

Rapid technological progress in white light-emitting diodes and its source in innovation and technology spillovers

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 Check for updatesMichael P. Weinold ^{1,2,3,4}✉, Sergey Kolesnikov ¹ & Laura Díaz Anadón ^{1,5}

Since their introduction to the market in 1996, white light-emitting diodes (LEDs) have greatly improved in performance, efficiency and manufacturing cost. Understanding the extent and mechanisms of rapid progress in white LED technology can provide valuable insights for accelerating innovation in other demand-side clean energy technologies critical for reducing global carbon emissions. Here we show, through cost and performance modelling based on data from literature review, patent analysis and expert interviews, that the efficiency of top-performing warm white GaN-based LED packages increased from 5.8% in 2003 to 38.8% in 2020. Over the same period, the manufacturing cost of low-to-mid-power LED packages decreased by 95.5% from US\$1.1 to US\$0.05 (in 2020 US dollars). We find that technology spillovers from other sectors accounted for at least 8.5% of efficiency improvements and nearly all consumer experience enhancements, playing an important role in widespread LED adoption in lighting.

A rapid reduction of global carbon dioxide emissions is urgently needed to mitigate the effects of climate change¹. Achieving such an ambitious goal requires both developing new clean energy technologies² and accelerating the deployment of existing supply-side³ and demand-side energy technologies⁴. To ensure rapid adoption of these technologies, substantial reductions in their costs and improvements in their performance are needed. This requires understanding how these cost reductions and performance improvements can be achieved^{5–8}.

Improvements in technology cost and performance, which in this study we generally call ‘innovations’, can occur via different mechanisms, including (but not limited to) learning by doing^{9,10}, research and development (R&D), economies of scale^{2,11} or technology spillovers^{2,12}. Different mechanisms can result in different kinds of innovations, characterized by what changes in the technology (for example, its architecture, design, materials, components or manufacturing processes) and the scale of resulting improvements (radical or incremental)¹³. For example, R&D efforts (sometimes also

called ‘learning by researching’)¹⁴ more often than other mechanisms have been associated with substantial or even radical improvements in technology performance. On the other hand, learning by doing is typically associated with continuous incremental improvements in the technology resulting from accumulated experience in technology demonstration, manufacturing and use. Both mechanisms, as well as economies of scale, can also lead to radical (that is, discontinuous) or incremental reductions in technology costs.

Among these mechanisms, the role of technology spillovers in innovation remains insufficiently understood⁶. Whereas the exact definition of technology spillovers in the literature depends on the context^{12,15}, we follow the approach of two previous studies^{6,15} and define technology spillovers as the application of external knowledge in a technology where knowledge is considered external if it has been initially developed or applied in other technologies, sectors or scientific disciplines. There is emerging evidence that understanding spillovers and knowledge networks beyond a particular technology

¹Centre for Environment, Energy and Natural Resource Governance, Department of Land Economy, University of Cambridge, Cambridge, UK.

²Chair of Entrepreneurial Risks, Department of Management, Technology and Economics, ETH Zurich, Zürich, Switzerland. ³Laboratory for Energy Systems Analysis, PSI Centers for Nuclear Engineering & Sciences and Energy & Environmental Sciences, Villigen, Switzerland. ⁴Chair of Energy Systems Analysis, Institute of Energy and Process Engineering, Department of Mechanical and Process Engineering, ETH Zurich, Zürich, Switzerland.

⁵Belfer Center for Science and International Affairs, Harvard Kennedy School, Harvard University, Cambridge, MA, USA. ✉e-mail: mweinold@ethz.ch

may be an important factor in understanding^{2,16} and shaping^{6,17} the future evolution of technologies. For example, spillovers can provide critical external knowledge inputs to the R&D process¹⁵, enable reuse of experience from different sectors in learning by doing² and lead to cost savings from repurposing the manufacturing equipment from other sectors⁶.

The aim of this study is to identify and, where possible, quantify the contribution of different mechanisms of innovation, including technology spillovers, to the historical progress in white LEDs used in general illumination. Lighting is a particularly important area for climate change mitigation efforts, as it currently accounts for 15–19% of global electricity consumption^{18,19}. It is also an area of rapid recent technological change. Since the introduction of the first commercial white light-emitting diodes (LEDs) in 1996²⁰, dramatic improvements in white LED performance and reductions in LED manufacturing cost, supported by energy efficiency regulations phasing out incandescent light bulbs, have led to the rapid expansion and diffusion of LED-based solid-state lighting (SSL) technologies^{21–23}. By 2020, highly efficient LED lighting was projected to save an estimated 93 TWh of energy per year in the European Union²⁴ and 580 TWh per year in the USA²⁵, which is comparable with the amount of energy produced in the same year by all photovoltaic installations in these regions. Notably, market adoption of LED lighting is not limited to developed economies²⁶. For example, the durability, low up-front cost and high efficiency of LED light sources have led to their early and widespread adoption in rural West African communities without access to grid electricity²⁷.

Despite this impressive history, the mechanisms of technological progress in white LEDs, a demand-side energy technology, have not received as much attention from researchers as in supply-side energy technologies, such as solar photovoltaics^{5,7}, wind energy^{28,29} or lithium-ion batteries^{6,8}. To the best of our knowledge, no study has comprehensively analysed the mechanisms or extent of historical progress in white LED technology (Supplementary Note 1 provides a brief review of previous literature on this topic). This is consistent with previous observations regarding the marginalization of end-use technologies in the analysis of energy innovation for climate change mitigation^{30,31}. Understanding the extent to which individual innovations contributed to overall improvements in white LED cost and performance, by which mechanisms these innovations occurred and what role was played by technology spillovers in this process will provide valuable lessons for innovation in other demand-side energy technologies and clean energy innovation in general.

To address these questions, we use a mixed-methods approach to track and analyse historical progress in a set of cost and performance metrics in warm white GaN-based phosphor-converted LEDs. We find that device efficiency in such LEDs increased from 5.8% to 38.8% between 2003 and 2020. Most of this increase in efficiency can be attributed to a series of specific innovations in white LED technology resulting from R&D efforts. Furthermore, 8.5% of the total 33 percentage point increase in LED efficiency, which amounted to 2.8 percentage points, was specifically due to innovations driven by technology spillovers. We also find that R&D efforts and technology spillovers led to nearly all improvements in consumer experience metrics in white LED lighting technology. Next, our bottom-up LED manufacturing cost model shows a 95.5% decrease in the cost of producing low- to mid-power classic-chip-architecture white LEDs from US\$1.11 to US\$0.05 (in 2020 US dollars) between 2003 and 2020. In contrast with improvements in LED device efficiency and consumer experience, where progress was driven mostly by R&D efforts and technology spillovers, we find that the dramatic decline in LED manufacturing cost was mainly a product of learning by doing that resulted in higher yields across manufacturing steps and economies of scale resulting from increases in sapphire wafer size. This pattern of contributions of different innovation mechanisms to cost reductions in white LEDs, an end-use energy technology, is very different from

similar observations in energy generation or storage technologies such as solar photovoltaics or lithium-ion batteries. These differences, along with our findings on progress in consumer experience metrics, indicate that innovation in LED lighting as a consumer-facing demand-side energy technology may require different approaches to R&D management and policy support than in supply-side energy technologies. Finally, we note that among nine cases of technology spillovers identified in our study, a majority occurred in areas with a deep understanding of the underlying physical phenomena. This indicates that investing in research that develops such physical understanding and a more deliberate search for relevant external knowledge may accelerate innovation both in LEDs and other related energy technologies.

Efficiency improvements

As we show in Fig. 1, the luminous efficacy of white LED-based light sources dramatically increased by three orders of magnitude in just over 20 years since the introduction of white LEDs to the market in 1996²⁰. This is considerably faster than historical progress observed in previous lighting technologies³². For comparison, the highest-performing LEDs today reach efficacies of 220 lm W⁻¹ (ref. 33), whereas an incandescent light bulb can only reach efficacies of up to 18 lm W⁻¹.

To track and analyse the sources of such rapid progress in white LED technology, we apply the mixed-methods approach described in Methods and collect data on historical improvements in individual sub-efficiencies of warm white phosphor-converted GaN-based LED devices (Supplementary Methods 2 and 3 explain the choice and describe these progress metrics, and Supplementary Note 3 provides a summary of the findings). We also identify white LED innovations and innovation mechanisms associated with these improvements (Supplementary Note 4 and Table 1).

Using this information, we calculate the overall lamp efficiency η_L for the best-performing mid/high-power phosphor-converted warm white LED devices in four years: 2003, 2010, 2016 and 2020. The waterfall diagrams of electric power input losses in Fig. 2 show how improvements in individual sub-efficiencies led to improvements in the overall white LED lamp efficiency from $\eta_L = 5.8\%$ in 2003 to 12.7% in 2010, 32.6% in 2016 and finally to 38.8% in 2020. No single loss channel dominates in terms of its contribution to the overall efficiency, in line with previous observations³⁴. We note, however, that the loss channels with a fixed physical limit on efficiency – for example, Stokes loss that determines the light conversion efficiency by phosphors – became relatively more dominant in 2016 and 2020 compared to 2003 and 2010. This is a direct result of large improvements in upstream sub-efficiencies (that is, in the left-side columns in Fig. 2).

Figure 3 shows the overall magnitude of the contributions of the identified LED innovations and technology spillovers to the improvements in LED efficiency over time across different sub-efficiencies. Most of these innovations, listed in Supplementary Note 4 and Table 1, were a result of R&D efforts, while a smaller number of innovations were driven by learning by doing. This observation suggests substantially higher relative importance of the R&D mechanism in white LED efficiency improvements compared to the learning-by-doing mechanism. Through the index decomposition analysis described in Supplementary Methods 9, we also find that out of the total LED efficiency increase of 33 percentage points from 5.8% to 38.8% between 2003 and 2020, at least 2.8 percentage points can be attributed specifically to innovations driven by technology spillovers, which corresponds to 8.5% of the total LED efficiency improvements between 2003 and 2020.

In Fig. 3 we also compare efficiency improvements across sub-efficiencies over time, contrasting them with the physical limits of the corresponding loss channels. Notably, since we focus on the best-performing devices typically discussed in the literature and because we lack reliable information about the distribution of input parameters, our point estimates do not show uncertainty ranges and

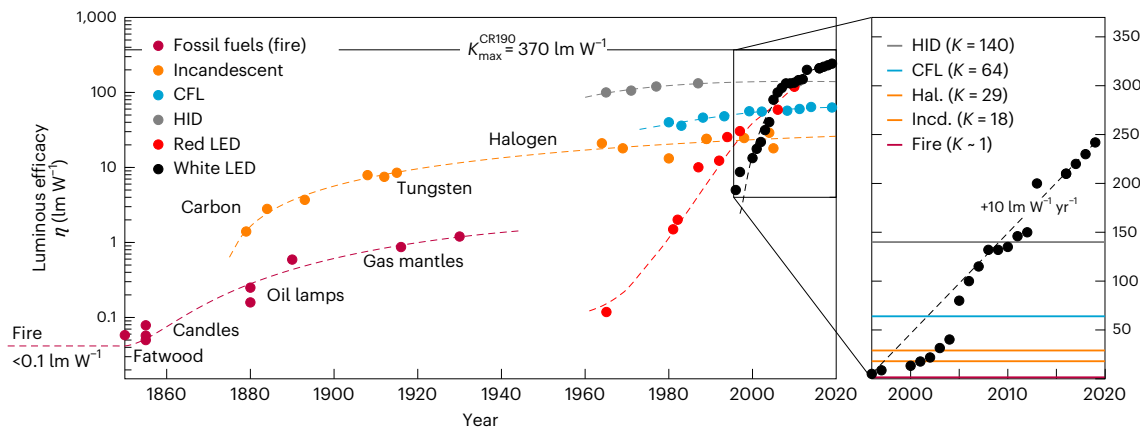


Fig. 1 | Historical progress in luminous efficacy η of the most widely used lighting technologies in human history. Data points indicate best performers by year of market introduction. Luminous efficacy of a light source η measures how efficiently the source converts energy into visible light that can be perceived by the human eye, taking into account the wavelength sensitivity of the eye (Supplementary Methods 3). Dashed lines are visual guides based on a third-order polynomial fit to the data trend. The physical limit on η for an ideal light source with a colour rendering index CRI = 90, denoted as K_{\max}^{CRI90} , is shown as a black horizontal line, as per calculations by Murphy et al.⁹². The magnified plot

shows progress in η in cool white LEDs from 1996 to 2020, with the dashed line indicating a linear rate of efficacy improvement of 10 lm W⁻¹ per year. For comparison, efficacies of best performers in legacy lighting technologies for 2020 are shown as coloured horizontal lines. Note the logarithmic scale of the vertical axis on the main plot and the linear scale on the magnified plot. CFL, compact fluorescent lamp; HID, high-intensity discharge; Hal., halogen; Incd., incandescent. Source: own synthesis of published data based on a visual approach proposed by Azevedo et al.⁹³. Supplementary Note 6 provides the full list of data sources and references.

Table 1 | LED innovations related to improvements in consumer experience metrics

Year	Name	Chemical formula	Description	Historical importance
1996	YAG:Ce	$\text{Y}_3\text{Al}_5\text{O}_{12} : \text{Ce}$	Yttrium aluminium garnet (YAG) phosphor activated with cerium	First LED phosphor, enabled white LEDs
1996	YGAG	$\text{Y}_{1-x}\text{Gd}_x\text{Al}_3\text{O}_{12} : \text{Ce}$	Gadolinium-doped YAG phosphor	First red-shifted phosphor, enabled warm white LEDs
2000	258	$(\text{Ba}, \text{Sr})_2\text{Si}_5\text{N}_8 : \text{Eu}^{2+}$	Europium-doped nitridosilicate phosphor	First red LED phosphor
2003	QD	Not applicable	Quantum dot (QD) phosphor	First use of quantum dots for LED light down conversion
2005	PFS	$\text{K}_2\text{SiF}_6 : \text{Mn}^{4+}$	Manganese-activated potassium fluorosilicate (PFS) phosphor	First ultra-narrow-band red LED phosphor
2013	SLA	$\text{Sr}[\text{LiAl}_3\text{N}_4] : \text{Eu}^{2+}$	Europium-doped cuboidal nitridolithoaluminate phosphor	Improved narrow-band red phosphor
2017	SALON	$\text{Sr}[\text{Li}_2\text{Al}_2\text{O}_2\text{N}_2] : \text{Eu}^{2+}$	Europium-doped oxonitride phosphor	High-performance ultra-narrow-band red phosphor

‘Year’ represents the earliest reported or patented application of innovation in white LEDs. These differ from the years shown in Fig. 4, which correspond to the earliest publication of spectral data for commercial LED products that relied on those innovations. ‘Name’ denotes common abbreviations used to identify each innovation in the literature. Detailed descriptions of the history of each innovation, with references, are provided in Supplementary Note 5.

should be interpreted as the expected values in a best-case scenario. Nevertheless, we find that there was consistent progress across all device sub-efficiencies in the period covered. Specifically, between 2003 and 2020, forward voltage efficiency increased from 70% to 99.5%, internal quantum efficiency from 55% to 90%, efficiency droop from 65% to 90%, light extraction efficiency from 60% to 90%, spectral efficiency from 74% to 83%, conversion efficiency (red) from 11% to 45%, conversion efficiency (green) from 19% to 61%. Notably, some sub-efficiencies for the most recent devices considered in our study are now within -10 percentage points of their respective physical limits. The exception is spectral efficiency which, at -17 percentage points below the physical limit, shows larger potential for further improvements, which is important from the perspective of guiding ongoing R&D efforts to improve white LED performance^{35,36}.

Consumer experience improvements

Historical progress in consumer experience metrics for white GaN-based LEDs is shown in Fig. 4. In general illumination applications, a high colour rendering index (CRI) in combination with a specific, tunable range of possible colour temperatures is desirable (Supplementary Methods 4). Both CRI and colour temperature metrics are determined

solely by LED device emission spectra, which, in turn, depend on the properties of phosphor materials used for the down-conversion of blue light generated by conventional GaN-based LEDs into white light.

This allows us to establish the links between all major improvements in the two consumer experience metrics considered in this study and individual LED innovations associated with phosphors used for light down-conversion in LEDs. The first commercial white LED produced by Nichia in 1996 used a YAG (yttrium aluminium garnet) phosphor activated with cerium that resulted in cool white light only³⁷. As shown in Fig. 4, after a series of innovations listed in Table 1, LEDs today can be tuned for high CRI performance and a range of desirable colour temperatures.

Taking together the detailed descriptions of the history of innovations in this list that we provide in Supplementary Note 5, we find that all innovations related to LED consumer experience improvements are primarily a result of R&D efforts, and only one of those innovations did not involve technology spillovers: the 2017 SALON phosphor compound^{38,39}. All other innovations contributing to improvements in the CRI and colour temperature metrics were either originally developed for non-LED applications or prominently used knowledge from areas of science and technology beyond LED or SSL (Table 2). This

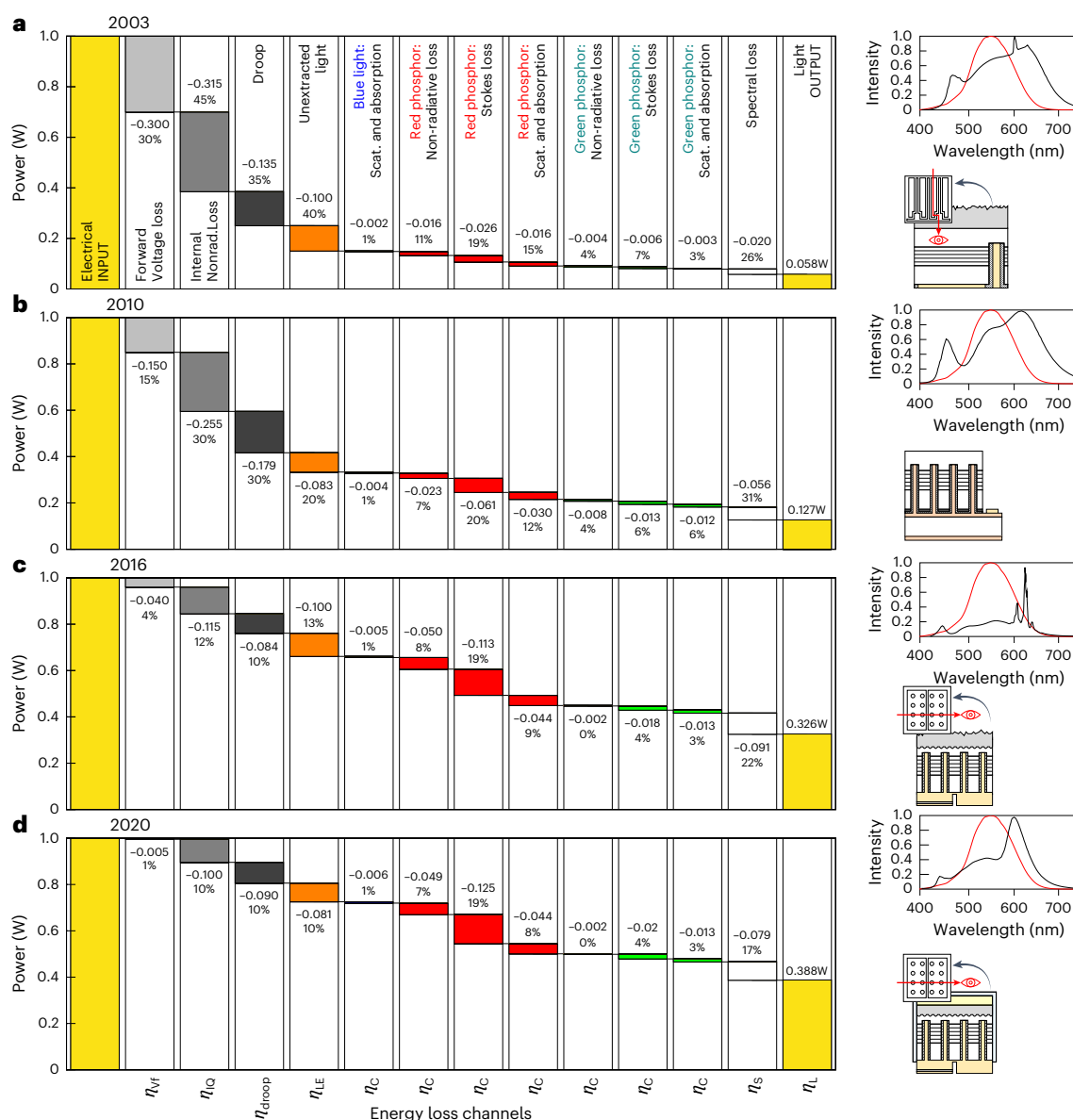


Fig. 2 | Historical waterfall diagrams of energy loss channels in a generic mid/high-power white LED package. a–d, Diagrams for 2003 (a), 2010 (b), 2016 (c) and 2020 (d). Losses are normalized to 1 Watt of electric power input. Represented energy loss channels, listed in each column in a, contribute to the following sub-efficiencies, listed below each column in d and defined in Supplementary Methods 3: η_{VF} , forward voltage efficiency; η_{IQ} , internal quantum efficiency; η_{droop} , efficiency droop; η_{LE} , light extraction efficiency; η_C , light conversion efficiency; η_S , spectral efficiency; η_L , overall LED lamp efficiency. Numbers for each loss channel indicate energy losses both in relative terms of input power (in percentage) at the point of the channel and as absolute values (in Watts). Percentages for loss channels labelled by red, green and blue text indicate losses of corresponding remaining red/green/blue light energy. Note that absolute losses for individual loss channels may not always add up

to the total loss due to the accumulation of rounding error. To the right of each waterfall diagram, the following representative LED architectures and light-source spectra used in calculations for each considered year are shown for reference: 2003, flip-chip with YGAG phosphor; 2010, flip-chip with 258 phosphor; 2016, flip-chip with PFS phosphor; 2020, chip-scale package flip-chip with SALON phosphor. On the spectral plots, the red curve shows the wavelength-dependent sensitivity of the human eye, whereas the black curve shows the spectrum of the light source. Details for each LED architecture are provided in Supplementary Note 2. Details on the phosphors for light down conversion are provided in Table 1 and Supplementary Note 5. Nonrad., non-radiative; scat., scattering. Source: own elaboration based on data on LED sub-efficiencies presented in Supplementary Note 3 and LED spectral data in Supplementary Note 5, with additional sources reported in Supplementary Note 6.

means that technology spillovers contributed to nearly all consumer experience improvements in LED-based lighting technology, thus likely having an important role in the widespread adoption of SSL in general illumination applications.

Manufacturing cost improvements

Historical improvements in LED efficiency detailed in the ‘Efficiency improvements’ section have been accompanied by a similarly impressive decline in LED manufacturing costs and retail prices. As shown in

Fig. 5, we find that LED retail prices have fallen by two orders of magnitude at an average annual rate of 27.3% during the 2008–2020 period⁴⁰.

Owing to the limitations of lamp retail prices as a metric of progress in LEDs discussed in Supplementary Methods 5, we focus our analysis on progress in white LED chip manufacturing costs instead. To track this progress and identify its sources, we develop a bottom-up white LED manufacturing cost model described in ‘Manufacturing cost model’ in Methods and Supplementary Methods 6. Fig. 6 shows the main results of our cost modelling for low- to mid-power classic-chip

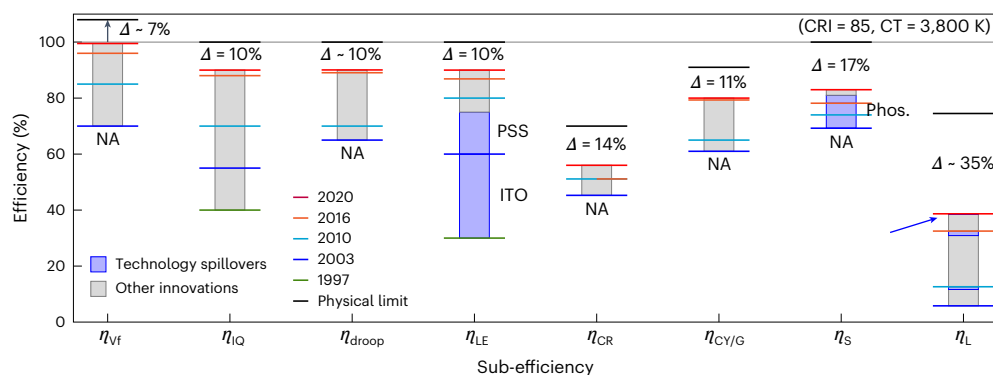


Fig. 3 | Contribution of innovations and technology spillovers to historical progress in sub-efficiencies of phosphor-converted warm white LEDs.

LEDs with test currents of at least 350 mA are considered. The following sub-efficiencies are represented: η_{Vf} , forward voltage efficiency; η_{IQ} , internal quantum efficiency; η_{droop} , efficiency droop; η_{LE} , light extraction efficiency; η_{CR} , conversion efficiency for red phosphors; $\eta_{CV/G}$, conversion efficiency for yellow/green phosphors; η_S , spectral efficiency. The overall LED lamp efficiency η_L is displayed in the right-most column. A horizontal line at 100% efficiency of an LED with a colour rendering index (CRI) of 85, and a colour temperature (CT) of 3,800 K is provided for visual guidance. Vertical bars represent cumulative contributions of LED technology innovations to efficiency improvements, with purple bars indicating specific innovations driven by technology spillovers and grey bars cumulatively indicating all other innovations identified in this study. Horizontal coloured lines indicate sub-efficiency levels of best-performing LEDs

for the four years used in Fig. 2: 2003, 2010, 2016 and 2020. For additional historical context, data for 1997 is included whenever possible. 'NA' denotes sub-efficiencies where 1997 data could not be calculated for the following reasons: η_{Vf} , η_{droop} depend on the device current, which was below 350 mA in 1997, making a comparison with contemporary devices difficult. η_{CR} , $\eta_{CV/G}$ and η_S are relevant only to warm white LEDs, which were not available in 1997. ITO, indium tin oxide; PSS, patterned sapphire substrate; Phos., phosphors. Note that the ITO current spreading layer affects different sub-efficiencies in different chip architectures. For example, in modern flip-chip architectures η_{LE} no longer depends on ITO (Supplementary Note 2). Physical limits on sub-efficiencies are indicated by black horizontal lines. Note that the physical limit of η_{Vf} is above 100% due to quantum effects⁹⁴. Δ represents the remaining gap between the most recent values and physical limits for each sub-efficiency. Source: own elaboration based on data represented in Fig. 2, Table 2 and Supplementary Note 3.

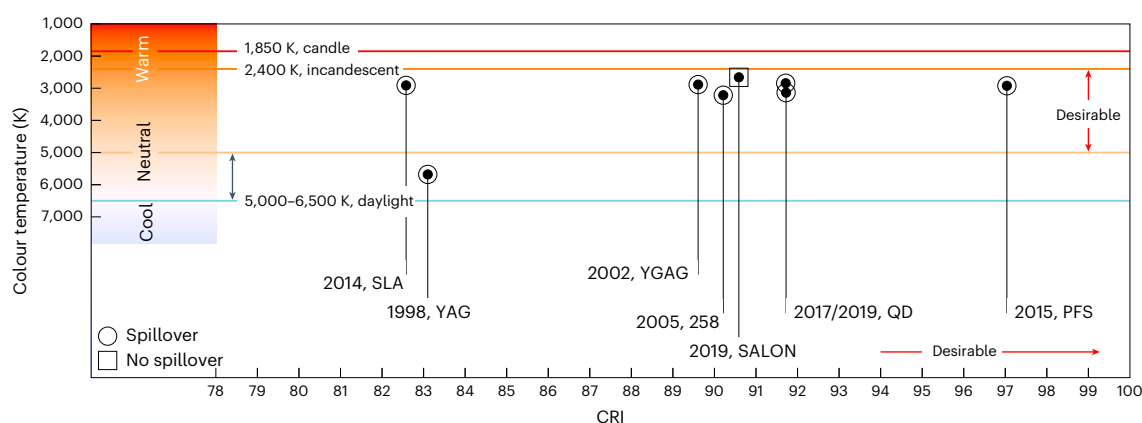


Fig. 4 | Historical improvements in consumer experience metrics of phosphor-converted white LED devices. Data points show the CT and CRI of the earliest identified commercially available white LED products with published spectral data that used phosphors listed in Table 1, each indicated by the phosphor label and publication year. Horizontal lines represent typical CTs of 'traditional' light sources, shown for reference. The desirable range of colour temperatures for

home illumination, indicated by a vertical red arrow, lies between two horizontal orange lines representing typical incandescent light and warm daylight colour temperatures. The horizontal red arrow indicates desirable higher CRI values. Source: own calculations based on spectral data provided in Supplementary Note 5 for white LED products with the following phosphors: YAG³⁷, YAG⁶⁸, 258⁸⁰, SLA⁹⁰, PFS⁸⁷, QD^{95,96}, SALON³⁸.

GaN-based phosphor-converted white LED packages. We find that the manufacturing cost of a single such LED decreased from US\$1.11 (in 2020 US dollars) in 2003 to US\$0.11 (2020 US dollars) in 2012 and US\$0.05 in 2020, a 95.5% overall decrease. Our model shows that for the wafer-level manufacturing steps illustrated in Supplementary Figs. 2–6, improved manufacturing yields and increases in the wafer size are jointly responsible for the largest contribution—that is, 91%—to the overall reduction in manufacturing cost per LED package between 2003 and 2020 (Supplementary Discussion 2).

In the case of manufacturing yield, the higher it is, the less inputs are wasted on the production of a single LED package. With the overall manufacturing yield dramatically improving from ~25% in 2003 to ~75% in 2020 (Fig. 6d), it is not surprising that the total yielded LED manufacturing cost declined considerably over this period.

In the case of wafer diameter, the larger the wafer, the more LED chips can be produced from a single wafer. The wafer diameter commonly used in LED manufacturing has been steadily increasing from 50 mm ('2 inch') in 2003 to 200 mm ('8 inch') in 2020 (Supplementary Fig. 14; note that the industry measures wafer sizes in mm but still commonly refers to, for example, a 50-mm = 1.9685-inch wafer as a '2-inch wafer'). We capture this effect in the model by calculating the associated number of die per wafer (DPW) for each representative wafer diameter⁴¹. With more than a 30-fold increase in the number of chips that can be produced from a single wafer (from 851 DPW in 2003 to 26,838 in 2020; Supplementary Methods 7), the whole-of-wafer processing steps now make up a much lower share of the total cost of manufacturing a single LED package, going down from 66.1% of the total cost in 2003 to 13.8% in 2020 (see wafer processing steps in

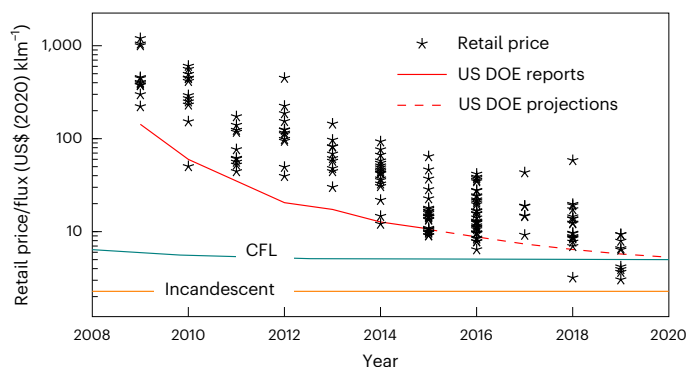


Fig. 5 | Historical changes in retail sales prices per luminous flux for LED-based luminaires, 2009–2020. The luminaires considered include light bulbs, spotlights and recessed lights. Red curved and dashed lines represent average retail sales prices and price projections for LED-based luminaires published by the US Department of Energy (DOE)⁹⁷. Shown for reference are the average prices for compact fluorescent (CFL) and incandescent light bulbs, with the latter assumed constant based on the average in the covered time period. Note that DOE price data (both historical reports and projections) are for traditional A19 light bulbs and do not include sales tax, placing them at the lower end of the retail price distribution. Individual data points capture price data for a broader range of luminaire types, many of which are more expensive than the traditional A19 light bulb. Source: own synthesis of the historical inflation-adjusted sales price data (in 2020 US dollars) for the EU, UK and US markets, collected from various consumer watchdog databases and publications. Supplementary Note 6 provides the full list of data sources and references.

Fig. 6a–c). As the DPW number increases, the packaging steps, which in the classic-chip architecture must be performed separately for each individual LED chip, make up a larger share of the total cost in 2020 than in 2003. However, as our interviewed experts noted, while growing LEDs on larger wafers is economically desirable, it is also associated with engineering and epitaxy challenges and high up-front cost of new equipment.

Surprisingly, R&D efforts to improve LED technology and associated technology spillovers are not found to have had a substantial impact on LED manufacturing cost reductions during the period considered. There are several explanations for this finding. First, the functional unit of our analysis is an LED chip itself, not a luminaire containing multiple chips. As LED efficiency and overall brightness have increased, a smaller number of chips can be used in luminaires to obtain the same level of the overall lamp light flux⁴². However, because we are investigating improvements at the level of single packaged chips, we do not capture the cost effects downstream of chip manufacturing, which may have been affected by R&D efforts differently. Second, we find that the increase in wafer size and higher overall yield that together account for as much as 91% of the total manufacturing cost reduction were both driven by advances in manufacturing equipment (for example, in epitaxy) that enabled economies of scale and by incremental manufacturing process improvements from learning by doing, rather than specific innovations in LED technology resulting from R&D or technology spillovers. This finding, separately supported by the observations of the interviewed experts in LED manufacturing, suggests that R&D efforts and other innovation mechanisms contributed to no more than the remaining 9% of cost reductions.

Notably, our bottom-up cost model is constructed to provide process-step resolution across three different LED chip architectures: classical chips, flip chips and chip-scale package flip chips. However, in this study, we were able to collect data and compare the outcomes only for the classical chip architecture. Collecting the full set of data needed to populate the model for the remaining two architectures

requires access to proprietary information from the industry. With this limitation, tracking manufacturing cost reductions for these two LED chip architectures remains a topic for future work.

Our findings about the mechanisms of cost reductions are further supported by a preliminary sensitivity analysis, presented in Supplementary Discussion 1, where we find that the sensitivity of the cost model to variation in its main parameters decreases over time with the DPW increase. In Supplementary Discussion 3, we also provide a comparison of our cost model results with past reports and projections published by the US DOE based on the LEDCOM cost model⁴³ and industry data reported as part of the DOE SSL round table meetings.

Technology spillovers

In the Methods, we describe how we identify and analyse technology spillovers and their contribution to innovation in white LED technology, following the frameworks developed by Stephan et al.⁶ and Kolesnikov et al.¹⁵. We find that at least nine white LED innovations, listed in Table 2, clearly involved technology spillovers. The three earliest spillovers made possible the use of YAG/YGAG phosphors in LEDs, thereby playing the key role in the development of the first commercial white LED lighting products, essentially enabling the SSL market and industry of today. As shown in the ‘Efficiency improvements’ section, six subsequent spillovers contributed to at least 8.5% of the total LED efficiency improvement between 2003 and 2020 and nearly all key improvements in consumer experience metrics. Interestingly, the identified technology spillovers contributed only to innovations resulting from R&D efforts rather than learning by doing or other mechanisms. To some extent, this finding can be a result of limitations in our methodology for the identification of spillovers, which may favour spillovers associated with more radical rather than incremental innovations, as explained in the Methods.

Among the spillover sources, we find that all nine spillovers in Table 2 had origins in the scientific disciplines such as various branches of chemistry, materials science, optics, photonics and solid-state physics, which indicates the importance of scientific knowledge in the development of white LED technology. Five spillovers also utilized external knowledge from technologies such as cathode ray tubes, fluorescent lighting, optoelectronic devices, nanotechnology and nature-inspired material design.

Finally, as the main factors that enabled the spillovers listed in Table 2, we identify public mission-oriented R&D funding; industry–academia partnerships; firm experience in multiple industries and markets; knowledge exchange events such as conferences; freedom of search in academia, often itself enabled by flexible public funding; and university alumni networks.

Discussion

In this study, we use a multi-method approach to synthesize evidence from multiple sources and reconstruct a detailed picture of the rapid technological progress in white LED technology throughout its history across a set of metrics related to LED device efficiency (Figs. 2 and 3), manufacturing cost (Fig. 6) and consumer experience (Fig. 4). Improvements in these metrics are traced (with contributions quantified, where possible) to specific white LED technology innovations resulting from R&D efforts, technology spillovers, learning by doing, and economies of scale in the manufacturing process.

We find that progress in LED efficiency and consumer experience metrics has been mainly driven by R&D efforts and technology spillovers. The relative contribution of technology spillovers to progress in these metrics differs in magnitude, with a rather small 8.5% share of the total efficiency increase but virtually all consumer experience improvements attributed to spillovers. Our results show that technology spillovers have been most prevalent in those efficiency loss channels that are well understood at the physical level (for example, light extraction or spectral efficiencies) (Fig. 3 and Table 2).

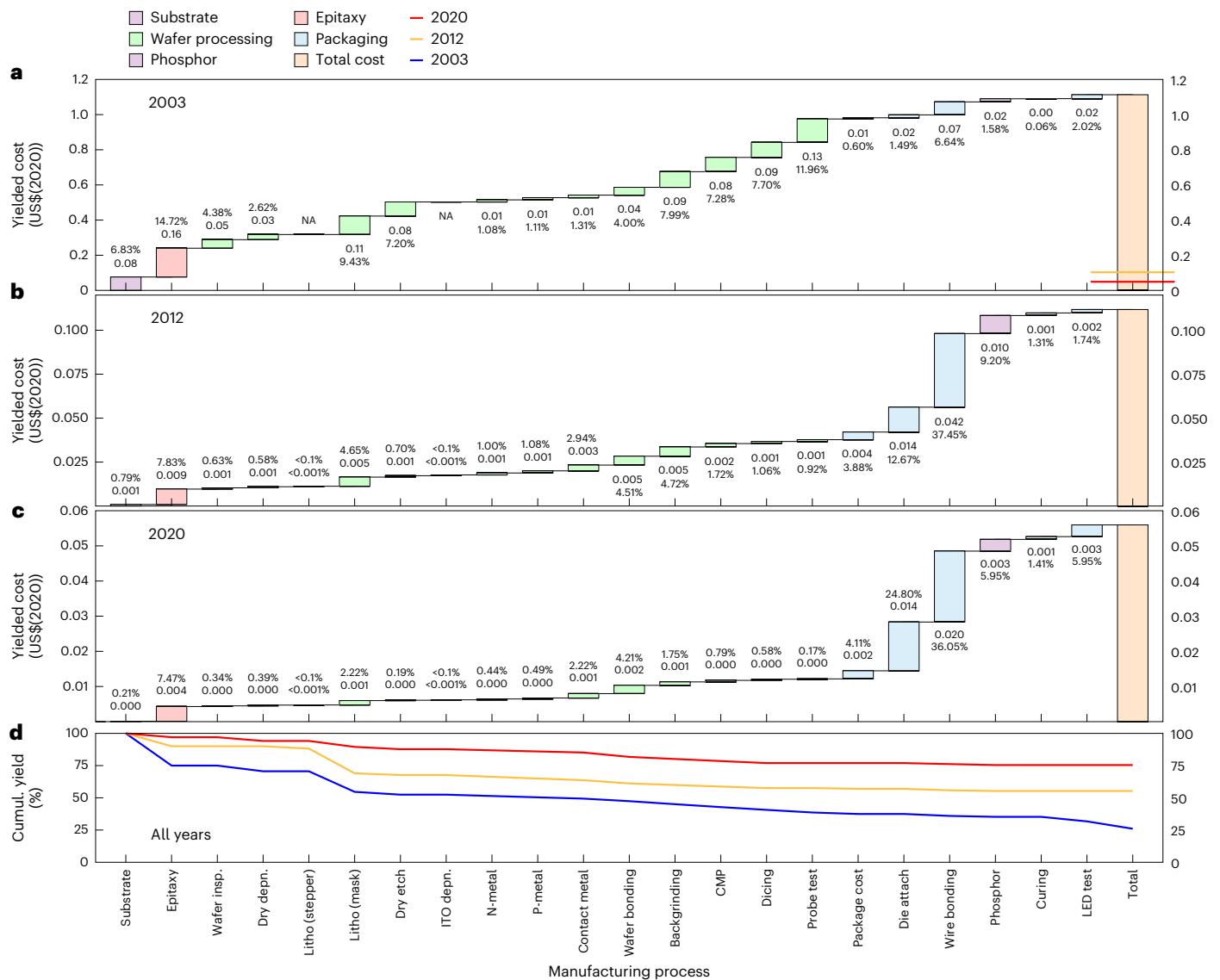


Fig. 6 | Historical changes in white LED manufacturing cost structure.

Presented cost calculations are an outcome of the cost model (Methods and Supplementary Methods 6) for a single low- to mid-power GaN-based, classic chip, phosphor-converted white LED package, assuming an ideal factory with state-of-the-art equipment at a US location. **a–c**, Waterfall diagrams of white LED manufacturing cost structure split by manufacturing process steps for years 2003, 2012 and 2020. Process steps on the horizontal axis are sequenced from left to right in the same order as in the modelled LED manufacturing process schematically represented in Supplementary Note 2. Numbers for each

process step indicate absolute and relative contributions to the total cost in the corresponding year. Note that numbers may not always add up to the total cost (US\$1.11 in **a** for 2003, US\$0.11 in **b** for 2012, US\$0.05 in **c** for 2020) due to the accumulation of rounding error. **d**, Cumulative manufacturing yield after each process step for years 2003, 2012 and 2020. Note: cumulative yield of the manufacturing process step is the product of all upstream manufacturing process-step yields. CMP, chemical–mechanical planarization; dephn., deposition; insp., inspection, litho, lithography; NA, not available.

In addition, we observe (but so far have not been able to quantify; see Methods for details) a modest but meaningful contribution of learning by doing to the efficiency improvements. Specifically, we find that improvements in efficiency loss channels that are governed by complex quantum effects at the atomic level (for example, internal quantum efficiency or droop) and at present can only be described heuristically have come mostly from incremental manufacturing process improvements resulting from learning by doing, with little evidence for spillovers. Examples of such improvements include the tuning of quantum wells and electron barriers in a LED device, which can be achieved by incremental changes in doping and epitaxial growth parameters⁴⁴ (Supplementary Note 4).

In contrast with improvements in efficiency and consumer experience, which were mainly driven by R&D efforts and technology

spillovers, we find that dramatic manufacturing cost reductions in white LEDs were primarily due to learning by doing allowing higher yields across manufacturing steps and economies of scale resulting from increases in the sapphire wafer size. The dominant role of economies of scale and learning by doing as the mechanisms jointly responsible for 91% of the total manufacturing cost reductions in white LEDs can be explained by the effect of demand-pull policies related to incandescent light bulb bans and energy efficiency regulations, which stimulated industry investments in LED manufacturing and scale up. In this way, demand-pull policies may have been as pivotal to progress in white LED lighting as in solar photovoltaics⁵.

Interestingly, comparable analyses of historical cost reductions for supply-side energy technologies show a very different pattern of relative contributions of innovation mechanisms to cost dynamics.

Table 2 | Technology spillovers involved in white LED technology innovations identified in this study

Inv.	S/O	Comm.	LED innovation	Spillover	Enablers	Origin	Ref.	Area of improvement
1926	1994	1996	LED phosphors	Use of phosphors for light down conversion in LEDs	Firm experience with phosphors	Materials science (S), cathode ray tubes (T)	35,62,63	Enabled light down conversion in LEDs
1967	1996	1996	YAG:Ce phosphor	Use of YAG:Ce phosphor in a first white LED product	Firm experience with phosphors; firm working in multiple industries	Chemistry (S), materials science (S), fluorescent lighting (T), cathode ray tubes (T)	35,37,64–66	Enabled white LED products. η_S , η_C
1967	1996	<2002	YGAG phosphor	Use of YGAG phosphor in first warm white LEDs	Firm experience with phosphors; firm working in multiple industries	Chemistry (S), materials science (S)	37,66–68	Enabled warm white LEDs. η_S , η_C
1982	1996	<2007	Patterned sapphire substrate (PSS)	Use of anti-reflective properties of substrate patterns in LEDs	Not identified	Optics and photonics (S), materials science and technology (S,T), nature-inspired material design (T)	69–73	η_{LE} , η_{IO} (depending on chip architecture; Supplementary Note 2)
1971	1999	<2003	Indium tin oxide (ITO) current spreading layer	Use of ITO current spreading layer in white LEDs	Public mission-oriented R&D funding; flexibility of public funding; industry–academia partnership	Optics and photonics (S), materials science and technology (S,T), optoelectronic devices (T)	72,74–76	η_{VI} , η_{LE} (depending on chip architecture; Supplementary Note 2)
1997	2000 2002	2005	258 phosphor	Use of luminescent ‘258’ nitridosilicate compound as LED phosphor	Flexibility of public funding; freedom of search; international industry–academia partnership	Chemistry (S), materials science (S)	77–80	η_S , η_C
1984	2003	2009	Quantum dot phosphor	Use of quantum dots for light down conversion in LEDs	Public mission-oriented R&D funding; communication at a conference; commercial success in a different market	Solid-state physics (S), photochemistry (S), nanotechnology (T)	81–84	η_S , η_C
1972	2005	2015	PFS phosphor	Use of knowledge in luminescent materials and skills in ‘wet’ chemical synthesis to synthesize PFS compound and optimize it as LED phosphor	Public mission-oriented R&D funding; international industry–academia partnership; university alumni networks	Chemistry (S), materials science (S)	85–87	η_S , η_C
2008	2013	2015	SLA phosphor	Use of knowledge about existing cuboidal nitride compounds to identify and synthesize structurally similar SLA phosphor	Industry–academia partnership	Structural chemistry (S), materials science (S), solid-state physics (S)	88–91	η_S , η_C

‘Inv.’ denotes the the year of initial invention, identified by the earliest literature source describing a specific invention or idea (for example, a particular chemical composition) in a field outside white LED lighting that eventually ‘spilled over’ (that is, got repurposed or applied) to white LED lighting. ‘S/O’ denotes the year of spillover, identified by the earliest reported or patented application of the initial invention or idea in white LED technology. LED innovations in the table are ordered by the S/O year. Note the two S/O years for the 258 phosphor, which represent two independently occurring spillovers that contributed to this innovation. ‘Comm.’ refers to the the year of commercial application, identified as the year of the first recorded application of the initial idea or invention in a commercial LED product. ‘Enablers’ column summarizes our findings on various factors that enabled or supported spillovers described in ‘Spillover’ column. ‘Origin’ column represents knowledge domains in which spillovers initially emerged, where (S) denotes a scientific discipline and (T) is an area of technology. ‘Ref.’ column refers to literature sources for the represented non-LED inventions, spillovers and white LED innovations. ‘Area of improvement’ column summarizes the impact of spillovers on different aspects of white LED technology, for example, improvements in particular sub-efficiencies. Supplementary Note 5 provides a detailed description of the represented phosphor-related innovations and spillovers.

For example, Kavlak et al.⁷ showed that for solar photovoltaic modules, increases in wafer size and manufacturing yield (with the latter associated with learning by doing) respectively contributed only 11% and 7% of cost reductions from 1980 to 2012, whereas innovations resulting from R&D that increased the efficiency of solar modules reduced the costs by 23%, with remaining cost declines explained by economies of scale and decreases in material input prices. Similarly, Ziegler et al.⁸ showed that technological innovations resulting from public and private R&D accounted for as much as 54% of cost declines in lithium-ion batteries from the late 1990s to early 2010s, whereas economies of scale contributed 30% and learning by doing associated primarily with improved manufacturing yields reduced the costs only by 2%. Such dramatic differences in relative contributions of the same mechanisms to the cost dynamics between white LED lighting, solar photovoltaics and lithium-ion batteries and our findings on the

progress in consumer experience metrics indicate that LED lighting as a demand-side technology may be more directly affected by end-user needs and demands than technologies focused on energy generation and storage. It may also have substantially different characteristics affecting its manufacturability and marketability that require different types of policy support and response than supply-side energy technologies. Whether our findings for white LED lighting are generalizable to demand-side technologies more broadly, and what are the reasons behind the observed differences in the patterns of technological progress in different types of energy technologies, remains to be explored in future research.

Our analysis of the sources and enabling factors of the identified technology spillovers highlights the critical role played by a deep understanding of the physical, chemical and optical phenomena underlying the operation of LEDs, and materials science and technology

and nanotechnology involved in the production of LEDs, for past and future advances in LED and SSL technology. Specifically, a deep physical understanding of LED device efficiency loss channels has enabled important innovations in LEDs that increased several sub-efficiencies in LEDs and will continue to do so, as expected by eminent experts in the field whom we interviewed. A practical implication of this finding is that additional research in these areas and a more deliberate search for relevant external knowledge may accelerate expected future advances in LED technology and its applications both in SSL and technology areas beyond general lighting. Corresponding technology spillovers can be deliberately stimulated, among other factors, by measures such as knowledge exchange events and long-term partnerships between academia and industry, dedicated mission-oriented public R&D funding, and ensuring certain freedom of search in academia. These observations also further reinforce broader arguments made against the dichotomy of basic and applied research^{45,46} and the calls for open, inclusive and flexible research cultures⁶.

Whereas additional work is necessary to determine if the patterns we find for innovation in white LEDs apply to other demand-side technologies, our findings already indicate potential broader implications. First, the fact that efficiency channels with greater physical understanding were more likely to be shaped by spillovers indicates that investing in research that develops such physical understanding can reduce the cost of entry for new researchers and inventors, facilitate spillovers and accelerate innovation. This could be even more important for small-scale consumer-oriented technologies or products (for example, cars, refrigerators, food) that may face relatively lower barriers to entry in research compared to, for instance, nuclear power or offshore wind. Second, we also find that innovation focused on consumer experience improvements was incredibly important for this demand-side consumer-facing technology and that those improvements mostly relied on integrating external knowledge through technology spillovers. This finding suggests that R&D and innovation in demand-side technologies, which have been, according to some scholars, ‘marginalized’³⁰, should target further improvements in consumer experience while focusing on discovering and integrating relevant external knowledge. A third possible hypothesis to test with future work on other demand-side technologies is related to a potentially larger contribution of demand-pull policies to improvements in the cost metrics over time through their impact on scale up and learning by doing compared to R&D. If corroborated in other technologies, this finding would add to the evidence on the major role of regulations, bans and financial incentives in shaping energy technology cost trajectories.

Finally, the lessons learned about the mechanisms of rapid progress in white LED technology may have broader implications both for other demand-side or energy efficiency technologies and for low-carbon energy technologies with similar characteristics such as the granularity of technology, its modularity or complexity^{30,47}. By comparing the role of these factors at a granular level across different low-carbon and energy efficiency technologies, we can identify and generalize key cross-technology patterns or differences that would help us formulate recommendations for industry and policymakers aimed at accelerating further clean energy innovation for climate change mitigation.

An important part of this future work would be to identify how to select the right unit of analysis for cross-technology comparisons. In this study, we analysed progress in LED lighting technology at the level of the core technology component, white LED package, and did it across a broad set of cost and performance metrics. By contrast, comparable studies^{7,8} focused on progress in the final products but only for the cost metric. Such a difference should not have meaningfully affected our comparison with these studies, as our research indicates that virtually all important LED technology improvements occurred at the chip and package level rather than in downstream

LED lamp components. However, future research, including potential cross-technology meta-analyses, would benefit from developing a formal methodological framework for such comparisons.

There are also several important avenues of future LED research that are opened up by our analysis. First, future work could expand the cost model by collecting and including data for a broader set of chip architectures. Second, a deeper dive into the role of learning by doing is needed both in the cost and performance analysis. Third, building on the work on the physical limits in LED sub-efficiencies, future efforts could focus on identifying priority areas for further performance improvements in LEDs and SSL in general.

Methods

Multi-method approach

The evolution of white LED device architecture and performance, and the progress in understanding the underlying physical phenomena, are relatively well covered in the scholarly literature and patents (Supplementary Note 1 provides a brief literature review). However, the information provided in these two types of sources alone is insufficient for our goals on at least three accounts. First, existing scientific publications or reviews typically focus only on specific individual LED performance parameters or overall device efficiency, rather than on providing a comprehensive coverage of all device parameters or sub-efficiencies for a particular LED product or design. Scientific publications describing particular innovations also do not always disclose the underlying device architecture or the features responsible for the gains in performance. Second, not all relevant innovations are patented^{48,49}. Our interviews with industry experts suggest that the propensity to patent is the highest for knowledge related to macroscopic device architecture and chemical composition of phosphors and the lowest for knowledge related to manufacturing process improvements and microscopic chip architecture that is difficult to reconstruct by reverse engineering. This means that relying only on patent literature would bias the identification of innovations by unduly emphasizing some areas of technology improvement and de-emphasizing others. Third, scientific publications and patents typically focus on experimental devices rather than commercial products. Whereas new LED features, designs and manufacturing methods reported in patents and publications can potentially result in major performance gains or cost reductions, it is difficult to ascertain if these improvements have since been adopted in the industry. Furthermore, information on LED manufacturing costs and the effect of process improvements on the total cost is highly proprietary. Estimates are occasionally reported in the scientific literature and company publications, but these often do not disclose which parts of the manufacturing process are responsible for the largest contribution to the overall cost or which improvements led to cost reductions.

To overcome the limitations of existing scientific literature and patents, in this study we rely on a multi-method approach to data collection and analysis, augmenting information obtained from a comprehensive review of the primary scientific literature⁵⁰, device datasheets, relevant patents and industry publications (see ‘Comprehensive literature review’ below) with information gained from semi-structured interviews with experts from academia and industry (‘Semi-structured interviews’), own calculations of LED device sub-efficiencies (‘Performance metrics calculations’) and bottom-up manufacturing cost modelling (‘Manufacturing cost model’).

To implement this approach, first, we identify three sets of metrics to quantify historical progress in LED lighting technology: (1) metrics of energy efficiency of LED devices, including the total device efficiency (‘lamp efficiency’) and the sub-efficiencies that describe different energy loss channels in a LED device; (2) metrics of lighting quality relevant to consumer experience, specifically the CRI and colour temperature; and (3) LED package manufacturing cost. The motivation for the choice of these metrics is discussed in Supplementary

Methods 2. Definitions and detailed descriptions are provided for the efficiency metrics in Supplementary Methods 3, the consumer experience metrics in Supplementary Methods 4 and the cost metric in Supplementary Methods 5.

We then choose the most widely adopted variant of white LED lighting technology, white GaN-based phosphor-converted LEDs, as the focal technological area for our analysis. Next, using data from the literature review, patent analysis and expert interviews either directly or as inputs into the calculations of LED performance and manufacturing cost, we track the historical improvements related to the chosen metrics in such LEDs from their introduction to the lighting market to 2020, the most recent year with data available at the time of data collection. The details of our findings at this step are provided in Supplementary Note 3 for progress in efficiency, Fig. 4 for progress in the consumer experience metrics and, for the manufacturing cost, in an online repository with our cost model data⁶⁰.

Whenever possible, we link the improvements we identified to specific white LED innovations and innovation mechanisms, including technology spillovers (Table 1, Supplementary Notes 4 and 5). When the mechanism of a specific innovation is not immediately clear from the data collected, we classify the improvements associated with this innovation as occurring via the R&D mechanism if these are characterized in the literature or by the interviewed experts as substantial improvements related to the underlying physical phenomena or LED device architecture, which by their nature are likely to be a result of targeted R&D efforts. Similarly, we classify the improvements as driven by the learning-by-doing mechanism if the evidence collected indicates that they resulted from incremental innovations related to LED manufacturing processes.

Notably, in several cases of efficiency improvements, we identify a series of continuous, most likely incremental changes occurring in the same area or component of technology over a long time in which it was not possible to distinguish individual innovations, their scale or specific mechanisms by which they occur (Supplementary Note 4 provides specific examples). For several continuous improvements of this nature, if these can reasonably result from either R&D or learning by doing, given the evidence we have, we assign both as possible mechanisms of innovation. Unfortunately, the uncertainty in assigning these two mechanisms to specific white LED innovations does not allow us to fully disentangle and quantify the contributions of R&D and learning by doing to the overall improvement in white LED efficiency. Because of this, we provide only a rough qualitative estimate of the higher relative importance of the R&D mechanism to these improvements compared to the learning-by-doing mechanism. This estimate is based on the total number of identified LED innovations associated with each mechanism across all sub-efficiency channels (>20 for R&D vs eight for learning by doing; Table 1 and Supplementary Tables 1 and 2) and the assumption, discussed in the previous paragraph, that R&D-related innovations are more likely to result in substantial improvements than innovations resulting from learning by doing.

Among other innovation mechanisms, we associate improvements directly related to the scale of LED production with economies of scale. Perhaps unsurprisingly, such improvements are found only for the LED manufacturing cost metric ('Manufacturing cost improvements' section provides details). Finally, for the identification of technology spillovers, we rely on conceptual and methodological frameworks proposed by Stephan et al.⁶ and Kolesnikov et al.¹⁵ that view spillovers as the process of knowledge transfer between knowledge domains. Specifically, we synthesize information from the interviews, the literature review, historical records, and citations in patents and publications to identify which white LED innovations were driven by external knowledge originating in areas of science, technology and manufacturing beyond white LED lighting (Table 2). This approach allows us to not only identify individual cases of technology spillovers but also analyse

the sources of external knowledge involved in these spillovers, what factors enabled or facilitated them, and how the identified spillovers contributed to progress in white LED lighting.

Importantly, the key condition for identifying a spillover in this approach is determining whether its contribution to the LED innovation was external to the focal technology domain at the time of its occurrence. As noted above, we define our focal domain narrowly as white GaN-based phosphor-converted LEDs. We consider innovation in this domain to be driven by a spillover if it involves a direct use or repurpose of knowledge initially discovered, developed or applied in other domains of science, technology or manufacturing. We restrict our analysis only to innovations specific to white LED technology and manufacturing and exclude 'second-order' spillovers that may contribute to general improvements in manufacturing technologies or equipment used to produce white LEDs. We do this to clarify the scope of our analysis and make it tractable. As an example, specific improvements in the epitaxial process to grow better white LED chips are considered in the analysis of spillovers, whereas general improvements in the epitaxial technology and equipment relevant to the manufacturing of a wide range of semiconductors, including but not limited to LEDs, are not included in the analysis if they do not consider the specifics of white LED manufacturing.

A notable limitation of our methodology for the analysis of spillovers is that it may favour the identification of spillovers associated with more radical rather than incremental innovations¹⁵. This is due to its reliance on historical documents, publications and expert interviews as the primary sources of information about specific innovations that have contributed to progress in a technology. In theory, in this approach, we capture codified knowledge about innovation in written sources and tacit knowledge in expert interviews. However, both types of information source tend to highlight technological breakthroughs associated with radical innovations rather than continuous incremental improvements, even though both types of innovation may equally benefit from technology spillovers. As a result, when applying our methodology, we may have potentially overlooked historically important spillovers associated with incremental innovations. Therefore, the list of spillovers provided in Table 2 should be considered as a selection of the key spillovers rather than a comprehensive list of all spillover contributions to white LED innovation. In the same way, our quantitative assessment of spillover contributions to LED efficiency improvements in 'Efficiency improvements' should be considered as a lower estimate of this contribution.

As the final step of our methodological approach, we synthesize information obtained with multiple methods to quantify overall historical progress in white LED technology over time across the three groups of metrics and identify which innovation mechanisms have driven this progress and how, specifically, technology spillovers contributed to it.

We briefly describe below how we implement each of the methods we use in our multi-method approach and provide further methodological details in Supplementary Methods 1–10.

Comprehensive literature review

We collected data on white LED performance and characteristics in a comprehensive literature review that included scientific publications, patents, conference proceedings from the largest semiconductor and optoelectronics conferences, industry periodicals and roadmaps, and company presentations and reports. This review was structured around three main goals: (1) tracking progress in white LED technology over time as indicated by the three groups of progress metrics; (2) identifying individual innovations that contributed to this progress and quantifying their impact on LED device performance and manufacturing cost; and (3) determining whether those innovations had knowledge origins within the focal white LED technology domain or in a field of science or technology external to white LEDs, indicating such innovations as an outcome of technology spillovers.

Relevant sources for the review were found in an iterative search process that involved two stages. The first stage was the search in specialized patent and publication databases and company websites, following the search procedure and database search queries described in Supplementary Methods 1. The second stage was the analysis of backward citations in the identified sources, starting from the reviews mentioned in Supplementary Note 1 and then iteratively repeating it for all sources newly identified in the first stage, until no further relevant new sources were found. We also relied on backward citations in these sources for the identification of technology spillovers, considering cited documents as indicators of knowledge origins of an innovation and analysing whether those documents belonged to the focal white LED technology domain or not.

Semi-structured interviews

To supplement our efforts in data-collection efforts from the literature review, verify our findings and identify additional spillovers, we conducted a series of semi-structured interviews^{51,52} with 13 eminent experts from academia, industry and the public research sector. Experts were initially selected based on their engagement in different sub-fields of LED research and manufacturing, as identified in the literature review. The list of experts was then expanded using a ‘snowballing’ tactic based on recommendations from already-interviewed experts. All interviews were conducted between November 2019 and April 2022, mostly by means of video conferencing but with two interviews held in person. The interviews lasted for about one hour each. We obtained informed consent of the experts to be interviewed in the following way. First, we contacted the experts we identified by email, describing the study and the details of the proposed interview, including its content and our arrangements for the anonymity of responses and data protection. After obtaining written consent from the experts to be interviewed, we then repeated the procedure at the beginning of each interview, describing the interview content and data protection arrangements and asking the interviewees to provide explicit verbal consent to proceed with the interview. As the purpose of the interviews was strictly to collect technical information relevant to historical progress in white LED technology, our research did not involve personal data of human participants. Ethical approval for this study was granted by the Research Committee of the Department of Land Economy at the University of Cambridge on 25 November 2019 in accordance with the guidelines specified by the School of the Humanities and Social Sciences of the University of Cambridge.

An anonymized summary of the background of the experts interviewed is provided in Supplementary Methods 10. Notably, all our interviewed experts came from Europe or the USA, with none representing Asia, which potentially may have biased our findings, particularly for the earliest and latest periods of white LED history dominated by LED manufacturers in Japan and China, correspondingly. However, this was not an intentional bias; unfortunately, none of the identified experts in Asia responded to our interview requests.

In terms of the interview content, the primary, structured part of the interviews explored which innovations were deemed most relevant to the evolution of device performance, consumer experience and manufacturing cost of white LED packages. Thereafter, interviewees were asked to consider the extent to which those innovations may have originated outside of their respective field of expertise and the LED industry more broadly—that is, which of the innovations potentially involved technology spillovers. The remainder of the interview was focused on learning about particular aspects of the manufacturing processes relevant to cost and performance modelling, the current state of the industry and the circumstances surrounding innovations and spillovers identified in the first part of the interview. Specific quantitative data were also often provided by experts, helping fine-tune the parameters of the manufacturing cost model and verify device performance data.

Performance metrics calculations

The contribution of individual technology innovations and spillovers to progress in the overall LED device efficiency over time is estimated by index decomposition analysis. Mathematically, this involves breaking down a chosen performance indicator into its constituent components, each representing a specific factor that contributes to the change in the indicator⁵³. Specifically, we use the additive logarithmic mean Divisia index method I (LMDI-I), also known as the Additive Sato-Vartia indicator⁵⁴. It was developed by Boyd et al. in 1987⁵⁵ on the basis of the Divisia Index, a method in statistical economics, and subsequently refined.

According to this method, for an overall device efficiency function $\eta = ab$ that is the product of sub-efficiency variables a and b , the contribution of the change in a single sub-efficiency variable a between times $t = t_1$ and $t = t_2$ can be estimated as^{7,56}

$$\Delta\eta_a = L(\eta(t_2), \eta(t_1)) \times \ln\left(\frac{a(t_2)}{a(t_1)}\right) \quad (1)$$

where $L(a, b)$ is the logarithmic mean of variables a, b . These terms contain no residuals, therefore, it can be shown that the overall improvement in the device efficiency due to improvements in individual sub-efficiencies is equal to the sum of these improvements in individual sub-efficiencies:

$$\Delta a + \Delta b = \Delta F \quad (2)$$

To document historical improvements in LED device performance accurately, we need data on all sub-efficiencies for the selected device architectures and periods covered. However, we found that the scope of data reporting in the literature is typically limited to selected metrics of interest, rather than the full ensemble of sub-efficiencies that determine the overall device performance. Where gaps in relevant data existed, we filled them with our own performance calculations for individual sub-efficiencies where possible. Specifically, the sub-efficiencies related to the emission spectrum of phosphor-converted white LED devices (that is, spectral efficiency and light conversion efficiency) were calculated from the spectral data, often reported in LED device specifications, using the colour-science package for Python⁹⁸. We also used the same approach to calculate the CRI and luminous efficacy of radiation of LED devices (Supplementary Note 5 provides the associated spectral data and calculation results). This approach allowed us to quantify the improvements related to consumer experience and phosphor development in white LEDs.

Manufacturing cost model

The structure of our bottom-up white LED manufacturing cost model with a process-step resolution, presented in Supplementary Methods 6, is generally based on the 2012 LEDCOM cost model⁴³. However, we expand it substantially both in scope and in its ability to capture historical trends. The model captures three historical time periods corresponding to different ‘eras’ in white LED manufacturing: the early period of the first high-power white LED products around 2003, the period of accelerating consumer adoption of LED lighting around 2012 and the most recent period around 2020, the year of our main data-collection efforts. For each of these three years, the most prevalent manufacturing equipment was identified through industry periodicals, archived website data from the Internet Archive, and expert interviews. Because the architecture of LED chips has changed significantly since the introduction of the first commercial white LED devices in 1996, three different chip architectures are considered in the model: classical chips, flip chips and chip-scale package flip chips (Supplementary Note 2 provides the details of each architecture and corresponding manufacturing process steps). The details of the manufacturing process for each architecture were collected from the scientific literature, textbooks and relevant patents. In addition, two LED life-cycle analyses^{37,38} were used to validate the model structure

and extract some of the necessary quantitative model inputs. These studies captured a large number of white LED manufacturing process steps and included the details on the use of metals, chemicals and electricity for each manufacturing step.

The cost model that we developed is based on a cumulative approach to yielded cost⁵⁹, which we describe in detail in Supplementary Methods 7. In this approach, the yielded cost C_{Y_i} of process step i is defined as the ratio between the total cost of step i C_i and the yield of step i Y_i . Thus, for each consecutive step, starting from $i = 1$, we get

$$C_{Y_1} = \frac{C_1}{Y_1}, C_{Y_2} = C_{Y_{2 \rightarrow 3}} - C_{Y_1} = \frac{C_1(1 - Y_2) + C_2}{Y_1 Y_2}, C_{Y_3} = \dots \quad (3)$$

Notably, the yielded cost per step is dependent on the step order and blind to downstream information⁵⁹. The yielded cost metric is also cumulative by definition; thus, the total cumulative yielded cost is calculated as:

$$\sum_i C_{Y_i} = \frac{\sum_i C_i}{\prod_i Y_i} \quad (4)$$

The overall outcome of the cost model is the cumulative yielded manufacturing cost per LED package for each of the three years considered. In our model, this metric includes all costs associated with producing the chip, including the operating costs of the factory. Costs associated with R&D, administrative overhead or other investment costs are not considered. We note that the purpose of the cost model is not to provide specific estimates of the white LED manufacturing cost for a factory of a specific size, geographic location or manufacturing capacity. It is instead intended to capture the impact of specific improvements in the manufacturing process flow on the overall white LED cost. Therefore, it models a hypothetical factory operating the most up-to-date equipment for each model year. Fixed-cost parameters are similar to those for a semiconductor factory operating in the USA. Even with these simplifying assumptions, the model reasonably identifies the impact that changes in single manufacturing process steps can have on the total LED manufacturing cost.

Another important limitation of our cost modelling efforts is that, even though the model captures three different chip architectures in its structure, in the present study we were able to collect, estimate and present the full set of quantitative inputs and outputs only for the classical chip architecture of low- to mid-power white LED devices. Populating the model with data for the remaining two chip architectures would require access to proprietary industry information.

Further details on our manufacturing cost model, including its structure and equations, manufacturing process flows for the chip architectures under consideration, input data, detailed calculations for the yielded costs and the model's limitations, are provided in Supplementary Methods 6 and 7. The cost model files with collected data are provided in an online Zenodo repository⁶⁰.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data supporting the findings of this study are included in the paper, its Supplementary Information and, for the LED manufacturing cost model, via Zenodo at <https://zenodo.org/records/8410657> (ref. 60). Source data are provided with this paper.

Code availability

The Python scripts that we developed to calculate light quality metrics are available via Zenodo at <https://doi.org/10.5281/zenodo.8410788> (ref. 61).

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Author contributions

All authors designed the study. M.P.W. and S.K. carried out the main empirical work under the supervision of L.D.A. Performance simulation software code was written by M.P.W. Data were collected and analysed by M.P.W. and S.K. All authors contributed to the writing of the manuscript.

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Competing interests

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Michael P. Weinold.

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- Excel-based LEDCOM manufacturing cost model (S. Bland, LED modular cost model, 2012), available at <https://web.archive.org/web/20121017072612/http://>

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Reporting on sex and gender	As the purpose of the interviews was strictly to collect technical information relevant to historical progress in white LED technology, no personal data on human participants, including their sex and gender, was collected or used.
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Population characteristics	As the purpose of the interviews was strictly to collect technical information relevant to historical progress in white LED technology, no personal data on human participants relevant to population characteristics was collected or used.
Recruitment	<p>All prominent experts in LED technology and manufacturing whom we identified in the sampling stage were contacted by email using their publicly available email contacts. Initial emails described the study and the details of the proposed interview, including its content and our arrangements for the anonymity of responses and data protection. After getting a written consent from the experts to be interviewed, we then repeated the procedure at the beginning of each interview, describing the interview content and data protection arrangements and asking the interviewees to provide an explicit verbal consent to proceed with the interview.</p> <p>As the experts invited to participate in the interviews voluntary chose whether to respond to our interview requests and/or be interviewed, our sample of interviewees was subject to self-selection bias, resulting in over-representation of experts from Europe and the US, with none representing Asia. In Methods section, we acknowledge this bias and discuss the following limitations of our findings that partially result from it: 1) our list of spillovers identified in the study is considered as a selection of the key spillovers rather than a comprehensive list of all spillover contributions to white LED innovation; 2) our quantitative assessment of spillover contributions to LED efficiency improvements in Section 2 should be considered as a lower estimate of this contribution; 3) our manufacturing cost model is developed for a hypothetical factory operating the most up-to-date equipment at a United States location.</p>
Ethics oversight	Ethical approval for this research was granted by the Research Committee of the Department of Land Economy at the University of Cambridge on 25 November 2019 in accordance with the guidelines specified by the School of the Humanities and Social Sciences of the University of Cambridge.

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Study description	We conducted a series of semi-structured expert interviews with prominent experts in LED technology and manufacturing to obtain specific technical information about historical progress in white LED technology. As the purpose of the interviews was strictly to collect technical information relevant to this purpose, our research did not involve personal data of human participants. Data collected in the interviews was both quantitative (specific values of LED cost or performance parameters) and qualitative (narrative information on the history of specific white LED improvements and the role of technology spillovers in these improvements).
Research sample	Thirteen prominent experts in the field of LED technology and manufacturing representing different sectors (academia; industry; public research sector; private technical consulting), all based in Europe or the United States. The sample was based on our need for specific technical and historical information about the progress in white LED technology and manufacturing, which in many cases could be obtained only from immediate participants of past events related to innovation in white LEDs, i.e., researchers and inventors who directly participated in key discoveries and inventions in this field. This limited the sample to a select few key prominent researchers and inventors in the field. Notably, the geographical composition of our sample (all interviewed experts were located only in Europe and the United States at the time of interviewing) was not intended; it was an outcome of self-selection bias, as none of the experts from Asia whom we had attempted to contact responded to our interview requests.
Sampling strategy	Our sampling strategy was based on the need to balance the coverage of key areas of progress in LED technology with the practical feasibility of getting access to prominent experts in the field who by now often occupy senior positions in their respective organizations and are thus rarely available for interviewing. The minimal target number of interviewees - 12 - was chosen based on

the following approach. We had specific questions related to the following three main areas in LED technology and manufacturing: phosphors, epitaxy, and LED device architecture and performance. We aimed to have at least two prominent experts from industry and at least two top experts from academia, public research or private consulting for each of the three areas to represent both research and industry perspectives on progress in white LED technology and manufacturing and ensure that experts cover different topics within the area of their expertise. Experts were initially selected based on their past engagement in different sub-fields of LED technology and manufacturing, as identified in the preliminary literature review. The list of experts was then expanded using a 'snowballing' tactic based on recommendations from already-interviewed experts, until the minimal target number of experts covering main sub-areas of expertise in the field was achieved. Due to self-selection bias, the final sample, presented in Supplementary Table 9, has skewed distribution of interviewed experts across sectors and technical areas. However, that was not an intentional bias, but a result of a small size of the target population of prominent white LED researchers and inventors.

Data collection	Eleven interviews were conducted using video conferencing. Two interviews were conducted in-person. All interviews were conducted only by the authors, with no external assistance involved at any stage. In all cases where the interviewees gave their informed consent to be recorded, the interviews were recorded. Written interview notes, prepared by the interviewers during the interviews and subsequently updated based on the recordings, were the main source of information about the interviews used in our analysis. All interviewees were made aware of the design of our study. Interviews had a semi-structured format with exploratory questions tailored to the area of expertise of each expert. Because of the exploratory nature of the interviews and highly specialized nature of expertise of each interviewee, no specific hypotheses were tested in the interviews and there was no need for blinding either interviewers or interviewees.
Timing	Interviews were conducted from November 2019 to April 2022 and lasted about 1 hour each.
Data exclusions	No data was excluded from the analysis.
Non-participation	All experts who initially responded to our interview requests and provided their informed consent to be interviewed proceeded with the interview and provided technical information requested.
Randomization	Randomization was not relevant to the study design as the interviews were designed only to gain specific technical information about historical progress in white LED technology and manufacturing from prominent experts in this field. No experiments with participants were conducted and no hypotheses were tested.

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