International Solid-State Lighting Alliance

SSL Industry Report 2025

Editor: J. Norman Bardsley

Contents

1. Introduction

2024 was a transition year for the lighting industry. Over the past 20 years, many governments and organizations have stressed the importance of reducing electricity consumption for lighting, recognizing the very low efficiency of traditional light sources. Funding for research was boosted across the globe and LED technology transformed the industry. Beginning around 2023, government agencies declared victory and drastically cut back this support. This was especially clear in the lighting program of the US Department of Energy and in the European Horizon Program. In May 2025 CLASP announced the conclusion of its Clean Lighting Program[1]. During the next few years, responsibility for the development of LED technology will lie almost entirely with the companies.

Monitoring the continued progress in energy efficiency has become much more difficult. A search of the internet site of the International Energy Agency[2] produces only this old statement.

"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."

The LEDs Magazine ceased production in December 2024 after 20 years of reporting on the industry[3]. One remaining resource is LED Professional Review. Although their annual in-person symposium has been discontinued, the magazine continues to provide valuable information in both printed and on-line formats. Fortunately, the China Solid-State Lighting Alliance continues to publish annual reports on the industry in China. Highlights from its report on 2024 are included below.

Oversight of the International Lighting Science Conference has now been assumed by the IEEE. The Sustainable Smart Lighting World Conference will be held on 8 – 10 December 2025 in Monastir, Tunisia[4].

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[1] https://www.clasp.ngo/updates/concluding-clic/

[2] https://www.iea.org/energy-system/buildings/lighting

[3] https://inside.lighting/news/24-12/leds-magazine-shuts-down-after-20-year-run

[4] https://ls2025monastir.com/

The data that is available seems to suggest that improvement in LED performance is slowing. The European Product Registry for Energy Labelling (EPREL) divides light sources by efficacy into seven groups. The following table shows that most lamps on the market today have efficacy below 110lm/W and that the proportion in the top three groups has risen only slowly since 2022.

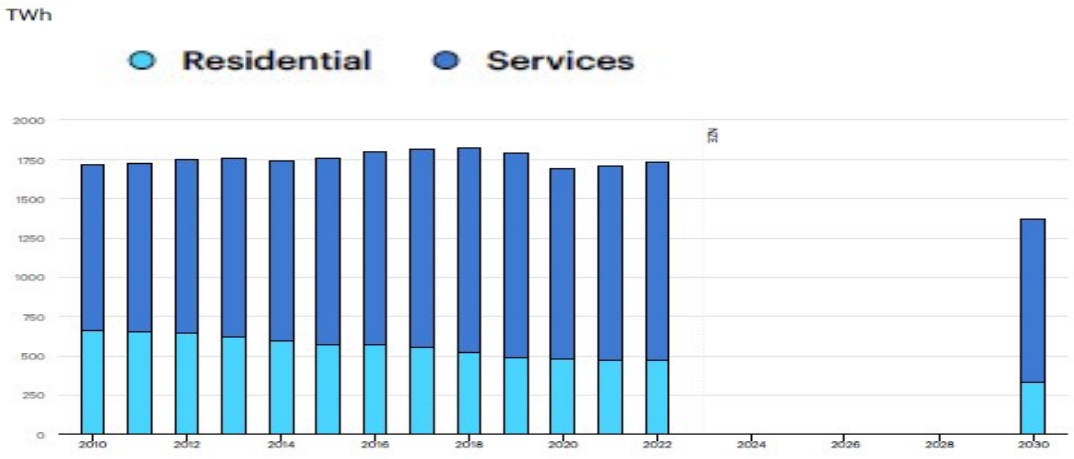
Class	Efficacy	Product Distribution (%)			
	lm/W	April 2022	Dec 2023	Dec 2024	Nov 2025
A	over 210	0.07	0.6	0.8	1.0
B	185-210	0.51	1.4	1.6	2.5
C	160-185	3.2	5.9	6.6	6.9
D	135-160	8.9	13.1	13.6	12.9
E	110-135	23.1	23.6	23.2	23.3
F	85-110	43.2	35.6	34.6	34
G	below 85	19.7	19.5	19.6	19.4

It should be noted that 98.5% of the lamps currently on the list are LEDs and 52.7% of these are in the lowest two classes.

Part of the reason for not pursuing the optimization of efficacy has been the development of "Human Centric Lighting" (HCL). In a recent article in LED Professional Review[5], Dr. Alexander Wunsch has argued that "*the pursuit of maximum energy efficiency leads to biologically impoverished light: the best energy efficiency class yields the worst spectral composition. High energy efficiency means low infrared (NIR) output and exaggerated short-wave components".* HCL has been promoted by the Good Light Group, led by Jan Denneman[6].

The conflict between HCL and efficacy optimization arises because the efficiency of blue LEDs is significantly higher than that of higher wavelengths. The status of research to narrow this gap is discussed in chapter 6.

The following chart from the IEA[7] confirms that there has been little, if any, reduction in the global electricity consumption for lighting. Some savings in developed economies have been offset by substantial increases in the demand for artificial lighting in countries with developing economies, especially in China. We estimate that the global average efficacy of artificial lights has risen from 48lm/w in 2005 to around 100 lm/W in 2025, while demand for light has also doubled, from 135Plmh to about 275Plmh.



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2 Review of Company Performance in 2024

2.1 LED sources

If one were to judge the health of the LED lighting industry by the manufacture of LED chips, 2024 was a good year. The revenues of almost all the leading producers rose substantially, as shown in the next table. The Chinese Solid-State Lighting Alliance (CSA) estimates that the total revenues of the chip companies in China rose by 10% to 32.4B yuan.

Company	Units	Sales			Operating Profits		R&D		%
		2024	2023	Change	2024	2023	2024	2023	2024
AMS Osram (OS Div)	M euros	1448	1386	5%	241*	233*	212*	227*	8.1
Ennostar	B NT$	24.39	22.31	9%	-4	-1.62	2.43	2.59	10.0
Everlight	B NT$	20.97	17.85	18%	2.46	1.79	0.858	0.787	4.1
HC Semitek	M yuan	4126	2903	42%	-611	-846	222	185	5.4
Jiangsu Azure	M Yuan	6756	5222	29%	629	194	407	306	6.0
Jucan Opto	M Yuan	2760	2481	11%	169	41	129	129	4.7
Jufei Opto	M yuan	3053	2512	22%	297	210	205	153	6.7
Sanan	M yuan	16107	14053	15%	966	1084	706	794	4.4
Seoul Semi	B KrW	1090	1033	6.0%	1.2	-53	86.9	93.7	8.0
Seoul Viosys	M KrW	699	504	39%	4.1	-73	53	57	7.6

*For AMS Osram, the sales are for the OS Division only, while the profits and R&D expenses are for the whole company

The performance of the packaging companies was more mixed, with total sales in China flat at around 78B yuan. Omdia reports that the revenues at the leading producer Nichia fell by 16% to US$1.41B. They rank AMS Osram as the second largest manufacturer, with sales of US$833M and Seoul Semiconductor third at $722M. Among the Chinese producers, Mulinsen's packaging revenues were up by 2.9% to 6.8B yuan.

The company ranked fourth by Omdia, Samsung Electronics announced in September 2024 that it will divest the mainstream LED business to focus more on core areas with better growth prospects, such as power semiconductors and Micro LED technology[8,9]. The company intends to end production of LED chips for general lighting by the first half of 2026. The TV LED lighting business will wind down by the end of 2026 and the automotive LED business will end by 2030.

2.2 LED Lighting Applications

The good news for chip manufacturers did not extend to downstream lighting markets. According to the analysis by TrendForce, the LED lighting market value in 2024 fell by 4.2% to USD 56.1B. This was

[8] https://www.trendforce.com/news/2024/10/24/news-samsung-electronics-exits-led-business/

[9] https://www.semicone.com/article-59.html

attributed to several factors: the US Federal Reserve's continued high-interest rate policy, severe deflation in China, persistent weakness in Europe amid economic and geopolitical turmoil, and the impact of yen depreciation in Japan. The three core markets—the US, Europe, and China—have long been the main sources of lighting demand, but all faced challenges in 2024 that dragged down overall LED lighting market value. However, as market demand improved somewhat in 4Q24 with accelerating LED penetration, the overall decline was slightly mitigated.

The next chart shows that this revenue decline was shown by each of the ten top suppliers.

Rank		Company	LED Lighting Revenue			Market Share	
2023	2024		2023	2024	YoY	2023	2024
1	1	Signify	6,165	5,982	-3.0%	32.9%	33.3%
2	2	Acuity	3,418	3,378	-1.2%	18.3%	18.8%
3	3	Panasonic	2,030	1,870	-7.8%	10.8%	10.4%
4	4	LEDVANCE	1,491	1,386	-7.1%	8.0%	7.7%
5	5	Zumtobel	1,218	1,200	-1.5%	6.5%	6.7%
7	6	Savant Systems	940	899	-4.4%	5.0%	5.0%
6	7	Opple	965	888	-8.0%	5.2%	4.9%
8	8	Current	843	802	-4.8%	4.5%	4.5%
10	9	Fagerhult	807	786	-2.6%	4.3%	4.4%
9	10	Toshiba	834	769	-7.7%	4.5%	4.3%
2024 Top 10 Companies Total LED Lighting Revenue			**18,710**	**17,961**	**-4.0%**	**100.0%**	**100.0%**

Changing technology and pressures on prices continue to have an impact on profit margins. The next table shows the revenues and operating profits for the last complete fiscal year for sixteen companies that publish financial data, with amounts in the local currency. Wherever possible, the data is given for the lighting division rather than the whole operations.

Company	**Units**	**Sales**			**Operating Profits**		
		2024	2023	Change	2024	2023	Change
Acuity	M US$	3841	3952	-3.0%	553	473	17%
AMS Osram (L&S Div)	M euros	1000	1165	-14.0%	241*	241*	3%
Bajaj Elec	M Rs	10225	10374	-1%	675	796	-15%
Crompton Greaves	M Rs	10183	9962	2%	1197	1053	14%
Dixon	M Rs	8610	7870	9%	610	590	3%
Endo Lighting	M yen	53735	51706	4%	4930	5203	-5%
Fagerhult	M SEK	8305	8560	-3%	670	901	-26%
Foshan Elec	M yuan	9057	9057	3%	259	259	-29%
Havells	M Rs	16532	16268	2%	2537	2474	3%
MLS	M yuan	16910	17536	-4%	608	836	-27%
Nationstar	M yuan	3472	3542	-2%	-30	17	-280%
Opple	M yuan	7096	7795	-9%	862	614	12%
Orient Electric	M Rs	9207	8294	11%	1123	963	17%
Signify	M euros	6143	6704	-8%	477	369	29%
Surya Roshni	M Rs	16896	15712	8%	1305	1214	7%
Zhejiang Yankon	M yuan	3176	3075	3%	171	184	-7%
Zumtobel	M euros	1097	1127	-3.0%	47	57	-12%

In their Blue Book for 2024, CSA estimated that downstream LED lighting market in China was around 514B yuan, a year-on-year decrease of 7.6 %.

Despite the overall decline, there were some bright sectors. TrendForce reported that the global LED horticultural lighting market size reached USD 1.32B billion in 2024, reflecting a year-on-year growth of 6.6%. Their analysis indicates that this recovery was not simply due to downstream restocking; rather, it represents a genuine and sustainable resurgence in demand.

According to TrendForce, the global smart lighting market size grew by 17.6% in 2024. Driven by the demand for energy savings, LED lighting products have increasingly incorporated dimming, color tuning, and smart control systems. The growth was primarily driven by lower costs of smart lighting products and steadily increasing energy-saving demand in the professional lighting market (including commercial, outdoor, and industrial segments) which spurred growth in IoT lighting, particularly in the outdoor and industrial sectors.

The challenges faced by the industry have not yet been acknowledged by most of the other market research companies, which still offer reports written several years ago forecasting steady rises in annual revenues. Readers are urged only to follow reports from companies with analysts who are experienced in the LED industry and closely keep up with current trends.

2.3 Overall state of the LED Industry in China

According to the financial reports of listed companies[10], 55 companies mainly engaged in LED achieved a total revenue of 152.894 billion yuan in 2024, a slight increase of 4.83% over 2023. More than 60% of companies maintained positive revenue growth. Driven by the continuous transformation and upgrading of the industry, the industry has made progress in high-end segments such as mini/micro LED, automotive lighting, plant lighting, and ultraviolet LED.

Despite the continued revenue growth, the industry's net sales margin and operating profit margin are still deeply in the negative range, at -7.2% and -6.8% respectively. Profitability has declined sharply, and the total net profit of listed LED companies totaled 3.3B yuan, a decline of 34% from 2023. 40% of the companies suffered a net loss.

According to OEC World[11], China exported $4.21B of LED light sources and lamps in 2024,down from $5.33B in 2023. The main destinations of China's were: United States ($1.07B, down from $1.55B), Japan ($201M, down from $244M), Thailand ($146M), Mexico ($139M), and France ($131M). Most unit volumes have increased, but the price reductions have been very aggressive. LED electric light sources (LED bulbs, LED tubes, and LED modules) saw an average export price decline of 49%. For example, the average export price of LED bulbs (HS code 85395210) dropped by 22% year-on-year, with price declines ranging from 10% to 30% in major markets such as the U.S. and Europe.

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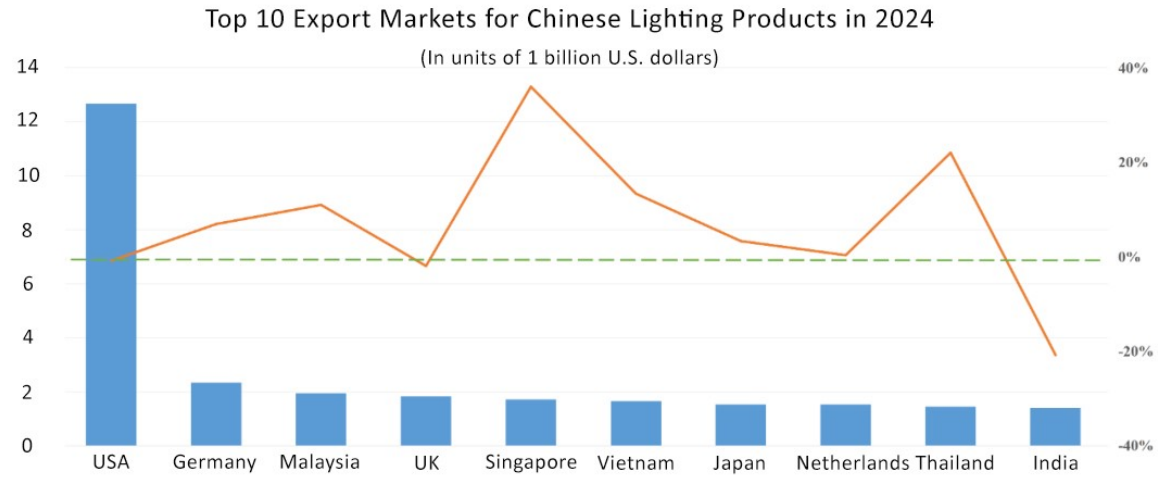
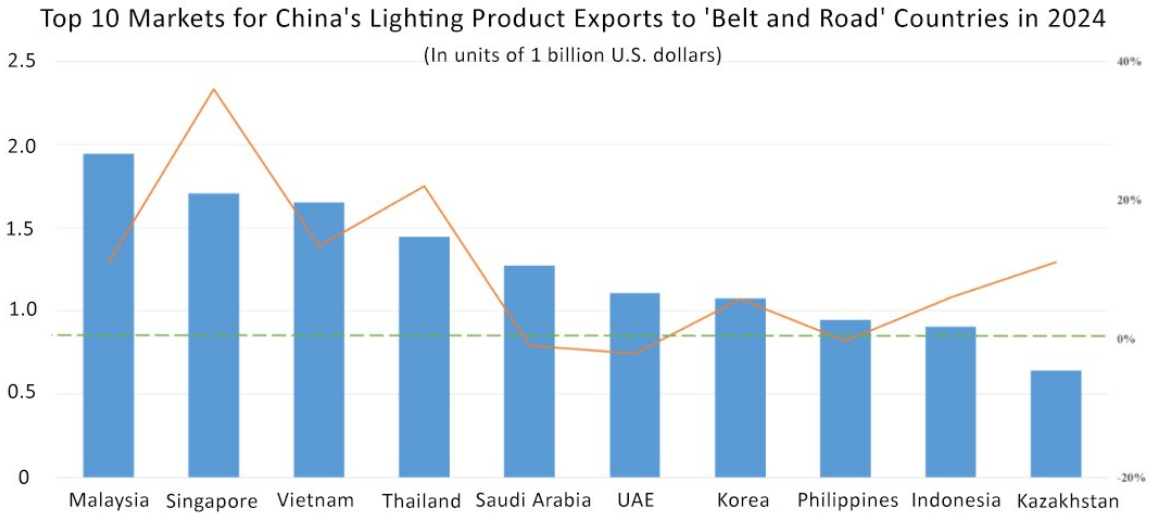
[10] www.china-led.net/news/202505/13/54280.html

[11] https://oec.world/en/profile/bilateral-product/led-light-sources-and-lamps/reporter/chn

Data from OEC World[12] and Shine Lighting[13] suggest that China's lighting product exports were valued at $56B in 2024, a slight decrease of 0.3% year-on-year. The export of lighting fixture products remained stable, with an export value of approximately $42B. Significant price reductions were offered to stabilize the market. Fixed lighting fixtures recorded a year-on-year increase of 9.8% in volume and 0.8% in export value, while portable lighting fixtures grew by 17.7% in volume and 2.2% in export value.



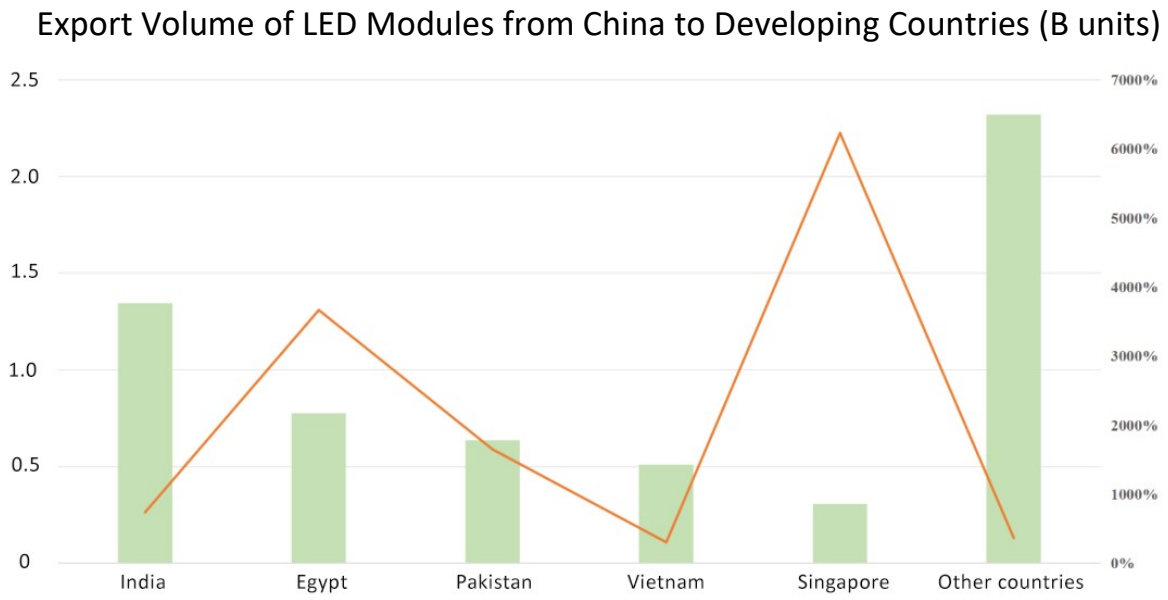
As shown below, exports to “Belt and Road” markets reached approximately $25.2 billion, reflecting a 3% year-on-year increase.



[12] https://oec.world/en/profile/bilateral-product/light-fixtures/reporter/chn

[13] https://www.shine.lighting/threads/china's-lighting-industry-a-deep-dive-analysis-into-2024-export-trends-and-2025-outlook.5355/

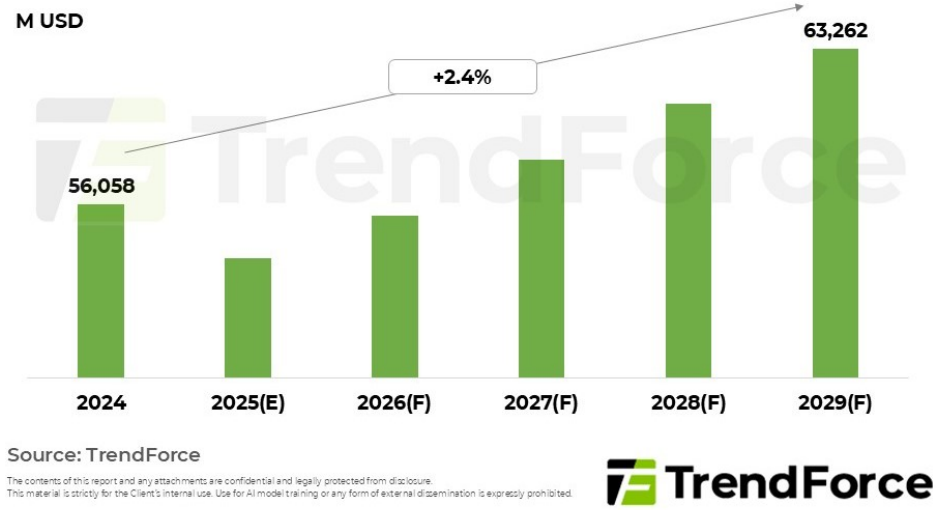
Many developing countries are developing their domestic lighting industry by manufacturing lamps and luminaires with LED modules from China. As shown below, India ranked highest in LED module imports from China in 2024, with 1.3B units imported. The total export value of China's LED modules reached approximately $480 million, with the U.S. being the largest destination at $70 million.



3 Company Progress in 2025

The changes in US tariff policies have caused concern for many companies in the lighting business. Quoting from LEDInside[14], "*the reciprocal tariffs policies launched by the United States in April have further exacerbated uncertainties over the global economy, leading to significant contractions in business investments and commercial activities. In1H25, the general LED lighting market failed to rebound as expected. The pace of new installations remained sluggish, while replacement demand in the existing installed market slowed down, resulting in continued market contraction and weak player revenue performance".*

As a result, TrendForce estimates that the overall value of the global LED lighting market will drop by 4.4%YoY to USD 53.6B in 2025. The impact on their forecast for the next several years is shown in the next figure[15]. They also reduced their estimate of the sales of LEDs in 2025 to $12.5B from $13.0B predicted in March.



The response of companies to these changes was made more difficult by the many changes in policy and conflicting statements by the US government. Many placed additional orders early in the year to mitigate the anticipated price increases, thereby reducing demand later in the year.

3.1 Highlights from Company Reports

One might have expected the effects to be most severe amongst Chinese suppliers and US manufacturers of lighting products. However, the leading US company Acuity Brands has shown renewed growth, as shown in the following chart. Note that Acuity's fiscal year runs from September to August, so that the only last two quarters shown here were completed in 2025.

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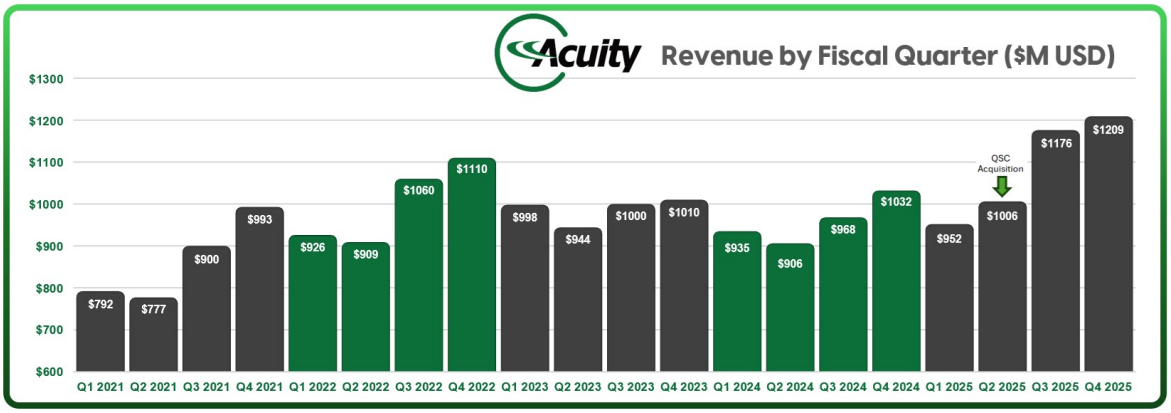
[14] https://www.ledinside.com/intelligence/2025/8/2025_08_18_ledlighting_en

[15] https://www.trendforce.com/research/download/RP250813AN



Much of Acuity's growth was due to the acquisition of QSC, a market leader in the design, engineering, and manufacturing, of audio, video and control solutions. QSC will become part of Acuity's Intelligent Spaces Group. Acuity's basic lighting business delivered 1.1% full-year revenue growth, but profitability increased substantially with an 18% rise in operating margin.

Many of the other leading downstream lighting companies have not done so well, as shown in the next table.

Company	Months	Units	Revenues			Profits		
			2025	2024	Change	2025	2024	Change
Acuity	6	M US$	2388	1999	20%	403	324	24%
Signify	9	M euro	4270	4488	-5%	286	299	-4%
MLS	9	M yuan	12178	12190	0	209	363	-42%
Opple	9	M yuan	3216	3366	-3%	369	385	-30%
Foshan	9	M yuan	6532	6887	-5%	141	247	-44%
AMS Lamps&Systems	9	M yuan	657	731	-10%	118	136	-13%
Fagerhult	9	M euro	5815	6266	-7%	412	533	-7%

The leading LED chip maker in China, Sanan Opto also showed rapid growth, with half-year revenues rising by 17% to 9.0B yuan. Its profits decreased by 4% to 176M yuan despite being helped substantially by non-recurring gains. Sanan's remarkable growth in revenues has been supported by its expansion into other applications of wide bandgap semiconductors, including SiC technology as well as GaN. Its future growth should be further boosted by the acquisition of Lumileds, strengthening its international patent position and its participation in the packaging market. According to TrendForce, Lumileds ranks among the world's top seven LED packaging companies. It ranks third in automotive lighting LED revenue, behind only ams OSRAM and Nichia. In smartphone flash LEDs, it is part of Apple's supply chain, ranking just below Nichia.

The next table shows some other LED manufacturers in China have also done well but results elsewhere have been mixed.

Company	Months	Units	Revenues			Profits		
			2025	2024	Change	2025	2024	Change
Sanan	9	M yuan	13817	11854	17%	89	247	-64%
Focus Lightings	9	M yuan	2499	2022	24%	178	155	15%
Jufei Opto	9	M yuan	2342	2294	2%	124	147	-13%
Foshan Nationstar	9	M yuan	2500	2694	-7%	52	69	-25%
HC Semitek	9	M yuan	4129	2953	40%	-196	-360	
Seoul Semi	9	B KrW	748	795	-6%	34		
Seoul Viosys	6	BkrW	356	336	6%	24.1	36.7	-34%
Ennostar	9	M $Tw	16972	18880	-10%	-1921		
Everlight	6	M $Tw	10096	10461	0	919	1002	-8%
AMS Opto	9	M euro	1045	1098	-5%	209	221	-5%

The following table has recent results from companies that do not report on a calendar basis

Company	Months	Units	Revenues			Profits		
			2025	2024	Change	2025	2024	Change
Endo Lighting	6	M yen	25138	24939	1%	2242	1918	17%
Bajaj	6	Crore	274	279	-2%	13	9	46%
Crompton Greaves	6	Crore	548	582	-6%	66	55	20%
Dixon	6	Crore	456	312	46%	66	45	47%
Havells	6	Crore	1058	1122	-6%	108	122	-12%
Surya Roshni	6	Crore	1030	980	5%	83	70	19%
Zumtobel	3	M euros	266	289	-7.8	-4	12.8	-131

3.2 Report from the Guangya Lighting Research Institute

The overall performance of the industry in China has been summarized in a long article by Wen Qidong, Executive Vice President and Chief Researcher of Guangya Lighting Research Institute[16].

“In the first half of 2025, sales of China's lighting industry were approximately 275B, a year-on-year decrease of 7.7% This has been the fourth consecutive year of negative growth since 2021.
Facing multiple pressures, including sluggish external demand amidst sharply rising global uncertainty, the outflow and fragmentation of production capacity and supply chains, intensified Sino-US tariff wars, overcapacity, and price deflation caused by a "rising East and declining West" trade dynamic, the lighting industry's foreign trade reached US$25.9B (186B yuan), a 6.3% decrease from same period last year . Domestic lighting sales continued to be constrained by factors including the ongoing real estate

[16] https://www.alighting.com/news_show.aspx?id=176877

downturn, investment constraints due to fiscal austerity, pressure on employment and income, weak consumer confidence, and increasing market fragmentation. Consequently, both volume and price declined, resulting in a total domestic sales volume of approximately 89B yuan, a year-on-year decrease of 12.8 %."

"Among the 9 listed companies in LED epitaxial chip-related businesses, 67% of companies saw a decline in revenue from LED epitaxial chip-related businesses , with an average decline of 10.7% . 33% of these companies experienced a decline in gross profit. The average gross profit margin was 17.0% , up 1.4 from 15.6% last year. The average capacity utilization rate of LED packaging lighting-related businesses was 92% , down 4 percentage points from last year, but still high . The total revenue of the LED epitaxial chip business of these above-mentioned listed companies was 7.98B yuan , a year-on-year decrease of 1.6% , accounting for more than 90% of the scale of the entire Chinese LED epitaxial chip industry and is still highly intensive in production capacity and capital."

"Among the 22 listed companies involved mainly in packaging, 59% of companies saw a decline in revenue from LED packaging-related businesses, with an average decline of 23.5%. 73%of companies saw a decline in gross profit margins in LED packaging -related businesses compared to38%. The average gross profit margin was 12.5%. The average capacity utilization rate of LED packaging lighting-related businesses was 70%, a significant drop of 12 percentage points from last year. In terms of overall revenue, 55% of these companies saw a decline in revenue, 68% saw a decline in net profit, and 36% suffered losses, compared to 33%, 25% and 50% in the same period last year, respectively. The LED packaging-related business revenue of the above-mentioned listed companies totaled approximately 12B yuan."

"In the general lighting sector, the first half of 2025 was characterized by revenue pressure and a sharp decline in profits. Among the 87 listed companies, 64% saw a decline in lighting-related business revenue, compared to 56% in the same period last year, with an average decline of 20%. 66% of the companies saw a decline in gross profit margins in lighting-related businesses, compared to 52% in the same period last year. The average gross profit margin was only 26.0%, down 2.2%. The average capacity utilization rate of lighting-related businesses was only 54%, down 5% from last year and far below the 75% manufacturing overcapacity warning line. In terms of overall revenue, 56% of companies saw a decline in revenue, 62% saw a decline in net profit, and 34% suffered losses, which expanded by 2%, 11% and 1%, respectively, compared with the same period last year. In addition, 62% of the companies have increased the proportion of their export revenue, indicating that going overseas has become an important way for companies to expand their business. The above-mentioned companies' lighting-related business (excluding car lights) revenue totaled approximately 29B yuan, accounting for 10.5% of the entire industry scale."

3.3 Exports of LED Products from China

A summary of data 2025 from the General Administration of Customs on lighting exports from China in the first 9 months of has been summarized by Wen Xidong[17]. Exports in September 2025 were $3.6B, the lowest monthly figure since March 2024, marking 17 consecutive months of decline. This represented a year-on -year decrease of 13.5. Month-on-month, exports were down 9.3 %. Of this total, LED lighting products accounted for $2.8 billion, a year-on-year decrease of 13.3%.

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[17] https://www.alighting.com/news_show.aspx?id=177092

In the first three quarters of 2025, China's total lighting product exports reached US$38B, a year-on-year decrease of 7.8%. Of this total, LED lighting product exports reached US$29.7B billion , a year-on-year decrease of 3.4%, compared to a -5.1 % growth rate in the same period last year. These exports accounted for 78.1% of total lighting exports, an increase of 3.5% compared to the same period last year.

In the first three quarters, only Africa recorded growth, while other regions declined, including Europe and Southeast Asia, which saw slight growth in the first half of the year. North America, East Asia, South Asia, Central Asia and Oceania all experienced double-digit declines.

In terms of exports to the US, in September 2025, lighting product exports to the US were US$730 million, a year-on-year decrease of 30.3%. In the first three quarters of 2025, cumulative lighting product exports to the US were only US$ 7.58B, a year-on-year decrease of 19.0%, and the proportion of total exports fell below 20% for the first time in history. China's share of US lighting imports has fallen from a peak of nearly 70% before 2018 to 50%, while Southeast Asia and India's share has risen from less than 2% to over 20%.

In the first three quarters of 2025, the average export price of most products continued to decline. The imbalance between supply and demand is a major factor in price competition. The biggest problem facing the industry this year is the unprecedented pressure on profits.

LED light sources now account for over 80% of total light sources. If it weren't for the unsustainable and abnormal surge in the number of halogen lamps in Vietnam and Cambodia, the proportion of LED light sources would have exceeded 85%.

Some monthly data on lighting exports from China is published online by the OEC. For example[18], in August 2025, China exported $294M of LED light sources and lamps, down by 9.2% since July 2025 and by 14.7% since August 2024. The leading destinations were United States ($69.7M), Japan ($17.1M), France ($13.2M), Brazil ($11.4M), and Poland ($10.7M).

For all light fixtures, China exported $2.94B Light Fixtures in August 2025, down by 12.7% since July 2025 and by 17% since August 2024. Dominant destinations were United States ($516M), Germany ($193M), United Kingdom ($132M), India ($110M), and Netherlands ($109M).

The breakdown of lighting exports from China between January 2024 and May 2025 can be seen in the following chart from the China Association of the Lighting Industry (CALI)[19]

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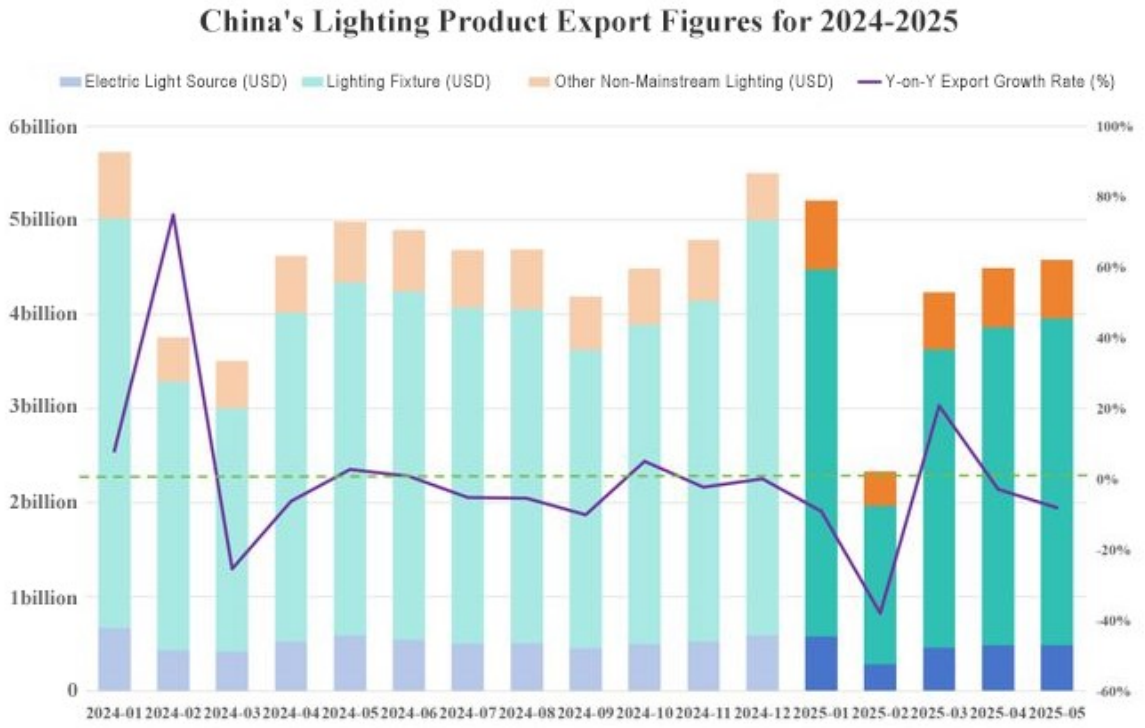
[18] https://oec.world/en/profile/bilateral-product/led-light-sources-and-lamps/reporter/chn

[19] https://www.tfbcustomlighting.com/n1910944/China's-cumulative-export-value-of-lighting-products-reached-approximately-USD-20-9-billion-From-January-to-May-2025.htm



The data from CALI underscores the effect of price reductions. Although electric light source product export volume reached approximately 10.8 in the first 5 months of 2025, a 7% year-on-year increase, the export value of around USD $1.7 billion, down 11% to US$11.7B.

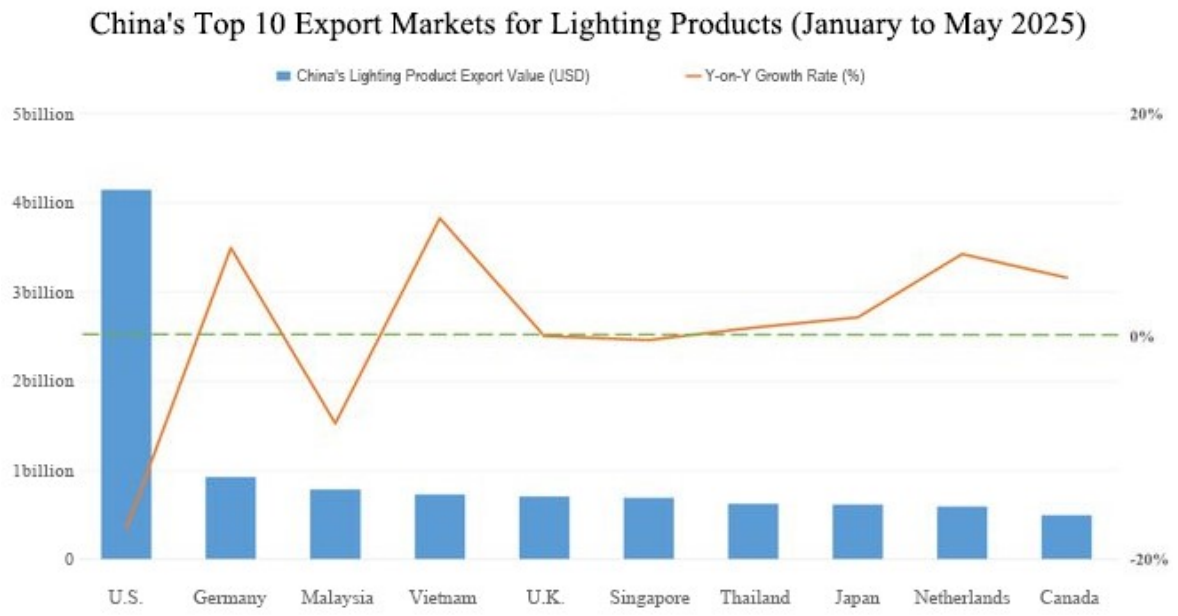
The next chart from CALI confirms the negative impact of exports to the US.

CALI reports that two specific categories of lighting products saw an increase in export value to the U.S.:

· Electrical table lamps, bedside lamps, or floor lamps designed to use only LED light sources: Export value reached USD 160 million, marking a 24% year-on-year increase.

· Other searchlights and spotlights designed to use only LED light sources: Export value reached USD 4 million, a 5% year-on-year increase.

The top 10 export destinations for Chinese lighting products are: The United States, Germany, Malaysia, Vietnam, the United Kingdom, Singapore, Thailand, Japan, the Netherlands and Canada. Total lighting product exports to these ten markets amounted to approximately $10.3 billion, down 6.5% year-on-year, accounting for 49% of China's total lighting product exports.



In terms of export growth rates, China's lighting product exports to markets such as the United States, Malaysia, and Singapore all experienced year-on-year declines, with decreases ranging between 2% and 12%. In contrast, exports to markets like Germany, the Netherlands, and Vietnam—representing the EU and ASEAN regions—showed year-on-year growth, with increases ranging between 0.8% and 11%.

Exports to Belt and Road Initiative (BRI) countries totaled approximately $10.4B, down 4% year-on-year, but the decline narrowed by 1 percentage point compared to the first four months.

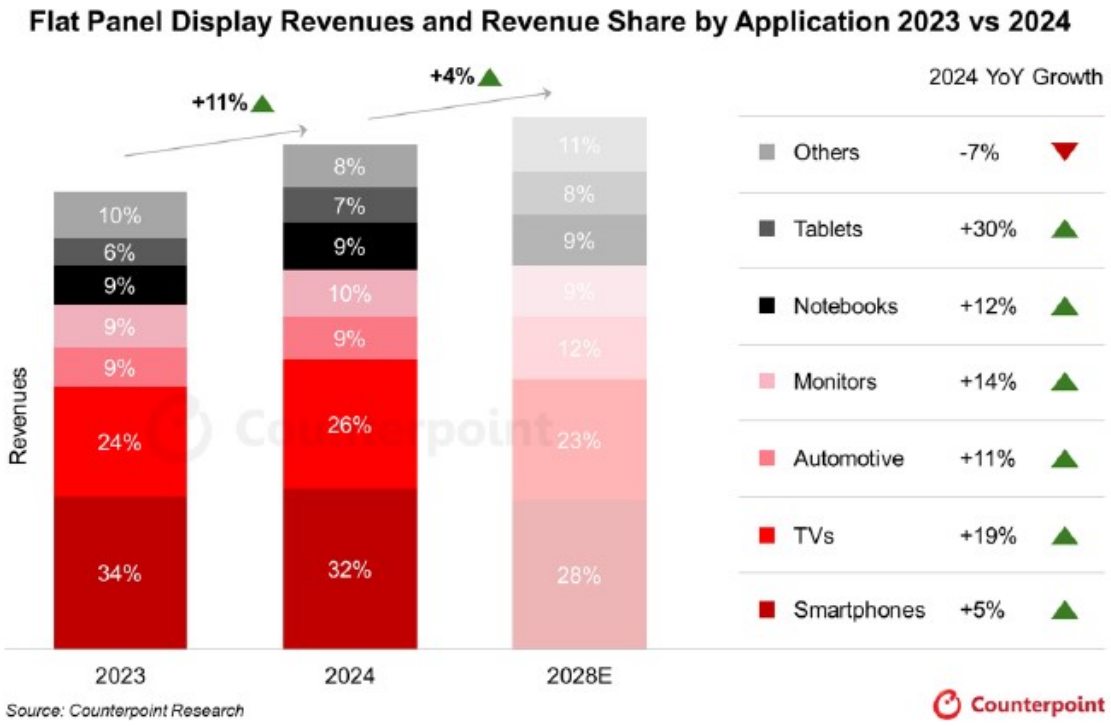
Exports to the European market reached approximately $5.2B, representing a 2% year-on-year increase, 1 percentage point higher than the growth in the previous four months.

4 Special Applications

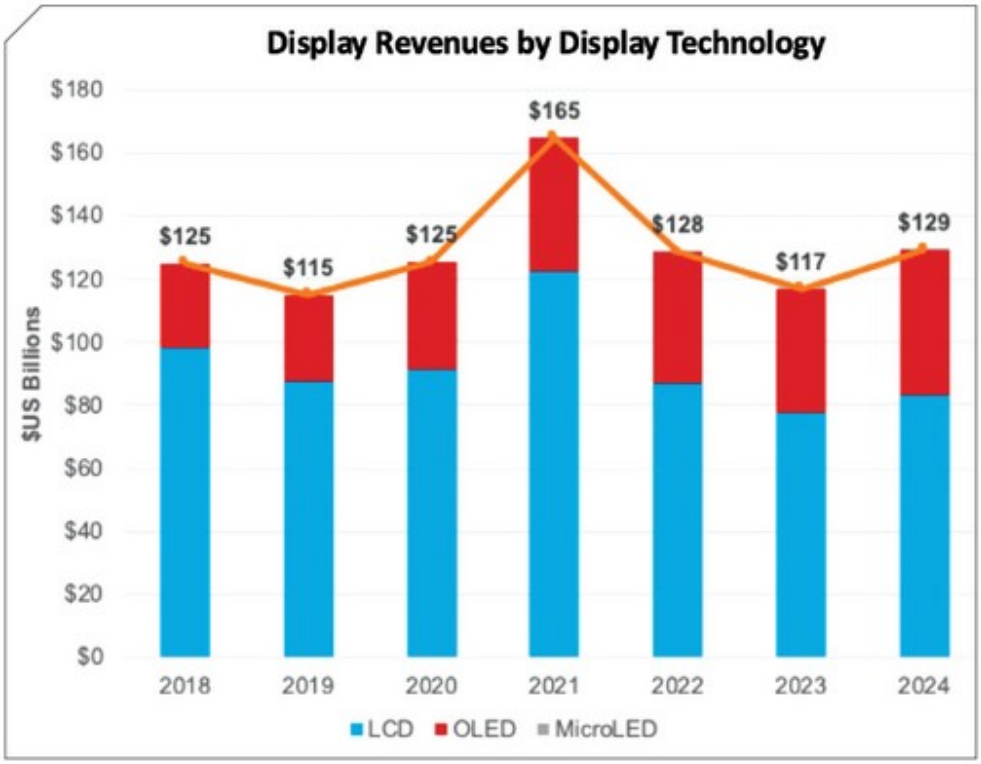
This chapter is devoted to technological advances and business development to several important sectors of LED lighting.

4.1 Displays

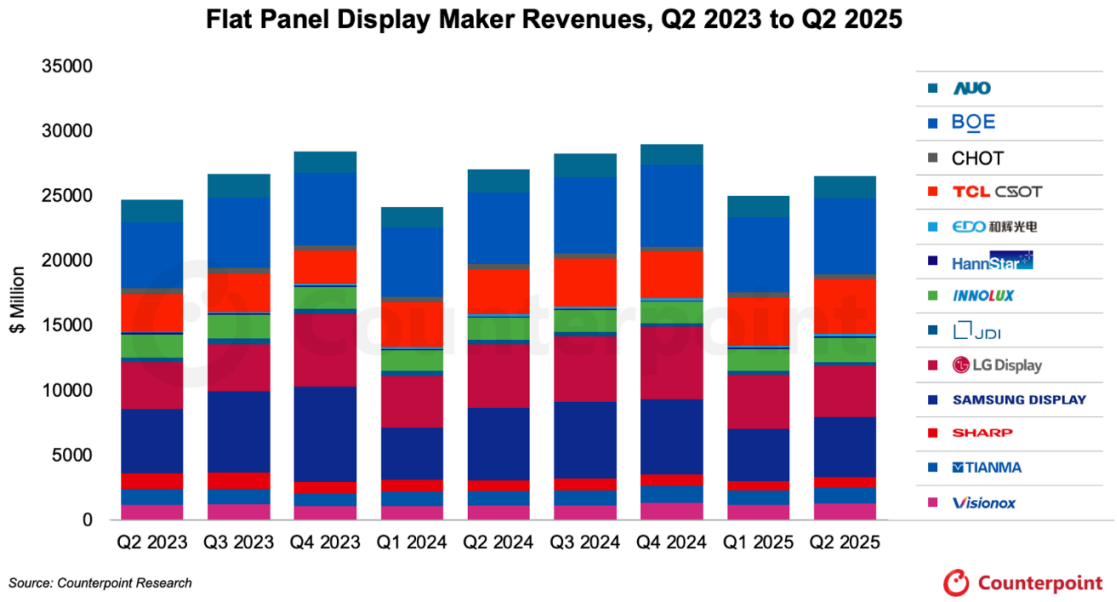
LED technology continues to drive developments in flat panel displays (FPD). According to Counterpoint Research, the overall FPD market grew by ~11% in 2024 after bottoming in 2023. As shown in the next chart, the growth was broad but led by tablets and TVs.



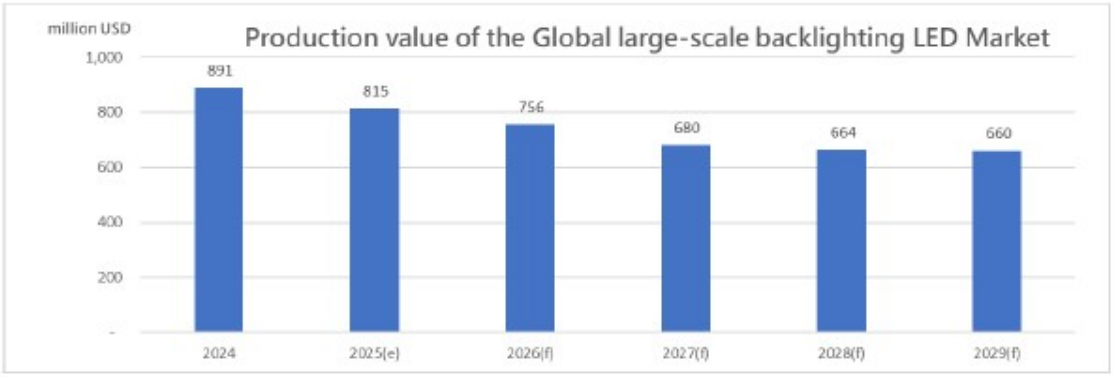
The following chart shows that although sales in 2024 were higher than in 2023, they were still below the peak year of 2020.



Counterpoint believes that the growth continued into the first quarter of 2025 but that revenues in 2025Q2 were down from the same period last year.



In most displays the LEDs are used to create a sheet of white light and the colour and intensity of each sub-pixel is controlled by liquid crystal modulators. However, the market for LED backlights is shrinking, especially in large-scale displays, as shown in this chart from TrendForce.

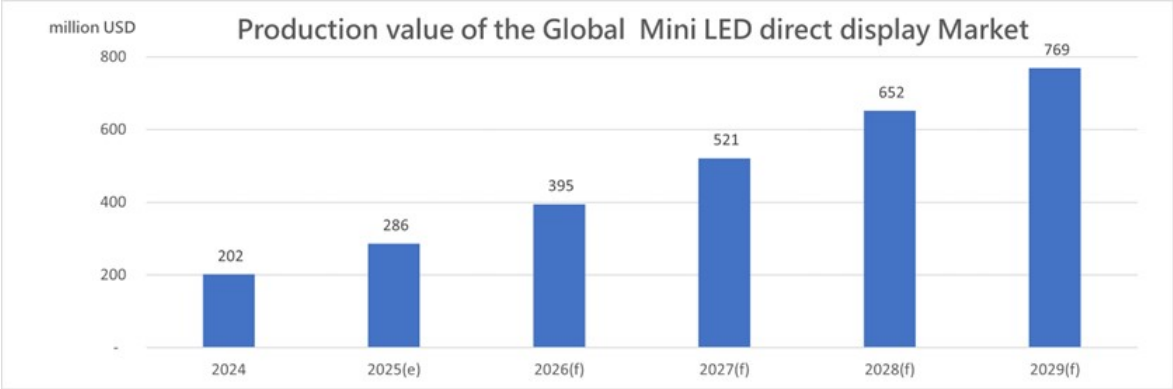


Source of data: TrendForce (March 2025)

The use of uniform white backlights is very inefficient and several alternatives are emerging. The first is through the use of organic LEDs (OLEDs) which provide surface emitters that can be patterned at the sub-pixel level. An approach with inorganic LEDs is to subdivide the backlight into zones with independent control of intensity. Taking this approach to its limit, one or more LEDs should be supplied for each sub-pixel.

This direct approach has already been implemented in large flat panels with pixel pitches in the range of 0.4mm to 3mm. Omdia has reported[20] that fine pixel pitch (FPP) displays accounted for 55% of the market for large LED video screens in Q1 2025, increasing by 8.1% YoY. The 1.50–1.99mm pixel pitch category grew by 11.1% YoY, driven by demand for all in one (AIO) corporate, conference room displays and outdoor poster displays. These offer a balance between resolution and brightness enabling new opportunities in retail, transportation, shelter and residential area scenarios.

Omdia expects that the market for mine-LEDs will continue to grow, as shown in this chart, published in March 2025.

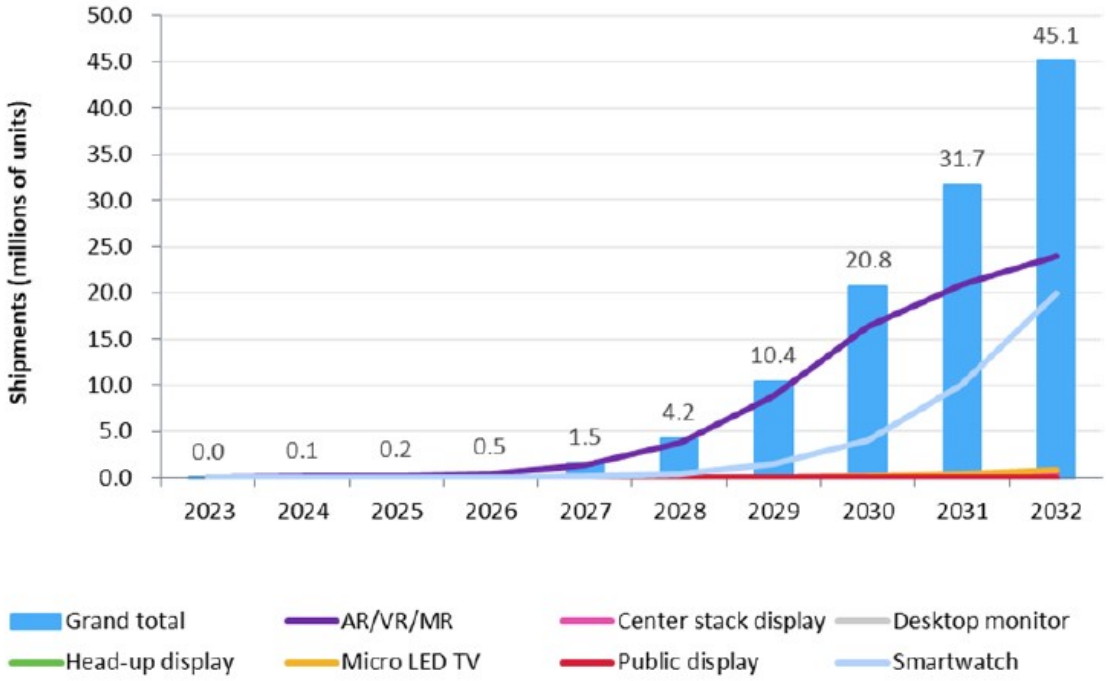


Large video screens are relatively expensive and extending this approach to smaller consumer displays a major challenge. For each display, millions of micro-LEDs must be manufactured and then transferred

[20] https://omdia.tech.informa.com/pr/2025/jun/omdia-led-video-display-market-grows-steadily-in-1q25-driven-by-microled-adoption-and-fine-pixel-pitch-demand

from the LED substrate to the panel. This technology is being pursued by many researchers, but substantial sales of micro-LEDs are not expected for many years[21].

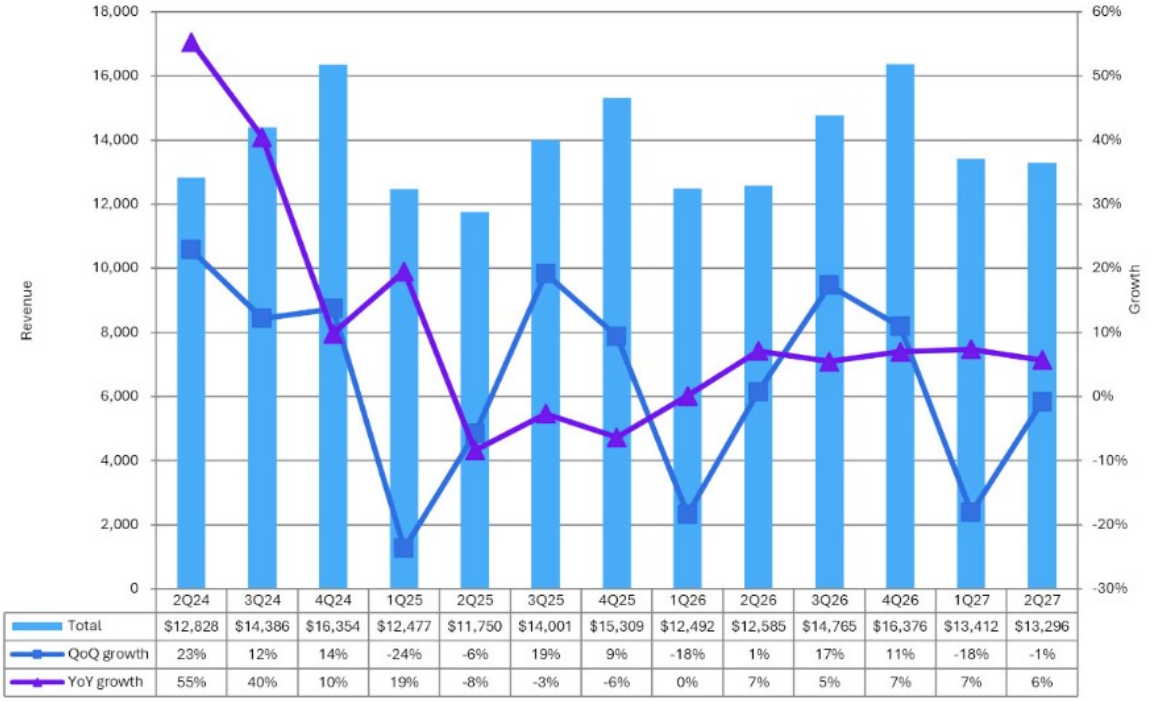
Figure 1: Micro LED display market forecast



Source: TrendForce, March 2025

In the meantime, OLED displays are already well established in the smart phone and high-end TV markets. The data from Centerpoint shows that the OLED share of the FPD market had risen to over one third by 2024 ($46B out of $129B). The following forecast of quarterly OLED sales from Omdia suggests that the growth may stall over the next two years

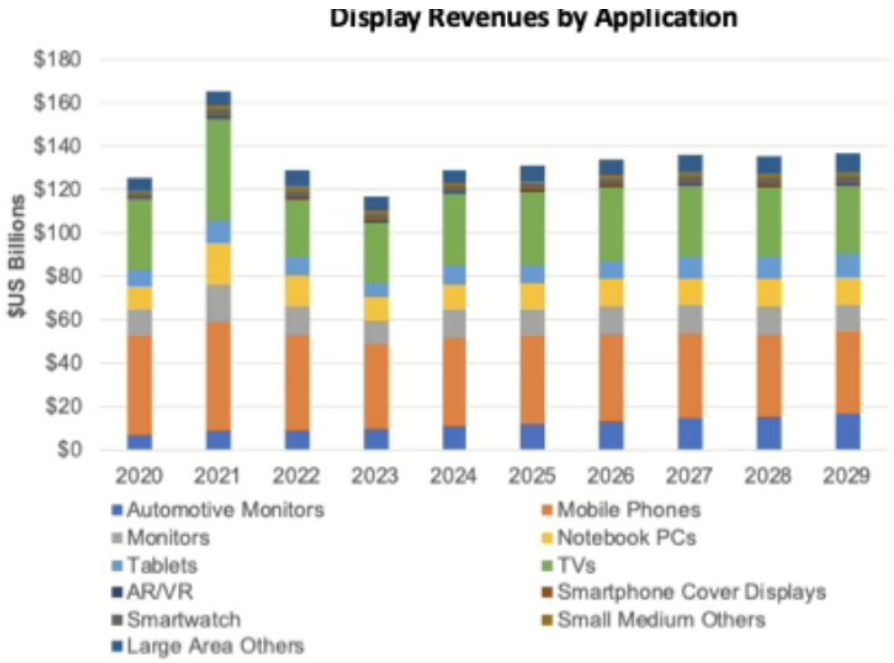
[21] https://omdia.tech.informa.com/om135768/display-dynamics--may-2025-continued-technological-improvements-are-essential-for-advancing-the-micro-led-display-market



	2Q24	3Q24	4Q24	1Q25	2Q25	3Q25	4Q25	1Q26	2Q26	3Q26	4Q26	1Q27	2Q27
Total	$12,828	$14,386	$16,354	$12,477	$11,750	$14,001	$15,309	$12,492	$12,585	$14,765	$16,376	$13,412	$13,296
QoQ growth	23%	12%	14%	-24%	-6%	19%	9%	-18%	1%	17%	11%	-18%	-1%
YoY growth	55%	40%	10%	19%	-8%	-3%	-6%	0%	7%	5%	7%	7%	6%

Source: Omdia

Counterpoint also believes that the whole FPD market may show little future growth over the next five years, as shown below.



Display revenue shares by application (Source: Counterpoint Research)

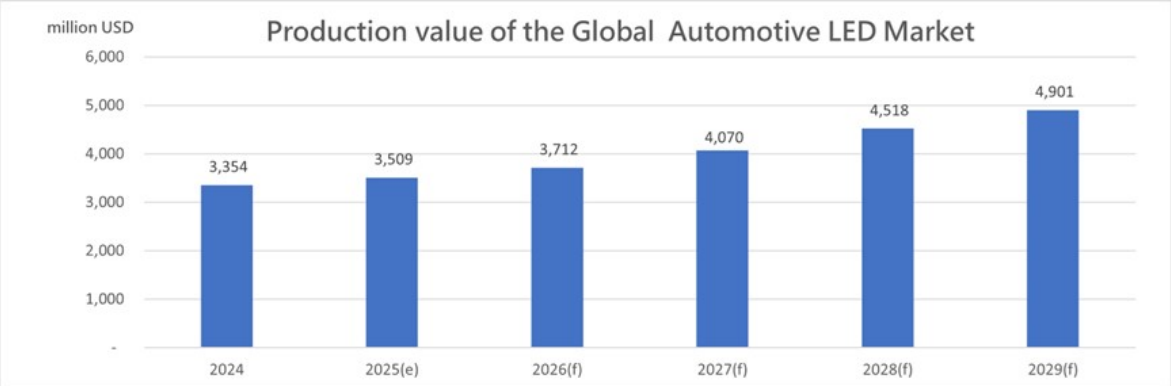
4.2 Automotive Lighting

According to TrendForce, global sales of automotive LED emitters were $3.4B in 2024. Their estimate of the market shares of the leading suppliers is given in the next table.

Auto LED suppliers by 2024 market share (Total market USD ~3.4bn; TrendForce)

1.	ams OSRAM	32%
2.	Nichia	23%
3.	Lumileds	10%
4.	Seoul Semiconductor	8%
5.	Dominant	7%
6.	Samsung LED	6%
7.	Stanley	3%
8.	Everlight	3%
9.	Jufei	2%
10.	Lextar	1%

TrendForce's forecast through 2029 is shown in the next chart.



The next table shows the annual revenues and profits for five of the leading suppliers of automotive lights in 2023 and 2024.

Company	Units	Annual revenues			Annual profits		
		2024	2023	Change (%)	2024	2023	Change (%)
Hella	M euro	3995	3887	2.8	126	132	-4.5
Koito	B yen	916.7	950.3	-3.5	49.1	63.3	-22
Stanley Electric	B yen	509.7	472.4	7.9	55.4	48.1	15
Valeo	M euro	5554	5541	0.3	733	737	0.6
ZKW	M euro	1550	1540	0.7			

The first half of 2025 seems to have been more challenging, with AMS, Hella and Valeo each reporting reductions in revenues, averaging about 5%.

As is discussed below, much of the innovation has come in the design of taillights and the introduction of adaptive beam (ADB) headlights. The latter can provide optimal illumination while preventing glare for other drivers and have proved to be popular in Europe and Asia. However, their introduction in the US has been slowed by conservative regulations from the National Highway Traffic Safety Administration (NHTSA).

The thin profile and high efficiency in red and yellow makes OLEDs a strong candidate for automotive taillights. However, their cost is still relatively high and adoption has been limited to high-end cars in Europe and Asia. The photo on the left-hand side below shows the Atala rear light from OLEDWorks on the Audi A6 e-tron.

The right-hand photo shows a taillight array manufactured in China by Yeolight on the Voyah car from Zhilin[22].

4.3 Horticultural Lighting

According to the latest data from TrendForce, the global LED horticultural lighting market size reached USD 1.32 billion in 2024, reflecting a year-on-year growth of 6.6%. TrendForce's analysis suggests that this recovery was not simply due to downstream restocking; rather, it represents a genuine and sustainable resurgence in demand. Their forecast for the next four years is shown in the next chart.

[22] https://www.oled-info.com/yeolight-technology

The forecasts by other market research companies for the sales of horticultural lighting systems vary significantly. The median estimate for the total market size for 2024 is around $7B with the LED share being in the range of 50-80%.

The following table[23] illustrates the challenges faced by suppliers. It shows the value of the orders and sales of Heliospectra by quarter over the past 4 years.

	Order Intake					Sales				
	Q1	Q2	Q3	Q4	Acc. Total	Q1	Q2	Q3	Q4	Acc. Total
2025	3 129	10 650	4 652		18 431	1 901	7 289	7 635		16 825
2024	26 828	8 076	3 704	3 695	42 303	7 198	4 402	14 330	6 481	32 411
2023	1 649	8 823	7 527	9 377	28 056	7 033	8 276	8 276	9 908	35 311
2022	2 041	9 262	9 262	12 677	34 423	5 562	6 819	6 819	9 998	25 728

Over the first 9 months for 2025, sales fell to SEK16.8M from SEK25.6M and losses mounted to SEK25.6M from SEK9.2M. The company's leaders are still optimistic for the future and Heliospectra's largest shareholder, Weland Stål AB, has committed to providing SEK30M of additional funding.

Horticultural applications represent perhaps the widest range of challenges for lighting designers. Optimization requires careful analysis of the position and beam shape of the lamps and the colour and intensity of the light. Dynamic control of all is needed, supported by the appropriate sensor system.

[23] https://heliospectra.com/investor-relations/financial-reports-documents/reports/

An example of these challenges has been provided in a recent report on LED lighting in the propagation of unrooted cuttings[24].

Despite increased crop yield and the energy savings offered by LEDs in comparison with traditional supplemental lighting, the extra cost of LED sources and control systems can impact profitability. Many suppliers offer guidance on system optimization, such as that from Sollum Technologies[25] and LightingExpert[26]. An analysis of the pros and cons of using LED grow lights in greenhouses has been given recently by Indoor Farming Systems[27]

The shortage of agricultural land led to a surge of interest in vertical farming. However, the cost of the buildings and lighting systems can be very high. Many of the start-ups that were formed to exploit this opportunity have either declared bankruptcy or continue to sustain losses. A presentation from the University of Missouri in St. Louis reported: *"In 2022, the indoor vertical farming sector attracted substantial funding of $2.4 billion. Yet, despite all the investment and excitement around this emerging farming method promising to redefine agriculture, many ventures failed to scale or stay profitable. Farms shut down, investors pulled out, and a pressing question emerged: why didn't vertical farming live up to expectations?*"

This report was partly based upon the results of a 2023 study on the economic feasibility and optimal supply chain design for indoor agriculture in Missouri[28].

The challenges of horticulture in purely artificial light have been reviewed in detail by researchers in Ningxia[29].

An international team of experts has recently analyzed 171 reports on vertical farming. They concluded that *"vertical farming has the potential to address food security challenges by providing a high-yield, high-quality food system. VF has enormous productivity potential and could deliver a robust food supply in crises, isolated regions, and harsh environments, and cater to niche dietary needs. Compared with traditional methods, its environmental advantages and high productivity make it a promising technology for an additional resilient food system while assuming the use of renewable energy sources and significant improvements in energy savings. Currently, high energy demand and costs, and technology requirements, restrict its immediate and widespread global application, especially in mitigating hunger in developing countries. A clear limit of crop productivity in VF is not yet fully definable, as reported yield experiments vary widely with growth conditions and their productivity response. In general, experiments did not aim at maximum productivity, lack critical information for data harmonization, and have uncertainties related to plant density, reference area, and edge effects. Protocol-based, systematic experiments, guided by the Sprengel–Liebig Law of the Minimum, are needed to understand the full productivity potential of VF. Further research is needed in the production and broader adaptation of this*

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[24] https://gpnmag.com/article/urc-propagation-light-management/

[25] https://www.sollumtechnologies.com/blog-posts/competitive-advantages-of-led-greenhouse-lighting

[26] https://www.ledlightexpert.com/best-practices-for-greenhouse-lighting-settings?srsltid=AfmBOopzxRpsJBLIUuEFLyJzlGsFdomdsk_1lwm5pwlWXAQ9vHs1YAjq

[27] https://indoorfarmsys.com/greenhouse-led-grow-light/

[28] Haitao Li et al, "The Economics and Optimal Design of Missouri Indoor Farming Supply Chains", September 2023

[29] https://www.sciencedirect.com/science/article/pii/S2468014125001220

innovative food system, with precise reporting standards in yield, area, pot spacing, nutrition, and time in VF publications. Vertical farming has the potential to positively disrupt future food systems."

A perspective from India has been published by a group of researchers from Tamil Nadu Agricultural University[30]. They believe that vertical farming may be particularly advantageous in regions with limited soil and water resources, benefiting marginalized populations.

At this stage, the choice of crops seems to be critical for the profitability of vertical farming. An analysis of production by two Italian growers[31] demonstrates the economic profitability of vertical farming systems involved into microgreens production. However, the authors warn that these findings may not be broadly generalizable. Leafy greens and herbs are among the other favoured crops.

4.4 Roadway Lighting

The roadway lighting market still offers great scope for LED systems. The estimates from market research companies of the number of installed LED streetlights and the potential for further sales vary substantially. Reports from Arthur D Little in 2019[32]" and from Lamp Light LLC[33], suggest there are now around 350M streetlights globally, and that over 200M of these still use traditional lamps. In addition, there are huge opportunities to introduce new roadway lights in developing countries and some of the earliest LED streetlights in the economically developed world are now reaching the end of their useful lives.

The recent ISA-BRICS workshop provided some interesting data on the adoption of LED streetlights in developing countries.

- India: According to Shyam Sujan, the former chairman of ELCOMA, over 30M LED streetlights have been installed in India and 35M more installations are planned by 2027. Many may be powered by solar energy
- Brazil: Caique Serati de Brito reported that only 20% of ~19M streetlights in Brazil are LED. The regional distribution of streetlights in Brazil is shown in the next slide

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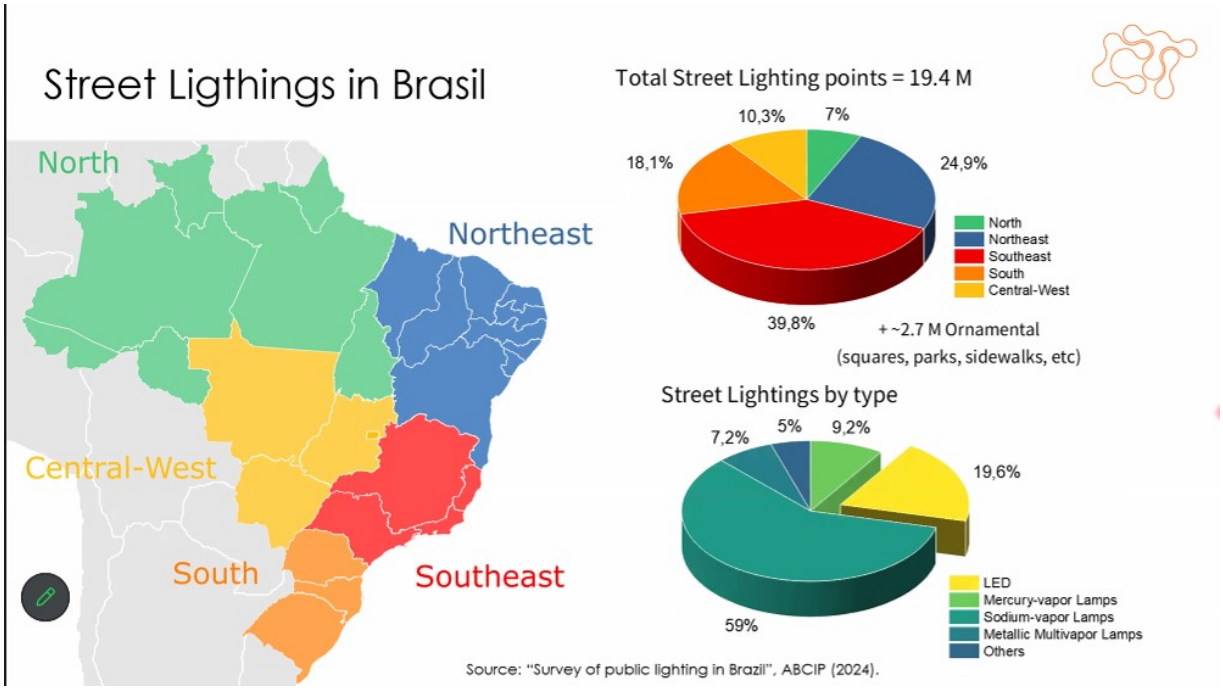
[30] https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2024.1400787/full

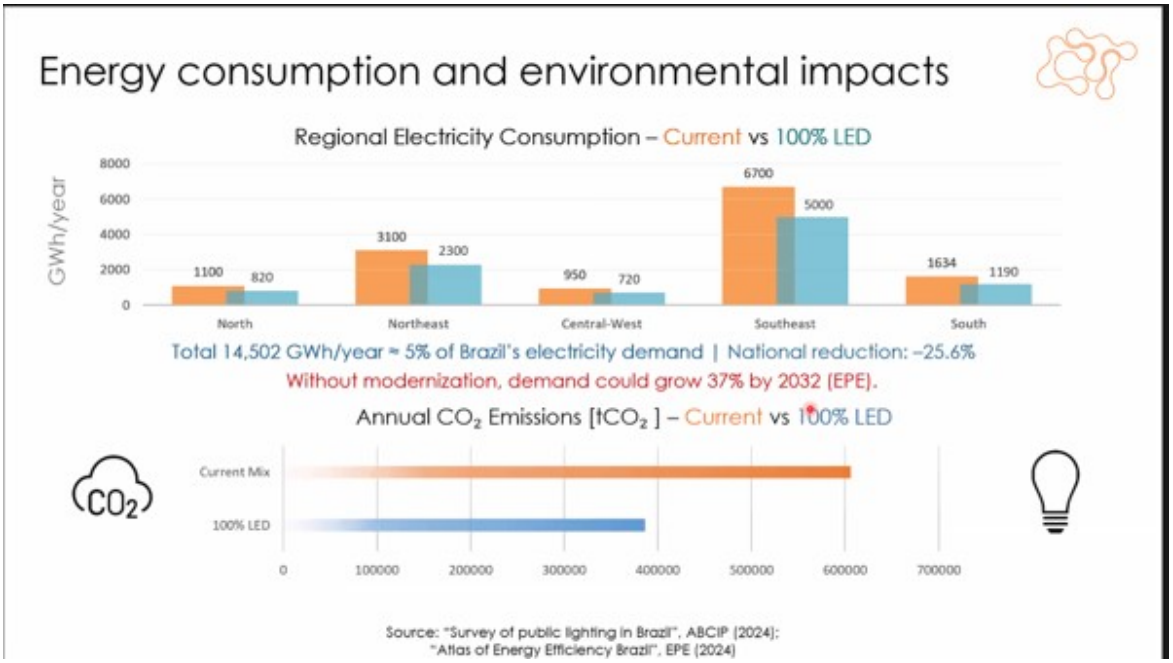
[31] https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2025.1584778/full

[32] www.adlittle.com/en/insights/report/evolution-street-lighting-market

[33] www.lamplightdecorativelighting.com/industry-news-blog/quarter-streetlights-smart-2030/



The number of Public-Private Partnerships to upgrade streetlights was 116 at the end of 2024, covering 138 cities. The energy consumption of the streetlights and anticipated savings from modernization are shown in the next chart.



- Iran: Mr Ramin reported that only 5% of ~14M streetlights in Iran are LED. Itan has the capacity to produce almost 200M LED lamps annually, but it is unclear what proportion of these are

suitable for roadway applications. The Renewable Energy and Energy Efficiency Organization (SATBA) plans to replace over 10M mercury vapor and sodium vapor lamps with smart LEDs. The anticipated savings include

- 5500 GWh of electricity consumption
- 2000MW from the grid's peak load
- 3.6M tons of CO_2 emissions
- 65% reduction in repair and maintenance costs
- no entry of heavy metals into the environment

- Indonesia: The opportunity for large projects is illustrated by the conversion of 150,000 mercury lamps in Jakarta which are connected using the Interact City management software from Signify. About 9M new streetlamps are needed elsewhere in Indonesia to meet minimum standards.
- China: Many large LED installations have been carried out in China. For example[34], by the end of 2024 Shanghai had deployed about 880,000 LEDs. 450,000 of these were installed between 2021 and 2023, saving 210 million kilowatt-hours of electricity. Many of these were supplied by Opple, which has installed over 1M smart streetlights in 130 cities.

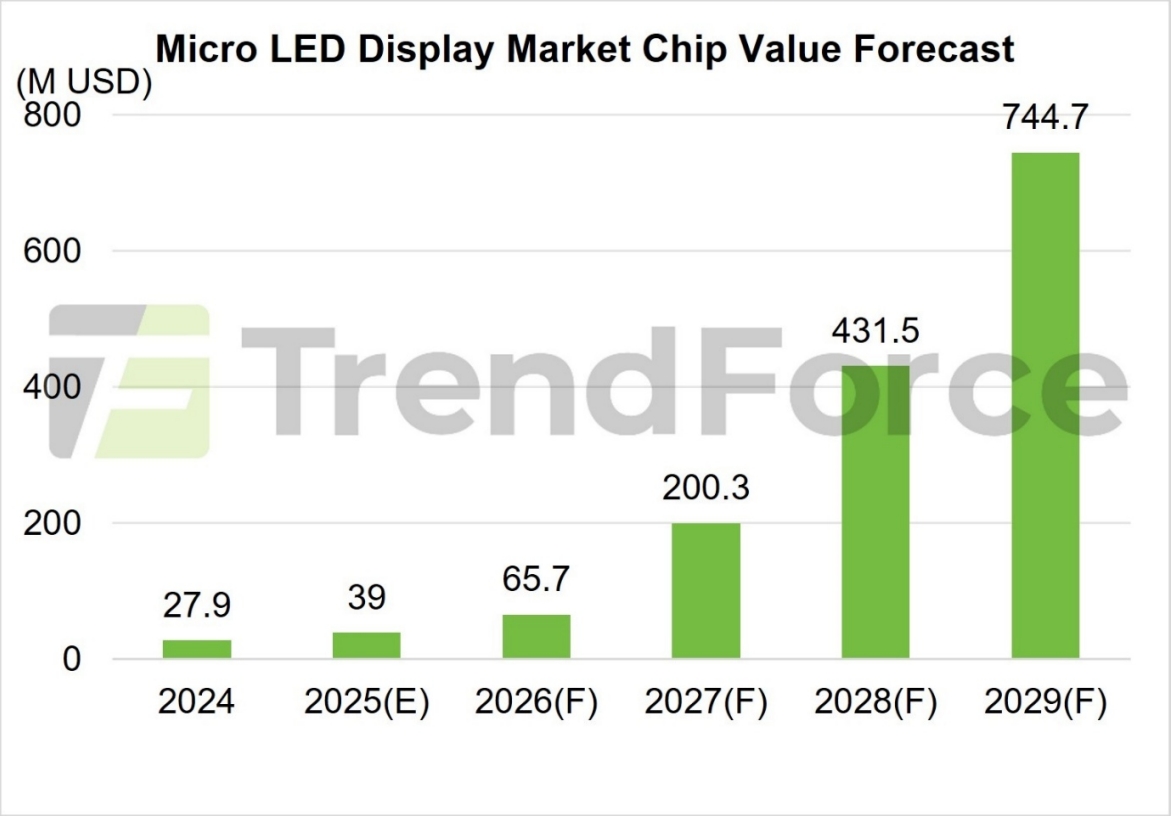
  Chinese manufacturers have supplied many of the LED streetlights installed across the world. For example, HP Winner has delivered over 10M light to more than 100 countries[35].

[34] https://www.alighting.com/news_show.aspx?id=176971

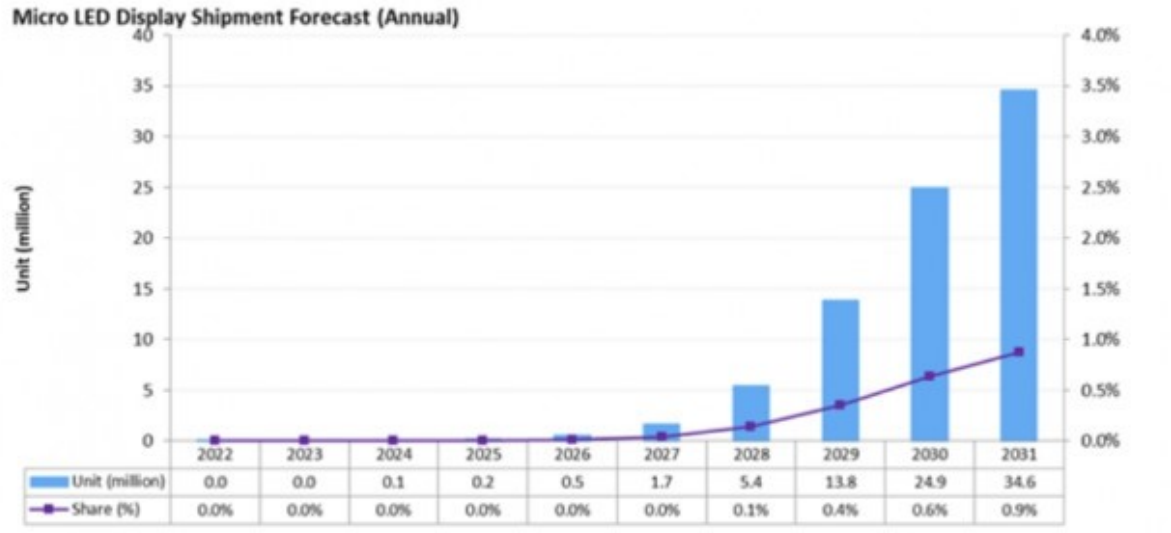
[35] www.hpwinner.com/led-street-lighting/

4.5 Micro-LEDs

Despite major investments by many companies in microLEDs, the technology for their manufacture and transfer is still at an early stage and commercial adoption has so far been low. Nevertheless, market forecasters remain optimistic as shown by the following chart, released by TrendForce in May 2025.

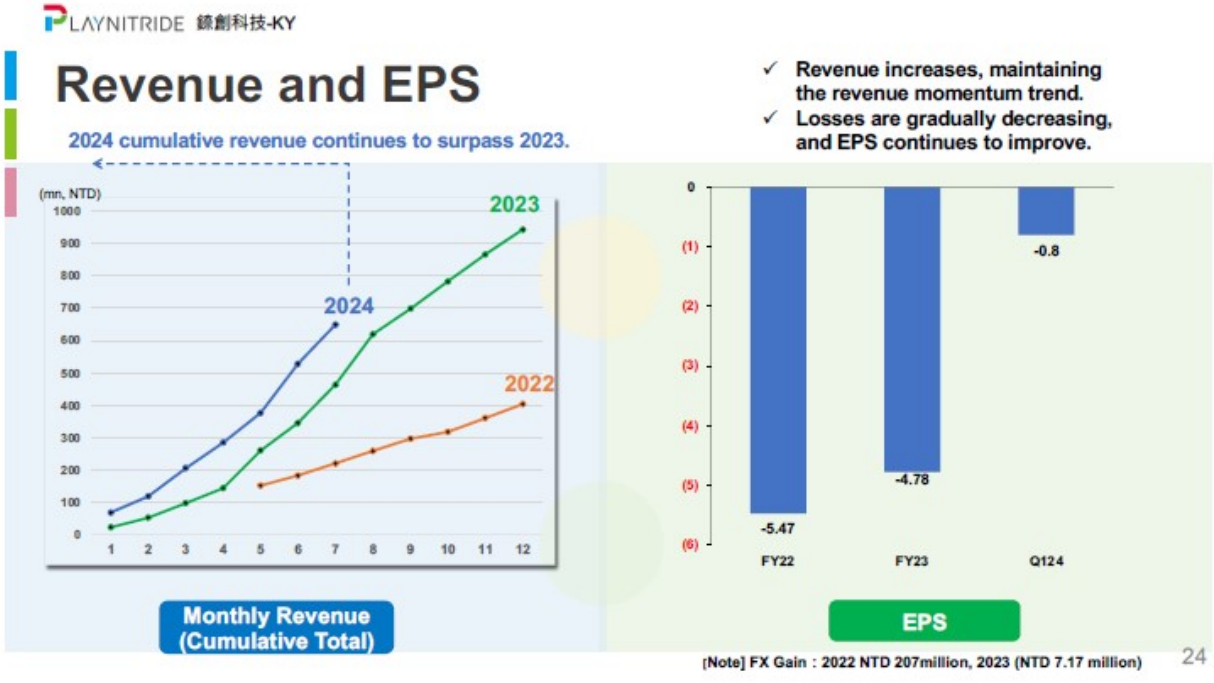


Forecasts of the growth of microLED displays have also been pushed out, as illustrated by this chart published by Omdia in January 2025.



Source: Omdia

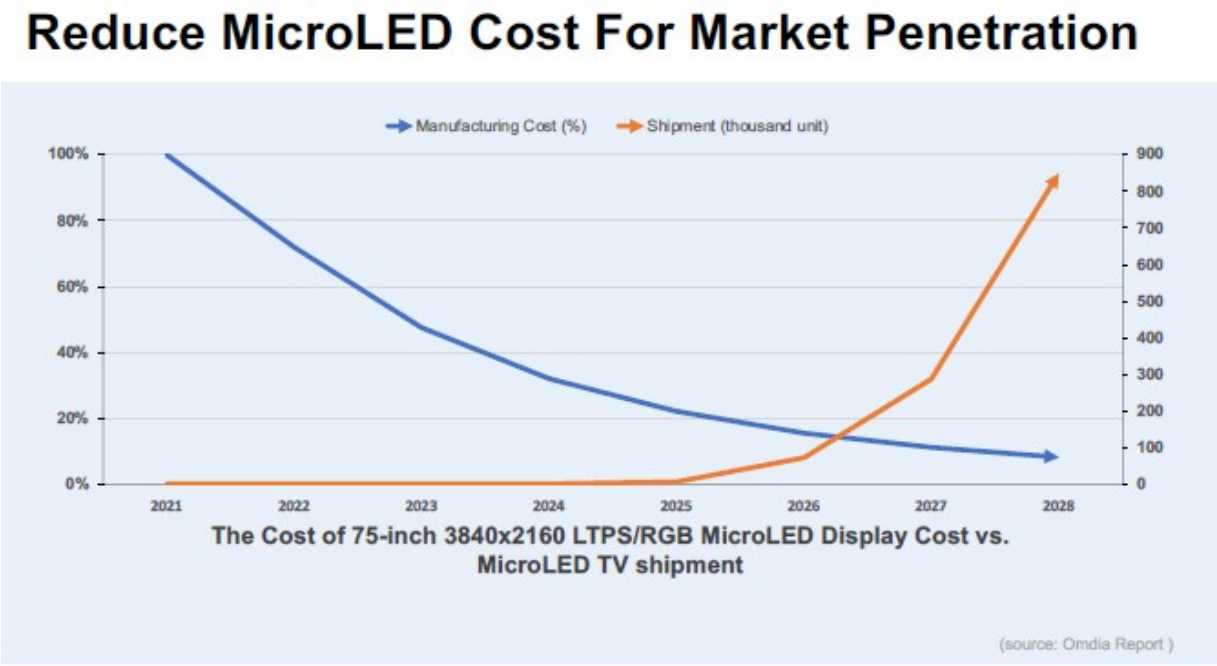
The challenges in developing a business in microLED technology can be illustrated by financial reports from PlayNitride. The next chart shows that the sales grew steadily between 2022 and 2024 and losses decreased substantially.



For the whole year of 2024, revenues were Tw$1768M, up from Tw$943M in 2023, while losses shrunk to Tw$60M from Tw$513M. The progress continued into 2025Q1 with sales up to Tw$300M from Tw$206M and losses down toTw$51M from Tw$86M.

However, the situation changed dramatically in the 2nd quarter of 2025[36]. Sales decreased by 37% to Tw$205M and their net loss rose to Tw$370 from Tw$31M a year ago. According to its shareholder Ennostar, PlayNitride's widening losses and revenue drop were caused by ongoing inventory adjustments and unfavorable foreign exchange rates as well as weak customer demand. It will be interesting to see their results for the whole of 2025

Cost is clearly a major factor in the success or failure of large microLED displays. The next chart from Omdia shows that significant progress has been made but much further improvements are needed.



The major application envisaged for microLEDs is in displays, but there is great interest in their potential use in medical diagnostics and treatment, as described in a blog from InZiv[37].

The potential medical applications have been summarized enthusiastically by researchers from Xiamen and Dongguan in an article in Advanced Photonics Nexus[38]: *"Micro-scaled light-emitting diode (LED) technology has emerged as a transformative tool in biomedical applications, offering innovative solutions across disease surveillance, treatment, and symptom rehabilitation. In disease surveillance,*

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[36] https://www.microled-info.com/playnitride-reports-its-financial-results-q2-2025-drop-revenue-and-increase-net

[37] https://inziv.com/blog/beyond-displays-the-surprising-role-of-microleds-in-medicine-and-biology/

[38] https://www.spiedigitallibrary.org/journals/advanced-photonics-nexus/volume-4/issue-05/054001/Recent-developments-of-micro-scaled-LED-based-technologies-and-mechanisms/10.1117/1.APN.4.5.054001.full

micro-scaled LEDs enable real-time, noninvasive monitoring of physiological parameters through wearable devices, such as skin-like health patches and wireless pulse oximeters; these systems leverage the miniaturization, low power consumption, and high precision of micro-scaled LEDs to track heart rate, blood oxygenation, and neural activity with exceptional accuracy.

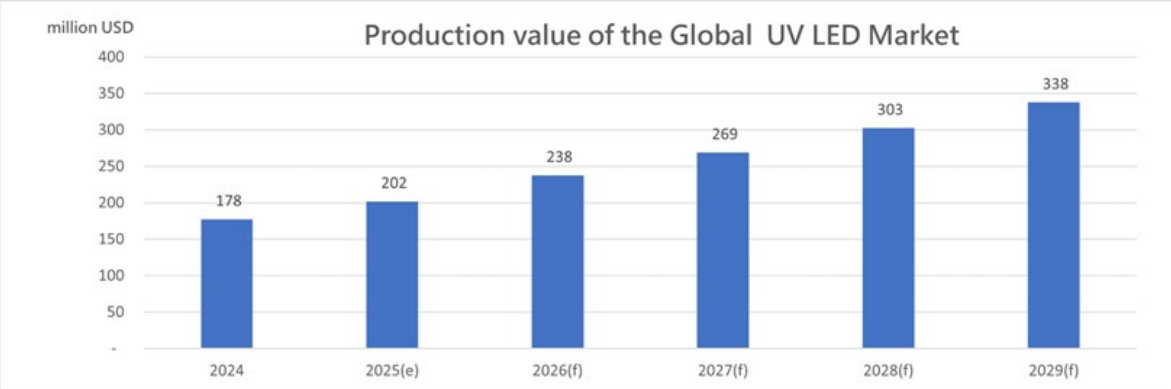
For disease treatment, micro-scaled LEDs play a pivotal role in optogenetic stimulation and phototherapy. By delivering specific light wavelengths, they enable precise cellular control for cardiac regeneration, neural modulation, and targeted cancer therapies, such as photodynamic therapy with reduced invasiveness.

In addition, wireless micro-scaled LED systems facilitate localized and sustained treatments for conditions such as diabetic retinopathy. For symptom rehabilitation, micro-scaled LED-based devices enhance functional and aesthetic outcomes, exemplified by optical cochlear implants for high-resolution hearing restoration and flexible photostimulation patches for hair regrowth. The performance of micro-scale LEDs also brings new possibilities to the field of brain–computer interface.

These applications highlight the versatility of micro-scaled LEDs in improving patient quality of life through minimally invasive, energy-efficient, and biocompatible solutions. Although there are still challenges in long-term stability and scalability, the integration of micro-scaled LEDs with advanced biomedical technologies promises to redefine personalized healthcare and therapeutic efficacy."

4.6 UV LEDs

In March 2025, TrendForce released the following forecast of the global market for UV LEDs.



TrendForce also provided insight into the trends in most major applications of UV-LEDs[39].

Among the market leaders, Seoul Viosys had a good year in 2024, with sales rising by 39% to KrW699B. It achieved a small profit of KrW4B, following losses in the previous two years. The revenue growth

[39] https://www.trendforce.com/news/2025/03/31/insight-2025-deep-uv-led-market-trend-and-product-analysis-water-sterilization-ushers-in-a-new-era/

continued into the first half of 2025 at KrW356B versus KrW336B in the previous year. Profitability fell in the first quarter but rebounded in the second.

Forecasts for global sales in 2024 of VUV lighting devices are mostly in the range of $1-2B, with the share of UV-C being around one third.

In October 2025, ams OSRAM claimed a technological breakthrough in UV-C LEDs. The LED delivers over 10% efficiency at 200 milliwatts power, a wavelength of 265 nanometers, and a lifespan exceeding 20,000 hours. The efficiency has been validated by Germany's National Metrology Institute Physikalisch-Technische Bundesanstalt (PTB).

This new LED seems to provide a significant improvement in efficiency over its major competitors. The NCSU434D from Nichia provides 135mW of output flux at 280nm with efficiency of 7.4%, while the CUD72F1B from Seoul Visosys delivers 25mW at 275nm with 4.5% efficiency. The S3535-H from Bolb has an output of 150mW at 265nm with efficiency of 6.6% from 150mW from input of 2275mW but has not yet been widely tested in the international market. However, these results are still well below that of traditional UV lamps, which offer wall- efficiencies of up to 40%.

The use of UV-C treatment for air treatment has been restricted because of concerns about damage to humans and other animals. New regulations have been released in the US by the Federal Drug Administration[40].

A trial of the effects of VUV disinfection of room air was carried out a childcare facility in Austria[41] . UV-C LEDs from Lumitech were installed in the room ceiling and operated overnight. Occupancy sensors were used to ensure that no humans were present while the LEDs were on. The results showed that when combined with manual cleaning, germ loads decreased by over 80% at the start of each day's session but rose steadily while the room was occupied.

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[40] https://www.infectioncontroltoday.com/view/fda-clearance-marks-new-era-uvc-disinfection-health-care

[41] Stefanie Kern, "How Automated, Chemical-free UV-C LED Systems Significantly Reduce Microbial Load in Real-world Conditions", Lighting Professional Review, 110, pp26-30

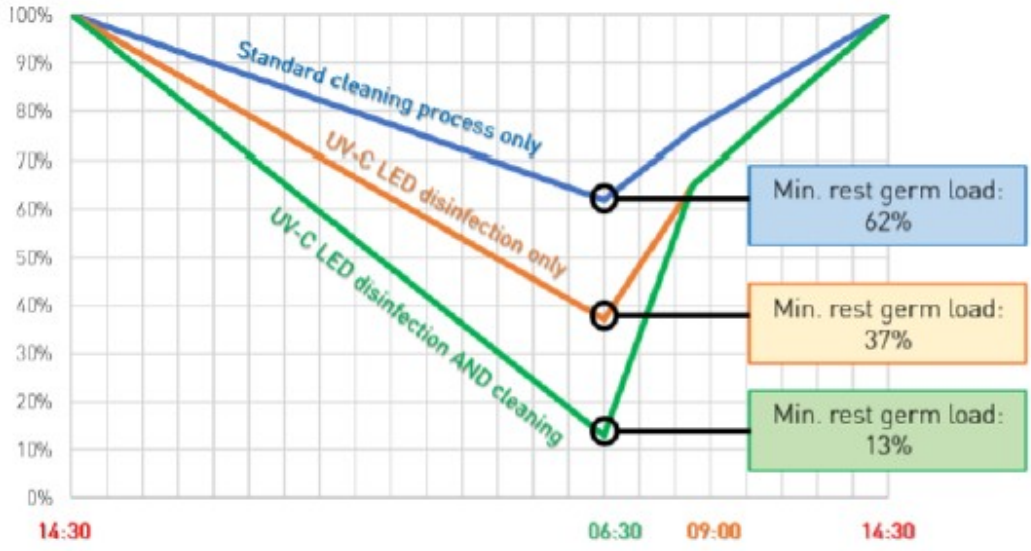

Figure 8: Comparison of resulting germ load curves for the different test setups.

Perhaps this study indicates that UV-C disinfection might be more effective if used continuously in an enclosed part of an HVAC system

Some researchers and suppliers[42] have argued that irradiation at wavelengths of 222nm or lower can be tolerated because the radiation is absorbed in the outer layers of skin and eyes that are discarded and replaced regularly. However, it is crucial to use specialized filters and control exposure levels to prevent harm.

The efficacy and safety issues of 222nm radiation were reviewed recently in the Journal of Hospital Infection by a team from the Huazhong University of Science and Technology[43]. They concluded that, compared with 254-nm UVC, 222-nm UVC not only exhibits comparable or potentially superior efficacy in disinfecting diverse micro-organisms but also causes less DNA damage to mammalian cells.

222nm light has also been proposed for use in dermatology and wound treatment, as reviewed by a team from the Korea University College of Medicine[44].

The health hazards of UV can be avoided by using them in enclosed environments, such as HVAC installations or water treatment. A thorough review of the design of devices for water treatment has been published in the Journal of Environmental management by researchers from the University of British Columbia[45].

Most of the research on UV LED disinfection has focused on drinking water applications, but UV disinfection is also commonly used in wastewater facilities. According to a report in Waste Treatment

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[42] https://uvmedico.com/news/far-uvc-and-eye-safety

[43] https://doi.org/10.1016/j.jhin.2025.04.004

[44] https://doi.org/10.25289/ML.24.009

[45] https://www.sciencedirect.com/science/article/pii/S0301479725016548?via%3Dihub

X[46], the overall market for industrial wastewater treatment is estimated to grow to $16.5B by 2026 and the average global cost of wastewater infrastructure is estimated to be upwards of $100B. This report describes the installation and testing of a 280nm UV LED reactor. The authors conclude that UV LEDs are an effective wastewater disinfectant at-scale and are comparable to conventional low-pressure UV systems.

4.7 Near IR LEDs

Most market analysts predict that the market for IR LEDs is increasing steadily and was around $750M in 2025. The leading manufacturers include AMS Osram, Ennostar, Everlight and Nichia.

It has been reported[47] that over 60% of security cameras worldwide use IR LEDs. 850 nm IR is often described as the preferred wavelength for the majority of video surveillance and CCTV systems, as it provides the best combination of sensor sensitivity and illumination distance. However, 940nm radiation is more difficult to detect and so is recommended for covert operations. In the automotive industry, IR LEDs are fundamental to night vision systems and other driver assistance technologies that enhance vehicle safety and performance.

Several industrial and consumer applications of IR LEDs have described by Digikey[48].

"Photoelectric smoke detectors - IR LEDs use the basic principle of object intrusion to detect the presence of smoke, utilizing an emitter and a photodetector in the same unit. Under routine operating conditions, the LED emits infrared radiation which causes the detector to produce an electrical current. The presence of smoke, however, disrupts the path of the radiation and scatters it. As a result, the net current registered by the photodetector decreases and triggers an alarm. IR LEDs are especially useful in this application due to their ability to penetrate smoke and detect smaller and denser particles.
Home appliances - In addition to their use in remote controls, IR sensors in washing machines can detect water levels, while robotic cleaners utilize IR sensors to avoid obstacles in the mapped path. Similar sensors in microwaves can detect an open door and issue alerts. Automatic faucets, soap dispensers, and hand dryers can all use the obstacle and proximity sensing capabilities of IR LEDs.
Safety light curtains - The IR LED safety light curtain works on the principle of object detection to prevent mishaps. It consists of an array of IR LED emitters with photodiodes serving as receivers. The LEDs emit synchronized and parallel IR light beams, covering the entire area that needs to be monitored. As a result, the grid is bathed in IR light, which is modulated to a specific and unique frequency that the photodiodes detect. When the IR curtain has an object in its field, it likely indicates an unsafe situation and can trigger warnings. For example, if a hand or an arm enters the beam field, the machine can shut down automatically to prevent injury.
Smart utility meters - IR LEDs are used in smart utility meters for bidirectional data transmission over short distances. IR LEDs transmit encrypted infrared light pulses, which are received by a photodiode on the data collection device. The pulses can relay a range of digital information, from energy consumption readings to diagnostic data. For added security, the IR pulses have a special signature that the detectors use for verification."

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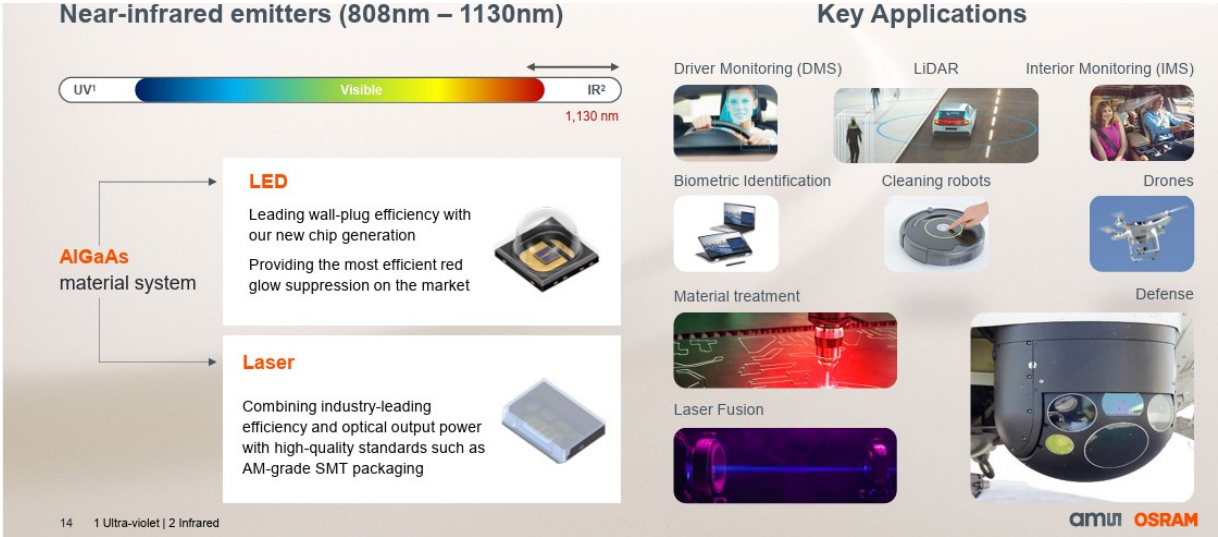
[46] https://www.sciencedirect.com/science/article/pii/S2589914724000264?via%3Dihub

[47] https://www.globalgrowthinsights.com/market-reports/ir-led-market-107003

[48]



Proponents[49] have argued that the strong tissue penetration capability of near infrared radiation (NIR) combined with extremely low heat generation make it an ideal choice for non-invasive therapy and bioimaging. For example, 730 nm light excels in skin phototherapy, effectively promoting collagen regeneration and improving skin condition. 850nm NIR LEDs serve critical roles in medical devices such as phototherapy units and pulse oximeters, as they can effectively penetrate the skin and detect hemoglobin concentration. In clinical treatment, the 810nm light band is widely applied in neuro-regeneration and dental therapy due to its selective stimulation of deep tissues.

The most commonly used semiconductor materials in infrared LEDs are GaAs, GaAlAs, InGaAs and GaAsP. Although efficiencies have traditionally been in the range of 30-40%, AMS Osram has introduced emitters with internal efficiencies up to more than 60%[50]. The SFH4715B provides a radiant flux of 1050mW with a peak wavelength of 858nm from an input power of 1.6W, while the SFH41847 has an output of 1565mW at 950nm from 2.8W of input power.

Other developments in commercial products have focused on miniaturization, improved thermal management, and integration with other components (e.g., photodiodes in proximity sensors).

The smaller devices for medical monitors have more modest efficiency. For example, the SFH4050 package from AMS Osram has dimensions of only 1.7 mm x 0.8 mm x 0.65 mm. The radiant flux is 60mW at 860nm from an input power of 180mW. Further improvements in efficiency at lower would increase the value of the technology in portable and battery-powered applications like wireless security cameras, wearable health records monitors, and remote sensing instruments.

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[49] https://www.superlightingled.com/blog/differences-between-nir-led-near-infrared-light-wavelengths/

[50] https://www.semiconductor-today.com/news_items/2024/oct/amsosram-221024.shtml

4.8 Smart Lighting Systems

The addition of sensors and controls to LED lights is becoming common across the globe. For example, Signify had installed 156M smart lighting nodes by 2024.

In China, the number of large-scale smart lighting companies reached a record over 3,600, representing a year-on-year increase of approximately 2%[51]. Amidst economic pressure, smart lighting companies saw revenue growth exceeding 7%. The overall industry's loss-making situation narrowed, with both the number and value of loss-making companies decreasing. In addition, there are around 100,000 small companies involved in smart lighting, leading to intense competition that may result in many bankruptcies.

According to a report released by the China Business Industry Research Institute[52], China's smart lighting market shipments reached approximately 34 million units in 2023, a year-on-year increase of 21%, and approximately 40 million units in 2024. Shipments are expected to reach 47 million units in 2025. Revenues were estimated to be US$22 billion in 2024 and may reach US$26 billion in 2025. Ceiling lights account for the largest share of the Chinese smart lighting market (28.8%), followed by switches (19.3%), downlights/spotlights (16.5%), bulbs (14.8%), and table lamps (9.9%).

Most large international companies are focused upon outdoor lighting as part of smart cities programs. According to the IoT analyst firm Berg Insight[53], *"the installed base of smart streetlights amounted to 32.9 million globally at the end of 2024. Growing at a compound annual growth rate (CAGR) of 20.9 percent, the installed base may reach 85.0 million by the end of 2029. Europe leads the adoption of smart street lighting technology and accounted for as much as 35 percent of the global installed base in 2024. North America is catching up with Europe and is growing robustly, accounting for around a third of global shipment volumes in 2024. China was at the same time home to almost half of the installed base of smart streetlights outside Europe and North America"*.

The Northeast Group maintains a database on the global market for both LED and smart street lighting covering 125 countries[54]. This includes 250 smart street lighting projects globally totaling more than 23 million streetlights that are ongoing or in the planning stages.

The development of smart and sustainable lighting is now the focus of the IEA-4E working group through the SSLC Platform, under the leadership of the four European experts shown below.

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[51] https://www.alighting.com/news_show.aspx?id=176825

[52] https://www.alighting.com/news_show.aspx?id=177080

[53] https://www.berginsight.com/the-installed-base-of-smart-street-lights-is-on-track-to-surpass-100-million-before-the-end-of-the-decade

[54] https://northeast-group.com/research-catalogue/

Prof. Georges Zissis

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Peter Bennich, Ph.D.

Deputy Chair, SSLC Platform
Management Committee

Nils Borg
Manager
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Michael Scholand, LC
Deputy Manager
SSLC Platform

The SSLC Platform is currently engaged in eight tasks

- Task 1. Lighting Product Database and Performance Tracker
- Task 2. Smart Lighting: Testing, Controls and Systems
- Task 3. Technology Roadmap Development
- Task 4. Lighting and Health Impacts
- Task 5. Energy, Material and Environmental Impacts
- Task 6. Recommended Quality and Performance Requirements
- Task 7. Interlaboratory Comparison
- Task 8. Support for International Standards, Metrics and Measurements

Their work was described in more detail at an ISA-BRICS Workshop in 2024[55]

As noted above, most of the early installations of smart lighting systems were in Europe and North America. The following table gives examples of projects in which the anticipated goals were met.

City/Project	**Projected Savings**	**Actual Savings/Result**	**ROI/Payback Period**
Los Angeles	60%+ energy cut	63% reduction, 47,000 tons CO_2 cut	Met targets, fast ROI

[55] www.iea-4e.org/wp-content/uploads/2025/02/SCHOLAND-SSLC-Platform-Overview-for-BRICS-ISA-Conference-in-Shenzhen-China.pdf

City/Project	Projected Savings	Actual Savings/Result	ROI/Payback Period
NYPA/Signify	Price reduction, >50M kWh cut	Exceeded cost savings, on budget	Shortened ROI, aggregation helped
Paris/Madrid	70% energy cut	70% actual savings	Met/exceeded projections
Sheffield, UK	50% energy cut	60% actual savings	On or ahead of schedule
El Paso, TX	2+ million USD/year	On or above track	Projected break-even met

Applications are now spreading across the globe. In October 2025, the ISA BRICS working group held a 2-day workshop on smart lighting which focused on streetlight applications. As a follow-up to this meeting, ISA is preparing a special report on smart and solar lighting in developing economies which should be available in the first half of 2026.

5 Effects on Human Health

There are many ways that artificial life can impact human health, either directly or indirectly. Most of the concern about potentially harmful effects relates to the impact of blue light during the evenings and night-time. A thorough review was published in 2024 by a team led by Christophe Martinsons[56]. This report was prepared as part of the IEA-4E Smart Sustainability in Lighting and Controls Program[57]. Other recent reviews have been provided by lighting designers in the IALD magazine[58] and a physician in the American Medical Association's Journal of Ethics[59].

5.1 Circadian Effects

The contrast between bright light during the daytime and dim light at night is critical in enabling optimal activity and refreshing sleep. Disturbance of the circadian rhythm clearly affects one's mood and acuity, leading to accidents or impaired performance. Many indirect effects have been suggested, but the severity of each deserves further research and elucidation. These include

- Cardiovascular and metabolic disorders- impaired vascular function, glucose metabolism and hormonal imbalance may lead to heart disease, diabetes and obesity
- Cancer – studies on shift workers have detected a higher risk of breast, prostate and colorectal cancer. Possible mechanisms for this increase in cancer risk include reduced melatonin secretion, disrupted circadian rhythms, chronic inflammation, and changes in the action of various genes
- Immune system and inflammation – impaired timing of immune cell activity may increase susceptibility to infections and slow recovery
- Gastrointestinal and digestive health – increased risk of ulcers, irritable bowel syndrome and indigestion
- Cognitive and mental health – poor circadian alignment impacts memory, attention and learning capacity and may accelerate cognitive decline.

Expert consensus[60] suggested in 2022 that daytime light exposure should be above a melanopic Equivalent Daylight Luminance (EDI) of 250 lux, measured at the plane of the eye. The IEA-4E team warns that *"If electric lighting is the only light source, this is a difficult target to achieve within current energy regulations in most jurisdictions, even with energy-efficient SSL products. Further research is needed to determine whether a shorter duration of exposure at this level might be acceptable.*

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[56] https://www.iea-4e.org/wpcontent/uploads/2024/06/HEALTH-REPORT-IEA-4E-SSLC-Platform.pdf

[57] https://www.iea-4e.org/ssl/

[58] https://iald.org/IALD/IALD/Store/Item_Detail.aspx?iProductCode=IR-2025-WP-LDH&Category=IR

[59] https://journalofethics.ama-assn.org/article/were-all-healthier-under-starry-sky/2024-10

[60] https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.3001571

Furthermore, more research is needed to know if there is an equivalency between shorter exposures at a higher level, and longer exposures at a lower level".

5.2 Photobiological Damage

The IEA-4E study concluded that *"The general population should not be concerned by potential risks to the skin arising from the use of LEDs in lighting. Only a small number of people suffering from photosensitive syndromes might see an aggravation of their pre-existing conditions triggered by the shortest wavelengths of visible light emitted by LEDs. Patients taking photosensitizing drugs should also be aware of a potential risk".*

Damage to the retina is of greater, but limited concern. Although there is little risk from the use of most LEDs in general illumination, further research is needed into the impact on highly sensitive groups, such as infants and those with retinal diseases.

The major risk comes from the use of lamps with wavelengths below 430nm. VUV sources that peak around 250-300nm should not be used in spaces occupied by humans or animals. However, as discussed in section 4.6, recent research has suggested that light of wavelengths around 222nm does not penetrate beyond the outer dead layer of human skin or the tear layer of the eye and may not cause any permanent damage.

5.3 Glare

The CIE makes a distinction between disability glare which reduces visual performance and discomfort glare which makes the observer feel uncomfortable without causing a reduction in their visual performance. Although the high intensity of individual LEDs can lead to glare for individuals close to the light, most luminaires use optical systems to spread the light.

The IEA-4E report concludes that *"SSL products, even with their specific spectral and spatial distributions of light, have not changed the occurrence of disability glare that has been experienced with high power luminaires used outdoors at night".*

The effects of glare from outdoor lights can extend over large distances, disturbing night-life and obscuring the night sky[61]. The higher brightness and greater blue content of many outdoor LEDs has increased concern about these effects. On the other hand, the optical systems in LED luminaires provide greater control over the distribution of light and can lead to substantial reduction in the production of stray light[62].

Glare from headlights has always been of special

[61] https://darksky.org/news/light-is-energy-esti
on-climate-change/

[62] https://www.creelighting.com/insights/article/
light/

concern, both to drivers and pedestrians. With traditional sources dimming systems have been used to ameliorate the effects. Pixelated LEDs with an adaptive control system offer a more effective way to minimize the risks from disabling glare.

5.4 Temporal Light Modulation

Temporal Light Modulation (TLM) arises from the responsiveness of the light source or lighting system to changes in the input power. It can result in flicker, rapid oscillations in brightness or colour of the light, but its effects can be more subtle. As discussed in the IEA-4E report, it can trigger a broad range of neurological, perceptual, health and cognitive outcomes. These commonly include eyestrain, headaches and fatigue. Sensitive individuals might experience more serious consequences such as migraine and photosensitive epileptic seizures.

TLM occurs with most electric light sources but has increased in complexity and importance with the development of LED devices. There is special concern with dimmable lighting systems, which are increasingly common as part of dynamic lighting and daylight-linked control systems. Pulse Width Modulation is the most common form of dimming for LED products and often introduces rectangular wave TLM to the light output. Rectangular waveforms show consistently show the most problematic outcomes for observers.

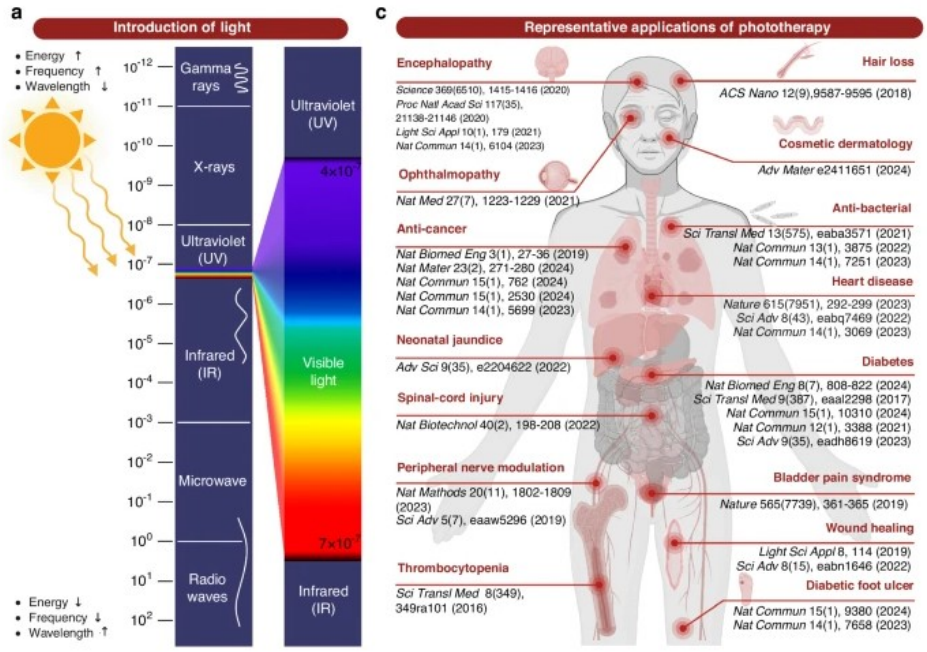
However, flicker may not be due to the LEDs but can also result from loose wiring, incompatible dimmer switches or voltage fluctuations in the external circuits,

5.5 Applications of SSL in Medical Treatment

Phototherapy offers advantages of non-invasiveness, cost-effectiveness, localized treatment, and potential across various medical conditions. However, its adoption is hindered by the large size, limited safety, and professional operation requirements of traditional phototherapeutic devices. Unlike bulky laser phototherapeutic devices, wearable and implantable LED-based devices overcome these limitations, offering improved safety, portability, and uniform light distribution. OLEDs are particularly suitable for wearable devices.

The applications of phototherapy have been reviewed recently by a team from Shanghai[63].

[63] https://www.nature.com/articles/s41377-025-01990-z



The flexibility offered by SSL sources means that the spectrum can be tuned for each application.

- UV light (200 - 400 nm) addresses skin conditions and tumors.
- Blue light (450 - 490 nm) is used for antibacterial therapy, neonatal jaundice treatment and in endoscopy
- Green light (495 - 570 nm) aids in retinal therapy and pain relief.
- Yellow light (570 -590 nm) enhances immune function and improves mood
- Red light (620 -750 nm) promotes wound healing, hair growth and deep-tissue phototherapy
- Near-infrared lights (700 - 2500 nm) are effective for pain management

LEDs have led to a significant improvement in lighting in hospitals and other health-care facilities[64]. The impact on operating rooms has been summarized by Lumitex[65]:

- Provide consistent, shadow-free illumination of the surgical site
- Render tissue colors accurately to support real-time diagnostic decisions
- Preserve depth perception for more precise and reliable spatial awareness
- Avoid excessive heat or glare that can cause fatigue or interfere with procedures

[64] https://facilitymanagement.com/leds-healthcare-facilities/

[65] https://www.lumitex.com/state-of-medical-lighting-reports

6 Advances in LED Technology

White LEDs are now available with efficacy above 200 lm/W. For example, the following table shows the performance of the latest 3030 chip from Cree[66]. The efficacy can be even higher at 242lm/W for CCT 5000K and CRI 70, but drops to 208lm/W CCT 3000K and CRI 90.

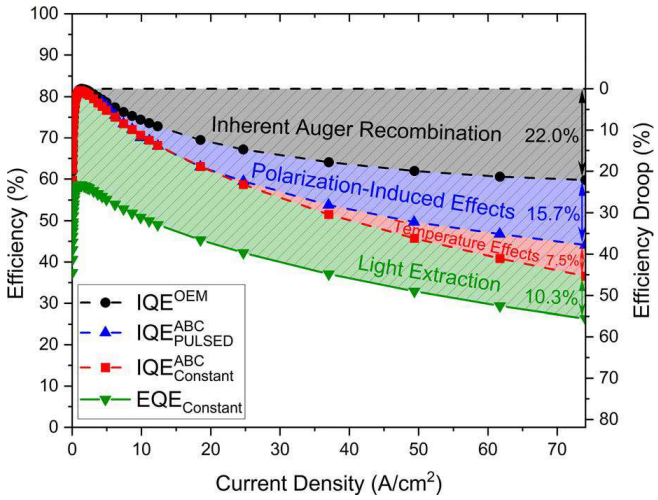
Product	Power Class	Test Temperature	Test Current	Typical Forward Voltage	4000 K, 80 CRI		4000 K, 90 CRI		Maximum Current
					Typical Flux	Typical Efficacy	Typical Flux	Typical Efficacy	
JB3030C 3-V E Class Pro9	0.2 W	25 °C	55 mA	2.66 V	34.2 lm	234 lm	31.2 lm	213 LPW	240 mA
JB3030C 3-V F Class Pro9	0.2 W	25 °C	55 mA	2.67 V	33.9 lm	231 lm	30.6 lm	208 LPW	240 mA

This variation results from the production of white by combining blue emitters with phosphors. The best blue LEDs have wall plug efficiency (WPE) of close to 80% while that for green or yellow LEDs is much lower. The conflict between efficacy and colour quality will continue until efficient emitters are available across the visible spectrum.

The following sections will highlight progress at for LEDs that peak at various wavelengths

6.1 Green LEDs

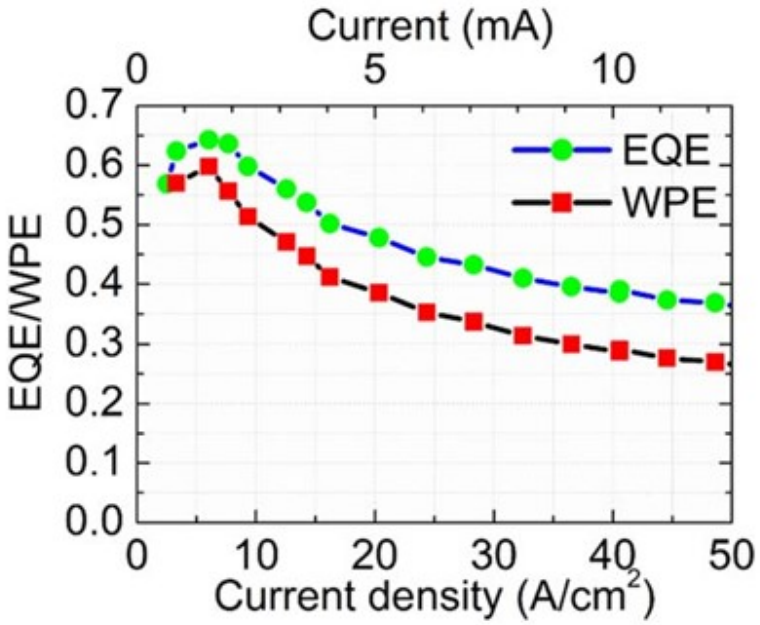
Although the WPE of some blue and red LEDs from Cree is over 80%, that of their XLAMP XP-E2 InGaN green LED is only 19% at 100 A/cm^2. A team from the University of Illinois at Champagne[67] has analyzed the losses in this system, as shown in the following chart.



[66] https://downloads.cree-led.com/files/ds/j/JSeries-3030-Pro9.pdf

[67] https://www.semiconductor-today.com/news_items/2025/jun/uiuc-120625.shtml

Research is underway in many laboratories to reduce these losses. By aluminum-treatment of the InGaN quantum wells, a team from China[68] has achieved 60% WPE at very low current density but this falls below 30% WPE at 50 A/cm^2.



Other researchers are developing alternative materials, including Cubic III-nitride active layers[69], perovskites[70], quantum rods[71] and quantum dots[72]. However, much further work will be needed before these materials can be used successfully in commercial devices.

Nichia has launched a white LED (NS2W806H-B2) designed for LCD backlighting[73] that contains a new green chip in addition to the existing blue chip. The peaky and narrow green spectrum is highly compatible with color filters, resulting in improved efficiency as a display module. However, the specs suggest that the efficacy is less than 20lm/W, with 10.6 lumens produced from 550mW.

6.2 Red LEDs

At least two suppliers have introduced red LEDs with WPEs that reach over 80%.
LPR 108: The XP-L Photo Red S Line LEDs represent a 6% improvement in typical Wall-Plug Efficiency (WPE) over the previous generation, reaching 83.5% at 700 mA and 25^{0}C. The OSCONIQ® P 3737

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[68] https://iopscience.iop.org/article/10.35848/1882-0786/adf593/pdf

[69] https://compoundsemiconductor.net/article/118346/newsletter

[70] https://doi.org/10.1002/adma.202506187

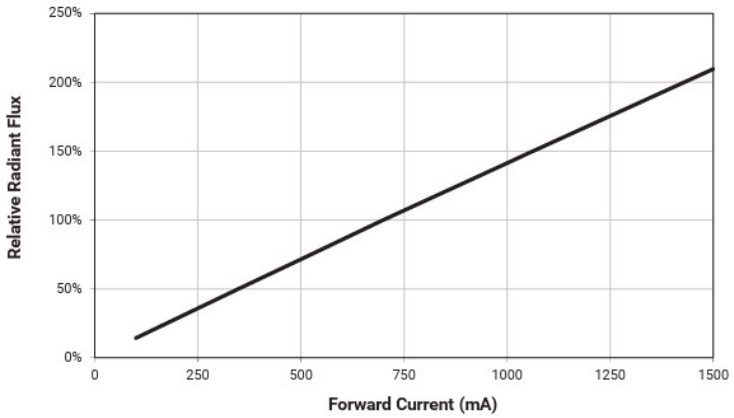
[71] https://www.alighting.com/news_show.aspx?id=176676

[72] https://advanced.onlinelibrary.wiley.com/doi/10.1002/adma.202503476

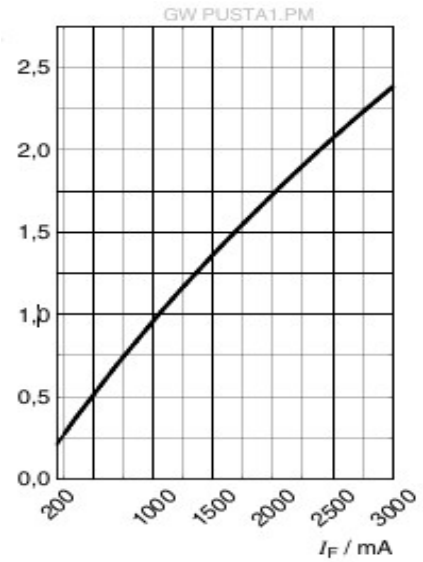
[73] https://www.nichia.co.jp/en/newsroom/2025/2025_012301.html

provides wall plug efficiency (WPE) of 83.2% in Hyper Red, enabling growers to achieve a photon flux of 6.13 µmol/s while reducing energy consumption.

The high efficiency of both sources holds up well as the brightness is increased, as shown in the next plots of radiant flux as a function of applied current .



Cree XP-L Photo Red S Line



AMS Osram OSCONIQ® P 3737

The impact of the various parts of the spectrum upon horticulture have been reviewed recently in Current Research in Biotechnology[74]. The range of Photosynthetically Active Radiation (PAR) is usually defined as 400-700nm. However, studies by Zhen and Bugbee[75] concluded that far red photons interact with shorter wavelength photons to increase the efficiency of photosynthesis. The results varied by plant species, and the effects were most noticeable when far red wavelengths of 700-750 nm were added to the full-spectrum range. Red leaf lettuce, corn, soybeans, and tomatoes had photosynthetic rate increases ranging from 20-30%. Kale had the highest rate of increase at 59%.

6.3 Blue OLEDs

Although inorganic LEDs are most efficient in blue, this is not the case for organic LEDs (OLEDs). Red and green phosphorescent OLEDs have high efficacy and long lifetimes, but the lifetime of blue phosphorescent OLEDs is too short for display applications. The fluorescent blue OLEDs are far less efficient, since photon emission only occurs from singlet excitons, while the dominant triplet excitons decay without producing light.

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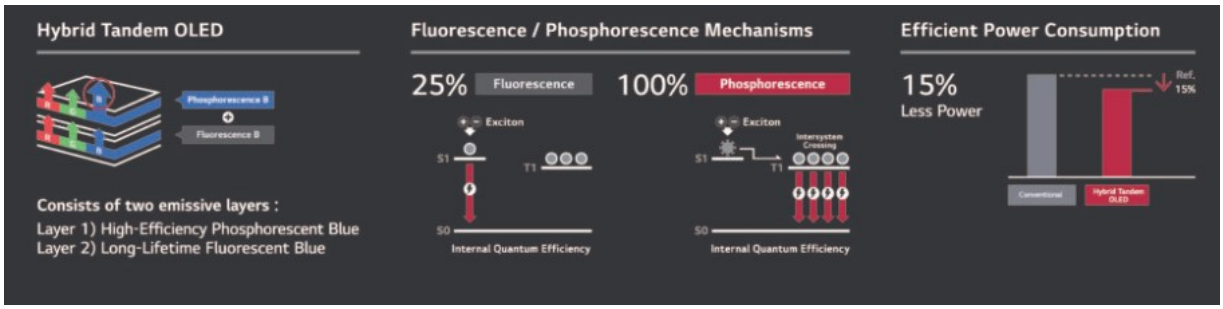
[74] https://www.sciencedirect.com/science/article/pii/S2590262824000108

[75] https://doi.org/10.1111/pce.13730

A partial solution to this problem has been offered by LG Display[76] though a hybrid two-stack OLED structure, with blue fluorescence in the lower stack and blue phosphorescence in the upper stack. By combining the stability of fluorescence with the lower power consumption of phosphorescence, it consumes about 15% less power while maintaining a similar level of stability to existing OLED panels.



6.4 Drivers

Although most LED drivers are still built around silicon MOSFETs and diodes, there is growing use in the use of wide bandgap GaN or SiC devices, epecially in high- power or high- density applications where they push conversion efficiency beyond about 92% and shrink size by up to ~40% versus silicon designs.

The status of the development of GaN-based drivers was described in recent article by Denis Marcon, General Manager of Innoscience[77]. He reports that efficiency can be increased typically from between 88-90% in a silicon MOSFET design to 93-94% with the GaN implementation. One high-power example is given of a reference design that reduces component count yet delivers 67% more power. The GaN LED driver requires 35% less PCB space and is 57% lower in profile than a typical silicon solution. Efficiency increases to 96%.

Although the potential advantages of SiC MOSFETs for use in LED drivers were identified ten years ago by researchers from the Wolfspeed[78], the current commercial devices from Wolfspeed are designed for application in electric vehicles, motor drives, power supplies and transportation. Their SiC materials are also used in radar, satellite and telecommunication applications.

The development of SiC technology has also been focused on high-power applications, but they are beginning to penetrate the mobile market through in backlights and charging systems.

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[76] https://news.lgdisplay.com/en/2025/05/final-step-to-achieving-dream-oled-lg-display-becomesworlds-first-to-verify-commercialization-ofblue-phosphorescent-oled-panels/

[77] https://www.led-professional.com/all/copy_of_led-professional-review-lpr-mar-apr-2025-issue-108

[78] https://www.powerelectronictips.com/driving-leds-with-sic-mosfets/