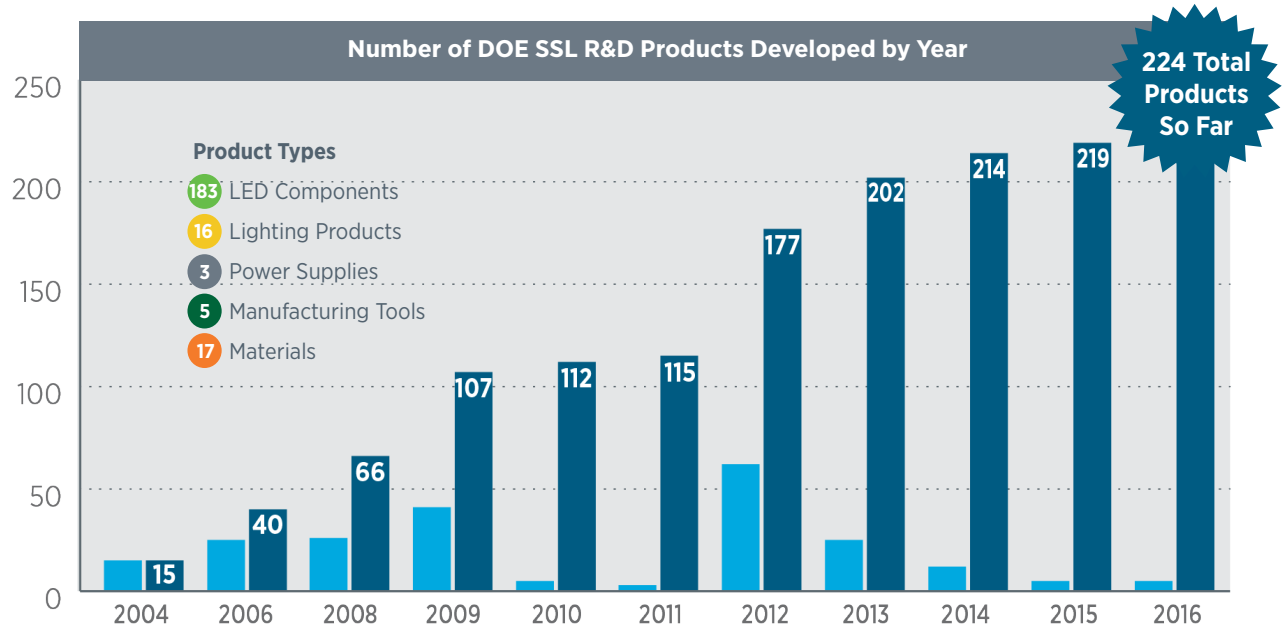
Solid-State Lighting Commercial Product Development Resulting from DOE-Funded Projects

The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program began funding SSL R&D in 2000, and to date has supported more than 250 cost-shared SSL projects in the areas of applied research, product development, and manufacturing R&D. This support has directly advanced the understanding and performance of SSL through the publication of articles in technical journals, the creation of intellectual property (with more than 260 patents applied for or awarded), and the direct development of more than 220 commercially available, state-of-the-art products. Those products—which include lamps, luminaires, LED components, power supplies, materials, and manufacturing tools—have contributed to about $2.8 billion in U.S. energy savings so far.

However, the actual impact of the DOE SSL Program is far greater than indicated by those figures, which only include products directly developed or enabled by DOE SSL R&D funding—and don't include the millions of derivative, influenced, or next-generation products that are based on projects that received direct DOE support. In many instances, DOE funding led to the development of widely used product platforms, or to materials that have gained widespread adoption, and are now found in tens of thousands of specific products, with millions of individual units sold. Likewise, DOE-funded improvements to production tools have increased product consistency, quality, and yield and have led to cost reductions in LED lighting components and products worldwide.



LED Components

LED components are at the heart of SSL technology, because they generate the light. Developing and producing advanced LED components has been a strength of U.S. LED manufacturers, particularly Cree and Lumileds. DOE SSL R&D to date has supported the development of 183 commercially available LED component products—which doesn't include follow-on products based on the original technology developed. Thus, DOE funding has actually influenced multiple generations of state-of-the-art LED component products, which typically exhibit advancements in efficiency, cost, integration, and performance.

The DOE SSL Program has supported a number of instances in which LED chip and package development led to the creation of a product platform used in successive generations of industry-leading LED package products, enabling vast amounts of energy savings. An example is the development of the Cree EZBright LED chip architecture, which enabled nearly a doubling in efficiency compared to the previous best Cree chip type (also supported by DOE funding) and proliferated into multiple LED package architectures, including the X-Lamp, XR-C, XRE, XP, MC, MT, and XM. These packages can be found in many Cree lighting products, including replacement lamps (e.g., LBR-30), downlights (e.g., CR-4 and LR-6), troffers (e.g., CR-22), and canopy lights (e.g., the 227, 228, and 304 series). The Cree chip and package products are also used by Cree customers in vast numbers of lighting products.

For Lumileds, DOE R&D support has directly led to the development of the LUXEON Q, LUXEON FlipChip, LUXEON Rebel, and LUXEON S1000 LED package products. All these products are commercially available, and offer luminaire integrators a range of features and price points that enable greater flexibility to address the vast range of lighting form factors and performance requirements. The specific advancements achieved in these products include new phosphor deposition approaches, high-voltage LED chip configurations, improvements to red LEDs, and improved manufacturing techniques.

With the help of DOE funding, Lumileds developed and commercialized PSS and epitaxy technology for high-power flip-chip LEDs, used in millions of energy-saving lighting products.

Another Lumileds LED package platform developed with DOE R&D support involves the use of patterned sapphire substrates (PSS). This important development has enabled

increased efficiency and light output at low cost, and has been so effective that Lumileds has transitioned most of its LED component products to PSS architecture.

These Cree and Lumileds LED platforms have been used in many millions of energy-saving lighting products and have been critical to LED lighting's success. And Cree, Lumileds, and other manufacturers continue to improve these platforms even further. DOE is currently supporting various approaches to improve integration of LED components into modules and luminaires to improve efficiency and reduce cost. DOE is also supporting the development of novel down-converter materials into LED packages to more effectively match the human eye response and increase efficacy. These are just two examples of the improvements that can still be achieved to continue the advancement of LED lighting technology.

Lighting Products

DOE SSL R&D funding has led to the direct development of 16 commercially available lighting products. With GE Lighting, DOE funding was focused on the development of an advanced red phosphor material. GE Lighting decided to use the phosphor material internally on their own products, and the benefits were quickly realized through the development of a whole family of energy-efficient GE Lighting products that are now on the market.

Technology innovations developed for the winning L Prize lamp have enabled subsequent generations of energy-saving Philips products.

Through an alternative R&D funding approach, the L Prize® competition, DOE supported the development of the Philips L Prize-winning lamp, which was submitted in 2009. Still widely regarded as the best general-purpose light bulb ever made, this A-lamp has high efficacy (>90 lm/W), long life (>25,000 hours), near-perfect color stability, excellent color quality, excellent light distribution, and high light output. The early development of the L Prize lamp directly enabled Philips to rapidly develop a family of energy-saving products based on what they had learned, and the basic lamp design has been used in numerous subsequent products, including the color-tunable Hue lamp.

The DOE SSL Program has also funded a handful of additional R&D projects that have not yet directly led to commercialized products. Some of these project concepts are still being developed and may yield products in the future, and some have led to alternative concepts that led to products—which happened with Cree, Philips, OSRAM, and Color Kinetics. Although these indirectly influenced products are not included in this analysis, they nevertheless are an important part of the total impact of DOE SSL R&D funding.

Power Supplies

Another important component of LED lighting products is the power supply. LEDs typically require power conversion from 120V AC to low-voltage DC, which affects the total efficiency of the system. The DOE SSL Program supported a Philips Lighting project to develop an efficient, small-form-factor, long-lifetime family of LED power supplies, which directly resulted in the development of three commercially available products and four derivative products (the latter not counted in this analysis). These low-cost products exhibit high conversion efficiency (>90%), long life (>50,000 hours), and compact form factor.

Manufacturing Tools

So far, DOE SSL R&D support has resulted in the development and commercialization of five manufacturing products that, collectively, have been used to produce billions of LED chips. DOE funding directly enabled Veeco's development of three specific product features that can be used with the company's state-of-the-art metal organic chemical vapor deposition (MOCVD) tools to produce LED wafers. These tools are sold worldwide and produce hundreds of millions of LEDs each year, and their advancements have

Veeco's MOCVD tools are sold worldwide, and produce hundreds of millions of LED chips each year.

led to improved control, uniformity, yield, throughput, and cost of ownership. Although Veeco's DOE-supported work has ended, the company continues to develop several of the original concepts. These tools are used by nearly every LED manufacturer to generate vast quantities of LED chips that are used in every type of LED lighting.

Ultratech and KLA-Tencor have also developed manufacturing tools with the help of DOE SSL R&D funding. Ultratech developed a low-cost lithography tool for manufacturing high-brightness LEDs—a high-value tool that has been sold to LED manufacturers worldwide. Likewise, DOE R&D support enabled KLA-Tencor to develop an inspection tool for monitoring incoming sapphire substrates in order to reduce defective parts and increase yield. This, too, is a high-value tool and has been sold worldwide.

The manufacturing tools developed with the help of DOE R&D support have already produced hundreds of millions to billions of LED chips that are used in LED lighting products. The improved performance and reduced cost of these LEDs has accelerated adoption and increased total energy savings.

Materials

DOE SSL R&D funding support has led to the development of commercially available materials used in the manufacture of LED packages and lighting products. The DOE SSL Program funded an R&D project with Lightscape Materials that resulted in the development of two phosphor products that are used as down-converters in LED packages. Lightscape developed novel nitride- and oxynitride-based phosphor down-converters that have excellent conversion efficiency as well as thermal stability, to maintain the color point of the LED package. Almost all LED packages use phosphors to create white light, so improvements in phosphor efficiency and performance have a large impact on the LED package efficiency and resulting luminaire or lamp efficiency. Thermal stability is often a shortcoming in phosphors, which leads to noticeable color shift as the LED or lighting product is operated at different temperatures. The Lightscape products were able to simultaneously achieve good conversion efficiency and color stability, making them a compelling option for LED component integrators.

WhiteOptics' highly reflective coating is used in thousands of different LED products, with millions of units sold.

The DOE SSL Program also supported WhiteOptics' development of a low-cost, stable, highly reflective diffuse coating material that maximizes the optical efficiency of LED luminaires while reducing glare. This robust material maintains its optical performance even at elevated temperatures and over long periods of time (>50,000 hours). Even a small improvement in the reflectivity of an optical coating can dramatically improve the optical efficiency of a luminaire, since multiple reflections are often required before the light exits. The WhiteOptics coating is 98% reflective, which means that the light output only diminishes by 2% with each "bounce"—whereas, for example, it diminishes by 10% per bounce with white paint, which typically is 90% reflective. The performance levels of this product have become the de-facto standard for this type of material, and the material is being used in thousands of products with millions of units sold.

Conclusion

While the DOE SSL Program provides R&D funding support, the real credit for the resulting products belongs to the researchers and product developers themselves. SSL technology is rapidly moving forward, and there are still significant opportunities to develop improved manufacturing tools, LED components, materials, power supplies, lighting products, and more—which can increase and accelerate the energy savings potential of SSL. The DOE Solid-State Lighting Program continues to identify and support those R&D projects that offer the highest potential impact.

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For more information
To learn more about the DOE Solid-State Lighting Program, see ssl.energy.gov

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