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 230 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 245[1] patents applied for or awarded), and the direct development of nearly 200 state-of-the-art products. Those products—which include lamps, luminaires, LED components, power supplies, materials, and manufacturing tools—have contributed to more than $2.8 billion in U.S. energy savings so far.

It is challenging to track the full range of impact resulting from DOE-funded R&D projects, particularly related to commercialized products. The DOE SSL Project Portfolio[2] focuses its R&D support on critical topic areas[3] and barriers to energy savings, but not every supported project directly results in product commercialization. The technical approaches explored are, by nature, novel and high risk. Some don't pan out, while others prove to be too expensive, inconsistent, short-lived, or of limited benefit.

However, even in such cases there may be aspects of the project that can be further developed and successfully applied—and even when there aren't, the results are still valuable in terms of educating the researchers and preparing them for their next steps. This, coupled with the fact that the full development of some product concepts extends beyond the duration of the DOE funding, makes it difficult to account for the full range of impact of DOE R&D support. Thus, the figures in the table below represent a conservative estimate; they are not comprehensive and are continually updated.

- They only include products directly developed or enabled by DOE SSL R&D funding.[4]
- They do not include derivative products, influenced products, or next-generation products based on those that received DOE support.

Product Type	# of Products	Manufacturers
Manufacturing Tools	5	Veeco, Ultratech, KLA-Tencor
Materials	17	Lightscape Materials, WhiteOptics
LED Components	158	Cree, Lumileds
Power Supplies	3	Philips Lighting
Lighting Products	16	General Electric, Philips Lighting
Total	**199**	

1 For more information, see http://energy.gov/eere/ssl/downloads/solid-state-lighting-patents-resulting-doe-funded-projects-0

2 For more information, see http://energy.gov/eere/ssl/downloads/2015-project-portfolio

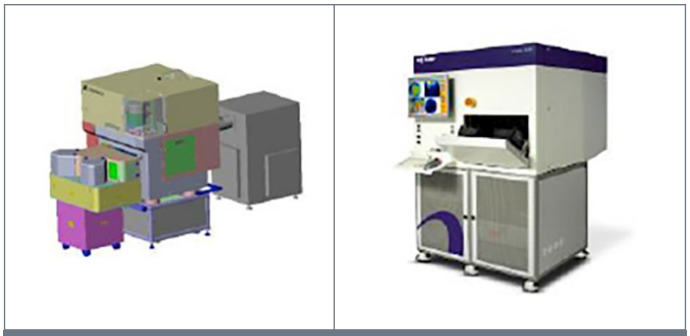
3 For more information, see http://energy.gov/eere/ssl/downloads/solid-state-lighting-rd-plan

4 Products counted in this analysis must be commercially available and their development directly supported by the DOE SSL R&D Program. Product counts were gathered through ongoing exit interviews with project performers.

Manufacturing Tools

Veeco MOCVD reactor

So far, DOE SSL R&D support has resulted in the development and commercialization of five manufacturing products. DOE funding enabled Veeco's direct 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 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.

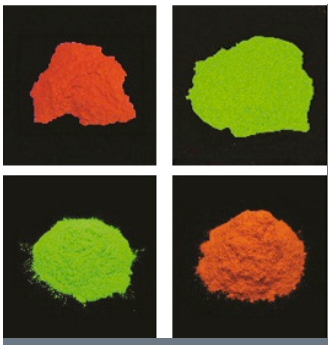


Ultratech's lithography tool (left); KLA-Tencor's inspection system (right)

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 produced hundreds of millions of LEDs 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



Phosphor developed by Lightscape Materials

DOE SSL R&D funding support has also 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 (with five variants) currently 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. The vast majority of 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.

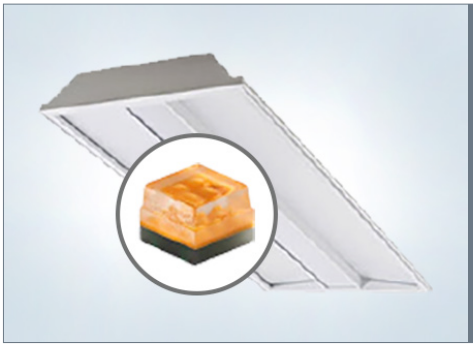
The DOE SSL Program also supported WhiteOptics' development of a low-cost, diffuse reflective material that maximizes the optical efficiency of LED luminaires while reducing glare. Widely used in lighting products, this robust material maintains its optical performance even at elevated temperatures and 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 has 98% reflectivity.

WhiteOptics' high-reflective coating

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 158 commercially available LED component products—which doesn't include subsequent 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.

With Cree, one early example of DOE support led to the development of the company's first-generation high-brightness EZBright® LED chips in 2006, which showed nearly twice the efficiency of the previous-generation XBright LED chips (also supported by DOE). Aspects of the EZ-Bright technology have been used in several subsequent package designs, including the XR-C, XR-E, XP-C, XP-E, XP-G, MC-E, MT-G, and XM-L LED packages,[5] and these packages have been used in many of Cree's energy-saving lighting products, including their canopy lights, CR Series troffers and downlights, and replacement lamps. These LED component products are also used in a vast number of lighting products manufactured by downstream integrators.



Cree's XQ-D LED, found in their AR Series troffers

More recently, a DOE-supported R&D project started in 2012 at Cree led to the development and commercialization of the XQ-D LED package. This package was developed specifically for troffer products and led to the development of a new package form factor with novel optical distribution and significant cost reduction.

For Lumileds, DOE R&D support has directly led to the development of the LUXEON Q,[6] LUXEON FlipChip, LUXEON Rebel, and LUXEON S1000 LED package products. All of these products are commercially available, and

Lumileds' LUXEON Q LED package

several more DOE-supported Lumileds products are in the works. These are all state-of-the-art products offering 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.

These Cree and Lumileds LED components, and the subsequent products that are based on them, have been used in millions of energy-saving lighting products and have been critical to LED lighting's success. Even now, Cree, Lumileds, and other manufacturers continue to improve LED components even further. DOE is currently supporting the use of patterned sapphire substrates to improve the efficiency and reduce the cost of LED components, as well as the integration 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 development of 16 commercially available lighting products. With General Electric, DOE funding was focused on the development of an advanced red phosphor material. GE elected 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.

GE Lumination Luminaire utilizing DOE-supported TriGain™ phosphor

5 For more information, see www.cree.com/LED-Components-and-Modules/Products/XLamp.

6 For more information, see www.lumileds.com/products/high-power-leds/luxeon-q.

Through an alternative R&D funding approach, the L Prize® competition,[7] DOE supported the development of the Philips L Prize lamp, which was submitted in 2009. Still widely regarded as the best general-purpose light bulb ever made, this 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.

Philips' L Prize lamp (far left) and related products

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.

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[8] of SSL. The DOE Solid-State Lighting Program continues to identify and support those R&D projects that offer the highest potential impact.

7 For more information, see www.lightingprize.org.

8 For more information, see http://energy.gov/eere/ssl/downloads/energy-savings-forecast-solid-state-lighting-general-illumination-applications.

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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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