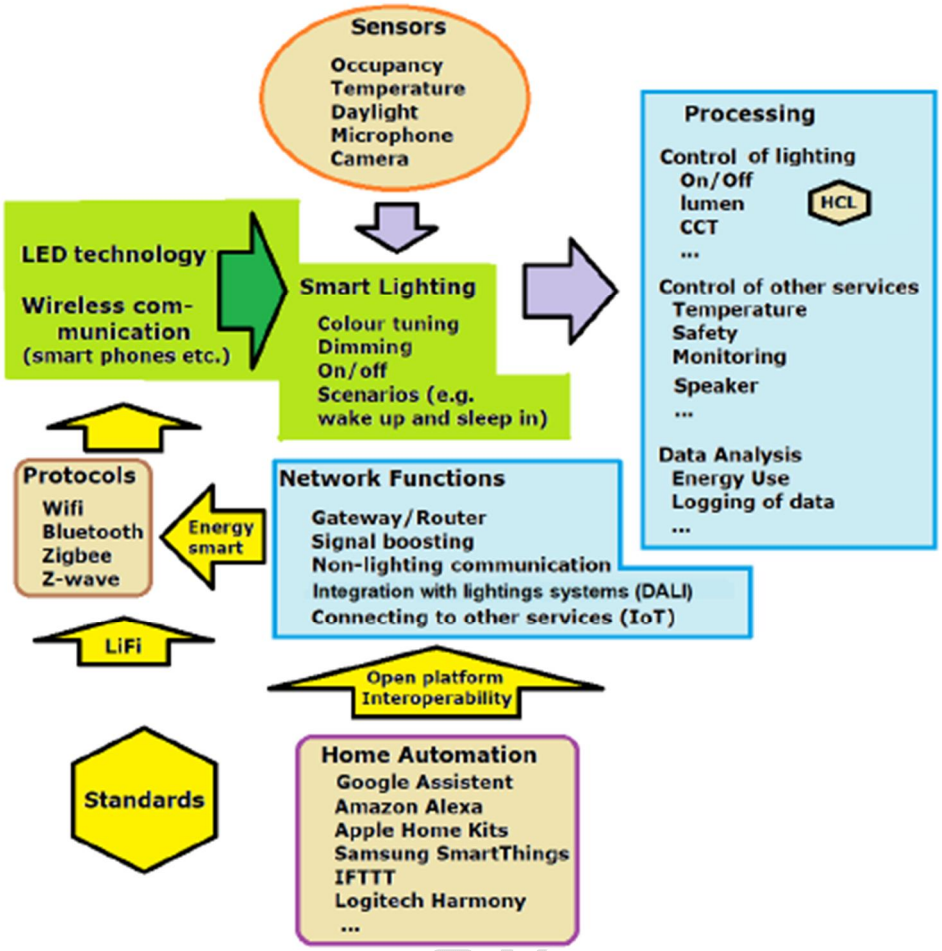
Smart lighting developed following the rapid improvements in both wireless communication and LED lighting. Smart lighting started with key functions such as colour tuning, dimming and scheduling when brightness and colour changes over time. Later, as shown the figure below, features were added including:

• Control by activation sensors (e.g. occupancy, sound, daylighting, camera …);

• Processing (lighting control, control of other services (e.g. speaker) plus data logging, analysis and reporting); and

• Network functions e.g. WiFi boosting, integrating with other services (IoT) and wired lighting systems (DALI), and integration in home automation systems.

Their vision of smart lighting is illustrated in the next figure.



Smart lighting has developed from the basic functions (green boxes) to be able to include many more features.

In this report we will not discuss the opportunities to use lighting fixtures to provide other services, as are possible in many designs of 'smart homes' and 'smart cities', but will just focus on the impact on illumination.

Mark Lien of the Illuminating Engineering Society provided a short description of the essence of smart lighting.

"A smart lighting system produces, at any moment, the right light: where it is needed and when it is necessary. It should adapt the quantity and quality of light to enhance visual performance in agreement with the type of executed tasks. It must guarantee the well-being, health and safety of the end users. It should not passively squander the resources of our planet. Instead, it should actively limit the effects of light pollution on the biotope or any other impacts on the environment."

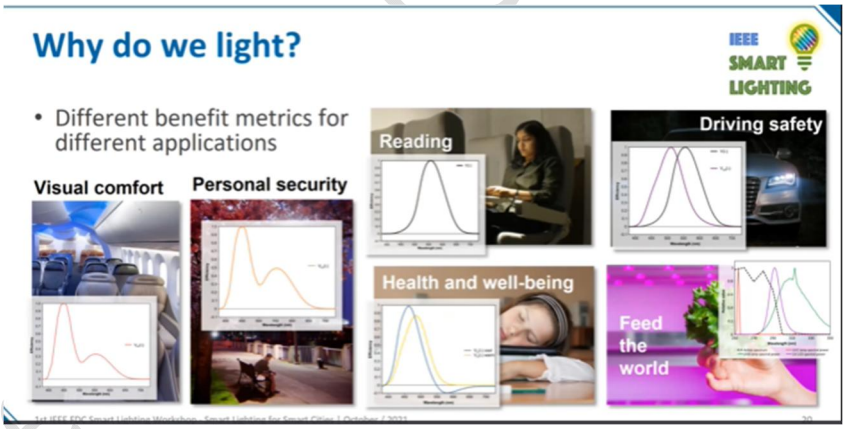
Our review of the status of smart lighting will distinguish between three aspects:

- Knowledge of the optimal illumination at any time and location.
- The availability of lights that can produce the desired illumination.
- Control of the lights to meet changing needs.

4.1 The Optimal Illumination for the Situation

The flexibility of LED lighting systems in terms of spectrum, intensity, location and directionality calls for in-depth analysis of the optimum illumination to support any activity in a given location. Mark Rea, from the Light and Health Research Center at Mount Sinai Hospital in New York, has suggested that the best place to start is not new features of the technology, but the potential benefits.

At the IEEE Smart Lighting Workshop in 2021[6], Mark pointed out that the choice of metric is important, since the optimum spectrum varies for each application.



The lumen and lux are by far the most common measures of intensity, since they based upon human perception, and may be best for many activities. But when the impact on circadian rhythms is important as well as productivity, the use of 'melanopic equivalent daylight illuminance' (M-EDI) may be more appropriate[7].

The eyes of animals are clearly different from those of humans. Special metrics are being developed for poultry[8], dairy cows[9], and animals in zoos[10] or used in laboratory research[11]. Some of the analyses recommend dynamic procedures to support the animal's circadian rhythms.

[6] A video of Mark's presentation can be accessed from https://www.linkedin.com/events/6838908678381322243/
[7] https://lucasgroup.lab.manchester.ac.uk/measuringmelanopicilluminance/
[8] https://www.layer-resources.com/en/articles/insight-light/
[9] https://stud.epsilon.slu.se/14206/7/Lindkvist_S_190125.pdf
[10] https://www.lpzoo.org/science-project/measuring-the-impact-of-light-and-sound-on-animal-welfare/
[11] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10931507/

The response of plants to light has little connection to human vision and has been summarized by Erik Runkle of Michigan State University:

"There is no single optimum light spectrum for plant growth. The best spectrum will vary based on different growth situations and the plant qualities desired by the cultivator. Often it is desirable to induce early flowering in plants to reduce production time. This can be achieved using far red in the spectrum. Adding blue light to the spectrum can promote compact plant growth, which is also desirable. However, these responses may vary for different species. In leafy greens, increased blue light resulted in decreased shoot mass, but it can bring out color or other desirable qualities. A balance must be found. Far-red light interacts with other wavelength ranges, especially blue light. The timing of different light spectra with respect to plant growth phase is an additional consideration. Light interacts with other environmental conditions. There may be trade-offs between biomass yield and quality attributes or other plant properties, such as desirably colored leaves."

Since the reception of the human eye has no relevance for plants, the use of lumens or lux as a metric is of little value. The standard approach is to specify the number of emitted photons in micro-moles (µmoles), which correspond to 6.02×10^{17} photons. Although it is useful to know the photosynthetic photon flux (PPF) as a function of wavelength, specifications often just give the total flux over the range 400-700nm under the name photosynthetic active radiation (PAR). This practice does not take into account radiation at higher wavelengths which may be significant for some plants. The efficacy of a horticultural light is expressed in µmole/J. The maximum value varies linearly with wavelength, from 3.3 µmole/J at 400nm to 5.8 µmole/J at 700nm.

There has been considerable controversy about the best spectrum for streetlights, usually concerning the colour temperature. Many environmental and astronomical groups say street lighting should be no more than 3000K, since evidence shows lights with a higher CT may disrupt the circadian rhythms of animals and increase skyglow. On the other hand, studies at Virginia Tech Transportation Institute concluded that 4000K and 5000K LED light sources had consistently longer detection and colour recognition distances across all colours of targets. They also noted that colour contrast plays an important role in the visual performance of drivers. In Australia the IPWEA SLSC Model Public Lighting Strategy aims to balance the different viewpoints, by recommending 3000K lights for parks and most residential roads, and 4000K lights for main roads.

Temporal changes of spectral intensity are an important characteristic of almost all applications of smart lighting, except perhaps for emergency lights. Artificial light should be used as a complement to daylight, not as a replacement. The optimal light intensity in specific indoor or outdoor locations usually varies with the number of occupants and their activities. The benefits of stroboscopic lighting are less clear and limited to special applications. This aspect is discussed in more detail below, in the section on controls.

The spatial distribution of illumination is also essential to smart lighting. This provides a 3-dimensional challenge, not just limited to specification of the horizontal and vertical illuminance. The third dimension can be especially important in horticultural applications, since shading may prevent the penetration of light to the whole plant in the later stages of growth.

Much of the discussion of spatial distribution concerns the uniformity of illumination within the lit areas and the avoidance of stray light. Mitigation of shadowing can be a worthy objective, but spatial contrast within illuminated areas is often just as important as intensity in aiding visual

perception. This is clearly recognized in some applications, such as displays, stage lighting and automotive headlights, but deserves more attention in many other areas.

4.2 Sources of Light

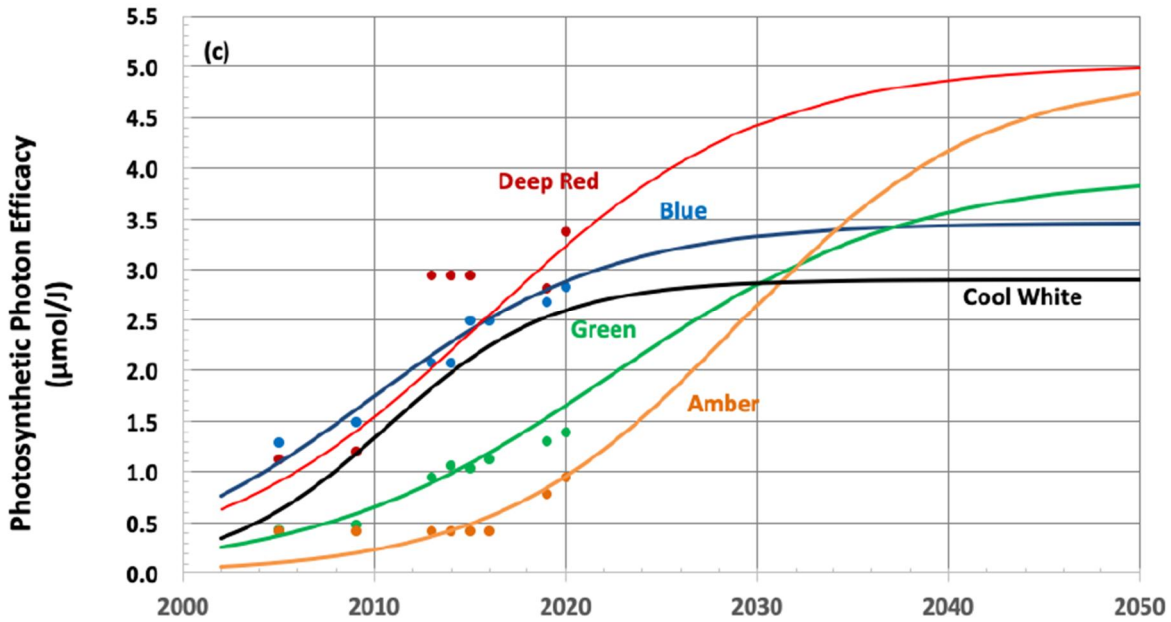
The second major component of Smart Lighting is a portfolio of light sources that can efficiently deliver the optimum illumination at an affordable price. Although significant development has been made in the development of LEDs, much more needs to be done.

Spectrum:

One way to assess the status of narrow band (monochromatic) LED sources is by looking at specific applications, such as horticulture and UV disinfection. The table below shows the status of single-color sources for horticulture in 2021, as presented by Morgan Pattison at the 2021 ISA Annual Meeting.

LED	λ or CCT	Efficiency (W•W-1)	Photon Efficacy (µmol/J)
Blue	450nm	74%	2.8
Red	660nm	73%	4
Far-Red	730nm	55%	3.3
Cool White	6500K/70	73%	2.9
Warm White	3000K/80	70%	2.8

The next chart shows that great progress has been made in red and blue, while more research is needed for amber and green.

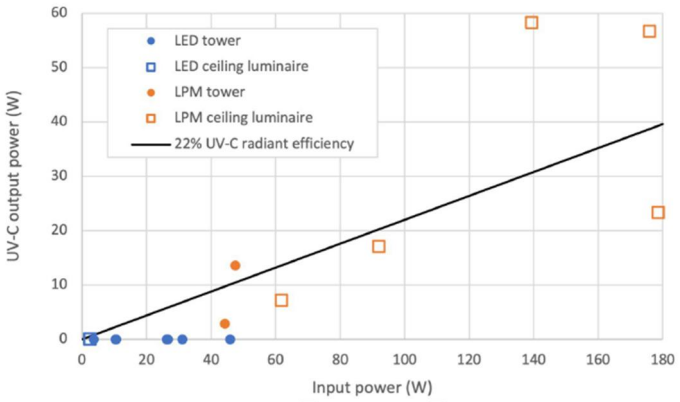


These data are shown for a reference current density of 350mA/mm^2. Higher efficiencies can be obtained by running at lower current density, but this may lead to a higher cost for each photon

produced. A paper discussing the variation of efficacy with current, and many other aspects of LED was published in the journal Horticulture Research[12].

To the best of our knowledge, the progress since 2021 has been only modest. For example, the new OSLON Square Hyper Red LED has a wall-plug efficiency of 76% at 660nm, up from 74% in the previous model.

The onset of the pandemic has enhanced the interest in the use of UV-C LEDs with wavelengths between 220nm and 290nm for disinfection. The next figure shows a comparison of the efficiency of systems using LED and low-pressure mercury (LPM) sources in a recent experiment carried out at the Pacific Northwest National Laboratory for the US DOE[13].



The efficiency of almost all LED sources that are available commercially remain below 10%. Some examples taken from company websites in April 2024 are shown in the next table.

Company	Model	Wavelength	Output	Input	WPE
		nm	mW	mW	%
AMS-Osram	CZHEF1.VC	265	100	1750	5.7
Nichia	NCSU434C	280	110	2030	5.4
Seoul Viosys	CUD7GF1B	275	16	610	2.6
Violumas	VS5252C48L3	275	87	4620	1.9

Perhaps manufacturers of disinfection systems based upon LPM sources will be able to argue for exemptions from bans on mercury use for several more years. Although LED systems have many advantages offsetting their low efficiency, more research will be needed before they can gain market dominance.

The availability of LEDs spanning the whole wavelength range from 200nm to 850nm will make it possible to design systems that can produce any desired spectrum at any given time. Perhaps the best examples of dynamic colour systems are in OLED TVs. Each pixel contains three or four sub-pixels with wavelengths chosen to span a large colour gamut. Circuits are printed to control the emission intensity from each sub-pixel and the whole device can be manufactured for around 0.01 US cents per pixel. Luminaires with programmable spectra are already available. For example, the

[12] https://www.nature.com/articles/s41438-020-0283-7
[13] https://www.energy.gov/sites/default/files/2023-09/ssl_caliper-guv-rd1-full.pdf

Dittosizer Light Player from Telelumen offers dynamic illumination with 24 channels of continuous spectrum, from UVA through visible to NIR[14].

Spatial Distribution:

Control over the spatial distribution is essential to smart lighting, both to achieve optimal illumination over the areas that need to be lit and to minimize stray light. Concern about light pollution has been growing. For example, in a July 2023 report from the UK on light and noise pollution, the House of Lords Science and Technology Committee noted that "light and noise pollution are currently neglected pollutants, but research indicates that they are causing significant health impact and they are of growing concern to the public."

The compact size of LEDs and the wide angular emission means that one needs to reexamine assumptions about the placement of the sources as well as the beam shape of the emitted light. For example, in horticultural applications the small size and low heat production of LEDs means that they can be placed close to the growing plants. Control of the 3-D spatial distribution of illumination in indoor farming was discussed in a recent article from Purdue University[15]. To avoid shadowing and allow for the changing plant size, they argue that close-canopy lighting can be an effective energy-saving strategy to complement overhead LED lights.

The importance of optimizing both the position of LED luminaires and the angular distribution of emitted light was illustrated in recent article by Don Peifer on the "Sparkle" luminaire system to replace arrays of linear fluorescent tubes[16]. Don writes "By designing around the strengths of solid-state lighting technology instead of the previous technology, we can realize breakthroughs in spacing criteria and application efficiency, thereby reducing lighting power density. This allows us to employ fewer luminaires, equating to less material used and wasted".

As shown in the following table, more uniform illumination levels can be created with fewer luminaires leading to substantial savings in power consumption.

TABLE 2. Ideal distribution vs. best-of-class linear LED and fluorescent linear.

	Work plane (fc)				Ceiling (fc)					
Product	Ave E	Max E	Min E	Ave:Min	Ave E	Max E	Min E	Ave:Min	No. of fixtures	W/ft²
Fluorescent	77	164	23	3.4	64	246	15	4.4	39	1.2
LED	40	62	19	2.1	36	88	9	4.0	52	0.4
Sparkle	24	58	11	2.2	17	23	6	2.7	16	0.16

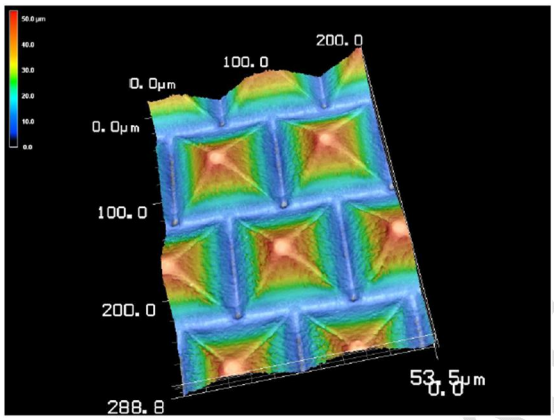
To enable custom implementations of the design, the Sparkle approach makes full use of 3-D printing.

The development of thin-film micro-lens arrays and free-form micro-optics has accelerated over the past few years. Some of the most recent products were demonstrated at CES in Las Vegas and at Light and Build in Frankfurt and were highlighted in the 2024 issues of LED Professional Review.

Microlens arrays (MLA) have been used for many years in display applications but are now being deployed in other areas. Jennifer Aspell, CEO of Brightview described how a small U. S. company has

[14] https://telelumen.com/products/
[15] https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1215919/full
[16] https://www.ledsmagazine.com/manufacturing-services-testing/article/14303557/emerging-technology-leveraging-led-and-3d-printing-technology-for-a-sustainable-ssl-paradigm-part-i

been able to grow substantially since 2018 by developing MLAs for a wide range of applications, including display, automotive, AR/VR and 3D sensing while maintaining their foundation in LED lighting. Brightview uses grey-scale photolithography to create MLAs that combine multiple functions, such as splitting and tilting the light, into a single component. Typical feature sizes are shown in the figure below.



These microstructures can be on anything from PET and PC to glass in very large formats – as large as 12 square feet. New designs can move through prototyping to mass production in days, rather than months, and so can be part of a local infrastructure to respond quickly to customer demands.

In Europe, the EU-funded PHABULOuS project was set up in 2020 to create a European pilot line for accelerating the manufacture of free-form micro-optics from prototypes to piloting and large volume production. "PHABULOuS specializes in producing free-form micro-optical components to enhance light forming efficiency and optimize compactness. The benefits of free-form micro-optics in lighting technology include improved efficiency, colour mixing, customizable light direction, and global lighting uniformity—all while prioritizing compactness. A key aim of the project was to implement six industrial use-cases that could demonstrate pilot manufacturing FMLAs in an operational environment, namely, AR, lenses for VR/AR headsets, automotive functional lighting, transportation lighting, luxury facades and for general illumination of a LED-Downlight.

As part of this program, IQS NANOPTIQS has launched the IQ System, which they claim to be the first nanotechnology lighting optics to be delivered as a modular kit. IQ System enables lighting manufacturers and designers to design and produce luminaires that are much slimmer, save material and energy, and provide precisely controlled light distribution for a wide variety of applications. The IQ System differs from existing optical modular systems in that it is based on optical nanotechnology. The products consist of three components, each with a specific function:

- A reflector for primary light shaping and control.
- An antiglare cover for enhanced visual comfort and a low UGR rating.
- Nanofilm at its core enabling it to achieve supreme optical precision and desired light distribution.

Other outcomes of the PHABULOuS pilot lines have been described in short Expert Talks from LpS Digital. Katharina Keller from Zumtobel discusses applications to general lighting[17], while Daniela Karthaus of Forvia Hella focuses on automotive lighting[18].

[17] https://www.youtube.com/watch?v=MS19W269_-k
[18] https://www.youtube.com/watch?v=yD2-wnWhcvA

4.3 Control Systems

It has been argued for many years that the implementation of lighting controls can add significantly to the energy savings that accrue with the adoption of LEDs. This is true in many cases, but the expected overall impact on power consumption has been disappointing so far. Many of the issues have been studied in depth by the IEA SSL Annex, the DesignLights Consortium (DLC) and the Pacific Northwest National Laboratory (PNNL).

A series of cost-benefit analyses of indoor lighting controls were published in the US in 2018. Five Field evaluations in five buildings with very different uses were conducted in the northeastern US by Pacific Northwest National Laboratory (PNNL) and DLC for U.S. DOE, between November 2015 and September 2017[19]. The equipment purchases, that were made with the help of rebates from the local utility company, enabled occupancy sensing, daylight sensing and task tuning. The next table shows the estimated savings from each modification.

Site	FL to LED Only	Task Tuning	Occupancy Control	Daylighting Control	Total: LED with All Controls	Notes
1 – Brewery	50%	(a)	10%	6%	66%	
2 – Office	64%	(b)	-2%	5%	67%	Pre-retrofit occupancy sensors
3 – Medical Office	29%	6%(c)	20%	7%	62%	
4 – Retail/Grocery	30%	33%	3%	~	66%	
5 – Office	43%	24%	-1%	4%	70%	Pre-retrofit occupancy sensors

The cost of installation per sq.ft. varied between $1.54 in the brewery to $7.99 in the retail store. The cost of electricity was between $0.12/kWh and $0.15/kWh. The following table shows the simple payback period (SBP) and savings to investment ratio (SIR), calculated both with and without the rebate.

Site Cost Effectiveness – Savings, Simple Payback, and Savings-to-Investment Ratio

Site	Annual Energy Savings		Product Life	SPB/SIR without Rebate		SPB/SIR with Rebate	
	(kWh)	$	Years	SPB (years)	SIR	SPB (years)	SIR
1 - Brewery	95,000	$13,800	20.0	11.5	1.74	6.9	2.90
2 – Office	39,500	$4,700	20.0	23.6	0.85	14.9	1.34
3- Medical Office	69,000	$8,200	20.0	11.3	1.77	6.7	3.01
4 – Retail/Grocery	439,300	$65,985	20.0	8.8	2.26	7.4	2.69
5 - Office	34,600	$5,190	20.0	22.5	0.89	13.0	1.54

PNNL also conducted an analysis of LED installation with controls in a Federal office in Fort Worth,

[19]https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/PNNL_Evaluation_Advanced_Lighting_Controls_11-2018.pdf

Texas[20]. The offices were divided into five zones, each with equipment from a different supplier. The installation costs and energy savings are summarized in the next table.

	Annual Savings				Installed Cost			Simple Payback Period		SIR (20-year life)	
	LED Annual EUI Savings	Control Annual EUI Savings	LED + Control Annual Savings $0.07 / kWh ($/ft²)	LED + Control Annual Savings $0.11 / kWh ($/ft²)	Area per Fixture (ft²/fixture)	Actual LED + Controls Installed Cost ($/ft²)	Est. LED + Controls Installed Cost ($/ft²)	SPB Actual $0.07 / kWh	SPB Est. $0.11 / kWh	SIR Actual $0.07 / kWh	SIR Est. $0.11 / kWh
Zone 3	0.63	1.07	$0.12	$0.19	73	$5.68	$4.48	48	38	0.42	0.53
Zone 4	1.34	0.44	$0.12	$0.20	106	$4.33	$3.08	35	25	0.58	0.81
Zone 5	1.98	1.16	$0.22	$0.35	94	$5.69	$3.48	26	16	0.77	1.26
Zone 6	1.04	0.93	$0.14	$0.22	60	$5.33	$5.45	39	40	0.52	0.51
Zone 7 (Mezz.)	3.67	0.42	$0.29	$0.45	63	$6.26	$3.05	33	16	0.60	1.23
Total Site	1.59	0.82	$0.17	$0.27	---	$5.46	$3.91	36	27	0.58	0.87

The electricity rate of $0.07 was typical for Texas at that time, while $0.11/kWh was closer to the national average. The rate is now considerably higher in many parts of the US and Europe, but installation costs have also risen.

More recently PNNL has participated in a program to evaluate the potential savings from the integration of lighting, HVAC and plug control systems. The results were summarised by Michael Myer at a DOE SSL Workshop in 2022[21]. In 4 of the 5 case studies, the payback period for lighting upgrades was reduced, by amounts varying from 30% to 80%.

A detailed study of the energy savings from networked lighting controls was published by the Northwest Energy Efficiency Alliance (NEEA) and the DLC in 2020. Their results were presented in terms of a control factor, which measures the fraction of energy that can be saved by the use of controls. The values for various types of building are summarized in the next table.

Building Type	Total Buildings	Unique Manufacturers	Control Factor* (% Savings)			
			Average	25th–75th Percentile**	High-End Trim Contributions	Other Control Strategies
Assembly	6	2	0.28	0.11 - 0.45	0.07	0.23
Education	14	5	0.41	0.19 - 0.58	0.19	0.32
Healthcare	2	1	0.52	0.48 - 0.56	0.33	0.24
Manufacturing	73	4	0.40	0.20 - 0.55	0.16	0.29
Office	57	8	0.64	0.53 - 0.81	0.46	0.36
Restaurant	3	2	0.59	0.47 - 0.68	0.27	0.30
Retail	29	1	0.44	0.39 - 0.48	0.22	0.27
Warehouse	10	2	0.68	0.53 - 0.79	0.38	0.48
Overall	194	12	0.49	0.35 - 0.69	0.27	0.32

Based on these studies, the US General Services Agency (GSA) published a document in December 2023 entitled "LED Lighting and Controls Guidance for Federal Buildings"[22] that should be relevant to

[20]https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/PNNL_Evaluation_Advanced_Lighting_Controls_11-2018.pdf

[21] https://www.energy.gov/sites/default/files/2022-03/ssl-rd22-myer-integration.pdf

[22] https://www.gsa.gov/system/files/LED%20and%20Controls%20Guidance%20for%20GSA%2012-06-23.pdf

many other commercial buildings. A slide presentation from a webcast describing the report is available on the web[23].

Network Communication Systems:

The success of many smart lighting systems will depend on the availability of inexpensive, reliable, rugged network communications that can be installed and maintained by electricians with only modest training and experience. Progress has been hindered by the proliferation of incompatible systems. The development of standard protocols would be very helpful. This table from the IEA SSL Annex summarizes some of the efforts that are underway.

		Protocol					
Characteristics		WiFi	LiFi	Bluetooth	Zigbee	Z-wave	6LoWPAN
Communication Media		Radio	High-frequency LED light Modulation (at a speed the human eye can't detect)	Short-wave-length UHF Radio 2.4 – 2485 GHz	Radio	sub-gigahertz frequency Radio around 900 MHz	Internet Low power Wire-less Personal Area Networks
Network	***Star***	X	X	X			
	Mesh				X	X	X
Data Rate (speed)	***High***	X	X	X			
	Low				X	X	X
Operating Range Distance	***Long***	X	X				
	Short			X	X	X	X
Power Consumption	***High***	X	X				
	Medium			X			
	Low			X	X	X	X
Reference/Standard		IEEE 802.11	IEEE 802.11	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.4

4.4 Adoption of Smart Lighting

Globally, the IEA SSL Annex has estimated that the market share of smart lighting technology is only 5-10%, but notes there is significant potential for higher levels of market penetration. Under the COVID 19 pandemic, many people worked from home and suppliers indicated that this gave a boost in the sales of smart lighting products. That sales boost has slowed now that the situation is returning to normal. Signify is proud to announce that their systems have connected more than 100M light points, but this is far less than 1% of the global base.

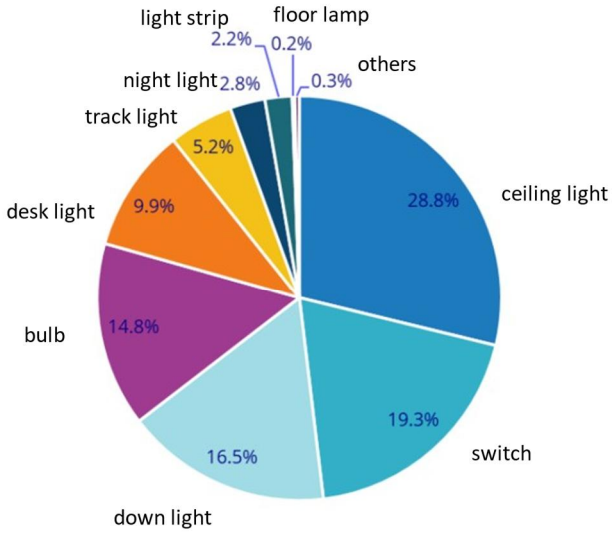
In 2019 the US DOE estimated that less than 1% of luminaires in the US were connected to control networks. They attributed the low adoption rate to their complex configuration, high cost, limited interoperability, and the availability of people who know how to efficiently design, install, commission, and operate them.

In evaluating network controls, it is important to perform a thorough cost-benefit analysis. In China, Liu Jiwu of Jiujiuhua Intelligence has warned that "providing intelligent lighting control systems has hidden service costs, whether it is pre-sales solutions, in-sales debugging, and after-sales maintenance.[24]"

According to IDC data, China's smart lighting market shipments are forecast to exceed 33 million units in 2023, with a year-on-year growth rate of over 20%. Among them, smart downlights and spotlights will become an important product component of China's smart lighting market, with a shipment share of approximately 16.5%. Smart track lights have entered a rapid development

[23] https://www.gsa.gov/system/files/31-LED%20Lighting%20and%20Controls%20Guidance%20for%20Federal%20Buildings-02-08-24.pdf
[24] https://www.alighting.cn/news/20240202/175875.htm

channel, and the growth rate of shipments is much higher than the average level of the smart lighting market.

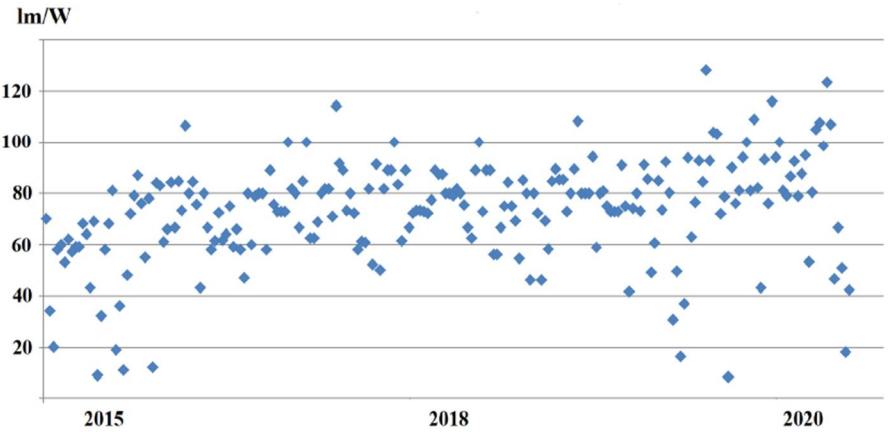


Market share forecast of China's smart home product shipments by category (2023)

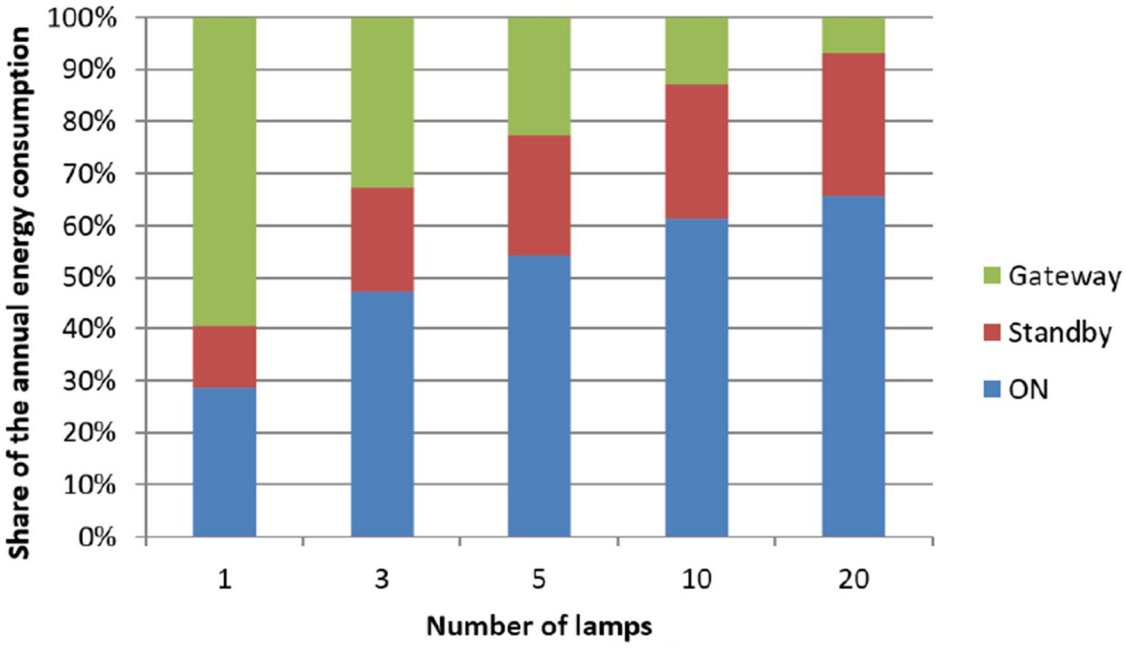
4.5 Lessons Learned

Many of the lessons learned in installing smart lighting systems have come from the operation of sensors or network communications, but a full discussion of these is outside the scope of this review. The impact on energy consumption was discussed in the 2022 report by the IEA 4E SSL Annex. Among the disturbing findings from a study of 224 smart lamps and luminaires were

- The average efficacy was only 73 lm/W, which was 10 lm/W less than that for non-smart lamps in the US Energy Star data base in the same period. The next figure shows the measured efficacy for 224 smart lighting products in the SSL Annex database



- In networked systems, the gateway and the stand-by power contributed between 33% and 70% of the total energy consumption, as shown in the chart below.



- In one-quarter of the tested products, dimming to 25% of full power led to a reduction of efficacy by as much as 74%.

4.6 The Way Forward

Because of the complexity of effective connected lighting systems and the importance of a realistic cost-benefit analysis, it is good to have access to impartial information to supplement that offered by vendors. There are at least two associations in the US that may be helpful.

The Lighting Controls Association (LCA), a council of the National Electrical Manufacturers Association (NEMA), is dedicated to educating the professional building design, construction, and management communities about lighting control technology, application, and benefits. It offers articles, videos and a trouble-shooting guide. In one of the articles on their website, Steve Mesh discusses the level of complexity that is beneficial and the extent of training that is needed for successful installations[25].

The DesignLights Consortium has created a networked lighting controls program and Qualified Products List. Alongside the QPL, their suite of resources and trainings help ensure that contractors and installers have the information they need to successfully implement this critical technology at scale. One of their resources is an on-line training course[26].

The state of California has been pioneering the development of standards and regulations to promote energy efficiency in many areas including lighting under "Title 24". Their requirements often are stressful for designers and installers and several users have published guides to help navigate them [27],[28].

[25] https://lightingcontrolsassociation.org/2024/01/24/steve-mesh-talks-nlc-complexity/
[26] https://www.designlights.org/wp-content/uploads/2021/01/Online-NLC-Training-Trade-Ally-One-Pager.pdf
[27] https://lumoscontrols.com/resources/title-24-lighting-requirements-all-you-need-to-know/
[28] https://www.stouchlighting.com/blog/what-are-title-24-requirements-for-lighting

Some other local authorities provide guidance as well as restrictions on NCLs. For example, the city of Seattle has prepared a helpful NLC Toolkit[29].

National and local governments in other countries are also developing standards and regulations on networked lighting. Readers are encouraged to share information on these, especially regarding helpful guides to help explain the local requirements.

[29] https://www.seattle.gov/documents/Departments/CityLight/LightingControlToolkit.pdf