ISA
International SSL Alliance

ISA Global SSL Industry Quarterly Report

(2023-3)

International Solid-State Lighting Alliance

SSL Industry Quarterly Report 2023-3

Editor: J. Norman Bardsley

1. Introduction:

This edition begins with a summary of the report by the International Energy Agency on the use of electricity for lighting in buildings in 2022. The data confirm our assessment that the major global effect of the efficiency improvement brought by solid-state lighting (SSL) has been to make more and better lighting available, rather than in saving energy. The report does not include outdoor lighting, which has contributed significantly to the growth in demand for artificial light. So, the second part of chapter 2 discusses some of the trends in outdoor lighting, which is causing concern about the environmental impact.

This year has seen a major step in the move to ban fluorescent lights, both to increase efficiency and to reduce the use of mercury. Real progress in realizing the goals of the Minamata Convention has been slow, but the sale of most types of fluorescent lamps is now banned in Europe. The call for action has been led from Africa and other parts of the developing world and has been orchestrated by a broad coalition of international organizations. Chapter 3 describes the implications of the replacement of fluorescent lights and reviews the progress that has been made.

Cent events have led to substantial increases in the cost of energy, including electricity. This has retarded the growth of some SSL applications, such as in agriculture and UV disinfection. Chapter 4 is devoted to an analysis of horticultural applications. A great amount of research has been carried out to show the potential benefits that accrue from the flexibility of LED lighting. Powerful systems have been developed for dynamic control of the intensity, spectrum and spatial distribution of LED light. These systems add to the initial cost of the lighting and may require additional training for farm employees. Thus it is important that the industry develop accurate and objective cost models for the new technology.

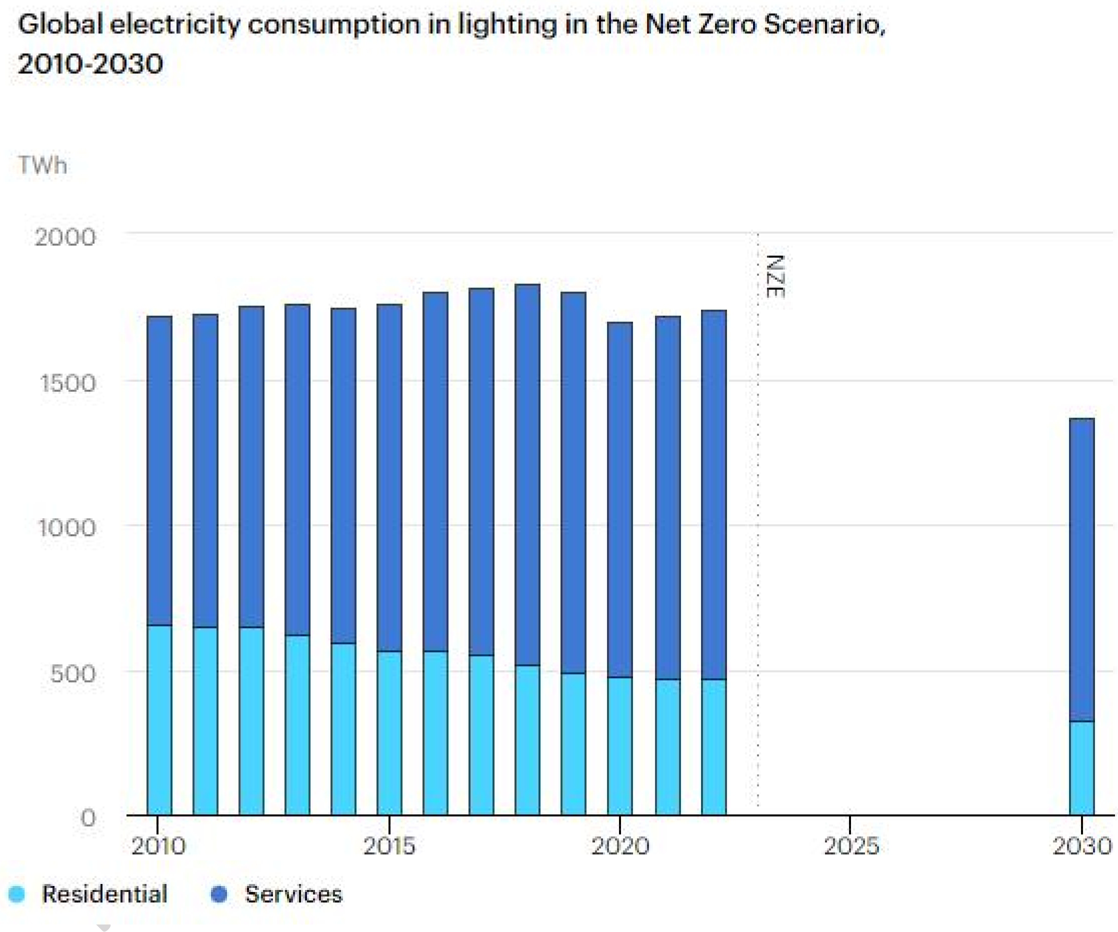
It should be stressed that the editor is not an expert on agriculture. Chapter 4 is not offered as an authoritative guide to horticultural lighting, but just uses recent reports to illustrate the issues that are involved and show examples of recent progress in the use of LED lighting systems.

2. Global Electricity Consumption for Lighting in 2022

Each year the International Energy Agency (IEA) issues estimates of the electricity used globally in buildings. They separate the buildings into two types, residential and services. The second category includes both commercial and government buildings. Outdoor lighting is not included. In this chapter, we will summarise the findings of the 2023 IEA report and sources of information on outdoor lighting.

2.1 IEA Annual Report for 2023

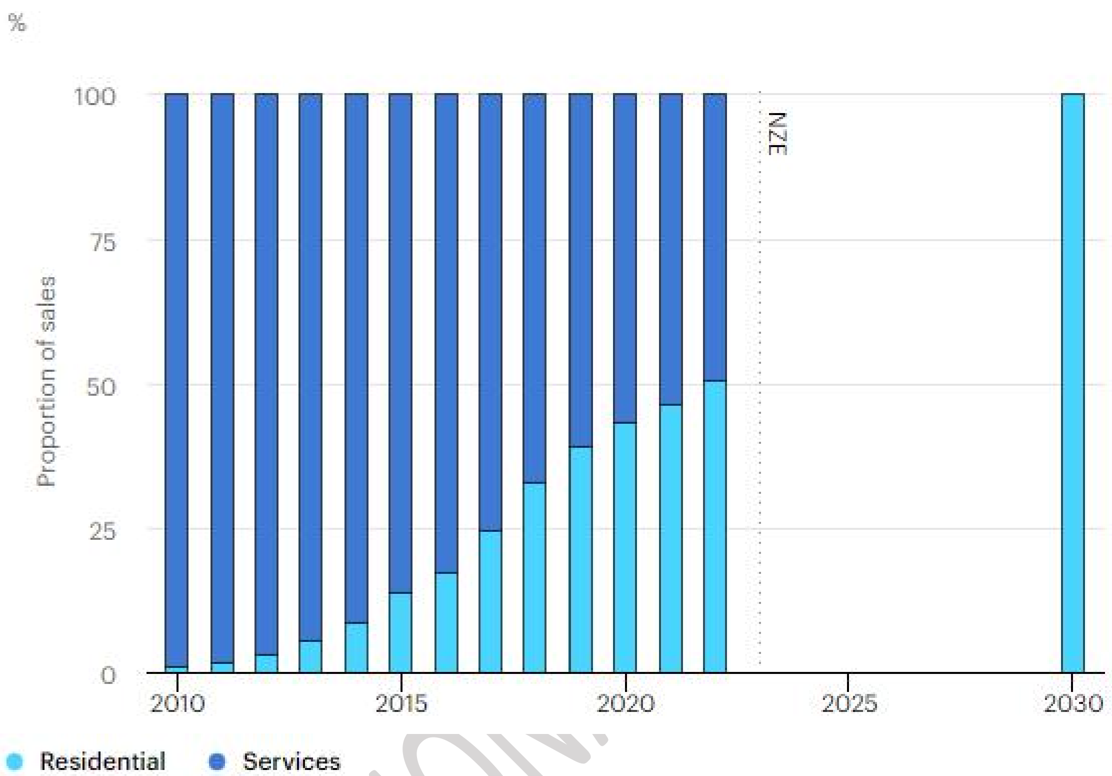
This chart shows the IEA estimates of the electricity used globally for lighting in buildings. The column for 2030 shows the target for 2030 in their Net-Zero CO_2 scenario. In 2022, the contribution from homes fell from 472TWh to 467TWh. However, that improvement was more than offset by the increase from 1242TWh to 1269TWh in non-residential buildings.



"Increasing building space and population are among the factors driving additional demand for lighting. With wealth increasing and the cost of lighting products falling, users can afford more lighting services – especially in emerging economies. This increased demand for lighting services is also being driven by rising populations and a growing number of households and especially floorspace. Building floor area has grown by about 60% in the past two decades and is set to increase by another 20% this decade, adding a total floor surface area of nearly 45 billion m^2, equivalent to about five times the floor area in

Indonesia today. These pressures are pushing up demand for lighting, highlighting the importance of deploying LED lamps in all markets to limit overall energy consumption.”

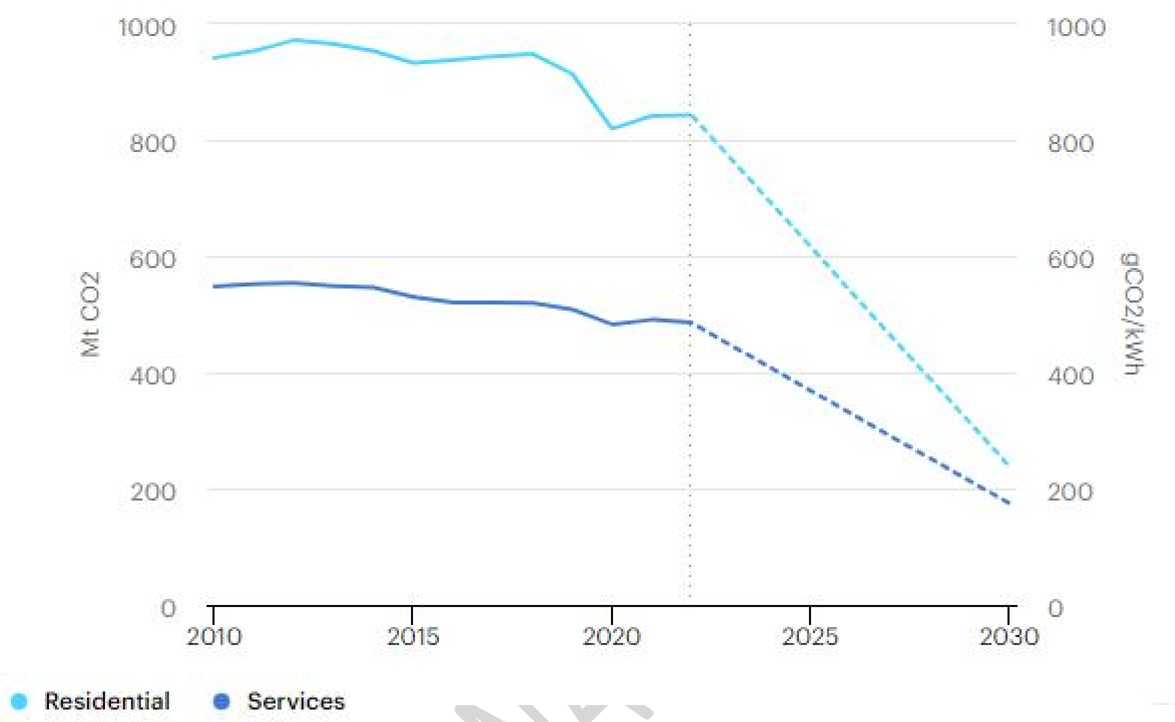
Global residential lighting sales share by technology in the Net Zero Scenario, 2010-2030



As shown in the next chart, IEA estimates that LEDs contributed 50.5% of lighting sales in 2022, up from 46.3% in 2021. They state that “To stay on track with the Net Zero Scenario, all lighting sales need to be LED technology by 2025, with higher efficacy levels by 2030”.

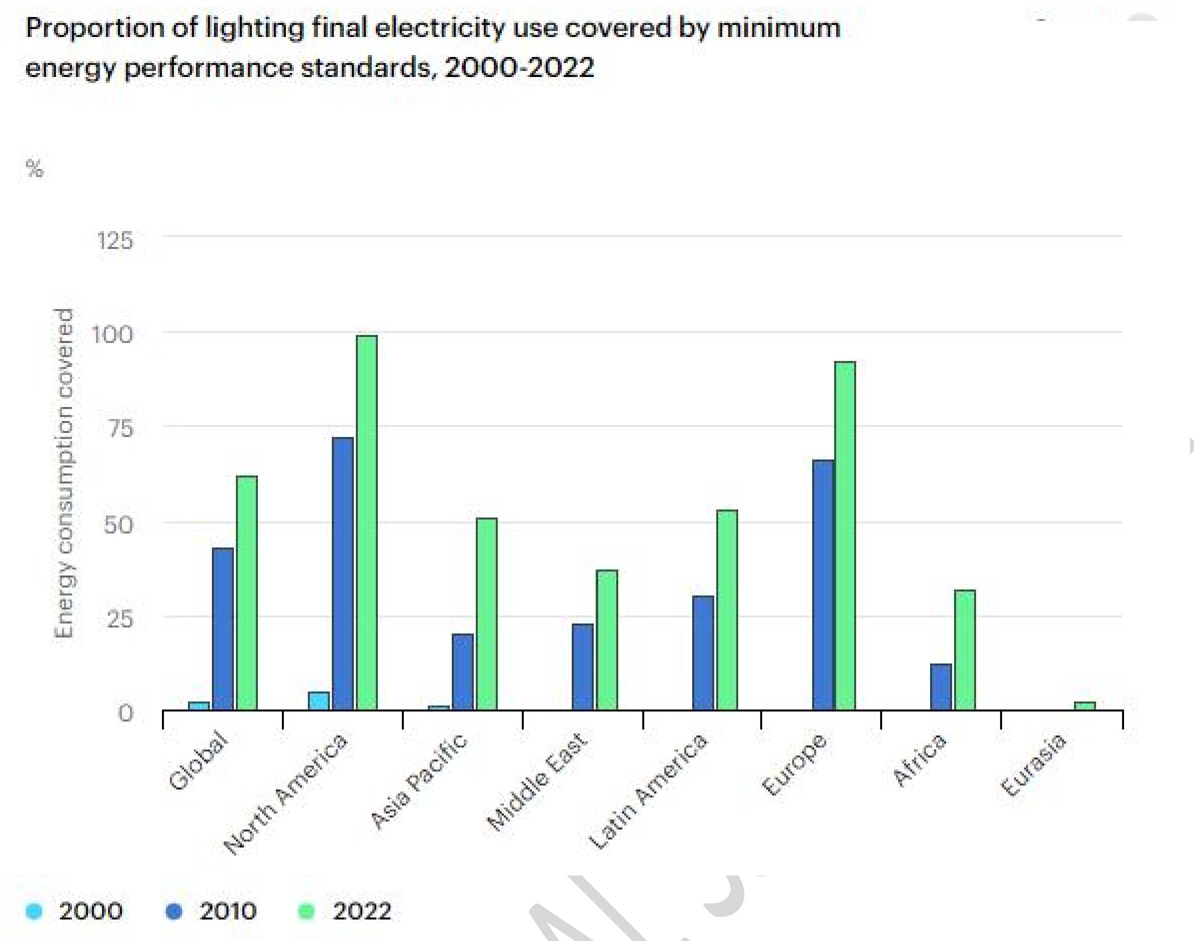
The need for accelerated progress is shown more clearly in the CO_2 emissions associated with lighting.

CO2 emissions and emissions intensity for lighting in the Net Zero Scenario, 2000-2030



The IEA estimates that the average efficacy of LED sources rose to 111lm/W in 2022 from 108lm/W in 2021. They believe that this "needs to reach 140lm/W by 2020 in order to reach the Zero-Net targets. Further advances could be made through advanced LED modules (e.g., consisting of multiple-chip packages on a printed circuit board), for instance, or continuous improvements in optics. Direct current (DC) grids also hold the potential to reduce losses from converting alternating current (AC) to DC (as LEDs run on DC)".

One of the means available to governments to encourage energy saving in lighting is to impose minimum energy performance standards. Over 60% of global consumption is now subject to such regulation, with the regional distribution shown below.



Further details on these rules are given in section 3.

2.2 Outdoor Lighting

The increased demand for outdoor lighting has led to concerns about the impact on animals and on the visibility of the night sky. Despite the efforts of many municipalities to reduce wasted light in the installation of LED luminaires, many observers believe that LEDs have negatively impacted the view of the night sky in many parts of the globe.

In August 2023, Lucia Barbera[1] reported that “Light pollution is threatening to do away with darkness and also has a significant impact on municipal budgets. Spain, for example, has nine million outdoor lights, which use up around 5,296 GWh of electricity each year, around 2% of the country's energy consumption.”

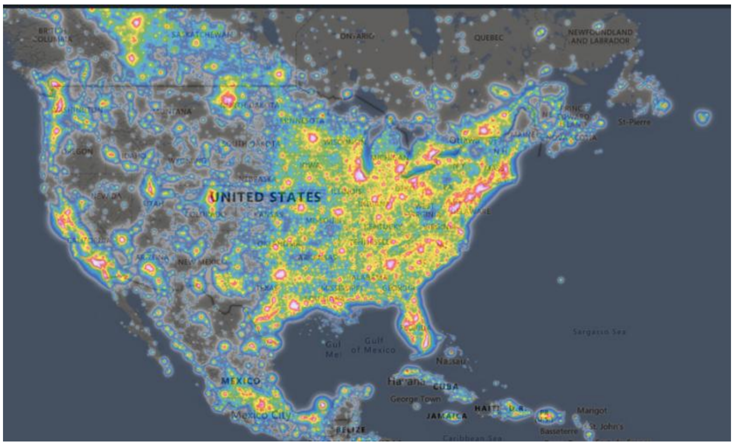
Although it seems clear that night-time light pollution is increasing, it is difficult to obtain accurate information on the impact of LEDs from satellite data, due to evolution in the imaging tools and the different spectra among light sources. Some critics have turned to subjective assessments of the visibility of stars to justify their concern. A recent article in Science Magazine[2] concluded that night-time light emissions rose by 9.6% per year between 2011 and 2022.

[1] https://tomorrow.city/a/where-is-most-electricity-wasted-in-cities

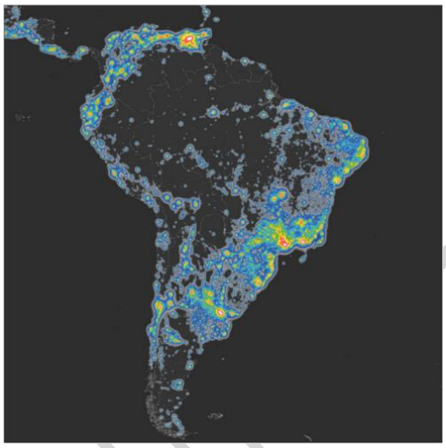
[2] https://www.science.org/doi/10.1126/science.abq7781

The following photos show satellite images of night lights for various world regions. The emissions are spread widely in North America, Asia and Europe, but are mostly localised to coastal regions in Africa and South America.

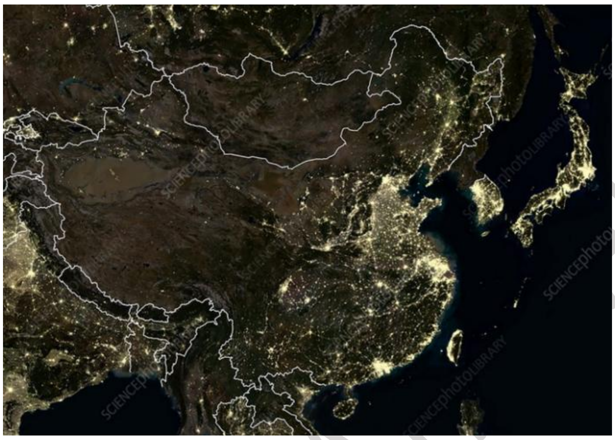
North America



South America

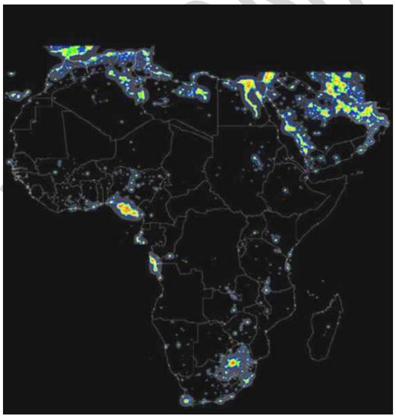


East Asia



South Asia

Africa



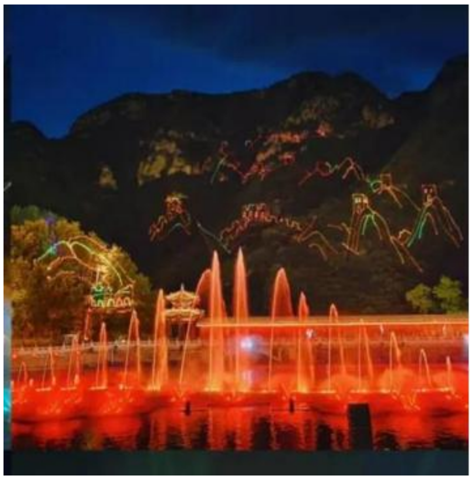
Europe

One trend that is increasing the environmental impact of LED lighting is the promotion of nighttime cultural tourism in China. According to the Ministry of Culture and Tourism, domestic tourism revenue was 2.3 trillion yuan, an increase of 96% over the previous year. Urban regions are major beneficiaries from this spending. According to a report on the

Aladdin Lighting Network[3], "With the promulgation of various policies to promote the development of the night economy, cultural and tourism night tour projects are frequently launched in many regions of the country, and "night tour" has become the way more and more people choose to play." Another article[4] reports that in the first half of 2023, nighttime cultural tourism consumption expenditure in Guangdong Province accounted for 61.62% of the total cultural tourism consumption expenditure, and the vitality of nighttime cultural tourism consumption has surpassed that of the daytime.

Cities are being innovative in competing in providing evening light shows for visitors. At the 20th China-ASEAN Expo, thousands of drones were launched to carry the lights. The photo below is from the CALI web site[5].

Much of the light created in such activities is meant to be seen from afar and some is even projected onto nearby mountains.



Some companies that focus on outdoor lighting have benefited greatly from this trend. For example, Roman Co., Ltd. achieved operating income of 202 million yuan in the first half of

[3] http://www.alighting.cn/news/20230829/175007.htm
[4] http://www.alighting.cn/news/20230829/175009.htm

[5] http://www.cali-light.com/index/index/newsart/id/25467.html

2023, a year-on-year increase of 127%, and a net profit of 36 million yuan, a year-on-year increase of 86%. During the reporting period, the company's main landscape lighting business continued to recover steadily, and the digital cultural tourism and digital intelligence new energy business segments achieved rapid and coordinated development.

China is also increasing investment in sports facilities. In the first half of 2023, the total number of sports venues across the country reached 4.509 million, a year-on-year increase of 6.7%. Huajing Industry Research Institute reports he global sports lighting revenues in 2023H1 were about 2.28 billion yuan, a year-on-year increase of 17%.

Even in the design of new indoor cultural venues, light is used to attract attention from outside, as well as for indoor illumination, as can be seen in these photos of the new Sanxingdui Museum.

In summary, many in the lighting community are working diligently to focus light and reduce wastage, while others are trying to spread the light widely. To assess the overall impact on global warming and light pollution, it would be very helpful to have accurate data on the global consumption of electricity for outdoor lighting and the amount of artificial light that is created.

3 Phase-out of Fluorescent Tubes

2023 may be a turning point in the long-awaited phase out of fluorescent tubes and the elimination of mercury from lighting products, with the ban on most sales in the Europe Union coming into force on September 1st. Some market research companies are sceptical that global sales will fall. Four recent forecasts predict that revenues will double in 7-8 years from the current value of around $7B with a CAGR of between 9.6% and 10.9%.

A series of valuable workshops has been arranged with many partners, including the Global Mercury Partnership, UNEP, United for Efficiency (U4E), the Clean Lighting Coalition (CLiC) and CLASP. They assess the status of the transition from fluorescent sources to LEDs, estimate the financial incentives to users in many countries and the environmental benefits in terms of mercury release and CO_2 production. In this section, we review highlights from the meeting entitled ‘Transitioning to

Mercury-Free Lighting in Asia-Pacific Countries' held in Geneva on June 20-21 [6]. Some additional information was provided in an on-line event on August 31 [7].

The next Table compares the amount of mercury in various products. The content of each lamp is relatively small, but there are so many of them that the total contribution is significant.

Mercury content in lamps versus other MAPs

Compact fluorescent lamp	5 milligrams or less
Linear fluorescent lamp	5-10 milligrams
thermometer	500 milligrams
thermostat	4 grams
Sphygmomanometers	50-140 grams
Flow meters	5,000 grams
Barometers	400-620 grams
Manometers	30-75 grams
Pyrometers	5-10 grams
Hydrometers	<1 gram
Psychrometers	<1 gram
Relays	.005->1 gram
Tilt switches	0.5-5 grams
Float switches	0.1-70 grams
Flame sensors	>1 gram

Mercury Policy Project

zero Hg mercury working group

3.1 The Challenge

The most recent thorough analysis of the global sales and installed base of fluorescent lights is for 2019 and was published in the 2020 reports from Strategies Unlimited on Lamps[8] and Luminaires[9]. In the Table below, the data for linear fluorescent tubes (LFL) is compared with that for LEDs.

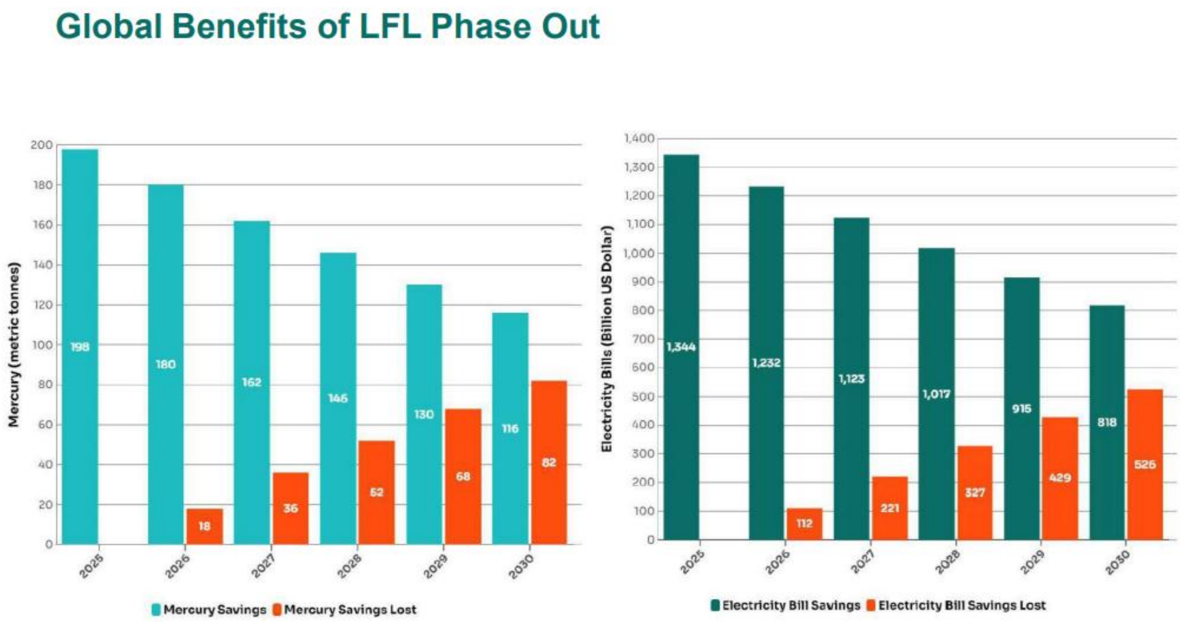
	Tubes				Luminaires			
2019	Unit Sales (M)		Installed Base (M)		Unit Sales (M)		Installed Base (M)	
	LFL	LED	LFL	LED	LFL	LED	LFL	LED
China	191	120	2464	236	71	198	2532	528
Rest of Asia/Pacific	614	88	2756	183	29	37	765	126
W. Europe	178	47	837	135	37	33	565	72
E. Europe	174	28	977	56	27	8	407	21
North America	267	72	1909	124	46	38	726	127
Latin America	174	33	997	49	10	7	229	15
Middle East & Africa	207	23	827	51	8	7	213	19
Total	1804	412	10767	834	229	328	5438	908

[6] https://www.unep.org/globalmercurypartnership/events/workshop/transitioning-mercury-free-lighting-asia-pacific-countries
[7] https://www.unep.org/globalmercurypartnership/events/unep-event/transitioning-mercury-free-lighting-virtual-event
[8] https://store.strategies-u.com/products/global-lamps-market-update-and-forecast-2020.html
[9] https://store.strategies-u.com/products/global-luminaires-market-update-and-forecast-2020.html

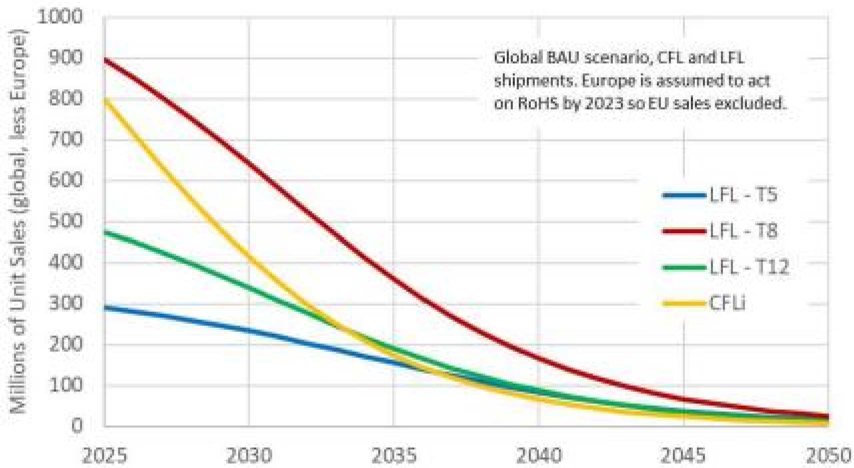
This data shows that less than 8% of the tubes and 17% of the luminaires had been converted to LEDs. Assuming that the luminaires contain an average of 3 tubes, the total number of installed LFLs was around 25 billion. The mercury content was around 200 tons, assuming an average of 8mg per tube.

Since it is vey expensive to recover the mercury from existing lamps and current recycling programs cover only a small fraction of discarded lamps, the benefits of the switch to LEDs are in avoiding the use of mercury in the replacement lamps.

Although our estimate of the mercury content in the installed base for 2019 is very approximate, the number of 200 tons is also given by the UNEP study for the benefits of a complete replacement beginning in 2025. The next chart shows their estimate of the savings in mercury emission and financial cost to the customers from a global ban, depending on the year in which that ban is introduced.



The next chart from the Workshop shows the anticipated sales of fluorescent tubes if no further actions are taken, except within the European Community.



A total of 14.8B further sales are expected if the rate of transition to LEDs is controlled solely by the lighting industry and their customers, without further constraints by governments.

There are several factors that have hindered the termination of the production of LFLs. Resistance of manufacturers to close profitable factories was one of the early issues. This has now mainly disappeared, as companies realise that long term viability and technology leadership are more important than continues profits from outdated products.

Another issue has been the unwillingness of governments to regulate industry or constrain the purchasing options of consumers. This has been particularly strong in Japan and the US. Although the rationale for such actions was set in 2013 at the Minamata Convention, the development of effective regulations is a complex task and the process has been slow almost everywhere.

Another hindrance has been the higher initial cost of LED replacements, even though the extra expense is soon recovered through lower operating costs. This is such a pervasive problem that the UNEP analyses have given high priority to estimates of payback periods and total lifetime costs. Some examples of their estimates are summarised in the next section.

3.2 Payback Periods

The next two Tables show the calculations of payback periods for seven Asia-Pacific countries and South Africa, as presented at the workshops. The results range from 2.2 months in the Philippines to 10.4 months in Japan. Since the assumption about power levels, hours of use and electricity cost vary little between countries, the variation in payback periods comes mainly from the assumed purchase cost for the lamps. Further comments are provided between the two Tables.

Country	China		India		Pakistan		Japan	
Source	LFL	LED	LFL	LED	LFL	LED	LFL	LED
Power (W)	36	16	36	18	36	16	40	18
Life (hours)	3,000	30,000	5,000	25,000	8,000	16,000	12,000	40,000
Price (local currency)	10	26	38	425	650	900	1466	1870
Price (USD)	1.37	3.57	0.46	5.14	2.12	2.93	10.0	12.8
Annual elec. (kWh)	118	53	118	59	118	53	131	57
Cost per kWh (local)	0.8		8.5		23		13.5	
Cost per kWh (USD)	0.11		0.10		0.075		0.092	
Ave. annual cost (local)	109	47	1034	565	3058	1474	2223	1032
Ave. annual cost (USD)	15	6.5	12.5	6.8	10.0	4.8	15.2	7.0
Years for average	9		7		4		10	
Payback period (months)	6.8		9.4		2.8		10.4	

Notes:

Power: Each analysis assumes power levels for the LEDs (15-18W) that are less than half those for the linear fluorescent lamp (36-40W). There seems to be no discussion of the consequent difference in light levels.

Life: The operating lifetime for the LEDs varies significantly, from 15,000 to 40,000 hours. This could be due to different expectations among customers, or decisions made in choosing the lamps for the analysis.

Price: The purchase price is given first in the local currency, and then in US dollars to facilitate comparisons. The lamp prices were collected between April and June of 2023, except in the case of South Africa where prices from September 2020 were used. The ratio of LED price to LFL varies from 1.28 in Japan to 11 in India. The contrast between prices in India and Pakistan is particularly interesting.

Electricity cost: Most analyses assume that the lamp is used for 9 hours per day, except for South Africa in which 10 hours per day is assumed. The cost per kWh varies between US$0.065 in South Africa and US$0.153 in the Philippines.

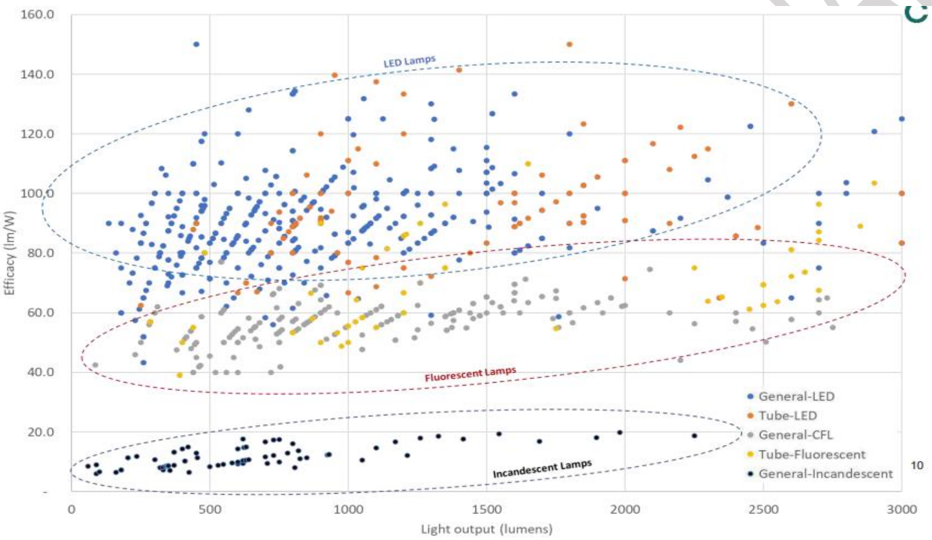
Average annual cost: This is also given in local currency and US$. The time period used for calculating the average varies from 4 to 10 years. This period is close to the expected operating lifetime for the LED lamp in all cases except Indonesia.

Country	Indonesia		Philippines		Thailand		South Africa	
Source	LFL	LED	LFL	LED	LFL	LED	LFL	LED
Power (W)	36	16	36	15	36	18	36	18
Life (hours)	13,000	15,000	13,000	15,000	13,000	15,000	16,000	40,000
Price (local currency)	20,150	41,500	120	190	65	145	49	119
Price (USD)	1.32	2.72	2.11	3.34	1.84	4.11	2.56	6.21
Annual elec. (kWh)	118	53	118	49	118	59	131	66

Cost per kWh (local)	1445		8.7		3.15		1.25	
Cost per kWh (USD)	0.095		0.153		0.089		0.065	
Ave. annual cost (local)	179273	93021	626	491	414	241	160	86
Ave. annual cost (USD)	11.8	6.1	11.0	8.6	11.8	6.8	8.4	4.5
Years for average	7		4		4		10	
Payback period (months)	5.5		2.2		8.3		10	

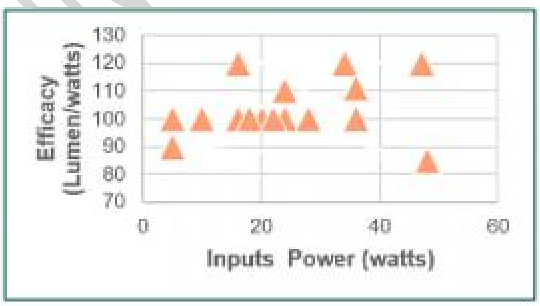
3.3 Efficiency Improvements

Since the goal is to replace most fluorescent lights with LED fixtures using less than half the power, the efficiency of producing and delivering the light needs to be increased by more than a factor of 2. The Clean Lighting Coalition has surveyed the markets for traditional lamps and LED replacements across the Africa, Asia-Pacific and Latin American regions. The data on light output and efficacy collected from 35 countries is shown in the next chart.

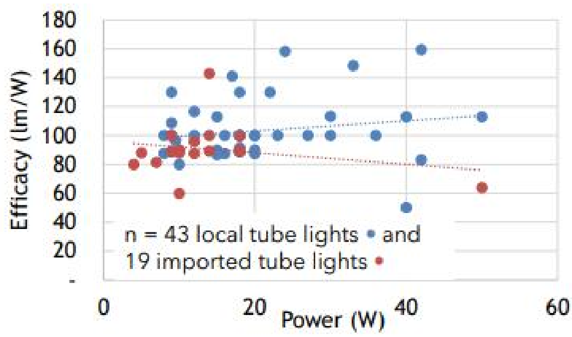


The average efficacy appears to be around 15lm/W for general incandescent, 60lm/W for fluorescents and 100lm/W for LEDs. So the replacement of incandescent lamps can be replaced by LEDs with the same light output and lower power consumption, this is more difficult for Linear fluorescents.

The Bureau of Energy Efficiency in India is conducting a survey of the efficacy of available LED lamp replacements for fluorescent tubes. Preliminary results are shown below, along with similar results from Indonesia.



India



Indonesia

Both sets of data confirm the concerns expressed above. It is interesting that the data from Indonesia shows that most LED replacements that are assembled locally perform better than those that are imported.

The performance of lighting fixtures containing LED sources can be seen in data collected in North America by the Design Lights Consortium (DLC)[10]. This organization was set up to encourage the development of high-quality lighting and is supported strongly by utilities and the lighting industry. Their database of LED ceiling troffers contains over 30,000 products. The efficacy of their recommended products has the distribution shown in the Table below.

Efficacy (lm/W)	<110	110-9	120-9	130-9	140-9	150-9	160-9	>170
% of products	2.9	24.1	37.1	21.7	11.9	2.1	0.2	0.1

It should be noted that the efficacy of these lights takes account of optical losses in the fixtures, for example in diffusers, and electrical losses in the drive circuits. Nevertheless, the numbers confirm our assessment that further work is needed to improve the efficiency of LED replacement for linear fluorescent lamps.

3.4 Progress Since 2019

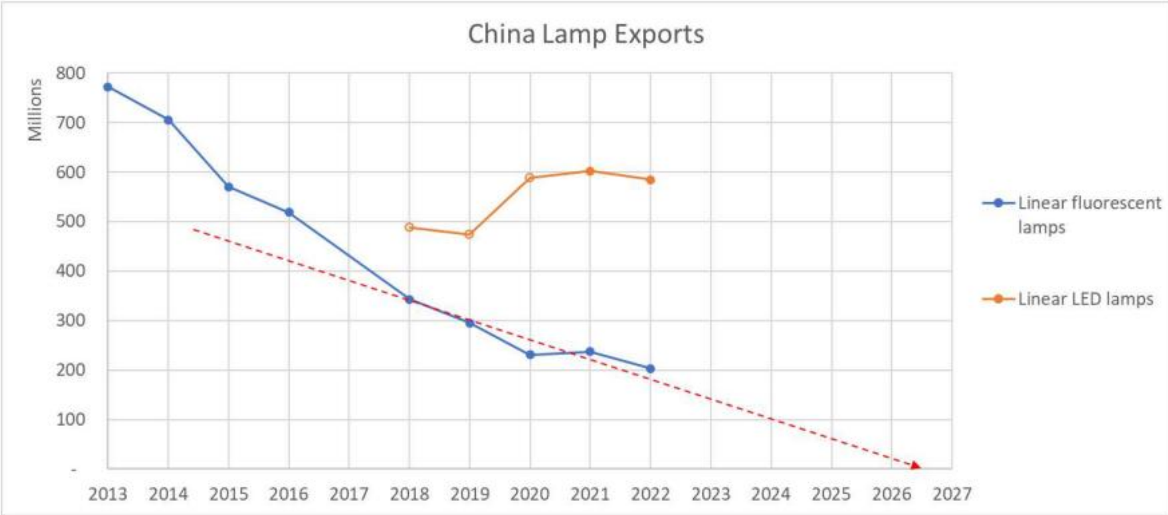
Since Strategies Unlimited ceased to produce their reports, it has become difficult to find comprehensive global data on the sales and stocks of fluorescent lights. As noted above, the market research companies that advertise their studies over the internet appear to agree that the move to restrict sales will fail and revenues from fluorescent lighting will continue to grow at around 10% per year. This perhaps is what they think the potential customers of their reports would like to read.

In most countries, production statistics for domestic sales are particularly difficult to obtain. Import/export data are more readily available but are mostly given in terms of sales value, rather units. The significance of the absolute values may be unclear, but the year-to-year trends can be helpful. Many of the import/export data cited here come from the website of Trend Economy[11] under the Harmonized Export Classification 853931.

3.4.1 China

Since China is the major producer of LED lamps, an indicator of the global acceptance of LED replacements for LFLs can be seen in their export data. As seen below, the number of LED linear lamps exported by China already exceeded that of linear fluorescent tubes. By 2022, exports of LFLs were down to about one quarter of the level in 2013.

[10] https://www.designlights.org/
[11] https://trendeconomy.com/

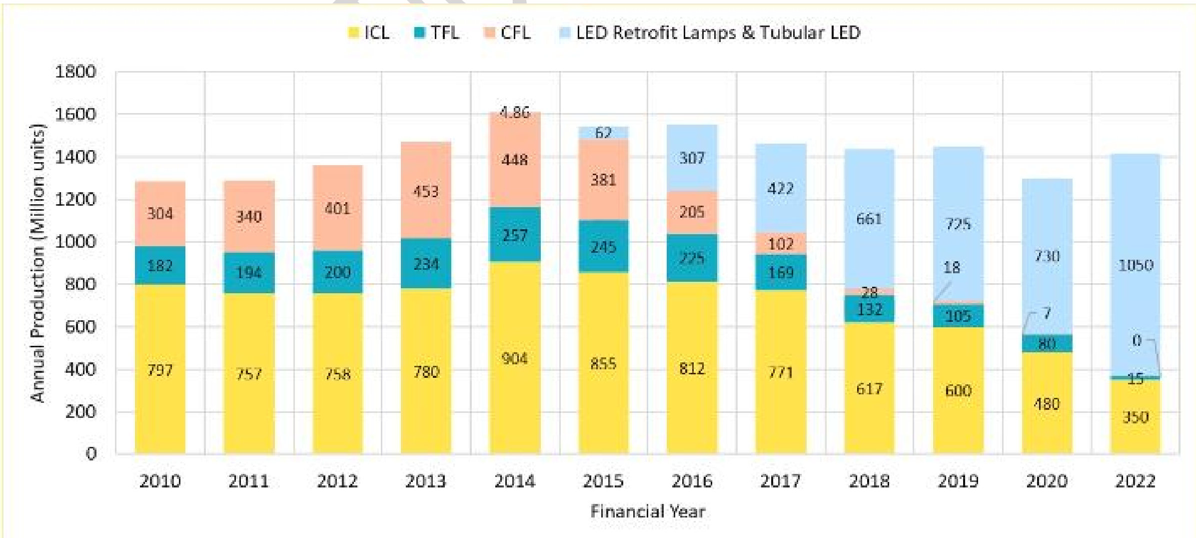


Trend Economy estimate that the value of the LFL exports fell from US$780M in 2019 to $US599M in 2022. The Aladdin Lighting Network reports[12] that the share of LFLs among China's lighting exports continued to fall in 2023H1 and is now less than 5%.

A joint study by CLASP and the China National Institute for Standardization (CNIS) reported[13] that "China's production of fluorescent lamps remains low and continues to decline –the fluorescent market share dropped by 25% in 2021 alone. The majority of fluorescent bulbs produced in China were exported to international markets, with less than 20% being sold domestically." The report anticipates that fluorescent lamp production lines in China will be shut down in the next 3-5 years.

3.4.2 India

India has been a global leader in converting its manufacturing facilities from fluorescent lights to LEDs. The following chart was shown at the CLiC workshop on August 31st by Kishore Kumar of CLASP India.



---

12 https://www.alighting.cn/news/20230721/174648.htm

13 https://www.clasp.ngo/updates/research-explores-feasibility-of-a-led-transition-in-china/

The production of compact fluorescent lamps (CFL) ceased around 2019, while that of LFLs is now down below 6% of its peak value. The LED share has increased to 75%, including around 700M LED Tubes and 350M general service lamps

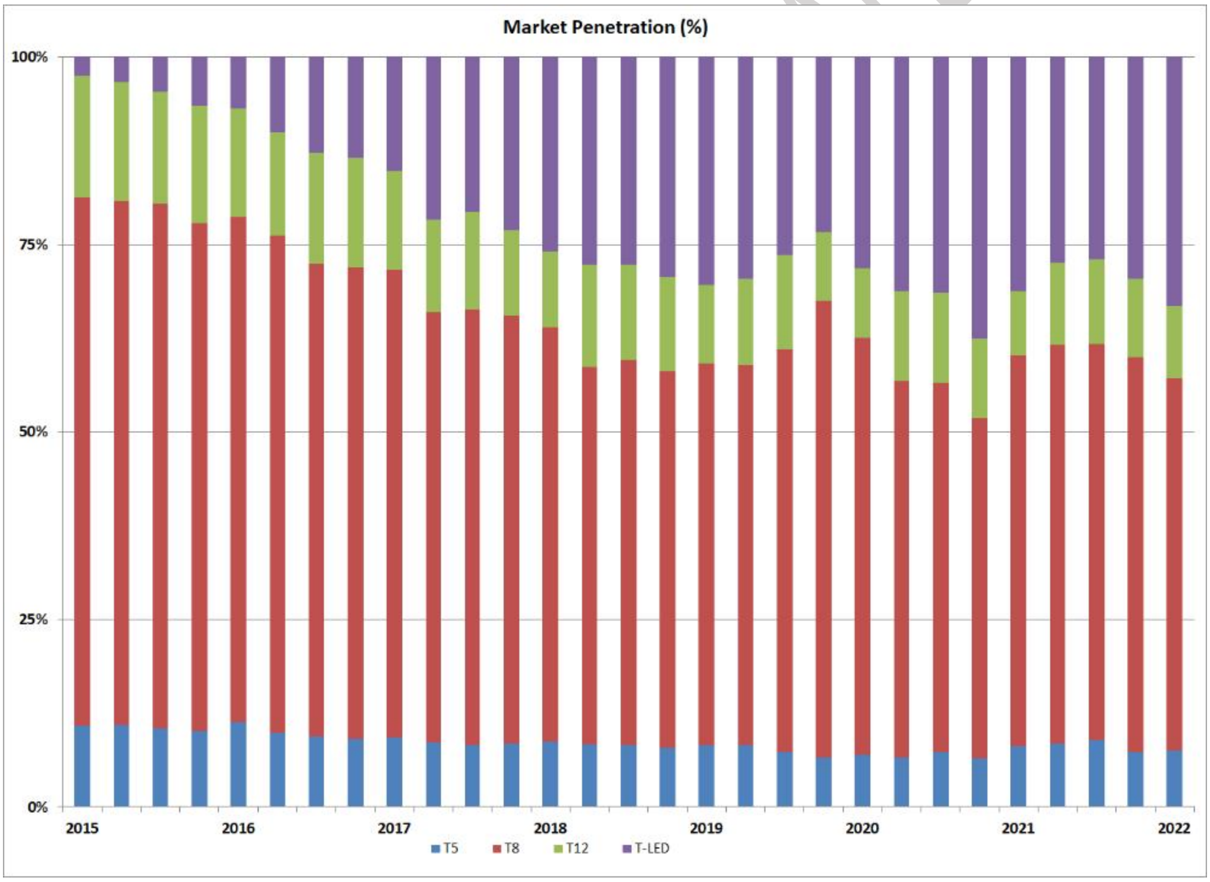
Some of the LFL manufacturing capacity is now used to generate exports, with the value rising to US$12.5M in 2022. The dominant destinations for these exports are the US, Malaysia, Thailand and Indonesia.

3.4.3 Japan

The Japan Lighting Manufacturers Association (JLMA) reports that the production of LFL tubes in Japan fell from 90M in 2019 to 43M in 2022, while sales fell from 99M to 59M over the same period. According to Trend Economy, the value of imported LFLs rose slightly from US$27M in 2019 to $38M in 2022, showing an increasing dependence on imports, which almost all came from China.

3.4.4 USA

The National Electrical Manufacturers Association collects data on sales of lamps through its members and publishes some summaries on its web site. The next chart[14] shows the breakdown of linear tube sales between 2015 and 2022Q1.



This data indicates that there was little progress in the adoption of LEDs in this market sector between 2019Q4 and 2022Q1.

Further evidence for the continued popularity of LFLs in the US comes from import data. The value of imports fell from US$127M in 2019 to US$94M in 2020, due to the disruption of the supply chain

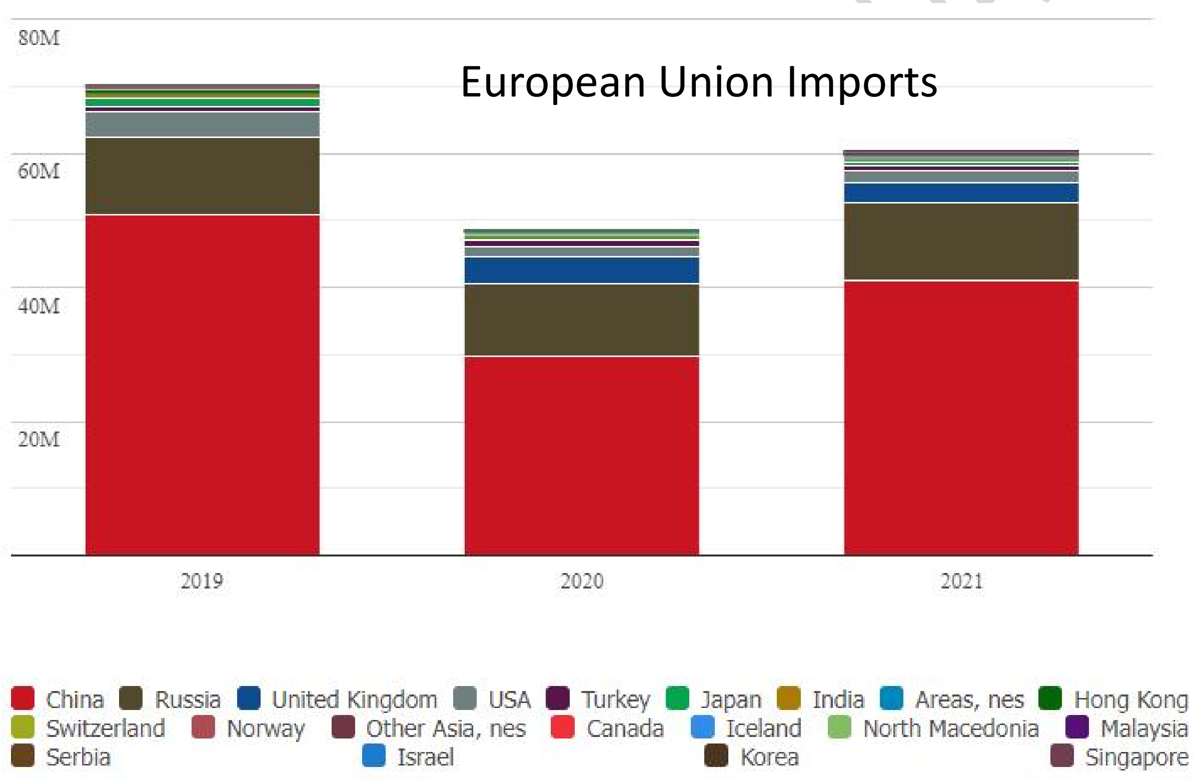
[14] https://www.nema.org/analytics/indices/view/t-led-lamp-shipments-index-increases-in-first-quarter-2022-compared-to-previous-year

by COVID, but then rose to US$126M in 2021 and US$138M in 2022. There is still some manufacturing of LFLs in the US, but the value of exports has fallen from US$36M in 2019 to US$19M in 2022.

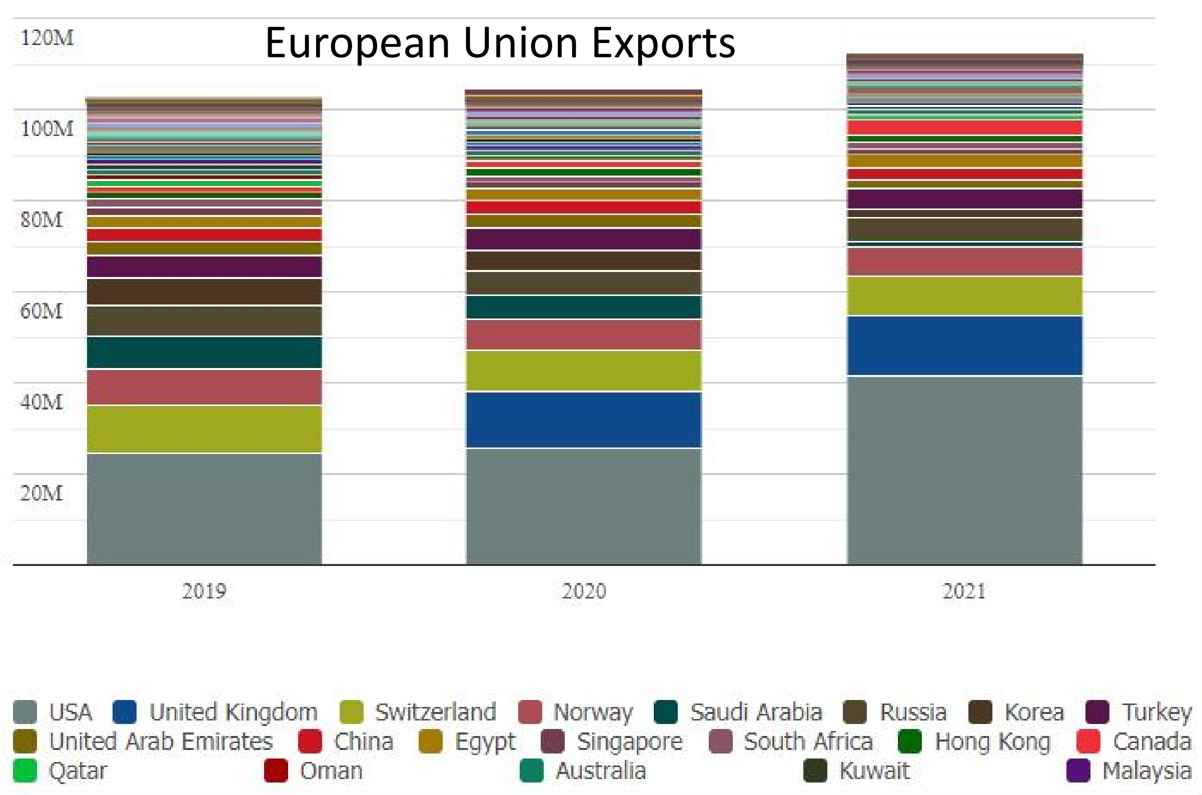
One encouraging development in the US is that the market leader, Acuity Brands, announced in April 2023 that it will be moving to a 100% LED product portfolio by year's end. The company plans to discontinue the manufacture of all fluorescent and HID luminaires in its portfolio by December 31, 2023. It is to be hoped that other companies will follow their lead.

3.4.5 European Union

The pattern of imports of LFLs in the European Union is similar to that in the USA. The next chart from Trend Economy shows that imports fell from US$70M in 2019 to $US48M in 2020, but then rose to US$60M in 2021. The rise continued in 2022, reaching US$76M. The dominant sources of these imports continue to be China and Russia, as shown in this chart.

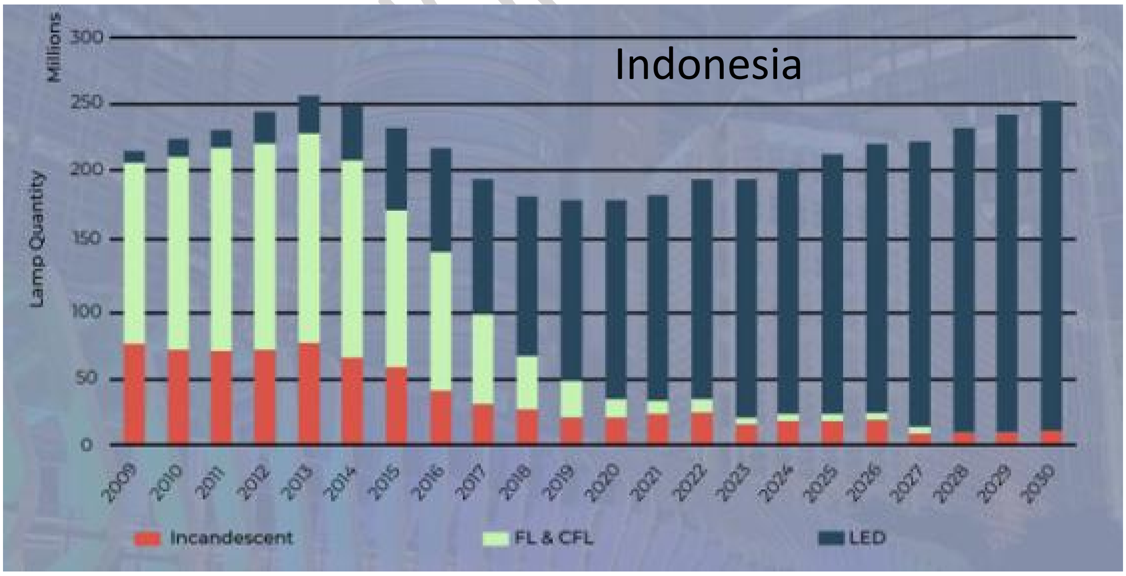


Only two factories still produce LFLs, one in Germany and one in Poland. These mostly serve US and European customers. Exports increased between 2019 and 2021 to compensate for the difficulty of trading with Asia. The distribution of exports from these plants is shown next. Exports dipped in 2022 to $US91M.



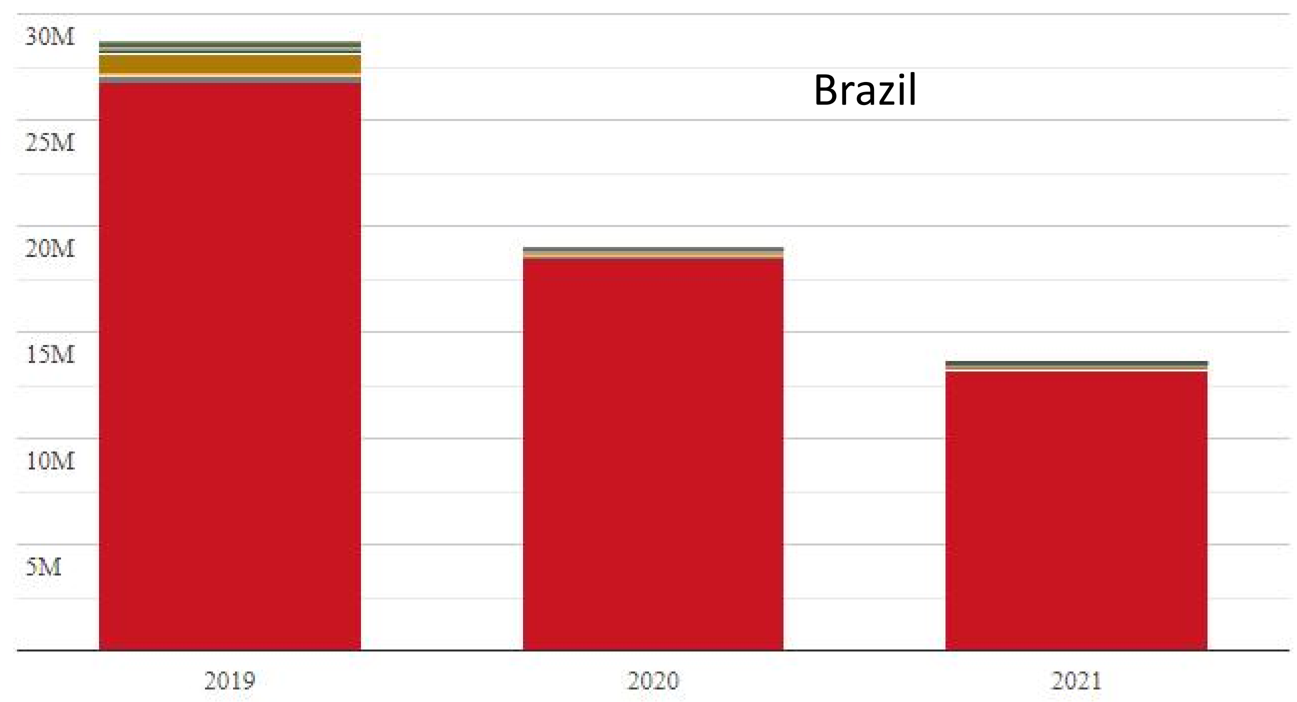
3.4.6 Southern Hemisphere

Several countries in the southern hemisphere are among the leaders in transitioning away from fluorescent lamps. For example, the following data for Indonesia was compiled by GAMATRINO (the Indonesian Integrated-Lamp Manufacturing Industry Association).



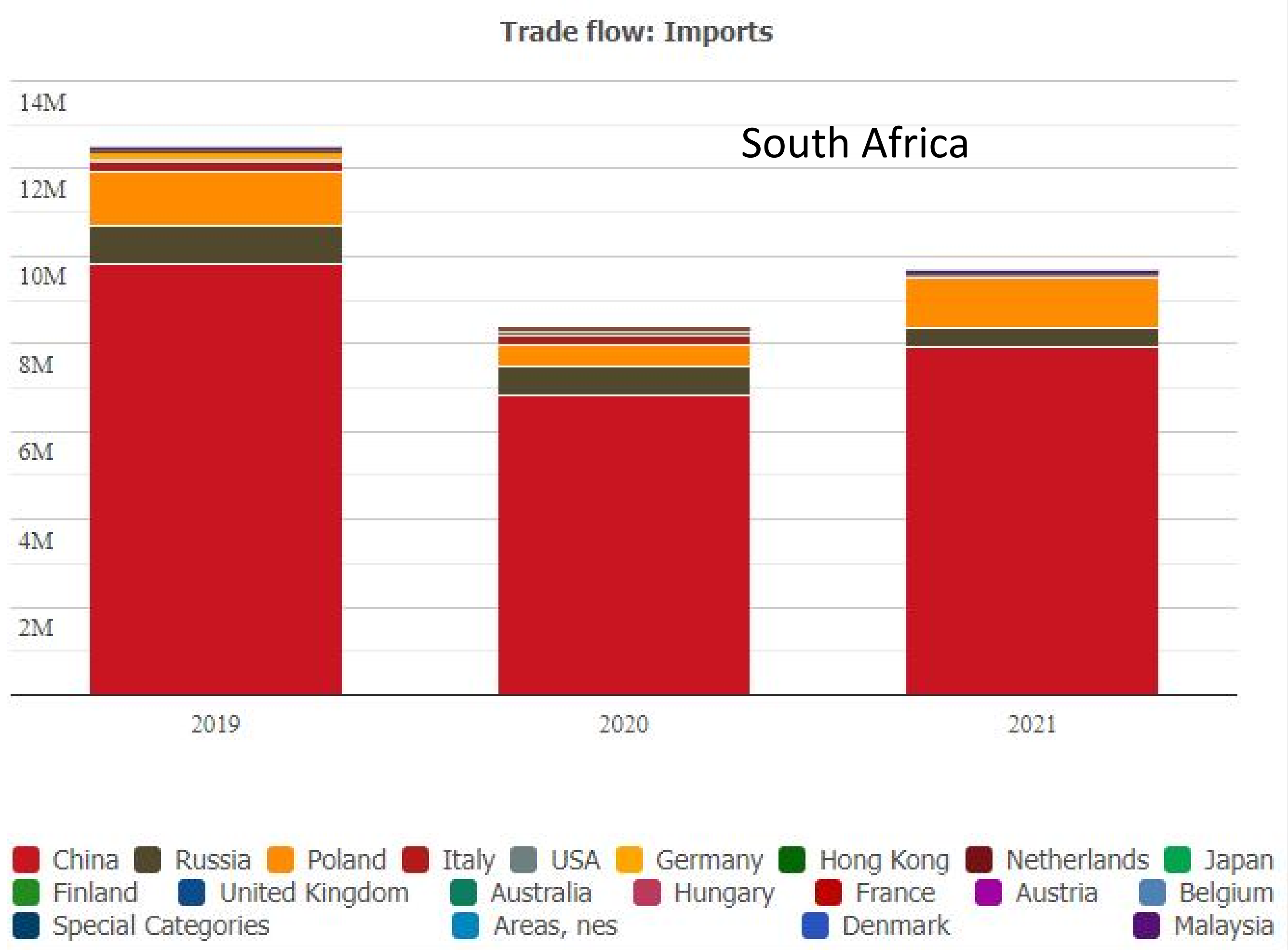
The reduction in the demand for LFLs is confirmed in the import data. The value of imports, which come almost completely from China, dropped from US$63M in 2019 to US$48M in 2020 and US$43M in 2021.

Imports of LFLs have fallen even faster in **Brazil**, as shown in the next chart.



The trend accelerated in 2022, with imports falling by more than half to US$5.8M.

Imports of LFLs to **South Africa** have also fallen. The reduction stalled in 2021, as shown in the next chart, but resumed in 2022, falling to US$6.2M.



3.5 Regulations

The regulations that are being imposed by national or regional governments fall into two classes, bans and minimum performance standards. Some are already in place, while others are still at the proposal stage. These regulations are complex and so this section just presents brief overviews.

The momentum for these regulations was set at the Minamata Convention in 2013. 142 parties have now assented to the program, as shaded in yellow in this figure. The fourth meeting of the Conference of Parties (COP-5) was held in Bali, Indonesia, in March 2022. COP-5 is scheduled to begin on October 31, 2023, in Geneva, Switzerland. As of September 7th, 2023, there were 146 parties to the Convention[15].

3.5.1 Bans of Fluorescent Tubes

Perhaps the most influential bans are those that were recently enacted by the **European Commission**. In December 2021[16], the Commission adopted 12 regulations under the RoHS Directive effectively banning fluorescent lighting for sale in the **EU** by September 2023. On a cumulative basis between 2023 and 2035, the much-delayed decision to phase-out these mercury-containing lamps will save approximately €18.2 billion, as well as 190 TWh of electricity and 1.8 metric tonnes of toxic mercury.

Details of the 2021 update to the RoHS Directive can be accessed through the web at:

https://environment.ec.europa.eu/news/clean-and-circular-electronics-commission-ends-use-mercury-lamps-mercury-free-alternatives-prevail-2021-12-16_en

or directly at:

ELI: *http://data.europa.eu/eli/dir_del/2022/284/oj*

Switzerland has harmonized lighting policies with the EU and so, presumably, will also adopt these stricter regulations.

The **UK** government issued stricter limits on the sale of fluorescent lamps in July 2023[17]. Most of the new restrictions will come into effect in February 2024.

In the **US**, the federal government is usually slow to introduce nationwide regulations relating to the environment or consumer constraints, and the lead is taken up at the local or state level. Four states have already enacted bans, Vermont (ACT120), and California (AB2208), Colorado (HB23-1161) and Hawaii (HB191 HD2). Legislation has been introduced in 9 other states.

Canada recently published a draft proposal to phase-out all compact and linear fluorescent lighting. The policy measure proposes to phase-out:

- Integrally ballasted CFLs on December 31, 2023,
- Pin-based CFLs on December 31, 2026,
- All T5 LFLs, 4-foot T8 LFLs, and 4-foot and 8-foot T12 on December 31, 2026

[15] https://mercuryconvention.org/en/parties
[16] https://www.eceee.org/all-news/news/eu-commission-adopts-regulation-to-ban-fluorescent-lighting-by-september-2023/
[17] https://www.legislation.gov.uk/uksi/2023/658/made

• All non-linear fluorescent lamps on December 31, 2026

In the preparations for **COPS-5** the **African Parties** have proposed extensions to the existing recommendations, as summarized in the next two Tables.

Completing Coverage of Fluorescent Lamps at COP5

Fluorescent Lamps – both Linear and Non-Linear

Lamp Type	Mercury Content	Wattage	Phase-Out	Status
LFL Triband	> 5mg	< 60 Watts	2020	Complete, 2013
LFL Triband	≤ 5mg	< 60 Watts	[2027] [2030]	COP5
LFL Triband		≥ 60 Watts		COP5
LFL Halophosphate	> 10mg	≤ 40 Watts	2020	Complete, 2013
LFL Halophosphate	≤ 10mg	≤ 40 Watts	[2025] [2027] [2030]	COP5
LFL Halophosphate		> 40 Watts	[2025] [2027] [2030]	COP5
Non-Linear FL		All		COP5

Draft African Lighting Proposal for COP5

Part I: Products subject to Article 4, paragraph 1

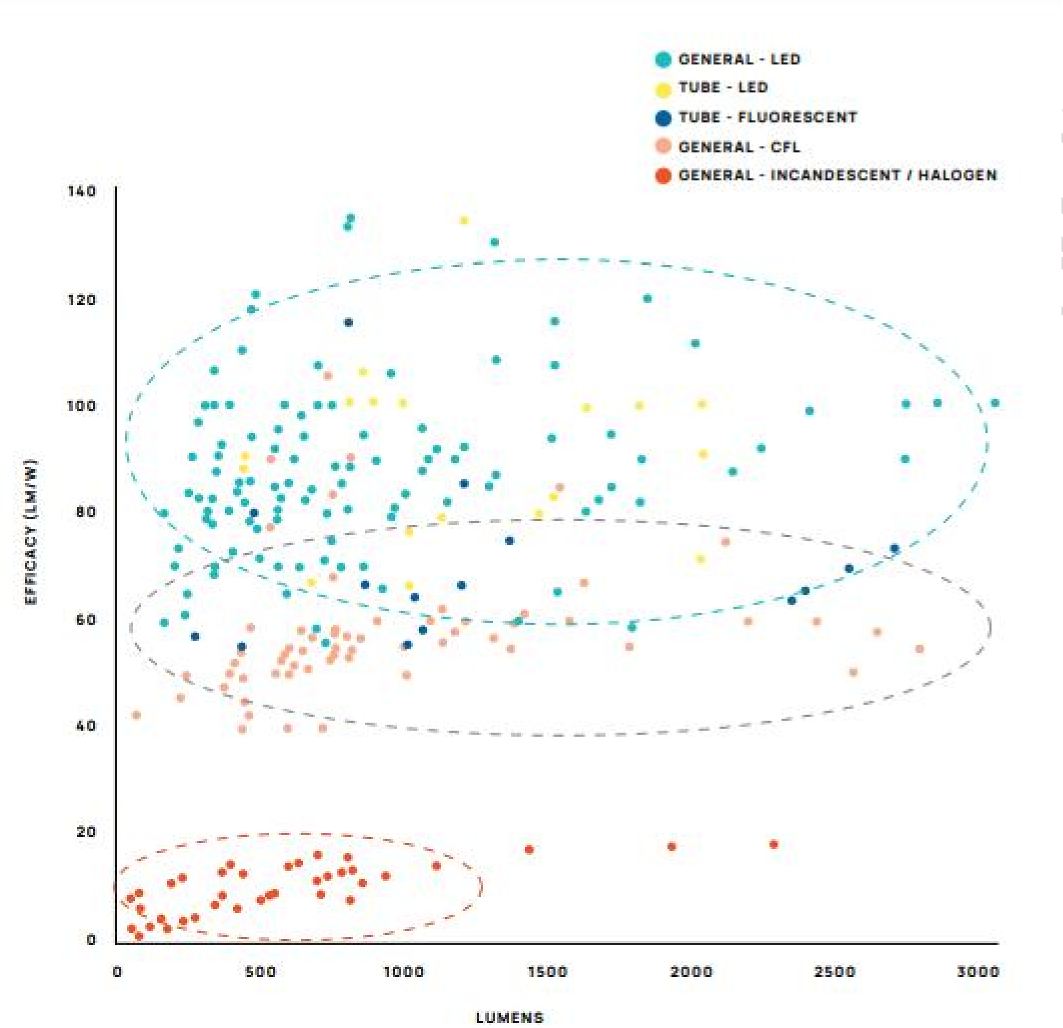
Mercury-added products	Date after which the manufacture, import or export of the product shall not be allowed (phase-out date)
Compact fluorescent lamps (CFLs) for general lighting purposes that are > 30 watts	2025
Compact fluorescent lamps with a non-integrated ballast (CFL.ni) for general lighting purposes that are ≤ 30 watts with a mercury content not exceeding 5 mg per lamp burner	2025
Linear fluorescent lamps (LFLs) for general lighting purposes: (a) Triband phosphor ≥ 60 watts	2026
Non-linear fluorescent lamps (NFLs) (e.g., U-bend and circular) for general lighting purposes, all phosphors and wattages	2026

3.5.2 Minimum Energy Performance Standards (MEPS)

Most constraints on the sale of lights come through the imposition of performance standards. Many of these are not sufficiently strict to have much effect on LFLs, but there are some exceptions.

In January 2023, the **UK** proposed limits that they claim to be the most ambitious across the globe. The minimum efficacy requirements would be 120lm/W from 2023, rising to 140 lm/W from 2027. There are modest concessions for mains voltage light sources, directional light sources, 'connected' light sources, light sources with a Colour Rendering Index greater than 93, light sources with a correlated colour temperature of under 2000K, and light sources with an output of less than 400 lm.

Many governments across Africa are moving to phase-out CFLs and LFLs through energy-efficiency policy measures. The following figure shows the efficacy of the lamps purchased in the region in 2021 by the Clean Lighting Coalition[18].



22 countries participate in UNIDO's "Energy Efficient Lighting and Appliances" project, developing harmonised lighting performance standards for SADC and EAC; phasing-out CFLs and LFLs by minimum efficacy requirements.

Southern Africa Development Community – 16 countries adopted regionally harmonised quality and performance standard HT 109:2021 in June, shifts markets to all LED.

On 1 July 2022, Energy Ministers of 7 East African nations[19] adopted mandatory lighting MEPS for their region. The minimum efficacy for lamps specified in act EAS 1064-1:2022 is shown in the next Table.

[18] https://cleanlightingcoalition.org/wp-content/uploads/sites/96/CLiC-Regional-Profiles-Africa.pdf
[19] The Democratic Republic of the Congo, the Republics of Burundi, Kenya, Rwanda, South Sudan, Uganda, and the United Republic of Tanzania

Table 1 — Minimum luminous efficacy of lamps

Type of product	Minimum luminous efficacy (lm/W) Phase 1 – 1 July 2023	Minimum luminous efficacy (lm/W) Phase 2 – 1 January 2025
General service lamps – Non-directional	90	105
General service lamps – Directional	75	85
Tubular lamps	115	130

On 18 June 2021, the Energy Ministers of the 16 Southern African Development Community1[20] adopted a new Harmonized Standard SADC HT 109:2021.

Table 1: Minimum luminous efficacy of Lamps and Luminaires

Type of Covered Product*	Minimum luminous efficacy (lm/W)	
	Phase 1	Phase 2
General Service Lamps – Non-Directional	90	105
General Service Lamps – Directional	75	85
Tubular Lamps	115	130
Linear Batten and Troffer Luminaires	105	115
Downlight Luminaires	85	95
High and Low-Bay Luminaires	120	130
Planar (or Panel) Luminaires	85	95
Outdoor / Streetlight Luminaires	105	115

**The scope of coverage of these lamps and luminaires is given in Section 1 of this Standard.*

In addition, several countries, such as South Africa, Ivory Coast and Namibia, are updating their national lighting regulations, phasing out fluorescent and transitioning to energy-efficient, mercury-free, LED. Countries like Burkina Faso, Ghana and Nigeria have strategies to support energy-efficiency under their energy policies.

ECOWAS (15 countries) is working to have regional regulation on energy performance. Legislation has already been enacted in Gabon and Nigeria.

In **Brazil** the Ministry of Mines and Energy has confirmed their intention to develop MEPS this year that would effectively ban all non-LED lighting products, such as LFLs, halogen lamps, and HID luminaires.

3.5.3 Other steps

Taxes can also be used to discourage the purchase of fluorescent lamps. In Pakistan, for example, the custom duty rate for LEDs and energy savers is 3% whereas it is 20% for all other bulbs. For domestic manufacturing of LEDs, the rate of sales tax is zero while it is 17% for import of LEDs.

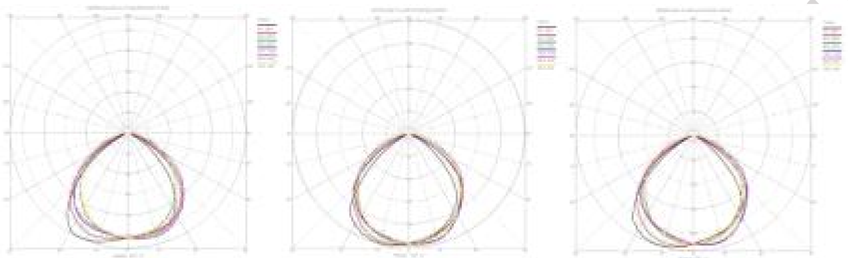
In the Philippines, House Bill No. 262 (pending approval) aims to require all government office to use LEDs instead of incandescent and CFL bulbs, and fluorescent tubes.

[20] Angola, Botswana, Comoros, Democratic Republic of Congo, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Tanzania, Zambia and Zimbabwe

3.6 Compatibility and Safety

Many of the objections to the enforcement of restrictions have been concerned with the safety and compatibility of LED replacements in existing lighting systems. The CLiC Workshops discussed these issues at length and only a brief summary is given here.

These concerns were raised by the Lighting Europe in the review process for the latest RoHS legislation. A lengthy response[21] was prepared by Peter Bennich and Michael Scholand on behalf of CLASP Europe and the Swedish Energy Agency. After a comprehensive study of LED tubes produced by the leading vendors (Philips, Osram and Sylvania) they concluded that over 91.4% of the installed stock of fluorescent lamp luminaires in Europe can be installed directly (no rewiring, just change the bulb). The LED tube retrofits are designed to match system optical output, as shown below:



T8 Fluorescent Lamp (3201-1-3) T8 LED Lamp (3402-1-2) T8 LED Lamp (3404-1-2)

The CLiC reports that "the small percentage (6-9%) of fixtures where LED tubes are not compatible can be replaced or can have the ballast by-passed, and use a mains-voltage LED tube so the fixture does not need to be replaced".

The CLiC summary of the global situation for ballast compatibility is:

- Magnetic ballasts – 100% compatible with LED
- Mains voltage – 100% compatible with LED
- Electronic ballasts – 91-93% compatible with LED
- Magnetic ballasts are the majority of the installed stock globally, but particularly in non-OECD countries
- Keeping the magnetic ballast in the circuit will contribute to system losses, but still more efficient than fluorescent

Safety standards for LED lamps and tubes have been developed by the International Electrotechnical Commission:

IEC 62560:2011 - IEC safety standard for self-ballasted LED lamps for general lighting services

IEC 62776:2014 – IEC safety standard for linear LED retrofit tubes

IEC 63220:202x – LED Light sources – Safety requirements ➔ (combines and updates IEC 62560 & IEC 62776)

One of the countries that have been slow to develop safety standards for LED is **Japan**. According to the CLiC

[21] https://mercuryconvention.org/sites/default/files/documents/submission_from_organization/SEA_CLASP_report.pdf

•Japan-centric policies and standards limits market availability and results in market lag compared to other economies

•Due to pending release of mandatory safety standard, end users have limited access to safe and affordable LED drop-in retrofit replacements– this leads to safety risk concerns as expressed in the submission to the Secretariat.

3.7 Disposal of Fluorescent Tubes

The challenges in the disposal of fluorescent tubes were summarised by Michael Bender at the CLiC Workshop on June 13.

One of the major concerns is to the health of workers involved in recycling.

'Recycling' workers have exceptionally high mercury exposures globally.

• During recycling, bulbs broken into small shards, mercury vapors released at high rate; lingers for weeks.

• Routes of exposure include inhalation of mercury vapors and skin contact with broken materials,

• Elemental, inorganic mercury absorbed into the human body through inhalation, digestion, or dermal exposure.

A detailed study of the risks experienced in Colombia was recently published in the International Journal of Environmental Research and Public Health[22].

Only a small proportion of lamps are recycled. Some estimates of recycling rates are:

40% European Union   28% South Korea   23% USA   11% Brazil   9% Japan

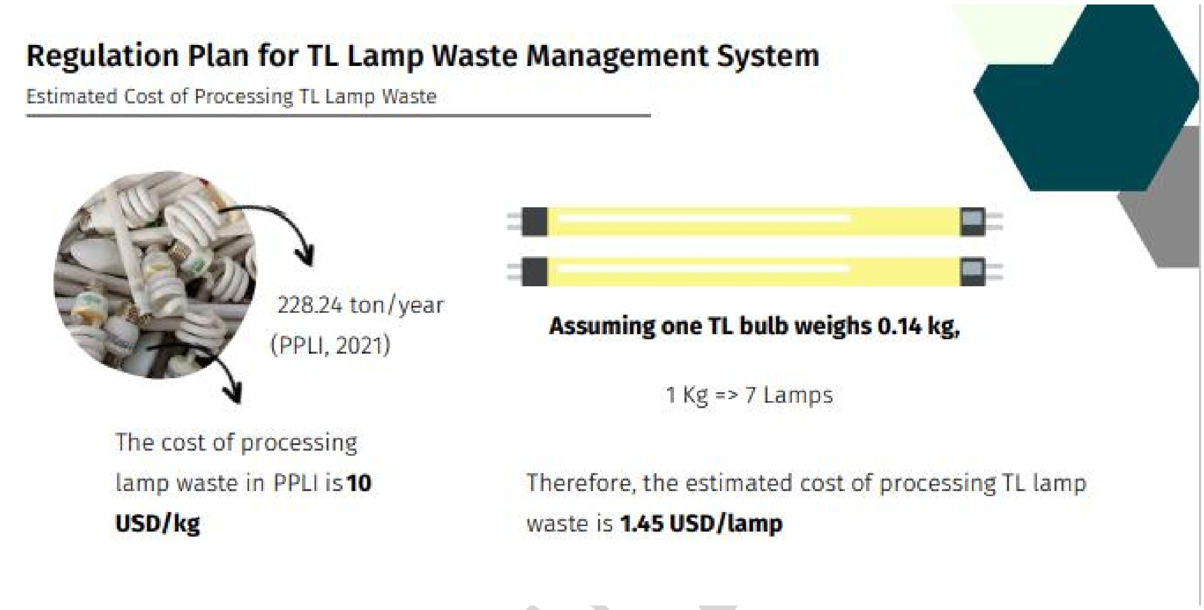
---

[22] https://www.mdpi.com/1660-4601/18/17/9295

7% Canada 4% China

Overall, about 20% of lamps are recycled in Organization for Economic Co-operation & Development (OECD) countries, while less than 5% are processed in developing economies.

In addition to the health risks for workers, another major factor discouraging recycling is the cost. This varies from $US0.52 in North America to around US$2.00 in Africa and Europe. The next figure illustrates the cost in Indonesia.



Given the high cost of proper disposal, developing countries are at risk of becoming dumping grounds for mercury-containing fluorescent lamps that no longer have viable markets in the OECD.

4 Horticultural Applications

In the search for new markets for LED sources and products, agricultural applications are on almost every list. Meeting the global demand for food will become more difficult as populations grow, the available land area for farming shrinks, and the climate becomes less predictable. This has led to increasing interest in indoor farming and in adding supplementary lighting to greenhouses. The higher efficiency and the flexibility in controlling the spectrum seem to make LED lights the ideal candidates for this application.

Most publishers of expensive market research reports have issued extremely aggressive forecasts of market growth and there has been lots of hype about the development of indoor farming. Many SSL companies have developed special sources for this application and fixture manufacturers offer a wide range of options.

The major goal of this chapter is to survey the status of these applications and assess the likelihood of substantial market growth.

4.1 Market Status for Agricultural Lighting

In this section, we will first examine the predictions of market research companies on the growth of the agricultural lighting market and then discuss recent trends as described in company financial reports.

4.1.1 Global Market Data

Recent market research reports suggest that the global lighting market for agricultural applications in 2022 was around $11B. The reports forecast a compound annual growth rate (CAGR) of around 12%, with an expected market size of $27B in 2030. The LED share of this market is still low. Predictions of the CAGR for LED vary widely, between 8% and 28%.

Estimates of the horticultural lighting market in 2022 vary from $2B to $7.9B, with forecasts of future CAGR between 15% and 29%. This is substantially higher than the anticipated growth rate for the whole lighting industry.

The on-line descriptions of these market research reports often include lists of the major players. Many of these lists include companies that are no longer in business. This suggests that the reports are not updated thoroughly and casts doubt on their accuracy. In addition, the wide range in revenue estimates confirms that there is a need for more reliable studies of the global lighting markets.

The following chart from CALI[23] shows the rapid growth of the plant lighting market in China since 2014, reaching $3.558B yuan in 2022 (US$490M).

[23] www.cali-light.com/index/index/newsart/id/25363.html

The forecast shown below, from Zhiyan Consulting, shows that this growth is expected to continue, reaching almost 110B yuan in 2030 (US15B).

Source: Zhiyan Consulting

A more recent report[24] from CALI gives a lower estimate of 1.6B yuan for the plant growth lighting market in 2022. Over 70% of the production by Chinese manufacturers is exported. The output of China's plant growth lamp industry in 2022 was approximately 55.6M units, while the domestic demand was only 15.1M units.

This second report from CALI Data states that the overall average market price of plant growth lights in China dropped from 109.2 yuan/piece in 2015 to 105.7 yuan/piece in 2022. This is mainly due to the large decline in the market price of LED plant growth lights. The price of LED plant growth lights has dropped from 352.2 yuan/unit in 2015 to 192.5 yuan/unit in 2022. This suggests that the price of LED fixtures is still more than twice that of the traditional fixtures.

4.1.2 Company Reports

As reported by Mark Halper in LEDs Magazine[25], large lighting companies, such as **Signify** and **AMS-Osram**, began to report softness in their horticultural lighting business in the autumn of 2022, as "growers balked at buying LED lighting — or artificial lighting of any sort — in the face of skyrocketing electricity prices. LEDs are energy efficient, but the cost of buying and running them in locations that have not used artificial lighting in the past has been dissuading customers". This weakness continued for both companies through the first half of 2023.

[24] http://www.cali-light.com/index/index/newsart/id/25424.html
[25] https://www.ledsmagazine.com/leds-ssl-design/article/14293312/horticulture-indoor-commercial-and-home-markets-slam-signify

Since AMS-Osram sold most of its lamp business to LEDVANCE and Signify, the major impact has been on sales of its red LEDs. The problem may be more severe at Signify, which recently acquired Fluence Bioengineering from Osram. Fluence is one of the world leaders in the development and sales of horticultural lighting. Signify has recently announced major changes in the management at Fluence[26].

The impact of unmet expectations for agricultural lighting has been more severe for some smaller companies. In early 2020 **Illumitex**, one of the most promising suppliers of horticultural lighting, decided to terminate its LED lighting operations, investing their resources to propel their artificial-intelligence platform instead.

"Known as FarmVision AI, the platform tracks everything in the production environment, from plant growth and scouting to inefficiencies in labour. No need for motors, tracks or registration markers, FarmVision AI uses wireless cameras that connect to their cloud. With installations ramping, we are seeing that FarmVisionAI is more valuable to farmers than LED lighting and we are refocusing our resources to accelerate deployments," said CEO Jeff Bisberg.

Unfortunately, this vision could not be implemented and the new company filed for bankruptcy in December 2020.

In late 2021, Hawthorne Hydroponics – a subsidiary of The Scotts Miracle-Gro Company – acquired assets of horticultural lighting company **Luxx Lighting** for $215 million. Founded in 2018, California-based Luxx Lighting was a producer and distributor of LED, high-intensity discharge (HID) and high-pressure sodium (HPS) lighting fixtures used in horticultural lighting applications. Only one year later, in December 2022, Hawthorne decided to shut down the Luxx Lighting brand. Hawthorne continues to support its Agrolux and Gavita brands.

One company that has risen to meet the challenges of horticultural lighting is **HelioSpectra**, based in Sweden. Their revenues in the first half of 2022 were SEK 8.9M (US$0.79M), down more than 50% from 2021H1. They responded by cutting operating costs and focusing their business on the European greenhouse market, with a special focus on the ornamental market, leafy greens and herbs. The company is also continuing to build strong relationships and expand our network with European and North American industry partners, including research organizations, crop consultants, grower associations, and greenhouse providers.

To support the new strategy, their development team worked hard in 2022 to finalize a SMART lighting solution for the professional greenhouse market. The result is a wireless control system using zone strategies and energy saving algorithms based on weather forecasts, natural light levels, and energy prices, to optimize the light environment for specific crops, all while minimizing energy consumption and cost. Their new MITRA Flex light fixture offers customers three spectra in one, making it perfect for customizable and application-based growing, such as end-of-day or end-of-production light treatments with far-red.

The company is also continuing to build strong relationships and expand their network with European and North American industry partners, including research organizations, crop consultants, grower associations, and greenhouse providers.

[26] https://www.ledsmagazine.com/horticultural-lighting/article/14298402/fluence-falling-more-into-the-sphere-of-its-parent-company

Heliospectra's sales in 2022H2 recovered slightly to SEK 10M (US$0.89M), but then increased substantially in 2023H1 to SEK 17.1M (US$1.53M), almost reaching that of 2021H1. The company's equity has increases three-fold over the past 18 months, but its stock price has not yet started to recover.

4.2 The Growth of Indoor Farming

The market for horticultural lighting can be separated into two main groups. The first is in providing supplemental lighting in greenhouses. This may shorten the time period to grow produce in all seasons, but the main value is in enabling efficient year-round production.

The second is in providing all the light for indoor plant growth, often with racks that are stacked vertically. The size of the operation varies from shipping containers to huge urban plant factories.

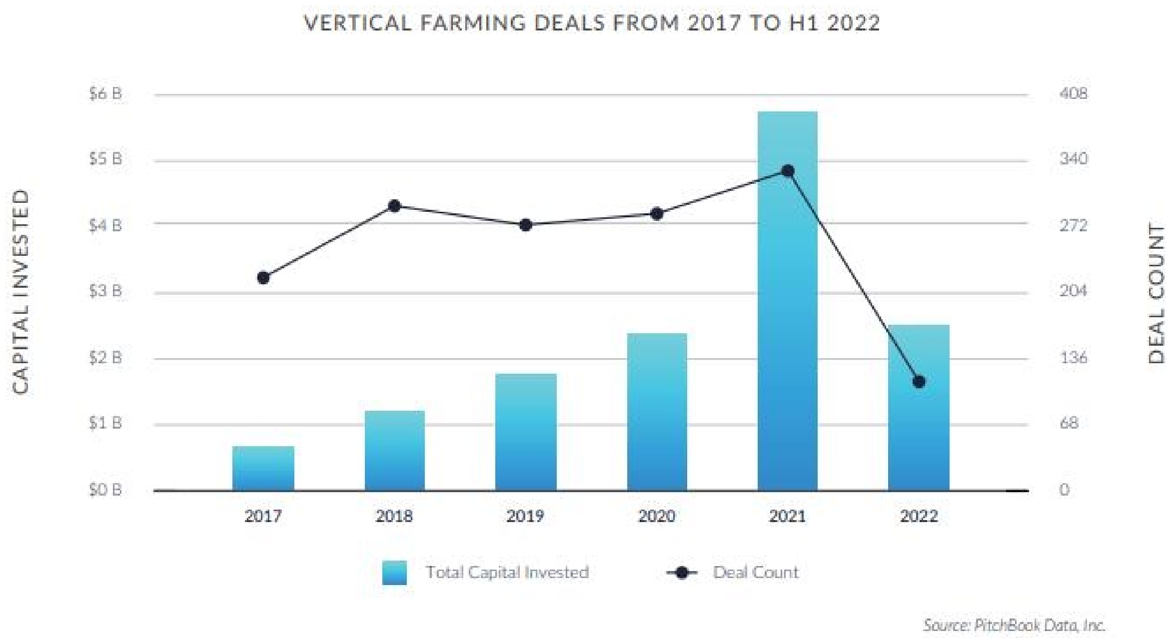
4.2.1 Investment in Vertical Farming

Vertical farming has certainly caught the attention of venture capitalists. In June 2022, Jahani & Associates published a survey of investments made since 2017[27]. Their report begins with the following table outlining the structure of the industry.

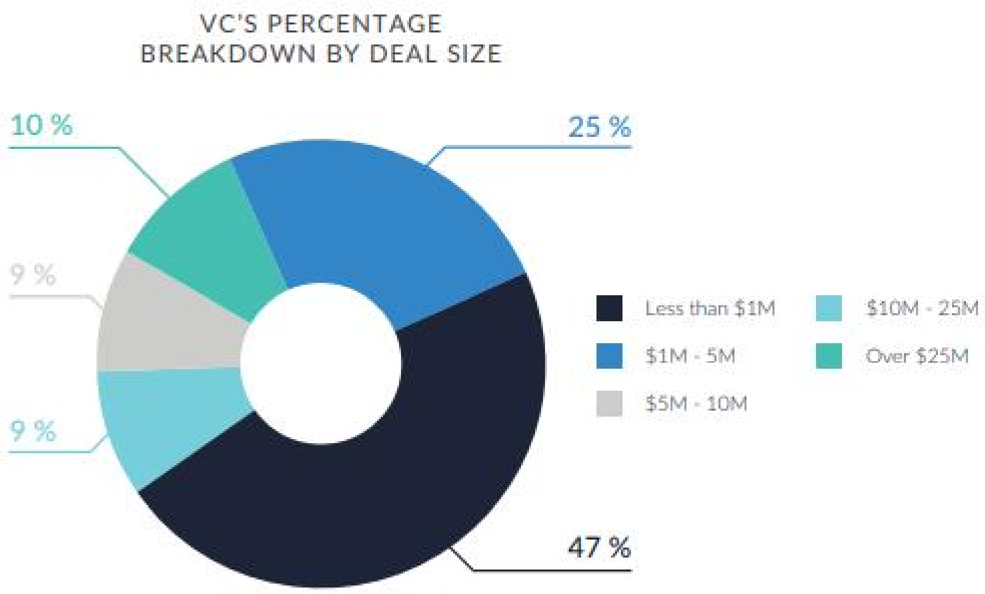
AGRICULTURAL METHOD	STRUCTURES	COMPONENTS
Hydroponics	Shipping-Container Based	Lighting System
Aeroponics	Building Based	Irrigations and Fertigation
Aquaponics		Climate Control
		Sensors

Between 2017 and June of 2022, US$14 billion was deployed across a total of 1,520 vertical farming deals with an average deal size of $9 million. The COVID-19 pandemic boosted investments in the vertical farms market between 2020 and 2021. The most active year was 2021, with $6 billion deployed across a total of 332 deal counts and an average deal size of $17 million.

[27] https://jahaniandassociates.com/wp-content/uploads/2022/07/20220719_Report_Global-Vertical-Farming-Market_JA.pdf



The distribution of the size of each deal is shown in the next chart. Approximately 72% of deal counts were attributed to small deal sizes up to $5 million. This indicates the availability of a remarkable number of different start-ups and innovative technologies. The lowest share of deal count goes to over $25 million deal sizes. This shows that the market is still fragmented with relatively few mature players. Several of the larger projects proved to be unwise, as is discussed in section 4.2.x.

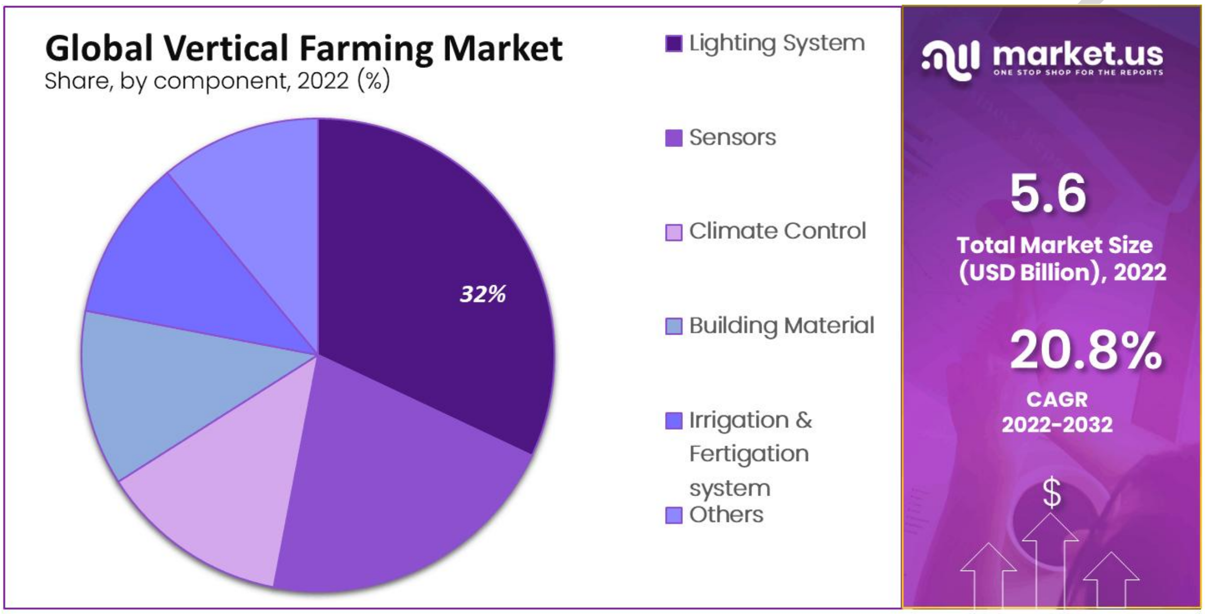


The supply of venture capital funding for indoor farming has contracted substantially since this report was published. According to PitchBook, through the first quarter of 2023, vertical farming deals declined by 91% year-over-year.

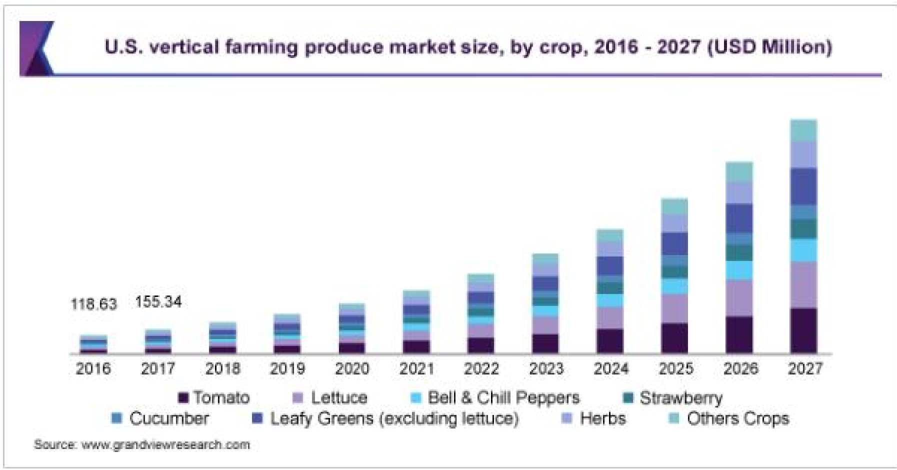
4.2.2 Market Research on Vertical Farming

There has been much hype concerning vertical horticulture for many years. In addition to numerous articles in the media, over 30 market research companies have offered expensive reports describing the expected growth of the industry. The estimates of the size of the industry in 2022 vary from US$3.2B to US$12B, with a median value of about US$5B. The anticipated CAGR for the next 5-10 years ranges from 10.3% to 27.8%, with a median value of ~23%.

In order to reach such large numbers, most reports include the cost of setting up a business as well as revenues. For example, the next chart is taken from the 2023 report by market.us[28].



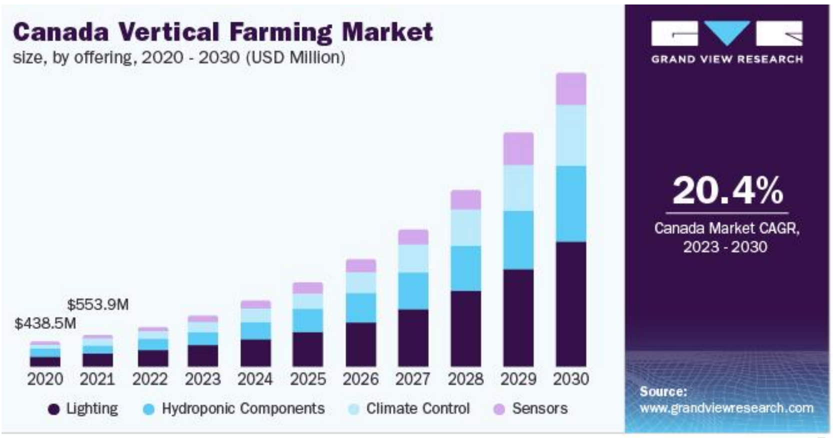
It is more difficult to find information on the revenues from products. The global revenues from the sale of products in 2019 was estimated by Grandview Research[29] to be US$1.02B, with a growth rate of 25.7%. The following chart from their 2020 report shows the breakdown by product type for the US.



Another indication of the important role of lighting in the economics of vertical farming is shown in the next chart from Grand View Research on the market in Canada.

[28] https://market.us/report/vertical-farming-market/

[29] https://www.grandviewresearch.com/industry-analysis/vertical-farming-produce-market



One aspect on which the researchers seem to be in agreement is that over half of the current market comes from shipping containers, rather than fixed buildings.

CALI reports[30] that China's vertical agriculture market size was approximately 13.2B yuan in 2022 and is expected to reach 17.8B in 2023. Plant factories are generally divided into five groups, producing sprouts, mushroom and medicinal fungi, leaf vegetables, berries and flowers, traditional Chinese medicine plant factory. There are "plant factories" in Beijing, Shandong, Jiangsu, Fujian and other places carrying out production and research and development. Planting varieties include lettuce, tomatoes, rapeseed, grapes, okra, peppers, etc. varieties, as well as some high-end flower seedlings. The number of plant factories in China was around 272 in 2021, with 48 new ones and an area of 215,400 square meters.

More broadly, including greenhouse cultivation, indoor farming is responsible for the production of about 260M tons of vegetables in China, accounting for 1/3 of the total production. The annual indoor production of fruits and melons is nearly 50 million tons. The current output value of protected horticulture industry alone exceeds 1.4 trillion yuan, accounting for more than two-fifths of the total output value of horticulture and more than one quarter of the total output value of agriculture. It's economic benefits per unit area are more than 20 times that of field crops.

4.2.3 A Reality Check for Vertical Farming

The past year has seen an increase in the number of reports and news articles questioning the profitability of indoor farming. An article by Adele Peters[31] entitled "The vertical farming bubble is finally popping" stimulated a lively discussion in print and social media. The article was stimulated by the sudden closure of **Fifth Season**, an indoor farm in Pennsylvania on a Friday in October 2022.

The farm, which had opened two years earlier, seemed to be running smoothly, growing tens of thousands of pounds of lettuce per year inside a robot-filled 60,000-square-foot warehouse. The brand was selling salad kits in more than 1,200 stores, including Whole Foods and Kroger. Earlier in the year, the company had said that it projected a 600% growth in sales in 2022. The branding was updated in October, and new packages were rolling out in stores. Solar panels and a new microgrid had recently been installed at the building. A larger farm was being planned for Columbus, Ohio.

But the workday never started on that fateful Friday. The managers announced that the company was closing immediately. After shutting down the electrical equipment and draining water lines, the plants were left to die. Dozens of employees were left scrambling to find new jobs.

[30] http://www.cali-light.com/index/index/newsart/id/25424.html
[31] https://www.fastcompany.com/90824702/vertical-farming-failing-profitable-appharvest-aerofarms-bowery

Fifth Season was not the first indoor farm to go out of business. Back in 2017, FarmedHere, one of the pioneers in the business closed a 90,000 square foot warehouse in Chicago with five layers of growing trays that had been renovated at a cost of $23M. Perhaps the biggest failure was that of Aerofarms which declared bankruptcy in June of this year after the failure of an attempt to merge with a Special Purpose Acquisition Company and go public with a declared value of $1.2B. Despite having previously received investments of $238M through 10 rounds of funding and claiming equity of $800M, the company's operational losses became unsustainable. In 2021 the estimated EBITDA-adjusted revenues were just $4M, while losses were $39M.

Overly aggressive operators of high-tech greenhouses can also come to grief. When it first launched in 2018, agriculture tech startup **AppHarvest** promised to transform the country's fruit and vegetable markets by building massive, multi-acre greenhouses tended by hundreds of employees, and Eastern Kentucky would become the center of it all. Although production did not start until late in 2020, the company raised over $625M, including $475M through going public in February 2021. The funds soon ran out.

In 2001, AppHarvest reported net sales of $9M. However, the direct cost of those sales was $42M and the total loss from operations was $200M. The situation improved only slightly in 2022. Net sales increased to $14.6B, but production costs rose by more to $57M. Overall loss from operations fell to $174M. In November 2022, the company announced a restructuring plan and began to sell its farms to pay of creditors. In July 2023, AppHarvest filed for bankruptcy, with $341M in debts.

Despite its huge operational losses, AppHarvest spent $60M in April 2021 to acquire Root AI, an artificial intelligence farming startup that creates intelligent robots to help manage high-tech indoor farms. This seems to have been another failed attempt to use artificial intelligence to make up for serious human errors.

Failures in vertical farming are not confined to Europe. Agricool, based in Paris, received around 35M euros in funding between 2015 and 2020 to grow strawberries, herbs and leafy greens in shipping containers. Agricool uses a closed-loop water system, meaning that they fill a tank for three months and use the same water over that period, which uses 99% less water. They minimize the cost of energy by dynamic control of the intensity and spectrum of the LED lights and the use of renewable energy sources. In 2020 the young company recorded a turnover of 162,000 euros for a loss of 7.72M euros. The losses continued and the company declared bankruptcy in January 2022. Agricool was rescued in June 2022 by VIF Systems (of the EPSA Group), a Lyon-based company that designs and installs vertical farms for controlled-atmosphere crops.

Infarm, a vertical farming business based in Berlin, shut down operations in Copenhagen, Denmark in April 2023. This is the latest closure in a series that also includes operations in the UK, France, the Netherlands, Japan and Frankfurt, Germany.

Munich-based start-up **Agrilution** was founded in 2013 to bring the idea of vertical farming into the home, but then had to file for insolvency proceedings in 2019 after a financing round could not be realised as planned. After the opening of insolvency proceedings, Miele took over the brand, the know-how and almost all employees and transferred them to the newly founded 100% subsidiary **Agrilution Systems** GmbH.

Miele provided intensive financial and technical support to guide the business model, product portfolio and workforce into a sustainable marketable future. But demand for the company's Plantcube products did not meet expectations, partly because of the high price of 3000 euros.

In order to make the Plantcube attractive to broader target groups, an additional series was to be launched at a significantly lower entry price. However, this could no longer be realised due to the skyrocketing costs of materials, energy and logistics. As a result, the decision was made not to pursue the plant business any further and Agrilution's operations ceased on June 30, 2023.

4.3 The Survivors

Founded in New York in 2015, **Bowery Farms** claims to be the largest vertical farming company in the US. It has received $640M in capital funding and is now valued at over $2B[32]. Continuing to scale up, Bowery doubled production in 2022 and is on track to double again this year from three mid-Atlantic commercial farms plus two research and development operations. Fresh strawberry packs and ready-to-eat salad kits were added to its product line of packaged vegetables and herbs. Distribution was expanded to more than 1500 grocery stores and major e-commerce platforms. The company now has over 500 employees.

To meet demand for its produce, Bowery is set to open two new smart farms in 2023 in Georgia and Texas. Bowery's farms are powered by 100% renewable energy.

Founded in San Francisco in 2014, **Plenty** has so far raised a total of $914 million in outside funding to develop its vertical farming technology and business. Its last round was a $400 million Series E raise at the beginning of 2022 from investors like Walmart and One Medical Group.

Until this year, commercial production and R&D were all located in a facility in South San Francisco. This has now been closed. In May 2023, a commercial factory with an annual capacity of 2M kg commenced operations in Compton, near Los Angeles. The facility is initially growing four varieties of leafy greens: Baby Arugula, Baby Kale, Crispy Lettuce and Curly Baby Spinach. An agreement has been reached with a real estate developer who will provide up to $1B to finance a second farm in Virginia with production beginning in 2024. Construction was started in August 2023 on a 120-acre site in Virginia. Several structures will be built, with the first planned to be a 100,000-square-foot vertical farm that'll be used to grow strawberries. The ultimate production target for the site is 9M kg per annum.

Founded in 2011 in Boston, **Freight Farms** is a technology provider, not a grower, with proven customer economics. It was the first to manufacture and sell "container farms": hydroponic farming systems retrofitted inside intermodal freight containers. Freight Farms also develops farmhand, a hydroponic farm management and automation software platform, and the largest connected network of hydroponic farmers in the world. The company has installed more than 600 farms in 40 countries, on behalf of individuals, entrepreneurs, educational and corporate campuses, and soil farmers. In 2021, Forbes reported that its units cost $140,000 and enable customers to earn annual revenues of around $100,000. Freight Farms has received over $43M in external funding, including $17.5M in Series B3 round in 2022.

In September 2023, Agrinam Acquisition Corporation and Freight Farms, Inc. announced a binding letter of intent for a business combination. IF executed, this could provide an additional $20M in capital for Freight Farms.

Founded in Brooklyn in 2009, New York, **Gotham Greens** operates sustainable greenhouses in urban locations, often on the roofs of existing buildings.

---

[32] https://www.cnbc.com/2023/05/09/bowery-disruptor-50.html

Gotham has received $440M in external funding, including $310M in its latest round in 2022. This will able the company to operate 13 high-tech, climate-controlled hydroponic greenhouses, totalling more than 16 hectares (1.8 million square feet) across nine states.

Founded in 2011, **BrightFarms** currently operates six high-tech greenhouse farms in New Hampshire, Pennsylvania, Virginia, North Carolina, Ohio and Illinois, with four new regional salad greenhouse hubs breaking ground to begin opening in 2024. BrightFarms' fresh lettuce options, from classic greens to crunchy mixes and salad kits, are available in more than 3,700 retail stores across the East Coast and Midwest. The company received about $200 in external funding before being acquired by Cox Enterprises in 2021. Its revenues in 2022 were estimated by Zippia to be $11.5M.

Founded in 2017, **Revol Greens** has quickly become the largest greenhouse lettuce grower in North America. It adopts advanced greenhouse technologies and growing method which allows facilities to use 90 percent less water than traditional field-grown greens. Grown in an animal and pest-free environment with no pesticide residues, and no herbicides or other harmful chemicals used in the process. Revol Greens currently grows more than 30 million pounds of non-GMO lettuce and greens annually with a coast-to-coast footprint. In May 2023, the company announced the opening in Texas of a 20-acre (8.1 hectares) greenhouse, which it claims to be the largest ever built. This brings the total area of the company's greenhouses to 50 acres (20 hectares). As of September 2020, Revol Green's total capital funding was $215M.

The global interest in vertical farming is being exploited by iFarm, which has provided technology for indoor farms in over 15 countries. The company was founded in 2017 in Russia by Alex Lyskovsky and his friends but moved their headquarters in Finland in 2019. iFarm received $5M in seed funding in 2019 and 2020. In 2022 iFarm was invited to join the incentive programme of Abu Dhabi's Hub71, the technology project led by Mubadala Investment Company and backed by the Government of Abu Dhabi. As a result, it decided to move its global headquarters to the UAE and launching a research and development facility in the Gulf state.

iFarm technology relies on automation, sensors and a proprietary farm management software, Growtune, to monitor and automate crop care, applying computer vision and machine learning and drawing on data on "thousands" of plants collected from a distributed network of farms. The farms it supports have a total growing area of over 13,000 m^2 and produce more than 127,000 kg of products each month. In April 2023, iFarm announced that it will collaborate with the Opus 2G Group to build the world's largest vertical farm in Tehuantepec, Mexico, with a cultivation area of 38,500 m^2.

The company publishes a great deal of useful information on its web site, especially concerning the costs of vertical farming. For example, an analysis of a potential farm in Estonia[33] concludes that the construction cost would be 700-750 euros per m^2 of growing area and that the payback period would be about 6 years.

[33] https://ifarm.fi/wiki/2022/01/vertical-farms-vs-greenhouses-part3

4.4 The Impact of LEDs

Clearly the development of LED lighting has added new dimensions to indoor farming. Partly because of the higher initial cost of LED lights, the lighting industry and university researchers have worked hard to identify and promote the benefits that accrue from the new technology, both in supplemental lighting for greenhouses and vertical farming.

4.4.1 LED characteristics

The new techniques exploit the flexibility in intensity, spectrum and spatial distribution of LED lights and can be deployed either in static or dynamic form.

Intensity: The control of intensity through dimming is useful in all indoor farming but is perhaps most useful in greenhouse applications. The potential benefits of dynamic lighting systems have been summarized in a recent white paper from the Canadian company, Sollum Technogies[34]. The intensity and spectrum of the light can be changed as plant growth progresses or can compensate for variations in the sunlight received in greenhouses[35]. The schedules can be preprogrammed or controlled by staff, possibly with the aid of sensors and machine learning through artificial intelligence systems.

Dynamic lighting systems can add substantially to the initial cost of the systems. Additionally, their complexity may require extra staff training and so also increase operating costs. The industry and its customers would be well-served by objective cost-benefits analyses of these systems.

Spectrum: Spectrum control is a powerful aspect in the design of LED lighting systems. It is clear that the spectrum that is optimal for humans is not the best for plants and neither is the sunlight spectrum, despite many centuries of plant evolution. But choosing the best spectrum for a specific crop is not straightforward. With so many vendors offering advice about the best lighting strategy, growers may be confused by apparently conflicting views. For example, Samsung maintains that white light should be used in many applications. According to their web site, "The initial investment for cost-effective full spectrum LEDs is much lower than that of other supplemental lightings. Samsung's white-based full spectrum LEDs also bring down the operation cost by reducing energy consumption with its industry-leading performances since LEDs that are general lighting are less expensive that those with spectra tuned to horticultural applications[36]. They also believe that full spectrum LEDs are better at stimulating photosynthesis, preventing disease, and making more bioactive compounds.

Signify has presented an opposing view for supplemental lighting in greenhouses. It has reported to LEDs Magazine that "energy consumption will dip noticeably if the greenhouse operator minimizes white LED light, which is more energy intensive than the red and blue spectra[37]". Signify based its assertion first and foremost on a basil study it conducted at its Philips GrowWise Research Center in Eindhoven. It cultivated the basil in three separate crops, each with the same 220 µmol/m2/s light level but with a different spectral mix of white, blue, and red. The highest yields came from a "deep red–blue" recipe, while "fresh weight decreases as the proportion of white light increases." According to the study, white light's main impact was a negative one: It increased energy

---

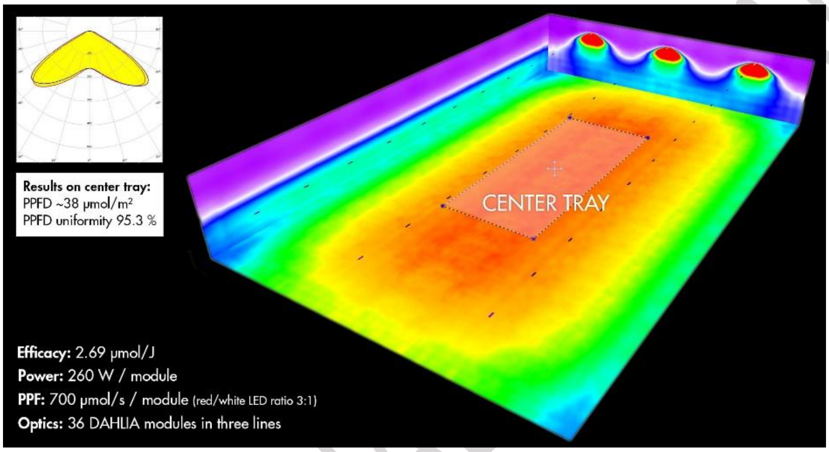
[34] https://www.sollumtechnologies.com/white-papers/introduction-to-dynamic-lighting
[35] https://www.sollumtechnologies.com/white-papers/dynamic-lighting-allows-growers-to-push-the-boundaries-of-energy-efficiency
[36] https://led.samsung.com/lighting/applications/horticulture-lighting/
[37] https://www.ledsmagazine.com/horticultural-lighting/article/14291223/avoiding-white-light-in-the-greenhouse-can-push-down-the-energy-bill

consumption. Signify claims that other studies — such as one by Holland's Wageningen University & Research[38] have shown the same general result with other crops and other light recipes.

One key to the value of white light is the impact of green light to the plants. One study at Utah State University found that Increasing the fraction of green photons promotes growth of tomato but not lettuce or cucumber.

Spatial Distribution: Care needs to be taken with respect to the position of the lights and the beam shape. In most applications, it is important to achieve a uniform distribution of light across the area occupied by the plants and minimize the production of stray light. This is normally accomplished by placing the lights above the plants and perhaps by directing the beams from LEDs near the edge.

Useful guides for the selection of LED optical systems have been provided by LEDiL[39]. LEDiL claims to be able to achieve 90% uniformity across multiple trays, as illustrated in the image below[40].



Lighting solely from above may not be the best solution for all cases, especially in the later stages of growth when shading by the upper parts of the plants prevent light from reaching the lower portions. This can be ameliorated by placing some lights below the plants or within the volume occupied by the plants. The latter approach has been termed inter-canopy, intra-canopy or close-canopy lighting. Because of the low heat output from LED lights, they can be placed closer to the plants than is possible with traditional lamps[41]. An interesting article on the history of inter-canopy lighting is available from Philips[42]. A more recent article from Fluence was published in Agritech Tomorrow[43].

The broad flexibility to modify these characteristics during growth raises the issue of the appropriate complexity of the control system. Some researchers and vendors argue that artificial intelligence (AI) can be used to supplement human experience. The potential benefits of AI have been discussed at

[38] https://www.ledsmagazine.com/horticultural-lighting/article/14277083/study-shows-14-increase-in-tomato-yields-with-interlighting
[39] https://www.ledil.com/wp-content/uploads/2022/09/Guide_for_Horticultural_lighting_v1.0_2022_WEB.pdf
[40] https://www.ledil.com/application-areas/horticultural-lighting-with-dahlia-tl110/
[41] https://urbanagnews.com/blog/news/purdue-university-new-led-strategies-could-make-vertical-farming-more-productive-less-costly/
[42] https://www.lighting.philips.com/application-areas/specialist-applications/horticulture/hortiblog/vegetables-and-fruits/3-reasons-why-intercanopy-lighting-is-effective-for-high-wire-vegetables
[43] https://www.agritechtomorrow.com/article/2023/09/how-intercanopy-lighting-can-help-your-grow/14848

length in a recent article in LEDs Magazine[44]. However, these systems could add significantly to the overall cost if they require an extensive set of sensors to monitor plant growth and the environment.

4.4.2 Crop Benefits

The potential benefits of indoor farming with LED lighting include:

- Shorter production times
    - The length of daily light can be extended beyond that delivered by sunlight. The optimal daily light duration varies considerably from one plant to another. For example, Sollum Technologies suggests that gerbera flowers thrive under an 11–12-hour photoperiod, whereas roses require a more extended photoperiod of 17-18 hours[45] to ensure proper extension and flowering.
    - The intensity of light from LEDs can be increased with less concern about overheating than with HID lamps.
    - The Urban Agriculture Research Institute of the National Chengdu Agricultural Science and Technology Center in Sichuan has demonstrated a plant factory plant breeding accelerator which can shorten the growth cycle of wheat from more than 100 days to more than 50 days[46].

- Higher yields
    - Researchers at Wageningen University have shown that placing about a third of a greenhouse's LED grow lights among high wire tomato crops rather than suspending all of them above the vines can increase the yield by an average of 14%. They noticed a 73% higher maximum photosynthetic capacity of the bottom leaves in the intra-lighting setup than in the toplighting-only section.
    - Indoor farming can substantially reduce the amount of land required to grow staple foods. According to the Global Land Assessment of Degradation[47], nearly two billion hectares worldwide have been degraded since the 1950s (representing 22% of cropland, pastures, forests, and woodlands). Climate change promises further loss of arable land.

      Researchers in Germany[48] have shown that wheat grown on a single hectare of land in a 10-layer indoor vertical facility could produce from 700 ± 40 t/ha (measured) to a maximum of 1,940 ± 230 t/ha (estimated) of grain annually under optimized temperature, intensive artificial light, high CO levels, and a maximum attainable harvest index. Such yields would be 220 to 600 times the current world average annual wheat yield of 3.2 t/ha.
- Crop quality can be improved and controlled more reliably.
    - As an example. the appearance, health, and texture of hydroponic lettuce can be improved by dynamic lighting recipes[49].

---

[44] https://www.ledsmagazine.com/horticultural-lighting/article/14295510/industry-insights-how-ai-facilitates-indoor-agriculture-efficiencies

[45] https://www.sollumtechnologies.com/case-studies/harnessing-the-power-of-light-intensity-and-spectrum-for-propagation-and-cut-flower-production

[46] https://www.cali-light.com/index/index/newsart/id/24898.html

[47] https://fluence-led.com/the-rise-of-vertical-farming/#:~:text=Vertical farming offers solutions in,to grow without soil altogether

[48] https://www.pnas.org/doi/10.1073/pnas.2002655117

[49] https://www.sollumtechnologies.com/case-studies/the-benefits-of-dynamic-lighting-in-hydroponic-lettuce-production

- There may be indirect benefits from growing crops close to the consumer. Natalia Falagan, of Cranfield University in the UK, has suggested that shorter supply chains could improve both food security and the quality of food, since the faster food reaches us, the less its nutrients deteriorate and the less unseen toxins, such as mycotoxins, develop[50].

- Greatly reduced use of water and fertilizer
    - The increasing global concern about water shortages is one of the drivers for the development of indoor farming. One of the greatest challenges is to find practical ways of reducing the need for water in rice production. The feasibility of indoor production of rice was analysed in detail by researchers at Chiba University back in 2014[51]. The current status was reviewed by Abdulrahman Al-hashim of King Saud University in Saudi Arabia[52]. Widespread use of this approach seems many years away but a recent trial at Yanjiagang Farm, a state-run farm in Harbin City, has demonstrated the potential value in raising rice seedlings[53].
    - At the China-Israel Jinhui Modern Agricultural Science and Technology Park in Tianfu the use of LED supplementary lighting has been combined with an automated drip system to supply of water and fertilizer[54]. The water consumption is only 1/5 of the water consumption for ground cultivation in ordinary greenhouses, and even some types of vegetables are only1/10 of the water consumption for ground cultivation, and the output of green leafy vegetables per unit area can reach 20 times that of ordinary ground cultivation.

- Control of pests and disease

It seems plausible that the use of controlled environments in indoor horticulture reduce losses from pests and disease, experts differ on how completely these problems can be eliminated.

- According to Eden Green Technology[55], "vertical farming may not completely eliminate crop diseases, but it does cut them down significantly and allows farmers to spot and treat them far quicker than in typical traditional farming operations. While it is still possible (though less common) for some pests to infest your greenhouse in a vertical farm, this is far less common indoors. Indoor vertical farms are usually more closely monitored than vast expanses of land outdoors. This means pests are typically spotted and dealt with more quickly in a controlled indoor environment. It also means diseases can be quickly identified and the affected plants isolated to prevent spread".
- IGrow News[56] confirms this assessment, concluding that "It has now become clear that lighting can also play a crucial role in Integrated Pest Management programs by reducing the impact of pests and diseases that can affect crop yields and profits. Using biological controls, such as natural predators or parasites, can help control pest populations, but lighting can make them more effective".

[50] https://www.bbc.com/future/article/20230106-what-if-all-our-food-was-grown-in-indoor-vertical-farms
[51] https://www.omicsonline.org/open-access/feasibility-study-of-rice-growth-in-plant-factories-jrr.1000119.php?aid=23453
[52] https://www.biotech-asia.org/vol20no1/a-review-growing-rice-in-the-controlled-environments/
[53] https://www.cali-light.com/index/index/newsart/id/25137.html
[54] http://www.cali-light.com/index/index/newsart/id/25289.html
[55] https://www.edengreen.com/blog-collection/how-vertical-farming-helps-prevent-yield-loss-from-diseaseh
[56] https://igrownews.com/horticultural-lighting-and-pest-management-in-indoor-farming/

- A more careful assessment has been made by a team from Cornell and Rutgers Universities[57],[58]: “Close attention must be paid to pest management. Without an integrated pest management (IPM) program, a vertical farm will almost certainly succumb to pest-related crop failure. The main pests encountered in controlled settings are fungal or arthropods (e.g., mites and gnats). Since vertical farms operate in a contained space, pests are almost always coming in from the outside, either on personnel, seeds, in the air, or in the water. Exclusion of these pests through air showers, coveralls, seed sterilization, air filtration, and water treatment can prevent pests from entering the facility. Exclusion of pests through various decontamination protocols should be the first line of defense, but it cannot be the only one. Eventually, pests will enter the facility and proper management is necessary to avoid crop loss. Proper environmental control is essential to avoid humidity buildup and condensation, which can favor fungal growth. Biocontrol agents can help control outbreaks of arthropod pests. However, they must be used as a proactive strategy, because introduction in reaction to an outbreak will typically not be fast enough to stop crop damage. Beneficial insects must be introduced prior to outbreaks and their populations must be maintained in the facility for maximum effectiveness”.
- Similar warnings have been expressed by Cultivated[59] : “Regardless of biosecurity practices, it is extremely difficult to completely prevent the infiltration of pests or disease at some point. Whether it be on humans, infected materials, air leaks in building envelopes, or ventilation, it is likely that eventually we will see an outbreak. Pathogens, such as small insects, bacteria, viruses, and fungi (including spores), are in our environments all of the time and without care will make their way into closed farms. Knowing that it is possible for pests to move into a farm at any time, it is important to continually monitor crop health. Thorough and more formal crop screenings should be included in weekly procedures, but the whole team should be trained to keep their eyes open for changes in crop health on incidence of pests during day-to-day operations. A clear chain of communication should be outlined to ensure the presence of an anomaly can be communicated quickly”.

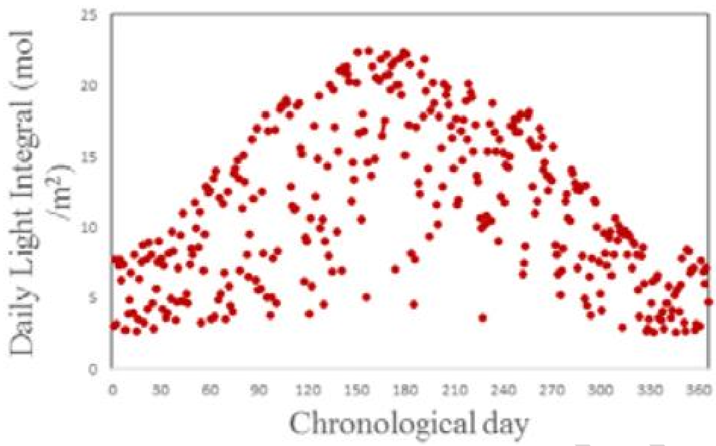
4.5 Cost Models

The most basic element in cost models for horticultural lighting is the efficiency of photosynthesis. Professor Bigbee, of Utah State University, estimates that each mole of photons can produce 16 grams of lettuce[60]. Assuming that the efficacy of the LED light fixture is 2.8 µmol/J, each kg of fresh product will require 6.2 kWh of electricity. The requirement for tomatoes is estimated to be 14 kWh/kg. Based on data from iFarm, the Food Institute[61] estimates that aragula grown in a container farm requires a total energy of 14-21 kWh per kg of saleable produce.

The Daily Light Integral (DLI) is useful in analysing the amount of supplementary light needed for effective greenhouse horticulture. A greenhouse crop’s light requirement can vary greatly. Propagation materials (cuttings and plantings) can require 8-10 mol/m^2/day, potted plants can

57 https://www.mdpi.com/2311-7524/8/4/322
58 J.M.Roberts, et al, Vertical farming systems bring new considerations for pest and disease management, Ann. Appl. Biol. 2020, 176, 226–232
59 https://cultivatd.com/detecting-pests-disease-indoor-farm/
60 https://www.energy.gov/eere/ssl/2020-lighting-rd-workshop-presentations-and-materials
61 https://foodinstitute.com/focus/meet-the-two-biggest-enemies-of-indoor-farming/

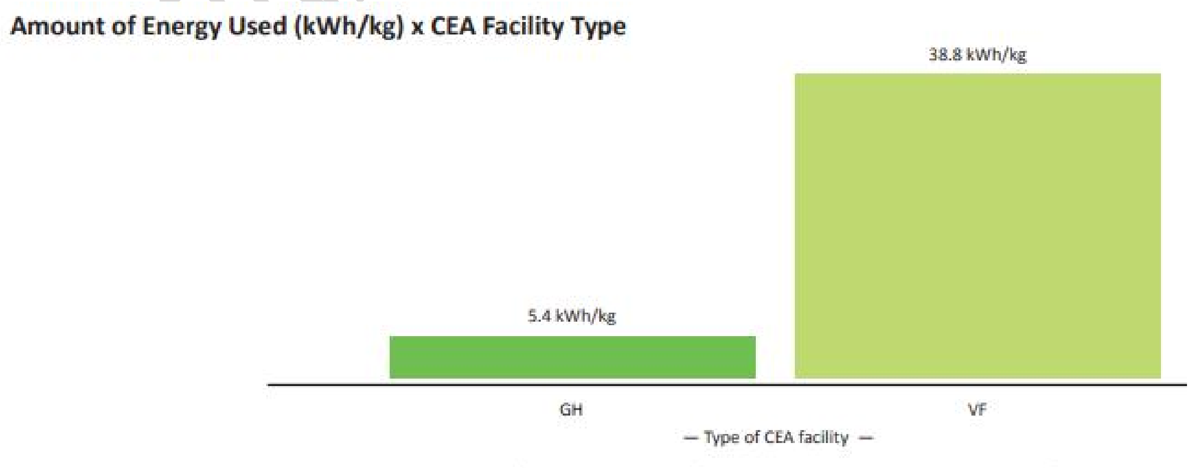
require 10-15 mol/m^2/day, leafy greens can require 15-20 mol/m^2/day, and tomatoes and strawberries can require more than 20 mol/m^2/day. These levels can often not be provided by sunlight, as shown in the next chart for Indiana (USA) that was used in a study by Krishna Nemali and Petrus Langenhoven at Purdue University [62].



The Purdue analysis begins by calculating the cost of delivering each mole of light. They assume that the light is provided by 320-watt LED lamps that costs $750 per fixture, have a life span of 50,000 hours and provide 500 µmol/m^2/s at a height of 4 feet below the lamps. Amortization of these lamps contributes $0.008 to the cost per mole. With an assumed rate of $0.13/kWh, the cost of electricity contributes $0.023 per mole, giving a total cost of 3.1c per mole.

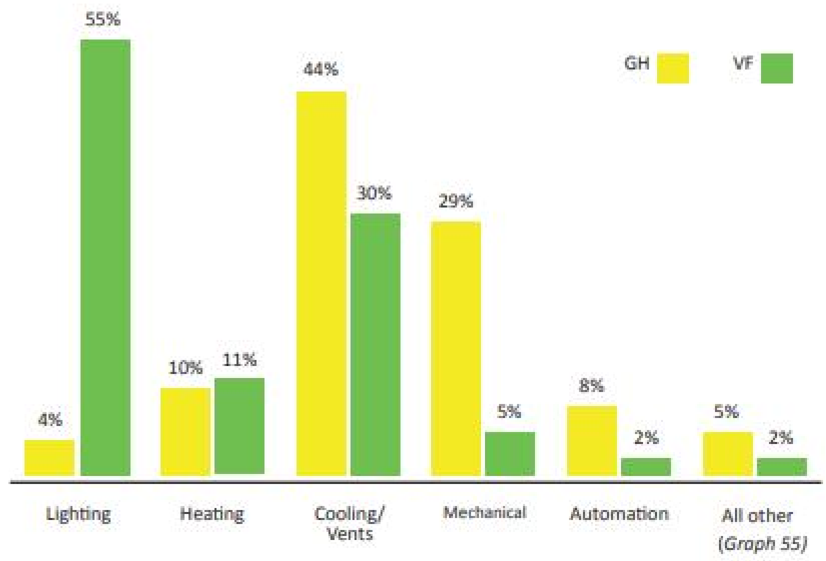
To assess the potential benefit of supplementary lighting, the team grew 15 varieties of lettuce under three daily light integral regimes of 5.6, 10.8, and 19.8 mol/m^2/day for 28 days (a total of 157, 302, and 554 mol/m^2 of light during the growth). The average fresh weight of all varieties was 0.90, 2.1 and 6.7 lb/m^2 at harvest in the 5.6, 10.8 and 19.8 mol/m^2/day treatments. These results suggest that lettuce can produce an additional fresh mass of about 6.8 grams for every mole of light incident on the plants. The electricity required is 26 kWh for each kg of extra product.

The next two charts from 2021 Global CEA Census report[63], published by Agritecture Consulting, show that the average energy used in controlled environment agriculture is much higher in vertical farms than in greenhouses and that most of the difference comes from lighting.

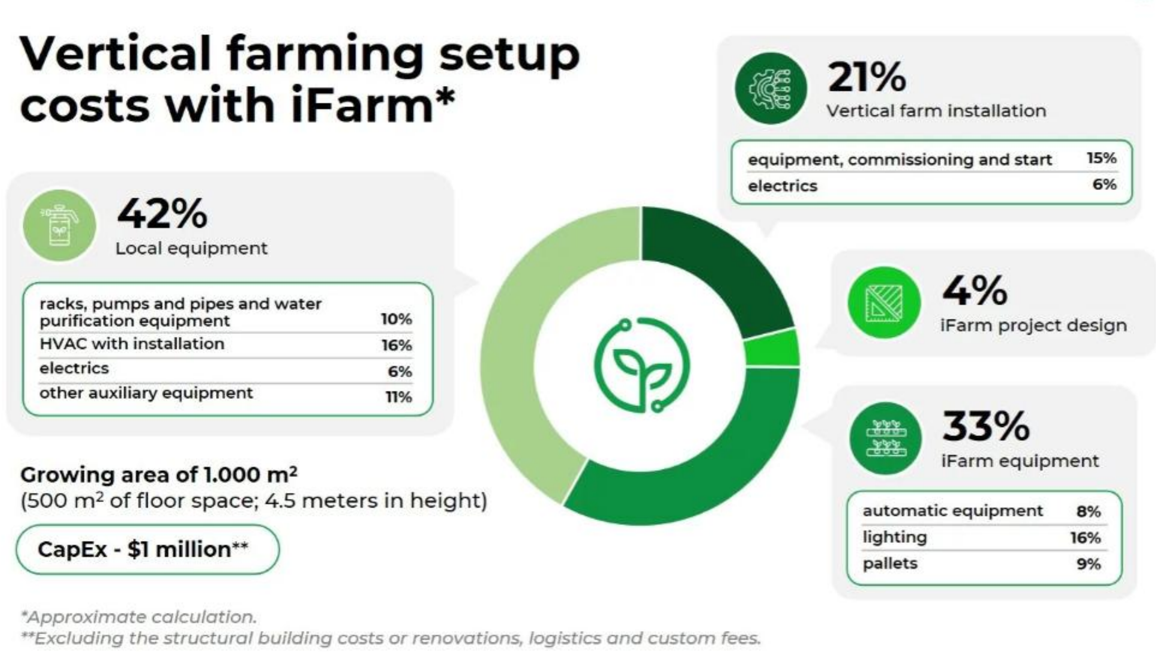


---

[62] https://www.extension.purdue.edu/extmedia/HO/HO-283-W.pdf
[63] https://www.agritecture.com/census



The impact of lighting on the capital cost of vertical farming is illustrated in the next figure from iFarm. This shows that lighting can be the most expensive cost in fitting a building for horticulture.



The growing reluctance of investors to provide capital for indoor farming is increasing the importance of comparing the extra in the initial cost of systems with more efficient energy use and of installing light sources with long lifetimes. This is illustrated by a recent study in Plymouth, Massachusetts[64], where the electricity cost was$0.24/kg.

These issues also come up in analysing the benefits of tailored spectra or dynamic lighting. Because of the desire of many growers to minimize the extra initial cost of LED replacements, Samsung has argued that the combination of white LEDs that are used in general lighting with a narrow red source can give the most economical solution. The extra purchase and maintenance costs of complex dynamic control systems must be weighed against the potential savings in electricity costs.

[64] https://cabatech.com/casestudies/why-lighting-technology-growth-costs-greenhouses-less/