THE ECONOMIC BENEFITS OF NIST'S ROLE IN THE MARKET TRANSITION TO SOLID STATE LIGHTING TECHNOLOGY

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This qualitative descriptive case study examines how the work of the National Institute of Standards and Technology in support of DOE's ENERGY STAR® program and the Solid State Lighting (SSL) industry has generated economic benefits for the U.S. economy.

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The Economic Benefits of NIST's Role in the Market Transition to Solid State Lighting Technology[1]

INTRODUCTION

Overview

The Department of Energy (DOE) and National Electrical Manufacturers Association (NEMA) are collaborating on a Next Generation Lighting Initiative to accelerate the development of white-light solid-state lighting (SSL) and position the U.S. as a global leader in this technology. SSL is an umbrella term for lighting that uses semiconductor devices to convert electricity into light.[2]

As directed by The Energy Policy Act of 2005, the Energy Independence and Security Act of 2007, and the American Recovery and Reinvestment Act of 2009, the DOE is supporting the design and manufacture of new SSL systems to accelerate market adoption and save energy.[3] DOE's goal is to reduce the total U.S. energy spent by lighting to half by 2027.

To legitimately compare the performance and cost-effectiveness of SSL with more traditional lighting technologies, and thereby to facilitate the transition to more efficient SSL products, new performance metrics and measurement methods were needed. To achieve these ends, the National Institute of Standards and Technology (NIST) worked closely with the U.S. Department of Energy (DOE) and national/international standardizing bodies to develop new standards for SSL; conducted research on color quality and measurement methods for high-power light emitting diodes (LEDs) and other SSL products; and developed new calibration standards and services to support the lighting industry's measurement needs.[4]

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[1]. This qualitative descriptive case study examines how NIST efforts in support of DOE's ENERGY STAR® program and the Solid State Lighting (SSL) industry generate economic *benefits* for the U.S. economy. No attempt is being made to estimate the *economic impact* of these efforts. Such an estimate would entail, at a minimum, the construction of time series of benefits *as well as costs*; the calculation of net benefits; and the development of economic impact metrics, as described in, Gregory Tassey, *Methods for Assessing the Economic Impacts of Government R&D* (Planning Report 03-1), NIST, September 2003. Rather, the purpose here is to explain how *economic benefits* are generated from NIST efforts and its interactions with other Federal agencies, SDOs, and industry. The economic benefits of NIST's efforts are illustrated on the basis of rough-order-of-magnitude (ROM) approximations of the economic consequence of a counter-factual scenario of what selected processes would have cost, and what economic benefits would not have occurred, or been delayed, had NIST not participated in the standards development process. These ROM approximations are developed on the basis of interviews with selected industry representatives and on the author's interpretation of secondary literature.

[2]. A light emitting diode (LED) is a p-n junction semiconductor that emits optical radiation, mainly in the visible range. They have a long operating life and require low operating current. Nick Holonyak invented the LED in 1962 while working as a consulting scientist at a General Electric Company laboratory in Syracuse, New York. See http://mntl.illinois.edu/ssdl/ and http://en.wikipedia.org/wiki/Nick_Holonyak. Early in their introduction to the market, LEDs were largely restricted to replacements for incandescent colored indicator lights. In 1999, breakthroughs in LED technology improved efficacy and color of *white LEDs* increasing their potential for replacing traditional general lighting sources. http://www.mts.net/~william5/history/hol.htm

[3]. Navigant Consulting, Inc., *Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030*, February 2010. (Prepared for the Lighting Research and Development Building Technologies Program Office of Energy Efficiency and Renewable Energy U.S. Department of Energy.)

[4]. Source: http://www.nist.gov/pml/div685/grp05/ssl.cfm

The purpose of this descriptive case study is to characterize how NIST's efforts created economic value and to make a rough-order-of-magnitude (ROM) estimate of the economic benefits of NIST's contributions to the development of two foundational SSL-related documentary standards: *Chromaticity of Solid State Lighting Products* (ANSI C78.377-2008), and *Electrical and Photometric Measurements of Solid-State Lighting Products* (IESNA LM-79-08), both published in 2008. This analysis concludes that, conservatively, the economic benefit of NIST's contribution to accelerating the development and publication of these standards is likely in the range of tens of millions of dollars.

Lighting Basics[5]

A simple definition of light is visually perceived radiant energy. This visible light is a small part of the electromagnetic spectrum and ranges in wavelengths from 360 nm to 830 nm. We see objects as a result of the visible light reflected by them.

The word *lamp* is derived from the Greek word *lampas* meaning torch. Seventy thousand years ago, a *lamp* was made from some non-flammable object filled with a combustible material and ignited. Today, a *luminaire* ("light fixture") is defined as a device that produces, controls, and distributes light. A complete lighting unit consists of:

- One or more lamps
- Optical devices designed to distribute light
- Sockets to position and protect the lamps and to connect them to a power supply
- Mechanical components required to support or attach the housing.

SSL competes with the many other kinds of lamp technologies. (See Appendix A, Principal Types of Lighting Technology.) SSL (LED) lighting is fundamentally different from these other light sources. It uses no mercury, no lead, no gas or filament; it has no fragile glass bulb; and it has no failure-prone moving parts. LED lighting is more efficient, durable, versatile and longer lasting than incandescent lighting. LEDs emit light in a specific direction, whereas a fluorescent lamp is "diffuse" and emits light and heat in all directions.

Lighting Measurement[6]

Luminaire performance can be characterized by a combination of photometric, electrical, and mechanical performance measures. The photometric performance of a luminaire describes the efficiency and effectiveness with which it delivers the light produced by the lamp to the intended target. The photometric and electrical performance of a luminaire describes the efficacy (lumens per watt) with which the luminaire generates light.

An LED produces light and heat which can be assessed with radiometric and photometric measures. A radiometric measurement characterizes the total energy across the spectrum of the light source. However, the human eye only responds to a sliver of the electromagnetic spectrum (visible light). Photometric measurement characterizes the visible portion of the spectrum, within the spectral luminous efficiency function. To measure the amount of visible light produced by an LED the measured radiometric output is weighted by an eye-based or photometric measure.[7]

[5] http://www.ies.org/lighting/

[6] The material in this section is based on Ken Dowling, "Metrics for Solid-State Lighting," LEDs Magazine, May 2005, http://www.ledmagazine.com/features/2/5/4

[7]. Photometry is the measurement of quantities associated with light. Photometry can be either visual, in which the eye is used to make the comparison, or physical, in which measurements are made by means of physical receptors like light meters.

NIST researchers took a leadership role in the development of *ANSI C78.377-2008, Specifications for Chromaticity of Solid-State Lighting Products*.[8] The purpose of the standard is to specify the range of colors (chromaticities) of white light recommended for general lighting with solid state lighting (SSL) products, as well as to ensure that the quality of light provided can be communicated to consumers.[9]

Historically, the CRI was widely adopted by the lighting industry to characterize the quality of a light source. However, it has deficiencies, especially with respect to LED sources.[10] Unlike florescent lamps, white LEDs are not manufactured in a narrow chromaticity range but are "binned" from much larger chromaticity variations in mass-produced LEDs.[11] The color bins used by different LED manufacturers were all different and not comparable. Adding to the complexity is the fact that traditional photometric standards were separated for lamps and for luminaires. The luminaire measurements with traditional lamps require measurement of lamps taken out from the luminaire. Most current SSL luminaires incorporate LED sources, which cannot be removed from the luminaire and required new test methods.

NIST's involvement in the DOE's lighting efficiency efforts stems from the fact that standards for white light chromaticity of fluorescent lamps, and photometric measurements of incandescent and discharge lamps could not be applied directly to SSL products. NIST was an important catalyst and participant in the development of standards for Chromaticity of Solid State Lighting Products (ANSI C78.377-2008) and Electrical and Photometric Measurements of Solid-State Lighting Products (IESNA LM-79). These will be the foundation for all solid-state lighting standards going forward.[12]

DOE and the Market for Lighting Products

Nationally, lighting consumes a substantial amount of energy, currently 22% of all electricity consumed in the U.S. White LED sources are expected to be twice, or more, energy-efficient than fluorescent lamps. Thus, SSL is expected to have a big impact on the nation's energy savings.

Up to now, luminaires have consisted of a replaceable light source held in position by a socket within the metal fixture enclosure. The first large market for LED sales is replacing the soon-to-be-banned incandescent A and PAR lamps, a market that will be there for many years to come. And like "Moore's law," that predicted dramatic reductions for semiconductor chip manufacturing costs for computers, "Haitz's Law" forecasts that the

[8] Yoshi Ohno, *NIST Role in Supporting Solid State Lighting Initiative,* CORM 2007 Annual Meeting, Gaithersburg, May 8-11, 2007.

[9] As discussed above ("Lighting Measurement"), chromaticity coordinates (x, y) were traditionally used to describe colors of light, but CCT and Duv can also be used. CCT and Duv are considered to be a more intuitive measure of color. These are the measure of color specified in the new ANSI chromaticity standard, and acceptable ranges of CCT and Duv are specified for the eight nominal CCTs. Accordingly, a nominal CCT is used to specify and communicate white light chromaticity information of a product as a CCT value closest to the target CCT of the product. A target CCT is the CCT value that the product is designed to produce. SSL products should have chromaticity values that fall into one of the nominal CCT categories specified in the new standard. SSL products with a given nominal CCT shall have the defined target CCT and Duv value and the values of individual samples must fall within the tolerances specified.

[10]. CIE 177: 2007, *Colour Rendering of White LED Light Sources.*

[11]. Semiconductor manufacturing processes yield individual LEDs that vary widely in performance. Categorizing LEDs according to performance ranges ("binning"), allows manufacturers to sell other than the highest-performing products. By trading off quality for cost, LED consumers and producers gain, so long as the performance dimensions are clear. The performance tolerances of previous chromaticity standards were both more narrow and less continuous than those contained in the new standard. The new standard employs "quadrangle" tolerance boundaries that are more consistent with LED manufacturing quality control practices than previous "elliptical" tolerance boundaries. See (ANSI NEMA C78.377-2008, Annex, A2.

[12]. "Standards Set for Energy-Conserving LED Lighting," NIST, *Tech Beat,* June 24, 2008; http://www.nist.gov/pml/div685/led_062408.cfm.

amount of light produced per LED will increase twenty-fold each decade, while the cost of that light decreases tenfold.[13]

Motivated in part by the requirements of the Energy Policy Act of 2005, the Energy Independence and Security Act of 2007, and the American Recovery and Reinvestment Act of 2009, the DOE has a goal of reducing by half the total energy spent by lighting in the U.S. by 2027. DOE is promoting SSL through its CALiPER testing program, the ENERGY STAR® certification program, the Next Generation Lighting Industry Alliance (NGLIA), and its support for standards development.[14]

But DOE has a long record of supporting the development and market transition of energy-efficient technologies. DOE's experience transitioning compact florescent lighting (CFL) technology into the market place played an important role in the ENERGY STAR® program's approach to SSL technology.

Lessons Learned from Transitioning CFL Technology

In 1991, the U.S. Environmental Protection Agency (EPA) initiated the Green Lights Program to encourage widespread use of energy efficient lighting.[15] In 1992 EPA introduced ENERGY STAR®, a voluntary labeling program designed to identify and promote energy-efficient products in order to reduce national carbon dioxide emissions. In 1996, U.S. Department of Energy (DOE) agreed to work jointly with EPA to promote energy efficient products using the ENERGY STAR® logo. Residential lighting fixtures were added to EPA's labeled products in 1997.[16,17]

Although CFL technology was introduced in the 1970s, it took 30 years to gain widespread acceptance in the U.S. residential lighting market.[18] In 1999, screw-based CFLs were added to the ENERGY STAR® program and garnered the participation of more than a dozen of the major CFL manufacturers and numerous utilities.[19] The program offered national branding and a single set of specifications to which manufacturers could design. The government and the utilities industry expended significant funds to promote CFL technology because of its energy savings over incandescent lamps. Estimates indicated that CFLs decrease lighting energy consumption

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13. Joe Knisley, "LED Update: Part 1", Electrical Construction & Maintenance (EC&M) Magazine, October 20, 2010.

http://ecmweb.com/lighting/led-basics-20101001/index.html?smte=wr

14. Navigant Consulting, Inc., *Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030*, February 2010. (Prepared for the Lighting Research and Development Building Technologies Program Office of Energy Efficiency and Renewable Energy U.S. Department of Energy.)

15. "Introducing the Green Lights Program," EPA, December 1993. (EPA-430-F-93-050)

http://nepis.epa.gov/Exe/ZyNET.exe/2000C67F.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1991+Thru+1994&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C91thru94%5CTxt%5C00000008%5C2000C67F.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=p%7Cf&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

16. Rich Brown, et. al., "Status and Future Directions of the ENERGY STAR® Program," Proceedings of the 2000 ACEEE Summer Study (also LBNL-45952; http://enduse.lbl.gov/EStar.html).

17. Operating the ENERGY STAR® labeling program jointly, EPA and DOE enter into agreements with program partners that allow the partners to promote products meeting certain energy-efficiency and performance criteria through use of the ENERGY STAR® label. EPA and DOE have focused their efforts in areas where efficiency improvements can be achieved cost-effectively, while offering the same or improved level of service. The mission of the ENERGY STAR® program is to realize significant reductions in greenhouse gas emissions and energy consumption by permanently transforming markets for energy-consuming products so that energy-efficient products are the norm. Essentially, the ENERGY STAR® program is a branding and information campaign to enable consumers to identify and purchase energy-efficient products. ENERGY STAR® continues to be regarded as the trusted source of unbiased information that helps Americans identify reliable, cost-effective, energy-saving solutions that also protect the environment by reducing greenhouse gas emissions. Through 2010, more than 20,000 organizations have partnered with EPA, resulting in significant environmental and financial benefits. See, Navigant Consulting, Inc., 2010, op. cit.

18. L. J. Sandahl, et. al., *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market*, June, 2006, Pacific Northwest National Laboratory (Prepared for The U.S. Department of Energy Under Contract DE-AC05-76RLO 1830).

19. Ibid.

by one-half or more for each incandescent lamp replaced. Yet, because of barriers to consumer acceptance, their market penetration has been modest, only about 2% of the national market in terms of unit sales by 2006.[20]

The barriers to CFL market acceptance are believed to be pertinent to the introduction of SSL technology. According to CFL manufacturers, various technical performance issues related to color rendition, light output, and radiant efficiency were resolved over time as a result of technical advances. But these improvements were uneven.[21] U.S. residential adoption of CFLs lagged compared to European and Asian markets. Among the explanations for the relatively slow rate of adoption are: differences in national coordination of promotional efforts, different cultural attitudes about resource consumption and, to some extent, relatively higher electricity prices in other national markets. Where CFL adoption was most successful, a broad, market-based, national CFL promotion program accompanied it.

In light of the market penetration experience of CFL technology, DOE launched the ENERGY STAR® program for solid-state lighting products in 2006, including SSL in the ENERGY STAR® Program's "Lighting for Tomorrow" competition.[22] NIST scientists assisted DOE by providing research, technical details and comments for the ENERGY STAR® specifications.

The Genesis of NIST's Engagement

According to DOE's SSL portfolio manager, James Brodrick,

> There is a tremendous amount of behind-the-scenes work in SSL to facilitate the progress that drives the market and makes the headlines. The development of standards and test methods that consistently characterize product performance and assure safety is a key part of that behind-the-scenes work. Establishing a set of ground rules keeps the entire industry singing from the same song sheet and imposes a certain amount of order on what could otherwise become a Wild West, anything-goes type of situation.[23]

NIST has been providing physical measurement standards in photometry and colorimetry for many years. As definitions of photometric and colorimetric units and standards are questioned, or found to be insufficient for the latest lighting technologies, NIST frequently gets involved to provide an "honest broker" role, and to provide expert knowledge and unique measurement capabilities.

The development of what became the new chromaticity standard (ANSI NEMA C78.377-2008) began in earnest in December 2005 when SSL industry representatives of ANSI's Lighting Working Groups C78-09 and C82-04 began to raise a fundamental issue about their lighting products compared to others: "What is the definition and quality of the color white?" To answer this, and related questions, NIST researchers Wendy

20. According to Sandahl, et. al., *op. cit.,* regional market penetration has been more significant: 5% in the California market and 12% in the Pacific Northwest market.

21. Sandahl, et. al., *op. cit.,*

22. James R. Brodrick, "SSL Technology Evolution," US Department of Energy, February 8, 2007.

23. James Brodrick is quoted in, Beck Ireland, "Up to Standards," *Electrical Construction & Maintenance (EC&M) Magazine,* Apr 21, 2011, http://ecmweb.com/lighting/solid-state-lighting-standards-20110401/

Davis and Yoshi Ohno were asked to report on their work to develop a new color characterization scale. Wider industry concerns included the communication of SSL color-related issues; "binning" concerns; and using SSL in conjunction with existing lighting technologies, all issues that are explicitly addressed in the new chromaticity standard.

According to industry participants, the genesis of photometric measurement standard (IESNA LM-79) appears to have originated in the early 2006 time frame as well. With the advent of LED lighting it was becoming obvious that existing lighting measurement standards did not allow consistent measurements across all LED producers in the industry. The standards that existed for traditional lighting were not applicable to LEDs. The desire to quickly develop measurement standards was a DOE priority. In March 2006, a Standards Development Workshop, hosted by the Department of Energy, brought together representatives of several standardizing bodies in lighting field including ANSI, IESNA, CIE, and NEMA, as well as NIST and the industry representatives, to launch standard developments needed for Energy Star.

NIST's Role in the Measurement of Solid-State Lighting Products

In order to participate in the DOE's ENERGY STAR® program, SSL products required their own standard test methods for measurement along with a laboratory accreditation program to certify laboratories to conduct the new standard tests for SSL products.

NIST made significant contributions to developing the first standard for measurement of SSL products along with the basis for a laboratory accreditation program. NIST researchers lead the Illuminating Engineering Society of North America (IESNA) committee in the technical development of its recently published, *IES LM-79-08 Approved Method for Electrical and Photometric Measurement of SSL Products*, the first standard for measurement of LED lamps and LED luminaires (not bare LED chips, packages, and modules). IES LM-79-08 provides standard test methods for photometric and colorimetric measurements of SSL products, including luminous flux (lm), luminous efficacy (lm/W), chromaticity, color rendering, and luminous intensity distribution. It also specifies operating conditions and methods (both integrating sphere systems and goniophotometer systems) for the measurement of SSL products. This standard has been recognized as the key standard for test methods of SSL products and is used by the ENERGY STAR® program as well as other DOE programs including Lighting Facts Label, and is widely used by the lighting industry in the USA.[24] NIST's National Voluntary Laboratory Accreditation Program (NVLAP) has incorporated the operating conditions and measurement methods described in IES LM-79-08 into the laboratory accreditation program for Energy Efficient Lighting Products–SSL. This accreditation program is required for the implementation of the ENERGY STAR® program.

NIST researchers also took a leadership role in the development of *ANSI C78.377-2008, Specifications for Chromaticity of Solid-State Lighting Products*.[25] The purpose of the standard is to specify the range of colors (chromaticities) of white light recommended for general lighting with solid state lighting (SSL) products, as well as to ensure that the quality of light provided can be communicated to consumers.[26]

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[24]. http://www.nist.gov/pml/div685/grp05/ssl_products.cfm; and *Understanding IES LM-79 & IES LM-80*, Eric Richman (Pacific Northwest National Laboratory), LIGHTFAIR International, Las Vegas, 2010.

[25]. Yoshi Ohno, *NIST Role in Supporting Solid State Lighting Initiative,* CORM 2007 Annual Meeting, Gaithersburg, May 8-11, 2007.

[26]. As discussed above ("Lighting Measurement"), chromaticity coordinates (x, y) were traditionally used to describe colors of light, but CCT and Duv can also be used. CCT and Duv are considered to be a more intuitive measure of color. These are the measure of color specified in the new ANSI chromaticity standard, and acceptable ranges of CCT and Duv are specified for the eight nominal CCTs. Accordingly, a nominal CCT is used to specify and communicate white light chromaticity information of a product as a CCT value closest to the target CCT of the product. A target CCT is the CCT value that the product is designed to produce. SSL products should have chromaticity values that fall

Tying the two foundational standards together, the measurements of color specified in the new chromaticity standard (ANSI C78.377-2008) are required to be in accordance with methods given in the measurement standard (IESNA LM-79-08).

THE BENEFITS OF NIST'S ENGAGEMENT WITH THE SSL INDUSTRY

The National Innovation System

Figure 1 captures the roles of the various contributors to the process of high-tech product market development. To understand the economic benefits of NIST's role in the market development process, it is helpful to briefly consider the economic rationales at work in the decisions about how investments tend to be shared between the public and private sector in each of the main elements of the figure.[27] Investments in *basic science* are predominantly made by public agencies and carried out by academic institutions.[28,29]

The next three elements in Figure 1 represent areas where private partnerships and private-public partnerships help reduce technical and business risks to justify the large investments needed to bring innovative high-tech products to market. *Core technology* (also known as "generic technology") embodies laboratory-proved concepts but not the subsequent marketable products that will be derived from the core technology.[30] Often, forms of collaboration arise to advance and finance technology development and mitigate the considerable technical risks inherent in such development. In some cases, where the costs, risks, and potential benefits are believed to be high, government agencies often join in the partnerships. The DOE's ENERGY STAR® program is one example.

Individual firms make investments with the goal of transforming core technologies into marketable products. The private sector's *product development* investments depicted in Figure 1 dominate this aspect of the technology life cycle but they are supported by collective, private sector-led standards development organizations (SDOs).) This is where NIST researchers tend to play a critical role. The role NIST played in the development of the chromaticity and photometric measurement standards is a prime example. While product development, production planning, and market penetration, all depicted in Figure 1, involve substantial private investments, the kinds of measurement technologies and tools develop at NIST are utilized throughout the R&D and market penetration process. NIST's role in developing the measurement know-how that underlies the chromaticity and photometric standards, provided great value to industry. It serves as an example of the public-private cooperation increasingly needed for successful market adoption of innovative technologies.[31]

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into one of the nominal CCT categories specified in the new standard. SSL products with a given nominal CCT shall have the defined target CCT and Duv value and the values of individual samples must fall within the tolerances specified.

27. For the fuller development of these policy rationales, see, Gregory Tassey, *The Economics of R&D Policy,* Quorum Books, 1997; and *The Technology Imperative,* Edward Elgar, 2007.

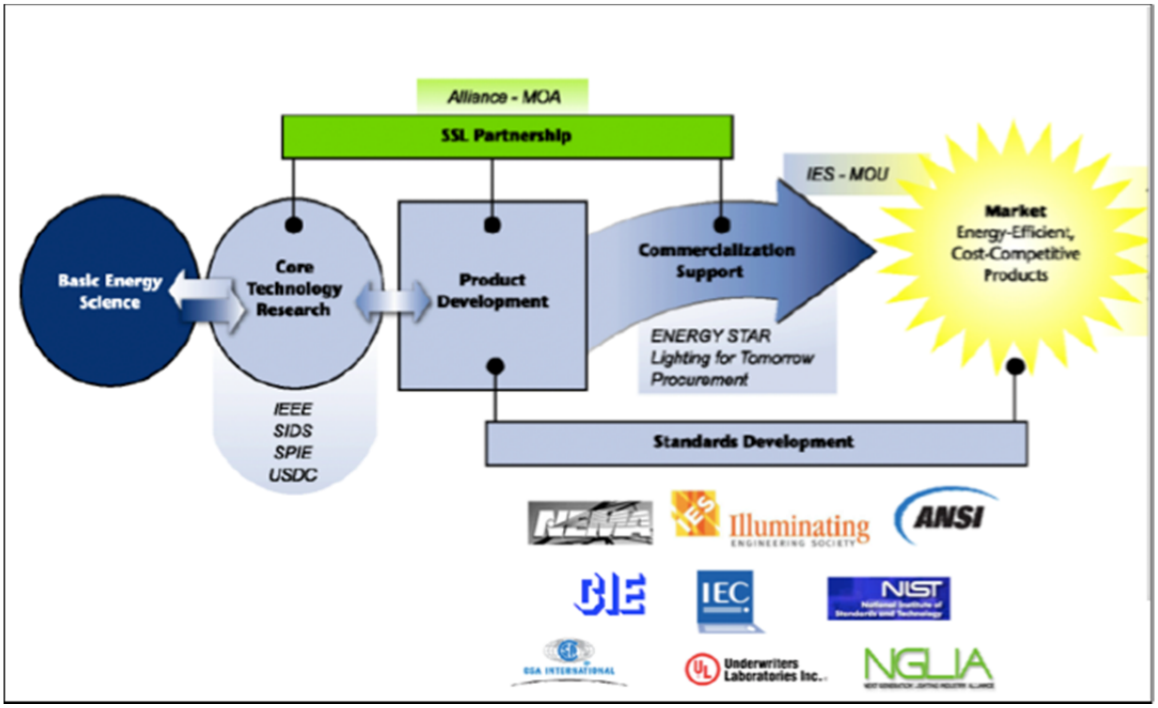
28. The economic benefits of advancing the state of basic science are large but the risks of transforming basic scientific knowledge into marketable products are very high and the time involved very long. As a result, only large diversified firms tend to invest in basic research, most is underwritten by public agencies. See Wesley M. Cohen, "Fifty Years of Empirical Studies of Innovative Activity and Performance," in *Handbook of the Economics of Innovation, Volume 1,* Hall & Rosenberg (Editors), Elsevier, 2010.

29. The economic policy justification is that, for a number of reasons, the return on the public's investment in basic research — all the net benefits summed across all investors and beneficiaries (the "social rate of return") — tends to be significantly higher than the net benefits that accrue to individual investors alone (the "private rate of return"). See, Tassey, 1997 *op. cit*., pp. 52-53; A. Link and J. Scott, *Public Goods, Private Gains*, Oxford, 2011, pp. 8-16.

30. It is helpful to think of core technology as a "technological commons" from which a collective of investors will derive private benefits as they transition from "proof of concept" in the lab to marketable products.

31. A recent assessment found that most winners of the R&D 100 Award in the last two decades have come from partnerships involving business and government, including federal laboratories and federally funded university research. See, F. Block and M. Keller, "Where Do

Figure 1. Contributors to SSL Product Market Development[32]



The SSL Value Chain

To understand the economic benefits that accrue to society from NIST's efforts requires a representation of the process by which value is created and "passed along" to products and services that are eventually consumed. The value chain depicted in Figure 2 is a snap shot of the complex process by which many economic actors contribute their "ingredients" to product and services integrators further up the chain. Those contributions "add value" that ultimately provides energy-efficient, cost-competitive products.

Beginning at the top, industry representatives distinguish different types of *lighting consumers* with different lighting needs.[33] Industry representatives characterize the final downstream link of the value chain differently but the five segments identified in Figure 2 are well recognized. Some companies are "vertically integrated" and provide products and services across multiple links in the chain, for example companies that make SSL components *and* luminaires *and* provide lighting design services. Other companies specialize; some vertically, others "horizontally" within a value added stage, for example, lamp and luminaire producers who specialize in outdoor lighting products. The major companies that produce luminaire and lamp products using LEDs include: Acuity, Cooper Lighting, CREE, GE Lighting, Hubbell Lighting, OSRAM Opto Semiconductors, Philips Lumileds, Sharp LED Lighting, Toshiba, Trilux New Light, and Zumtobel Group. They are global companies supported by a global supply base.

Innovations Come From? Transformations in the U.S. National Innovation System, 1970-2006," *Information Technology and Innovation Forum (ITIF)*, 2008.

[32]. Yoshi Ohno, *Photometry Short Course, 2011*, NIST, 2011.

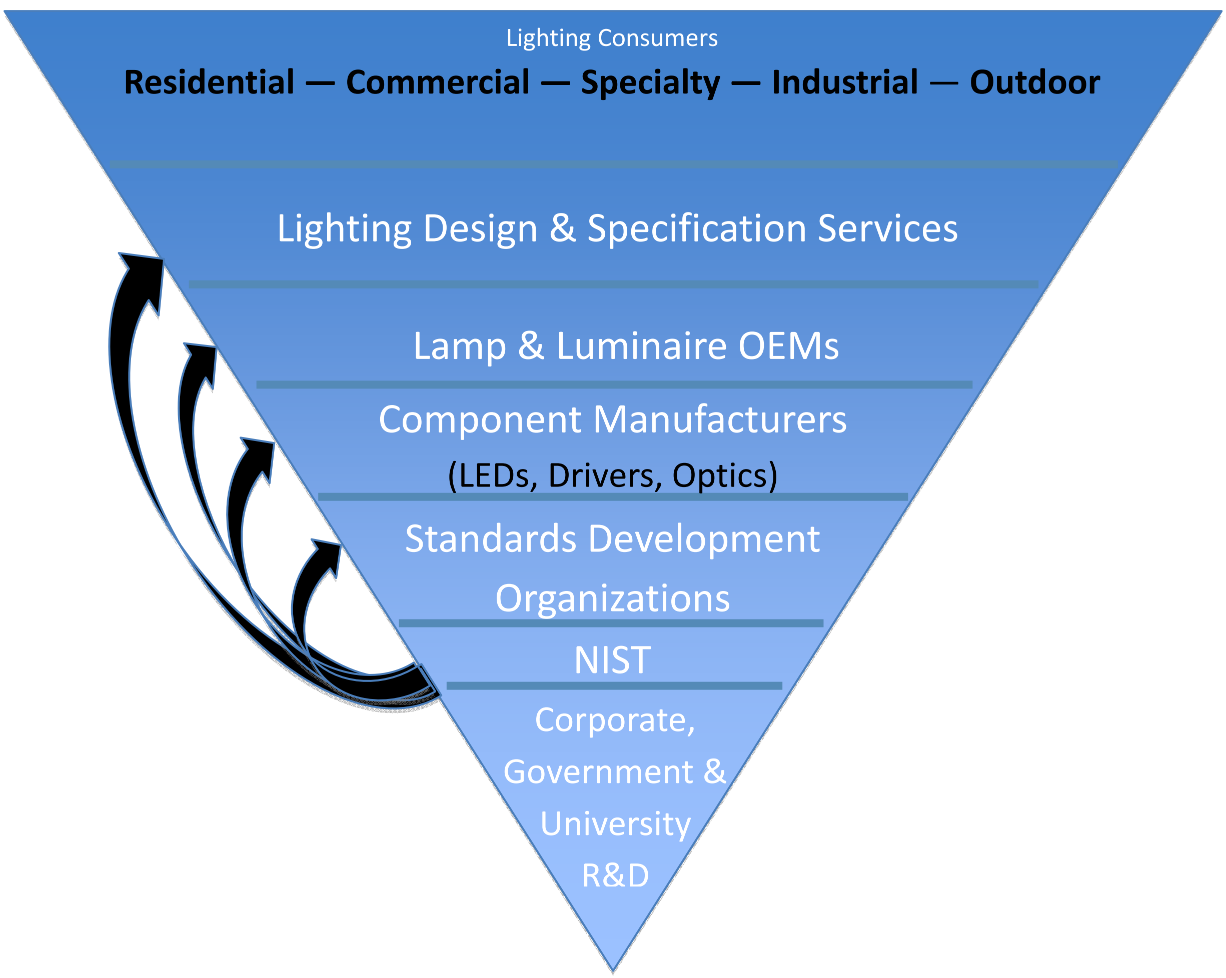
[33]. This simple depiction of the SSL value chain doesn't do justice to the DOE's ubiquitous role in the SSL industry. DOE funds basic and applied research and the ENERGY STAR® voluntary Solid-State Lighting (SSL) Luminaire program, which went into effect in September 2008 advocates for SSL consumers and suppliers alike. ENERGY STAR® program personnel worked with standards organizations to identify industry needs, and funded NIST's role in support of the new chromaticity and photometric measurement standards. DOE has influence across the SSL value chain.

Major LED producers include, CREE, Nichia, OSRAM Opto Semiconductors, and Philips Lumileds. There are many smaller producers as well. Some companies in the LED components category buy LED chips from LED producers, build LED boards, and assemble the boards into the luminaires marketed by major lamp and luminaire companies.

As depicted in Figure 2, standards development organizations (SDOs), like NEMA, and the Illuminating Engineering Society (IES), organizations accredited by the American National Standards Institute (ANSI) as official standard setting bodies, support, and are supported by, all downstream manufacturers, service providers, and lighting products consumers in the value chain.[34]

NIST work, in turn, benefits the SDOs, and, often independently, lighting manufacturers, service providers, and consumers, by providing calibration services; by developing measurement technology; by maintaining national representations of weights and measures agreed to by international standards bodies; and by performing the role of "honest broker" in technical disputations related to measurement, when differing perspectives clash, as is often the case, in the process of consensus standards formulation. As discussed above, in terms of NIST's role in the development of "infratechnology," NIST also supports scientific and engineering laboratories that are the root source of many lighting innovations.

Figure 2. Solid State Lighting Value Chain



[34]. For a primer on how standards are developed in the U.S., see, Maureen A. Breitenberg, *The ABC's of Standards Activities* (NISTIR 7614), August 2009, National Institute for Standards and Technology.

Creating Value[35]

According to knowledgeable industry representatives, the new chromaticity and photometric measurement standards began to create a level of homogeneity among SSL products and practices that did not exist prior to the standards. According to one industry representative:

> "The day C78.377 was approved, [we] changed all product bins to match the ANSI bins. Prior to the issuance of LM-79 and LM-80, all LED companies tested SSL fixtures however they wanted to. There was no common procedure for testing lumen maintenance of LEDs. [Lighting companies and their suppliers] just did whatever they wanted. With the new [standards] there was a level and comparable "playing field"."

Another practitioner expressed much the same perspective in other terms:

> "LED manufacturers realigned their internal LED color bins to the quadrangles (or at least segments of quadrangles) defined in C78.377. This makes comparison across manufacturers easier, quicker, and less costly. It's the first step toward interchangeability and multiple suppliers, thus will drive costs down."

This not only changed the practices of manufacturers but also, "changed the way we communicate with our customers. …LED manufacturers recognized that customers were going to demand LEDs from bins that align with the quadrangles defined in C78.377."

Prior to the introduction of the new standards, each LED manufacturer defined the quality of their LEDs differently, or some suppliers only supplied selected luminaire integrators. This resulted in a "stove-piped" industrial structure which made purchasing LEDs from different manufacturers very difficult. This situation made it difficult to compare price and quality differences among suppliers. Comparable product performance was hard to assess and low quality producers were not penalized, putting unfair pressure on high-quality producers. With the new standards, the comparability of light quality per dollar between the products of two suppliers became possible.

In addition to sorting out the relative standing of various SSL luminaire and component producers, sorting out the relative standing of SSL replacement products vis-à-vis incumbent lighting technologies was another important consequence of the new standards. As discussed above, part of the conscious effort to avoid the kinds of barriers to acceptance that afflicted the market penetration of CFLs (e.g., low quality products, inaccurate performance claims, product label content, and non-standard test methods) are all addressed by the new SSL standards.

The resulting changes in business practices as a result of the adoption of the new standards translated into improved value for the various SSL market participants in different ways:

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[35]. The basic insights into how the new chromaticity and photometric measurement standards create value are drawn from email exchanges and interviews with industry participants who were involved in the standards development process. It was a condition of those interviews that their views would not be attributed to them or their companies. Therefore, quotations from "industry representatives" and "industry participates" are anonymous. Some email exchanges quotations are reformatted to improve the flow.

> "*Lamp manufacturers* are able to gauge LEDs for compatibility, cost, and color. This drives interchangeability and multiple suppliers. *Fixture or replacement lamp manufacturers* see lower-cost components, color defined components, and, again, interchangeability. Additionally, more innovation is made possible. *OEMs or luminaire distributors* have lower cost products [that allow their] energy efficient SSL products to compete with existing lighting technologies. *End users* see a lower cost, more energy efficient products. Since the standards drive color consistency, and color quality is important for acceptance into the market place, the standards go a long way in opening the market."

Summarizing the many ways that the new SSL chromaticity and photometric measurement standards have created value, another industry participant observes:

> "The users of SSL products [in all product categories] have benefited tremendously with the adoption of SSL standards. There is now a common language that is spoken around the world that allows for a direct 1:1 comparison of different products. This has not only helped reduce confusion on the part of the consumers, but has also helped us drive towards improved quality and lower costs."

Systematically estimating the value to industry enabled by ANSI C78.377-2008 and IESNA LM-79 is not intended within the scope of this descriptive case study. But it is possible to make a rough estimate of some of NIST's contribution to the consensus standards-making process that resulted in the new chromaticity and photometric measurement standards; and to use that result to fashion a sensible rough-order-of-magnitude approximation of the scale of the dollar benefits attributable to NIST's role in the standard-making process for SSL products and services.

Industry representatives who were involved in the development of ANSI C78.377-2008 and IESNA LM-79 characterize NIST's role as follows:

> "NIST offers a uniquely unbiased, scientific view of the standards development and vastly increases the speed at which these standards were developed. Additionally, [NIST subject matter experts are] highly respected in the lighting community and can provide an excellent "voice of reason" that moves the development process along. I dare say that C78.377 would have been delayed up to 2 years without NIST assistance."

Another standards committee member voices a similar perspective:

> "Anyone who has ever worked on standards development knows it can be a long and grueling exercise. The chromaticity specification was particularly difficult in that all the stakeholders … had, to some degree, their own agenda. Despite this, these documents were developed very quickly. It took us about 1.5 years to get these completed. Without [NIST's] expert experience I estimate it would have taken us at least one year longer."

Based on communications with industry representatives responding to counterfactual questions about what time and resource expenditures would have been made by industry "without NIST," it is estimated that ANSI C78.377-2008 and IESNA LM-79 would have taken 14 additional months to finalize, and would have cost industry committee participants more than $1million worth of their time to develop the new standards. (Almost $300,000.00 in the case of ANSI C78.377 (Chromaticity) and more than $800,000.00 in the case of IESNA LM-79 (Photometric Measurement)). By playing the role of "honest broker," mediating positions put forward by interested parties in the standards development consensus-making process — some uninformed, some opportunistic (so-called "specsmanship") — NIST effectively reduced the time-consuming costs of the consensus-making process.[36]

These consensus-making efficiencies are only the first-order consequences of NIST's participation. Where ineffective standards are promulgated, substantial second-order consequences would also likely ensue. Market transaction costs (the costs of identifying and assessing the cost and quality of products) would be higher, resulting in fewer sales and lower revenues.

If the new chromaticity and photometric measurement standards were delayed by 14 months, it seems reasonable to assume that some fraction of the growth of the market for SSL fixtures would also have been suppressed. Industry participants in the standards development process reason as follows:

> "C78.377 and LM-79 helped to provide a source of confidence to lighting specifiers, and this confidence helped to boost the market for LED luminaires in the late part of 2008 through 2010. If C78.377 and LM-79 were delayed by one year, I think that the market for LED luminaires might have only grown by half of what it did [immediately following its publication]."

Table 1 shows sales estimates of the North American market for LED luminaires and LED replacement lamps, 2008-2010. If we very conservatively assume that *only* the North American sales, and *only* the year 2009 would have been affected by a delay in the publication of the new chromaticity and photometric measurement standards; and, to avoid double counting the benefits of the new SSL standards to society, we consider only an approximation of the value added from sales in 2009, the second order economic benefits of NIST contribution to the new standards would be measured in the tens of millions of dollars (($1,171,901) x 0.4 x 0.5 = $54 million).[37]

Table 1.

North American Market for LED Luminaires and LED Replacement Lamps

Year	Sales (Millions of Nominal $)
2008	901
2009	1,171
2010	1,482

Source: Strategies Unlimited, March 12, 2012

36. These consensus-making efficiencies are only the first-order consequences of NIST's participation. Where ineffective standards are promulgated, substantial second-order consequences would also occur. Market transaction costs would be higher, and industry sales and revenues would be lower, than in the case of more effective standards.

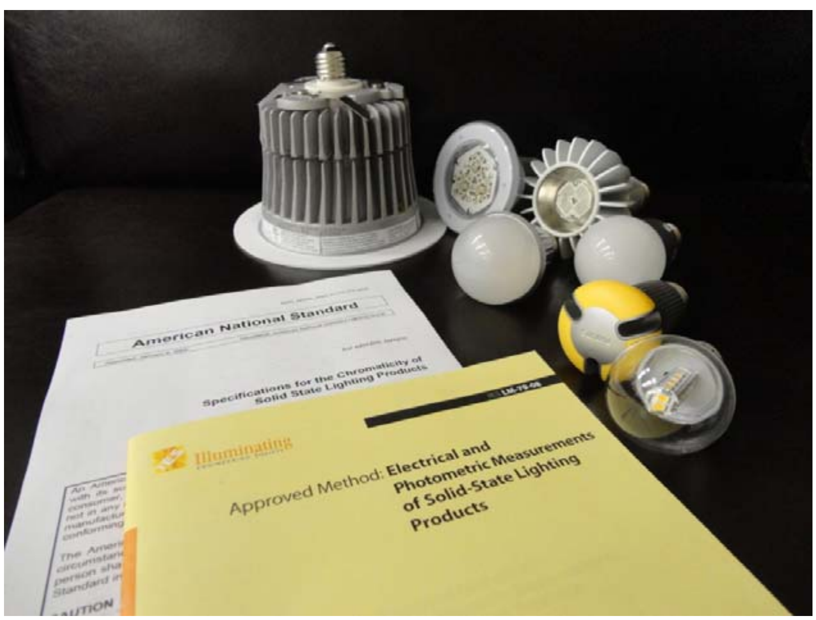
37. The average percent of value added/gross output for NAICS 335, *Electrical Equipment, Appliances, Components*, 2004-2010 is 0.4. That fraction is used to estimate the value added from North American sales in 2009: 0.4 x (1171-901) = 108. If, as industry representatives hypothesize, sales would have been halved by the delay in the promulgation of the new standards, the ROM benefits of NISTs participation in the standards development process is on the order of $54 million for 2009 alone. If the delay would have affected late 2008 sales, or had an impact that spilled over into 2010 and beyond, the benefits of NIST's role in the development of SSL standards would be greater.

SUMMARY

As the national economy transitions to more energy-efficient products (particularly disruptive technology-based products), government and industry have complementary roles to play in mitigating the market frictions and social costs that accompany this process. Standards development plays a critical part in reducing the risks and costs of the product commercialization process, especially where underlying generic technologies are significantly different than the ones supporting conventional products.

Solid state lighting is a case in point. This revolutionary lighting technology holds the promise of dramatically reducing the immediate costs and long-term environmental burdens of our energy consumption needs. But the new technology entails different consumer and industry practices, from assessing the relative cost and quality of competing light fixtures and replacement bulbs, to the design, manufacture, and testing of new and improved lighting products, to the procurement of component parts and materials.

Working with the Federal government's ENERGY STAR® program, as well as national and international companies, as part of the consensus-making standards process, NIST is making important, economically valuable, contributions to the lighting market's transition to solid-state lighting. NIST's internationally recognized measurement expertise and capabilities, as well as its reputation for the highest quality independent technical judgment, eased the transition to SSL technology, lowered the cost of commercialization, and improved market acceptance of SSL products. These, in turn, resulted in more rapidly increased sales and the earlier realization of energy savings benefits. The economic benefits of NIST's contribution are estimated conservatively in the tens of millions of dollars in the lighting market alone![38]



[38]. Reiterating an important point made at the beginning of this analysis, only the *benefits* of NIST's support to industry are considered here. These large economic benefits are *not net benefits* since the relevant NIST and industry costs are not taken into account.

APPENDIX A. PRINCIPAL TYPES OF LIGHTING TECHNOLOGY

Lighting Technology	Description
Incandescent lamps	Also called "A" lamps or "general service" lamps, they produce light when a filament is heated by an electric current, causing it to glow or "incandesce." Normally, the filament is made of a coiled or double-coiled tungsten wire.
Reflector ("R") lamps	Incandescent lamps with a built-in reflector to collect and focus the light from the filament, giving a simple, directional characteristic to the beam.
PAR (Pressed Glass Aluminized Reflector) lamps	Reflector lamps formed from two pieces (lens and reflector) of pressed, thick, heat resistant glass able to be used outdoors in the rain or snow.
Halogen lamps (or tungsten halogen lamps)	Incandescent lamps that operate at higher pressure and temperature than standard incandescent lamps, producing a whiter light and longer life. The filament material is tungsten. The halogen gas in the lamp significantly reduces the deposition of evaporated tungsten onto the glass bulb, resulting in more light.
Fluorescent lamps	These produce light by passing an electric arc through a mixture of an inert gas (argon or argon / krypton) and mercury (a tiny amount). The mercury radiates ultraviolet energy that is transformed to visible light by the phosphor_coating on the bulb. There are two general categories of fluorescent lamp: linear and compact.
Linear fluorescent lamps	Fluorescent lamps that come in a range of wattages and sizes. Four and eight foot lamps are most common for commercial uses such as office buildings and warehouses.
Compact Fluorescent Lamps (CFLs)	CFLs operate on the same principle as regular fluorescent lamps, but are more "compact." CFLs were intended to provide an energy efficient replacement for general use incandescent lamps.
High-Intensity Display (HID) lamps	HID lamps produce light directly from the arc itself, due to the high pressure under which these lamp types operate. There are three basic types of HID lamps: mercury, metal halide, and high-pressure sodium (HPS).
Light Emitting Diode (LED)	An LED is a solid-state semiconductor device that converts electrical energy directly into light or photons through the use of semiconductor materials that combine in a way to release energy in the form of visible light.