

The Transition to Solid-State Lighting

White light emitting diodes offer efficient use of electrical energy and lower lighting costs as well as reduced atmospheric pollution.

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ABSTRACT | Lighting constitutes more than 20% of total U.S. electricity consumption, a similar fraction in the European Union, and an even higher fraction in many developing countries. Because many current lighting technologies are highly inefficient, improved technologies for lighting hold great potential for energy savings and for reducing associated greenhouse gas emissions. Solid-state lighting shows great promise as a source of efficient, affordable, color-balanced white light. Indeed, assuming market discount rates, engineering-economic analysis demonstrates that white solid-state lighting already has a lower levelized annual cost (LAC) than incandescent bulbs. The LAC for white solid-state lighting will be lower than that of the most efficient fluorescent bulbs by the end of this decade. However, a large literature indicates that households do not make their decisions in terms of simple expected economic value. After a review of the technology, we compare the electricity consumption, carbon emissions, and cost-effectiveness of current lighting technologies, accounting for expected performance evolution through 2015. We then simulate the lighting electricity consumption and implicit greenhouse gases emissions for the U.S. residential and commercial sectors through 2015 under different policy scenarios: voluntary solid-state lighting adoption, implementation of lighting standards in new construction, and rebate programs or equivalent subsidies. Finally, we provide a measure of cost-effectiveness for solid-state lighting in the context of other climate change abatement policies.

KEYWORDS | Climate change mitigation; consumer adoption; energy efficiency; solid-state lighting

I. INTRODUCTION

Lighting consumes more than 20% of all electricity generated in the United States.¹ This corresponds to just under 800 TWh per year. The fraction is similar in the European Union (EU), and even higher in some developing countries, since lighting is one of the largest uses of electric power [3]. The International Energy Agency (IEA) [3] has estimated that worldwide lighting is responsible for emissions of approximately 1900 Mt CO₂ per year, “equivalent to 70% of the emissions from the world’s light passenger vehicles.” Eighty percent of these emissions from lighting are associated with electricity generation, but the IEA estimates that about 20% come from the 1% of global lighting that is produced by the direct combustion of paraffin and oil lamps used by the 1.6 billion people who have no access to electricity [3]. Hence, dramatically improved lighting system efficiency, together with electrification that replaces oil lamps with electric lamps, could make a big contribution to controlling global CO₂ emissions. A large literature illustrates the cost-effectiveness of greenhouse gas mitigation through the use of energy efficient technologies such as improved lighting [4]–[13].

Climate change is not the only concern moving lighting onto policy agendas. While oil plays a relatively minor role in U.S. electricity generation, natural gas, imported from increasingly unreliable parts of the world, fuels slightly more than 20% of U.S. generation [14] and 39% of generation in the EU member states [15]. While great progress has been made in reducing emissions of SO₂ and NO_x from power generation, local and regional air pollution,

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¹Estimated using [1] and [2].

including emissions of heavy metals such as lead, are an ongoing concern. Again, improved end-use efficiency can help to reduce those emissions.

Conventional incandescent bulbs, which convert only between 1% and 5% of the electricity they consume into usable light (when compared with the maximum efficacy of 408 lm/W for a near white light source), have been the initial focus of policy attention. This attention is clearly justified, since households and the commercial sector are responsible for 37% and 35% of the U.S. total electricity consumption.¹ Smil [16] argues that the provision of illumination is one of the most promising areas for future improvement in energy efficiency, suggesting that by the middle of the twenty-first century, the average lighting efficacy in rich countries could be 50% above today's level. The role of lighting technologies is also emphasized in recent California policy initiatives, as Title 24 [17]; and at the federal level in the 2005 Energy Policy Act [18], which creates a Next Generation Lighting Initiative that will support R&D to accelerate the rate of improvement in white solid-state lighting, and the 2007 Energy Independence and Security Act [19]. As a result of concerns about CO₂ emissions, energy security, and conventional air pollution, legislatures and regulators in Australia, Brazil, Canada, Ireland, Italy, New Zealand, the United States, and Venezuela have all recently moved to implement a mandatory phaseout of most standard incandescent bulbs over the coming decade. Most of the remaining countries in the EU are likely to adopt similar policies. However, currently available replacement technologies will not meet all consumers' needs. Scientists, engineers, and policy makers are increasingly looking to solid-state lighting for better solutions.

This paper begins with a brief account of the evolution of electric lighting technologies over the past century. It then discusses key lighting systems' characteristics, before going on in Section IV to discuss the likely future evolution of the performance of light-emitting diodes (LEDs) that produce white light—either by combining monochromatic LEDs or by using a down-converting phosphor layer. Many consumers do not choose long-lived technologies on the basis of standard market discount rates. We discuss consumer choice and the literature on implicit discount rates in Section V. Then, in Section VI, we present engineering-economic estimates of the future cost of light from the perspective of both commercial and residential customers. Other factors, such as total energy use and greenhouse gas emissions, are also important from a social perspective. Thus, Section VII explores the social cost-effectiveness of white LEDs. Then, in Section VIII, we estimate the potential energy savings and greenhouse gas reductions that could be achieved under different types of policies. We conclude the paper with recommendations on policy implementation for a rapid and widespread adoption of more efficient lighting in the near future.

II. BRIEF HISTORY OF LIGHTING TECHNOLOGIES

A. Incandescent Lamps

While Edison is credited with the development of the first commercially practical incandescent lamp in 1879, many others had worked on the idea over the preceding century [20]. Early bulbs used carbon filaments, which had limited lifetime and could not be operated at a high enough temperature to produce fully satisfactory light. General Electric patented the first tungsten filament for commercial use in 1906. Further improvements followed, including the use of inert gas in the bulb and the use of coiled tungsten filaments. While manufacturing costs continued to fall, the *efficacy* (the ratio of light output to the input electric power) with which incandescent bulbs convert electricity into light has reached an asymptote at just under 18 lm/W (Fig. 1).

B. Fluorescent Lamps

General Electric developed low-voltage fluorescent lamps in the 1930s. These were first marketed as “tint lighting” for decorative purposes. However, it soon became apparent that fluorescent lamps also held great potential for general lighting. The electric power industry became seriously concerned that the rapid proliferation of more efficient fluorescent lighting might reduce demand and thus negatively impact power sales. They were also concerned that the need for reactive power imposed by ballasts would increase current flows on their lines without resulting in marketable real power. As Bijker [21] has detailed, a series of negotiations followed between the power industry and GE and the GE licensees (the Mazda companies) in which it was agreed not to market fluorescents aggressively until much brighter “high intensity” lights, that required more power, could be developed. Today, with power companies and lighting firms experiencing much reduced market power, with much stricter antitrust law and enforcement, and with power companies struggling to meet load, such collusion between lamp manufactures and power companies is not a serious issue. Indeed, given the challenge of building new power plants, and growing concerns about CO₂ emissions, many U.S. power companies are actively promoting more efficient lighting. However, while fluorescents, and especially compact fluorescents, are now being actively promoted, their conversion efficacy is unlikely to grow much above 100 lm/W (see Fig. 1).

C. Solid-State Lighting

While Round [22] reported observing “cold light” emission from a cat-whisker point contact SiC crystal detector diode as early as 1907, the invention of the light-emitting diode is now attributed to Losev, a largely forgotten Russian scientist [23]. Losev [23] correctly posulated that the luminescence was not the result of

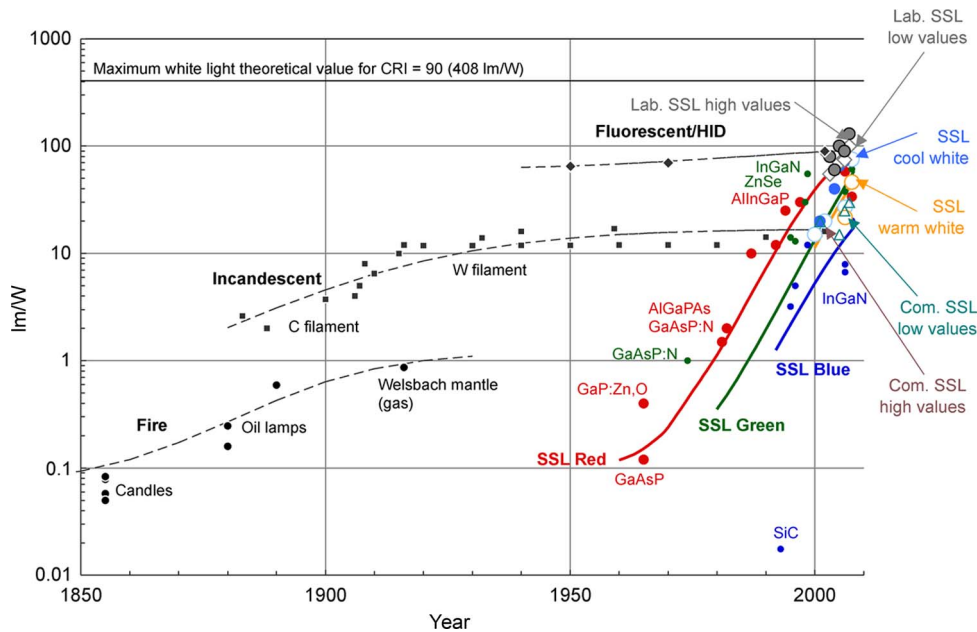


Fig. 1. Efficacies of selected lighting technologies between 1850 and 2006. Values for fire, incandescence, fluorescence, high-intensity discharge (HID), and red, blue, and green solid-state lighting (SSL). (Provided by J. Y. Tsao of Sandia National Laboratory. White LED values adapted from [29] and [30].) Lab. = laboratory; Com. = commercial. Note that efficacies are a function of the wattage, which is not shown in this figure. The theoretical limit for white light for a CRI of 90 is defined as in [34].

incandescence but was due to another process “very similar to cold electronic discharge.” Loebener [24] notes, “There is little doubt that Losev . . . was consciously pursuing work on light emitting diodes for communications applications. Between 1927 and his death [from starvation during the siege of Leningrad] in 1942, he published sixteen papers and obtained four patents on LED’s, photodiodes and optical recorders for high frequency signals.” This early work was largely forgotten, and until recently credit for the discovery and development of the LEDs went to a number of Western investigators, including Lehocvec *et al.* [25], Braunstein [26], and Holonyak [27].

In 1962, Holonyak, while with General Electric’s Solid-State Device Research Laboratory, made a red emitting GaAsP inorganic LED [27]. The output was very low (about 0.1 lm/W), corresponding to an efficiency of 0.05% [27]. Changing materials (to AlGaAs/GaAs) and incorporating quantum wells, by 1980, the efficacy of his red LED had grown to 2 lm/W, about the same as the first filament light bulb invented by Thomas Edison in 1879. An output of 10 lm/W was achieved in 1990, and a red emitting light AlInGaP/GaP-based LED reached an output of 100 lm/W in 2000 [27]. In 1993, Nakamura demonstrated InGaN blue LEDs [28]. By adding additional indium, he then produced green LEDs and, by adding a layer of yellow phosphor on top of the blue LED, he was able to produce the first white LED. By 1996, Nichia developed the first white LED based on a blue monochromatic light and a YAG down-converter. Fig. 1 illustrates the evolution in the conversion efficacy of

different lighting technologies since the mid-nineteenth century. Today, red and green LED efficacies are as good as or better than fluorescent and high-intensity discharge technologies. Commercialized white solid-state lighting is expected to reach those levels in just the next few years, and still is far from reaching theoretical limits that have already constrained future improvements in incandescent and fluorescent lamps.

III. LIGHTING SYSTEMS CHARACTERISTICS

A. Efficiency and Lifetime

The efficiency with which a system converts useful energy into a desired service, such as transportation, heating, cooling, or light, can be a useful metric. However, efficiency in its own right is not the primary concern of most individual consumers or of society as a whole. Consumers and policymakers care about cost, about non-market externalities such as environmental pollution and energy security, and about a variety of service attributes. In the case of illumination, one of the service attributes of great interest is the quality of the light.

For much of the past century, the price of electricity was continuously declining. There were also relatively low levels of concern about the local and global environmental consequences of generating electricity, and most fuel came from domestic sources. In such circumstances, highly

inefficient incandescent lamps were a perfectly acceptable source of light. Today, none of those conditions still obtain. As a result, improving the efficiency with which electricity can be converted into light in a cost-effective way, and with acceptable color balance, has become an important issue for public policy.

In discussions of efficiency, it is important to be careful to compare systems on an equal footing. Too often, the efficiency of an entire lighting system (which includes electronics, source, and fixture) gets compared with that of just a source.

Luminous flux, measured in lumens, represents the light power of a source as perceived by the human eye. A monochromatic light source that emits optical power of 1/683 W at 555 nm has a luminous flux of 1 lm [35]. We define *device efficacy* as the ratio between the luminous flux (in lumens) of light output to the input electric power (in watts). The device efficacy does not account for losses due to the fixtures. Similarly, we define *system efficacy* as the overall ratio between luminous flux and input of electric power, but accounting for the losses in the fixture. The distinction between lamp and system efficacy is clearly important, since a high source efficacy is not always an indication of the overall system efficacy. Fig. 2 reports the range of efficacies for incandescent, fluorescent, and

LED sources. The numbers in the central columns report the range of efficacies of commercial devices. The numbers in the column on the right report overall system efficacy, that is, the amount of light output from the system per watt of 60 Hz ac input power. The numbers on the first and third column represent ballast and fixture efficiencies.

Because bare lamps produce glare and are esthetically unpleasing, most devices are not used alone. Rather, they are placed in a variety of fixtures. In experimental studies commissioned by Color Kinetics, Inc., ITL Boulder evaluated a number of common fixtures and found that the associated light losses ranged from about 10% to over 60%. The rightmost columns in Fig. 2 degrade the values for incandescent and fluorescent systems, reported in the center column, by those amounts. If LEDs are placed in similar fixtures to those in use today, one can anticipate a similar range of fixture losses. However, given that LED systems are only now coming into widespread use, designers have the freedom to develop new fixtures for LED systems with much lower fixture losses. In Fig. 2, we have used a minimum fixture loss value of 5%, consistent with the recently released U.S. Department of Energy (DOE) target [30], and a maximum value of 60%, consistent with replacing conventional sources with LED sources in the least efficient existing fixtures.

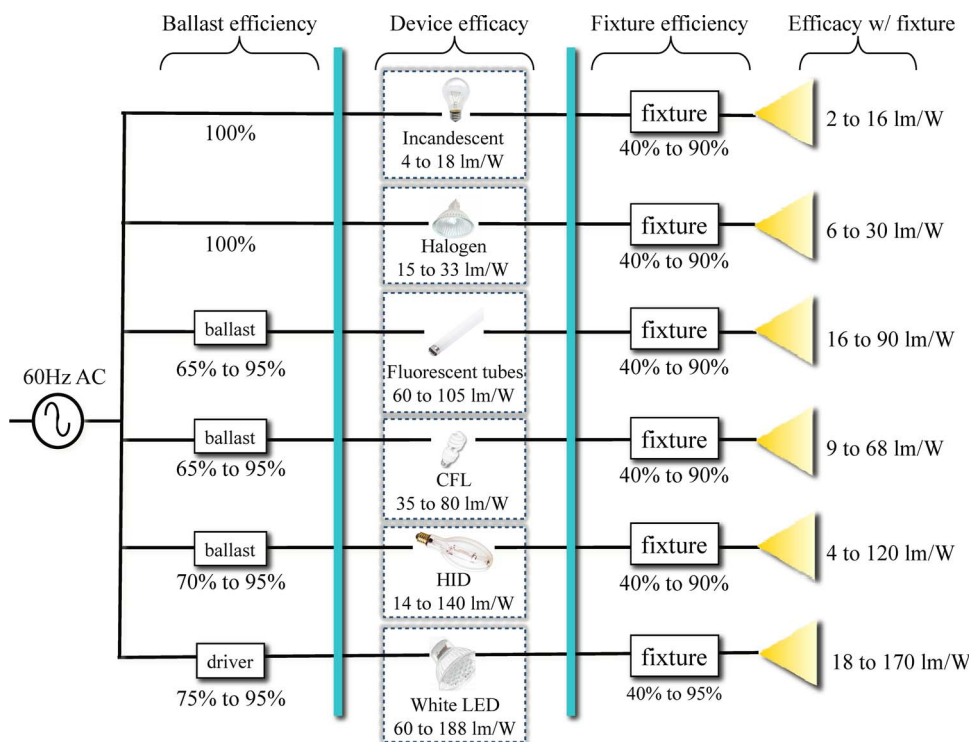


Fig. 2. Efficacy of lighting devices and fixtures. Values in the leftmost column report the range of efficiencies for ballasts and electronic drivers. Values in the central column report efficacies for different lighting devices. The values in the third column report ranges of fixture efficiencies. The values in the rightmost column report the overall system efficacies of lighting systems. The 188 lm/W for the LED device efficacy corresponds to the target for white LEDs for 2015 from [29] and [30].

The light output of most sources decreases over the course of their lifetime. This decrease in lumen output, or lumen depreciation, varies with technology and results from different factors for each. In the case of incandescent lamps, the lumen depreciation ranges from 10% to 15% of the initial output over the course of the ~ 1000 h lifetime. This mainly results from depletion of the tungsten filament over time and the accumulation of evaporated tungsten particles on the interior surface of the bulb. Fluorescent lamps usually experience less than a 20% depreciation over their 10 000 hour lifetime. However, depreciation is generally less than 10% for the case of high-quality fluorescent tubes using rare earth phosphors [31]. The lumen depreciation in fluorescent lamps arises from photochemical degradation of the phosphor coating and the glass tube, as well as the accumulation of light-absorbing deposits within the lamp. In the case of LEDs, lumen depreciation is generally due to a poor removal of the heat generated at the LED junction, leading to an increase in the lamp temperature, which results in a lower light output. Because of their long lifetimes, the lumen depreciation for white LEDs is still being studied. The DOE Solid-State Lighting CALiPER Program is currently testing several products. Interim results report that seven out of the 13 products tested were producing more than 96% of their initial output after more than 5000 h of operation [32]. Of course the overall output from a lighting fixture also depends on how much light is absorbed by the fixture. This fraction can increase over time as glass or plastic covers become dirty and as reflecting surfaces degrade [33]. If fixtures are not regularly cleaned and maintained, this contribution to overall degradation can exceed that of the source.

The efficacy of incandescent lamps has been stable for decades, ranging from 4 to 18 lm/W depending largely on the wattage of the bulb. Considering the 683 lm/W theoretical maximum efficacy, this translates to only about 0.2% to 2.6% of the electric energy consumed's being converted into useful light. These lamps work by heating a metal resistive filament in a glass envelope containing a low-pressure inert gas. The only way to significantly increase efficiency would be to run the filament hotter. Most filaments are made of tungsten, which, at 3695 K, has the highest melting point and lowest evaporation rate of metals. Of course, the filament cannot be run quite that hot. Most bulbs operate at temperatures between 2000 and 3300 K. By replacing the inert gas with a halogen, which limits evaporative loss and redeposits tungsten on the filament, the operating temperature can be increased to about 3450 K. So far, no one has developed a practical way to further increase filament operating temperature and efficiency in incandescent bulbs.

Incandescent bulbs fail either as a result of mechanical vibration, which breaks the filament, or as a result of evaporation of tungsten from the filament. Evaporation can be dramatically increased at hot-spots if the filament is

not uniform. Lifetimes for conventional incandescent bulbs are typically between a few hundred and several thousand hours [3]. Because the halogen gas reduces evaporative losses from the filament, tungsten halogen bulbs can achieve somewhat longer lifetimes. Fluorescent lamps use a stabilized low-pressure gas discharge in a tube of a noble gas and mercury vapor. Electrons ionize mercury atoms, which upon relaxation to their base state emit a photon in the ultraviolet at a wavelength of $253.7 \cdot 10^{-9}$ m. The interior of the discharge tube is coated with a phosphor that, when irradiated with ultraviolet (UV), emits visible light. The current in the discharge must be limited since the resistance of the discharge column drops as the current increases. Typically current is limited through the use of an inductive "ballast" that also often involves an autotransformer to increase the operating voltage. Modern compact fluorescents achieve the same function with solid-state electronics. Early fluorescent lamps used phosphors that emitted a broad spectrum in the blue, producing "cool" light. Today, the use of mixed phosphors has led to the creation of fluorescent lamps that produce a "warmer" light (i.e., more emission in the red). Under optimal conditions, accounting for losses in both the conversion of input electrical energy into UV radiation and the conversion of UV into visible light, fluorescent lamps operate with an efficiency of roughly 13% (if one considers the theoretical maximum of 683 lm/W), approximately five times higher than the conversion efficiency of incandescent lamps (see Fig. 3). The efficacy of a fluorescent bulb depends heavily on the power: it ranges from 35 to 40 lm/W for low power units (from 4 to 5 W) and from 75 to 100 lm/W in bulbs with larger power (from 70 to 125 W) or electronic ballasts (from 10 to 60 W). Lifetimes of fluorescent lamps range from 3000 to 30 000 h [3].

Failure, or dramatically reduced performance, typically results from deterioration of the cathode or its emitting surface. Mercury loss to walls and other internal components, decay in the conversion efficiency of phosphor, and, infrequently, failures in electronic components, can also limit lifetime.

White LEDs have undergone dramatic improvements in efficacy since they were first developed in 1996 (Fig. 1). Today the efficacy of a cool white LED is around 80 lm/W [30]. By 2015, the DOE is projecting cool white LEDs to be at 174 lm/W [30]. These advancements will come from improvements in internal quantum efficiency (the ratio of injected electrons to emitted photons in the active region), extraction efficiency (the efficiency of extracting generated photons from the active regions out of the packaged part), phosphor advancements, and improvements in scattering efficiency (the efficiency of extracting photons from the phosphor versus all the photons coming from the chip). Fig. 4 outlines the way in which DOE anticipates that a number of these improvements will be achieved. In addition to improvements in efficiency, improvements in packaging are increasing the lifetime of LEDs to 30 000–50 000 h.

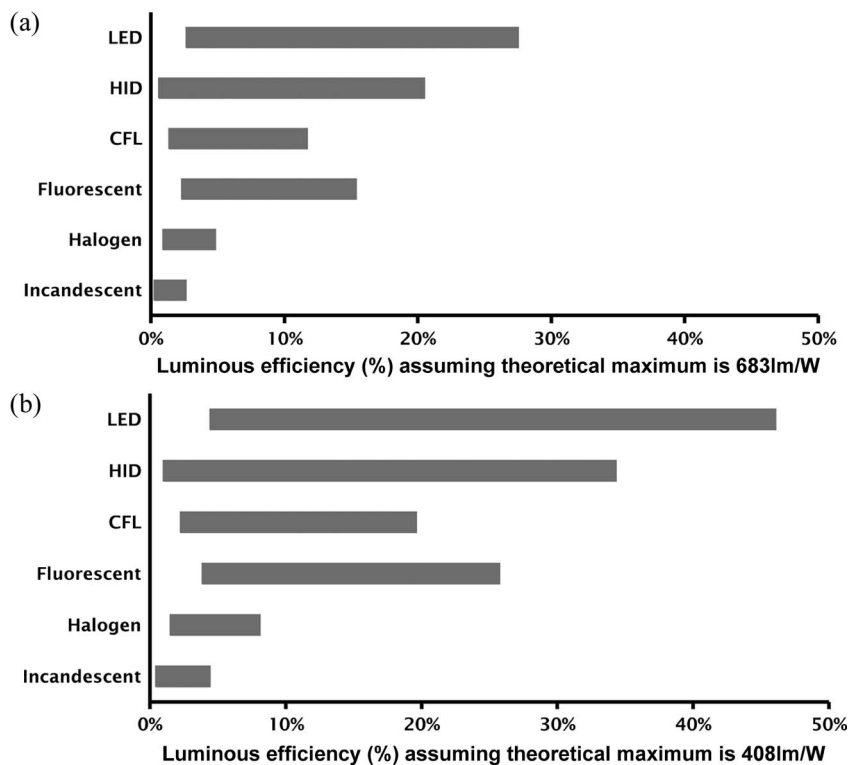


Fig. 3. Overall efficiencies of lighting systems (lower bounds) and devices (upper bounds) when assuming that the theoretical maximum efficacy is (a) 683 or (b) 408 lm/W. HID: high-intensity discharge lamps; CFL: compact fluorescent lamps.

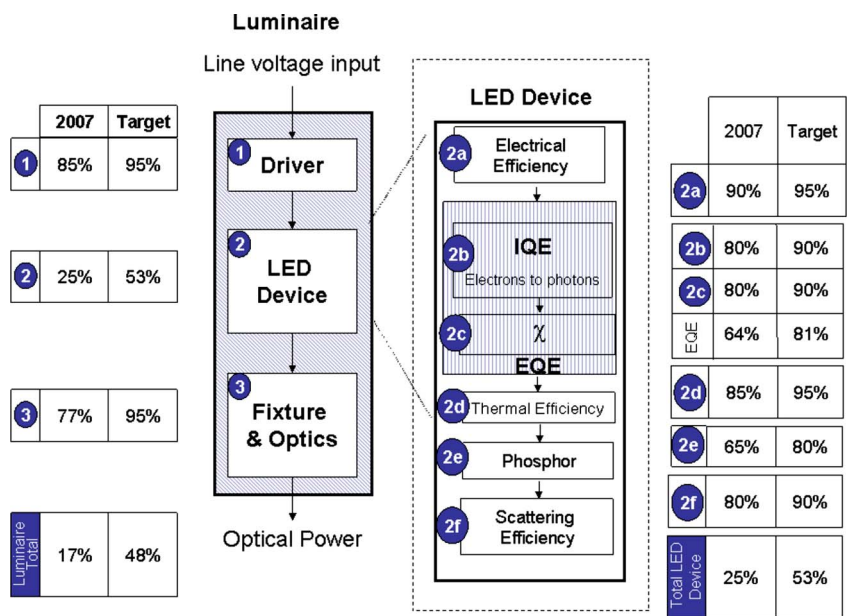


Fig. 4. Phosphor converting LED luminaire efficiencies for 2007 and DOE's 2015 targets for steady-state operation. The targets assume a CCT of 4100 K and CRI of 80. Currently, CCT ranges from 4100 to 6500 K and CRI sands at 75. (Figure from [30].)

B. Color

Efficiency, lifetime, and cost are not the only factors that determine adoption of lighting sources. The perceived color of light and the way in which illuminated colored surfaces appear are also important. Indeed, for years, this was the principle obstacle to the widespread adoption of compact fluorescents.

Solar radiation at the top of the atmosphere has a spectrum that is close to that of a black body with a temperature of 5500 K. Absorption lines in the ultraviolet resulting from ozone and in the infrared resulting from water vapor, carbon dioxide, and other “greenhouse gases” limit much of the radiation that reaches the earth’s surface to the “visible spectrum.” The curves in Fig. 5 compare the spectrum of incident solar radiation and radiation that reaches the surface.

Of course, it is no accident that we call much of this spectral range the “visible spectrum” since the human eye evolved in the context of the earth’s natural illumination.

Photoreceptors in the human eye include three types of cone cells (termed S, M, and L for short, medium, and long wavelength receptors, respectively), which produce peak responses when illuminated respectively by light that is violet ($\lambda \approx 420\text{--}440 \times 10^{-9}$ m), yellow-green ($\lambda \approx 534\text{--}545 \times 10^{-9}$ m), and yellow-amber ($\lambda \approx 564\text{--}580 \times 10^{-9}$ m).

The curve in Fig. 6 displays the sensitivity of the human eye, commonly termed $V(\lambda)$, which corresponds to the response of the cone cell M. Maximum sensitivity occurs at $\lambda = 555 \times 10^{-9}$ m in the yellow-green. Note that just as the intensity of surface sunlight falls off dramatically in the violet, so too the sensitivity of the eye falls off rapidly in the violet.

LEDs that directly produce colored light have narrow spectral outputs ($\approx 20 \times 10^{-9}$ m). By mixing the light from monochromatic blue, green, and red LEDs, and adjusting the

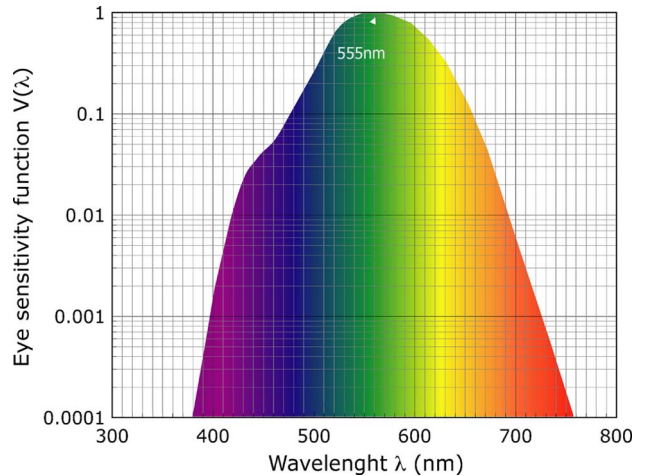


Fig. 6. Photopic sensitivity of the human eye ($V(\lambda)$) as a function of wavelength (λ) across the visible spectrum. (Adapted from [36].)

intensities appropriately, the eye will see what appears to be white light (Fig. 7). However, because these sources produce almost no illumination over intervening portions of the visible spectrum, they will not yield properly perceived color if the resulting “white” light is reflected from a surface whose color lies in one of the gaps in the combined spectrum.

A variety of strategies have been devised to describe how well a particular light source renders colors. None does a perfect job of addressing all issues. Perhaps the most common is the color chromaticity space developed by the Commission Internationale de L’Éclairage (CIE) [36]. This two-dimensional space (Fig. 8) is based on a set of three nondimensional “color matching functions” that collectively sum to unity. One, termed “y,” corresponds to $V(\lambda)$ and the other two correspond more loosely to the response of the S and L cones.

Points around the outside of the CIE space correspond to pure monochromatic colors. White light falls in the center of the space. It is also common to plot the locus of the maximum intensity of radiation from a black body radiator (Wein’s law) as a curve through this space. Similar trajectories can be plotted in other spaces commonly used to describe color perception.

Incandescent bulbs produce emission spectra that are quite close to that of a black body radiator. Thus, it is common to refer to the emissions from such bulbs in terms of a “color temperature.” Sources of white light whose spectra are not close to that of a black body are sometimes characterized by a “correlated color temperature,” according to where they fall on the lines crossing the Wein’s law black body emission curve in Fig. 8.

The color rendering properties of the light sources of interest in this paper (i.e., sources with color temperatures ≤ 5000 K) are measured by illuminating a number of standard color chips with a reference black body source that has the same color temperature as the light source of interest. This is

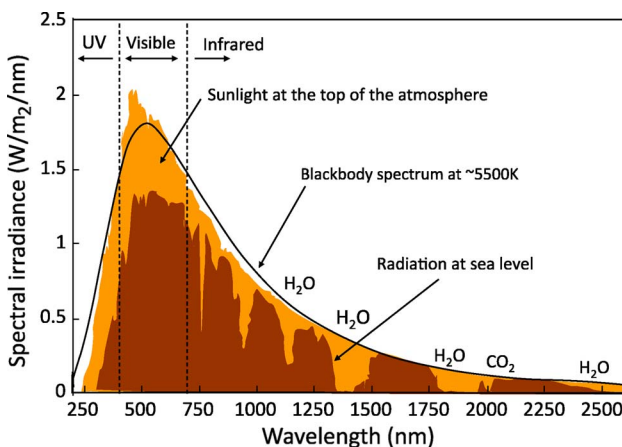


Fig. 5. Solar radiation at the top of the atmosphere (orange), and at the surface (red) as compared with a black body at 5500 K. Absorption in the UV is by O_3 and in the infrared primarily by H_2O and CO_2 . (Adapted from http://upload.wikimedia.org/wikipedia/commons/4/4c/Solar_Spectrum.png.)

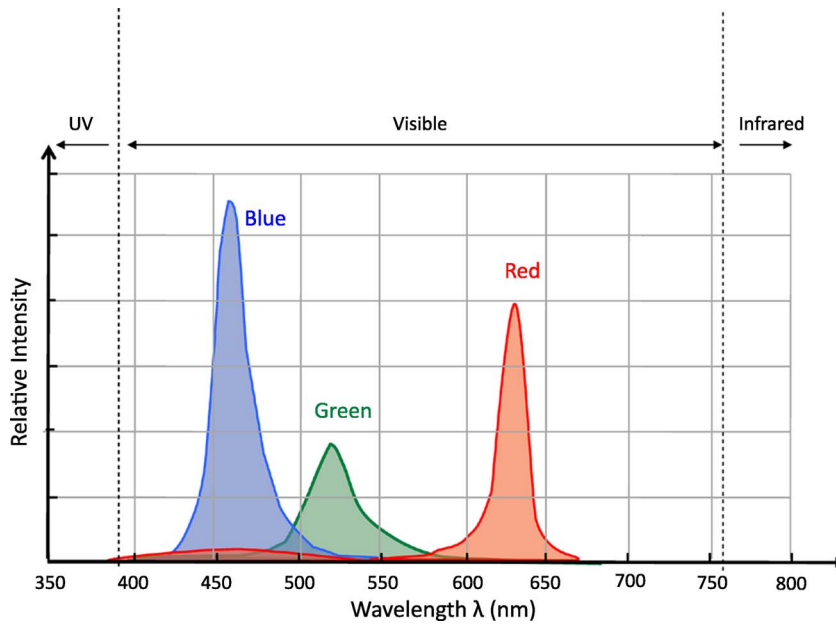


Fig. 7. Typical spectrum of “white” light created by mixing the output of red, green, and blue monochromatic LEDs. (Adapted from [37].) Relative intensity is represented in arbitrary units.

then compared with the result obtained by illuminating an identical color chip with the light source of interest. The Euclidian distance between the chromaticity coordinates of

the source being tested and the reference in the CIE color chromaticity space is then calculated for a set of standard reference chips. While there are a total of 14 standard chips, historically only eight (or sometimes nine) of the more pastel colors (i.e., colors that lie toward the interior of the CIE color chromaticity space) have been used. A general color rendering index (CRI) is often computed as

$$CRI = 100 - 4.6\overline{\Delta CD}$$

where $\overline{\Delta CD}$ is the average of the distance between the location of the observations in the CIE space (or in various other transformations of that space). The result is normalized so that a source that has a black body spectrum that is the same as that of the reference has a CRI of 100. Other sources then have CRIs that are less than 100. Because the way these other sources render colors may be different for sources with different spectral compositions, two sources with the same CRI may render some colors in notably different ways. This may also mean that in some applications, consumers may prefer light from a source with a lower CRI to that from a source with a higher CRI. Using CRI as a measure of light quality means that any deviations of object color appearance from how it appears under a light source with a blackbody spectrum (or any other source used as reference) is considered bad. In practical applications, however, increases in chromatic saturation may yield better visual clarity and enhance perceived brightness [39].

Recently, there has been a move to include the full set of 14 standard chips and include more saturated

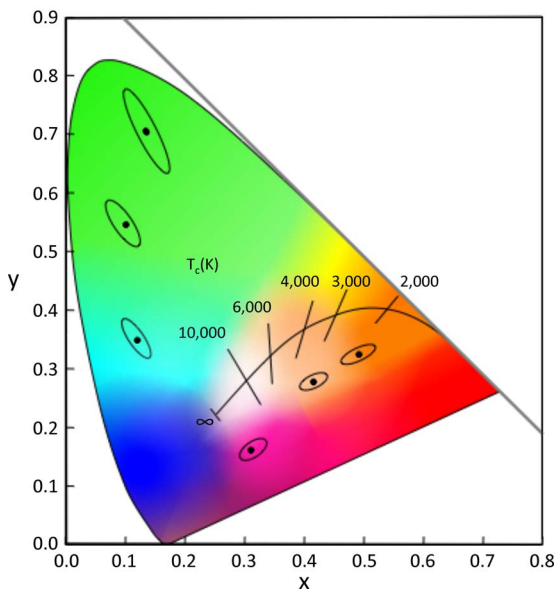


Fig. 8. CIE color chromaticity space. Definitions of the x-y axis are provided in the text. Saturated colors are arrayed along the outside of the arc. Black body emission (Wein's law) falls along the curved line. The lines crossing the Wein's law curved line correspond to different “color correlated temperatures.” Ovals are examples of McAdam's ellipses, enlarged by a factor of ten. Within these ovals the eye does not distinguish color variations. (Adapted from [38].)

colors (i.e., that lie toward the exterior of the CIE color chromaticity space) so as to better include the narrow-band properties of some LED sources. Furthermore, the National Institute of Standards and Technology is currently working closely with the lighting industry and CIE to develop a new light quality indicator, the color quality scale. This scale will include several aspects of color quality, namely, color rendering, chromatic discrimination, and observer preferences [39].

To make white light with reasonable color rendering properties using LEDs, one of the current strategies is to add one or more phosphors that absorb photons from a narrow-band LED and then reradiate photons of lower energy across the visible spectrum. Figs. 9 and 10 illustrate two device geometries. The latter displays a design from Philips Lumileds that uses a conformal coating process that eliminates the blue-ring effect (blue light from the LED driver that makes it through, largely around the outside).

The simplest strategy to produce the appearance of white light is to use a blue or violet LED and design the phosphor layer so that some of the light energy from the LED passes through the phosphor. By adjusting the relative amount of direct radiation from the LED that passes through the phosphor, it is possible to shift the output through the white region of the CIE color chromaticity space. By adding additional types of phosphors, somewhat flatter spectra can be produced across the visible range, with improved color-rendering characteristics.

A region within the CIE color chromaticity space across which the eye is not able to distinguish a difference in color is termed a MacAdam ellipse (see Fig. 8, where the examples of ellipses shown have been enlarged by a factor of ten). The size of this region is relatively large in the green upper portion of the space but becomes quite small

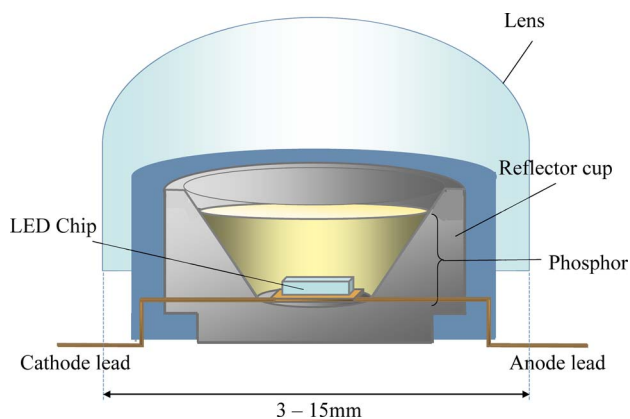


Fig. 9. UV-phosphor-based white light-emitting diode. A phosphor or a mixture of phosphors fills the reflector cut. To produce the appearance of white light, phosphors absorb the UV-purple light and reradiate photons of lower energy across the visible spectrum.

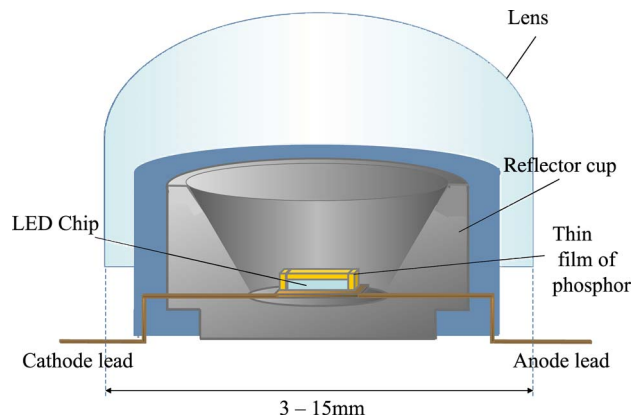


Fig. 10. UV-phosphor-based white light-emitting diode. To eliminate a blue-ring effect, a conformal coating process is used (thin film of phosphor). To produce the appearance of white light, phosphors absorb the UV-purple light and reradiate photons of lower energy across the visible spectrum.

in the lower portions of the space, including in the white light regions, where the long axis lies roughly tangent to the curve of black body spectra. This means that human observers can readily detect even small vertical variations in the light, either upwards toward the green or downwards toward the red in this space.

This high human sensitivity complicates the problem faced by LED manufactures. Today, blue LEDs are made of indium gallium nitride (InGaN) containing quantum wells that facilitate the recombination of electrons and holes, resulting in the release of photons of blue or green light.² The color of the photons emitted depends upon the amount of indium (or other materials) that has been added. Current fabrication methods do not allow perfect control of the composition or distribution of these materials across the 2–4 in wafer on which large numbers of LEDs are simultaneously grown. Hence, once they have been completed and cut (diced) into separate devices, each LED must be individually tested, their emission measured, and sorted into bins. This, of course, adds considerably to the cost of the device.

To make a white LED, one or a mixture of several types of phosphor are deposited onto the LED during the packaging process. The composition of these phosphors, and their deposition, is also not perfectly uniform. Hence, after the devices are packaged, a second round of binning is done to sort by spectral output.³

Fig. 11 compares typical spectra from a white LED with an incandescent lamp and a fluorescent lamp. In an

²These materials develop a significant number of dislocations, and there is ongoing uncertainty about why GaN-based LEDs are able to emit brilliant light with dislocation densities as high as 10^9 cm^{-2} . For details, see [27].

³For examples of binning of white LEDs, see [40, p. 5] and [41, p. 22].

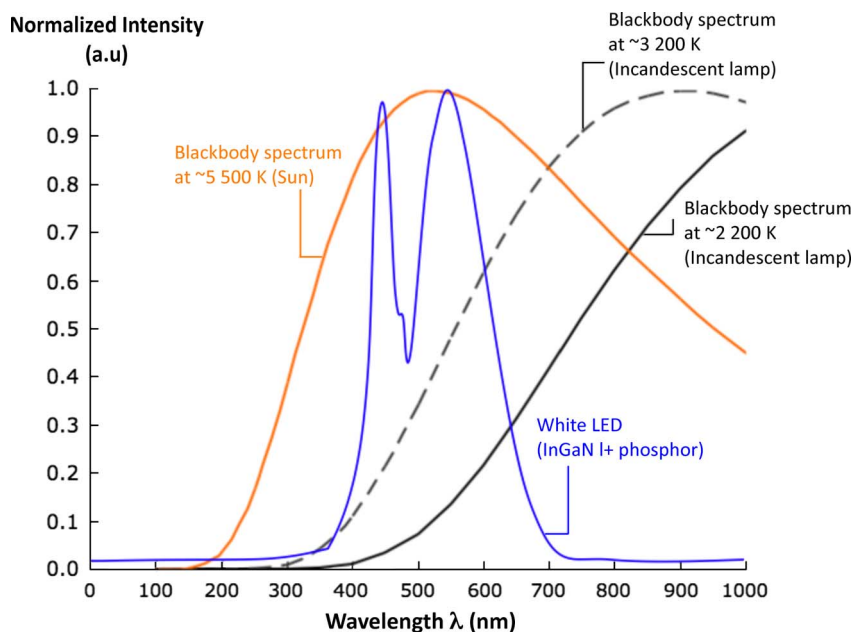


Fig. 11. Normalized intensity in arbitrary units (au) for a blackbody radiator at 5500 K (Sun), for a blackbody radiator at 3200 K (warm white incandescent lamp), for a blackbody radiator at 2200 K (cooler white incandescent lamps), and for a white LED, where the perception of white light is achieved using a blue LED + phosphor.

incandescent lamp, the heated filament radiates with approximately the Planck blackbody spectral distribution (slightly blue-shifted). Because of the limit on the temperature at which the filament can be operated, the peak output is in the infrared, at a wavelength of about 10^{-6} m, and the spectrum across the visible range is steeply sloped toward the red. In contrast, early fluorescent lamps with just one phosphor tended to produce color that was bluer. Warmer fluorescent lamps use phosphors that yield an emission spectrum that produces relatively more light in the red, resulting in a “warmer” light.

Many people prefer warmer light (i.e., light with more red), especially for illuminating pale skin [42]. Thus, morning and evening outdoor light, which is more red due to the filtering effect of the longer path through the atmosphere and the associated scattering by fine aerosols, is typically preferred by many to the flatter spectrum of midday sun. In the United States and Europe, where many people have pale skin, the temperature of white light from TV monitors is set at 6500 K. In contrast, in Japan, the temperature is moved to 9300 K. This may also be one reason why illumination by incandescent light, which is peaked toward the red, remains more popular in North America than in Japan.

C. Comparison of the Key Characteristics of Lighting Technologies

Table 1 provides comparison of the principle characteristics of commercially available lamps, including the technologies discussed above.

D. RF Noise and Flicker

The switched-mode power supplies used for LED lights, the electronics used in compact fluorescents, and the dimmer switches used with incandescent bulbs all emit high-frequency electromagnetic radiation and impose high-frequency waveforms on power lines. While these radio-frequency emissions are typically not a problem, in some situations they can be problematic, and the growing use of such electronics means that the issue warrants continued attention.

The Federal Communications Commission (FCC) and other national regulatory bodies are concerned about interference due to radiated emissions in the communication bands between approximately 3 MHz and 1 GHz for radiated emissions and conducted emissions for those between approximately 150 kHz to 30 MHz. Manufacturers are required to test the emissions from their lamp systems to ensure that they do not produce radiated or conducted emissions as defined by internationally harmonized standard EN55022 [45].

Because the filament in an incandescent bulb has considerable thermal inertia, dimmers that use a chopped waveform typically do not produce noticeable flicker. Flicker is sometimes visible (especially to younger eyes) from fluorescent bulbs and can be a greater problem with 50 Hz power (100 Hz flicker) than with 60 Hz power (120 Hz flicker). Flicker can also be observed from some LED systems but can be reduced with careful power supply design.

Flicker index is a ratio that has been established to measure the variations in output of a source. It is defined

Table 1 Main Characteristics of Lamps

Lamp	Type	Power (W)	Efficacy (lumen/W)	Lifetime (thousand h)	CCT (K)	CRI
INC	-	3 - 150	4 - 18	1	2 400 - 3 100	98 - 100
Halogen	-		15 - 33	2 - 6	3 000 - 3 100	98 - 100
HID	-	40 - 400	14 - 140	6 - 28	2 900 - 5 700	15 - 62
LID	LPNa	26 - 180	70 - 200	7.5 - 30	1 700 - 7 500	75 - 95
	T12	14 - 90	60 - 105	7 - 20	3 000 - 6 500	62 - 75
	T8				3 000 - 6 500	75 - 98
	T5				3 000 - 6 500	75
CFL	ballasts integrated	4 - 120	35 - 80	5 - 15	3 000 - 6 500	75 - 90
CFL	external ballasts	40 - 95	60 - 80	10 - 20	2 700 - 6 500	80 - 85
White SSL	LED	1 - 20	160 (lab), 20 - 55	20 - 40	5 000 - 6 000	70 - 80
	OLED	1 - 20	<18	<4	3 000 - 6 000	~80

INC: incandescent; HID: high-intensity discharge; LID: low-intensity discharge; LP Na: low-pressure sodium; CFL: compact fluorescent lamps; SSL: solid-state lighting; LED: light-emitting diode; OLED: organic LED; CRI: color rendering index; CCT: correlated color temperature. (From [3], [29], [30], [43], and [44].)

as the ratio of the area of the waveform of light output that lies above the average light level divided by the total area of the waveform of light output over one cycle and is expressed as a number between zero and one. The Illumination Engineering Society of North America recommends the flicker index be held below 0.1 to minimize any perceptible flicker from light [46]. With the proper regulations and control of the output stage of a switch mode supply, solid-state lighting systems can easily be developed to achieve these levels.

IV. EXPECTED EVOLUTION OF WHITE LEDS

Because light-emitting diode technology is rapidly evolving, projections of solid-state lighting efficacy, cost, and lifetime are frequently updated. Haitz *et al.* [47] note that since the invention of red LEDs in the late 1960s, light output has increased by roughly a factor of 20 every decade, while the cost per lumen has fallen by about a factor of ten. The same trends seem to be followed by white LEDs. Several projections are available of how white LEDs are likely to perform in the near future (see Figs. 12 and 13) [29], [30], [43], [44]. Today, in the laboratory, solid-state lighting has reached efficacies of 160 lm/W,⁴ whereas commercialized solid-state lighting has efficacies of 20–56 lm/W, last between 30 000 and 50 000 h, and cost 47 \$/klm [29], [30].

Expanding on Fig. 1, Fig. 12 summarizes the efficacy values achieved by white LEDs as well as projections of the likely future efficacies.

According to DOE 2006 targets [29], the lifetime of commercial cold white lamps is expected to increase

linearly from 30 000 to 50 000 h between 2005 and 2008, and remain at 50 000 h thereafter. There are also ranges of cost projections, as shown in Fig. 13. The prices and efficacies in DOE 2006 targets [29] assume that white LED devices are operating at a correlated color temperature (CCT) of approximately 5000 to 6000 K and a CRI of 70 or higher.

V. CHOICE OF LIGHTING TECHNOLOGIES

There are several metrics that can be used to estimate the cost of light supplied by different lighting systems. DOE [29], [30] and participants in the solid-state lighting program generally refer to the upfront cost (\$/klm) and to the “cost of light” metric. The cost of light is defined as

$$\text{Cost of light} = \left(\frac{10}{\text{lamp lumens}} \right) \times \left(\frac{\text{lamp cost} + \text{labor cost}}{\text{lifetime}} + \text{energy use} \times \text{energy cost} \right)$$

where *lamp lumens* is the light output of the lamp in lumens, *lamp cost* is the initial cost of the lamp in \$/lamp, *labor cost* is the labor cost necessary to replace the lamp in \$/lamp, *lifetime* is the theoretical lifetime of the lamp in thousands of hours, *energy use* is the power consumption of the lamp in W/lamp, and *energy cost* is the cost of electricity in \$/kWh.

By this metric, today’s solid-state lighting is already cheaper (20 \$/Mlmh) than incandescent (27 \$/Mlmh) or halogen lamps (23 \$/Mlmh) [29], [48]. However, this metric is inadequate because it does not consider the hours of operation of the technology or the time value of money.

⁴Cree, http://www.cree.com/press/press_detail.asp?i=1160427137863.

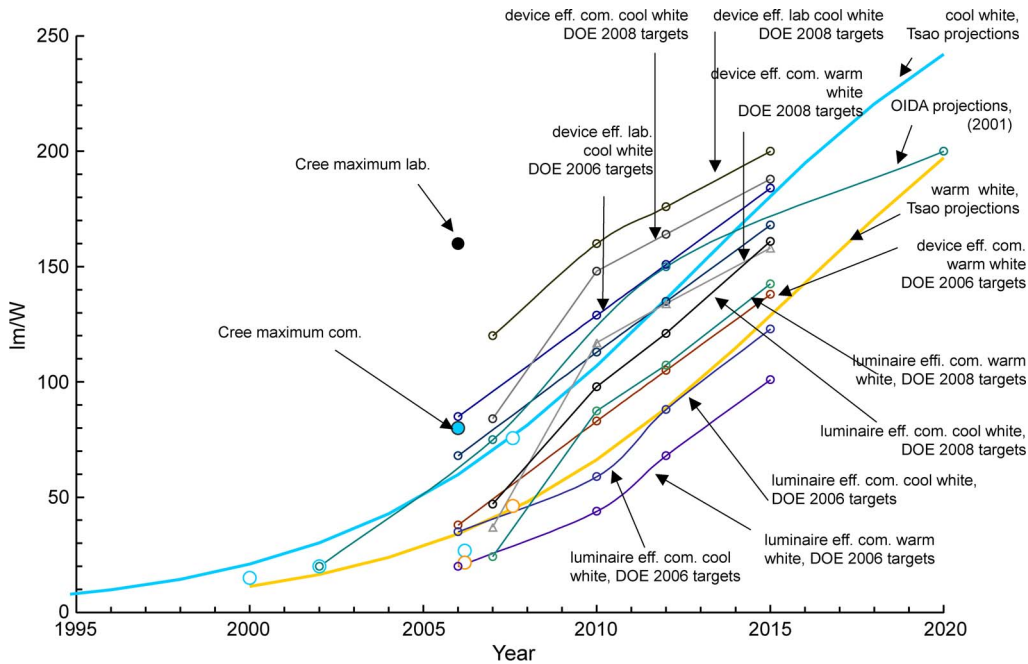


Fig. 12. Laboratory and commercial efficacy projections for cold and warm white LEDs made for OIDA [44], DOE [29], [30], and Tsao [43].

Mishan [49] and Rubin and Davidson [50] provide descriptions of different decision rules and the appropriate discount rates to use under different circumstances. In a standard approach, the discount rate will depend on the alternative opportunities open to the decision maker. While the explanation provided by Mishan [49] and others is appropriate for investment choices by economically rational actors, it does not explain why decision makers at the commercial and residential level are often slow to voluntarily adopt energy efficient products such as CFLs.

To incorporate the time value of money, a discounted utility model can be used. However, the most widely used model, developed by Samuelson, lacks descriptive realism—which Samuelson himself acknowledged [51]. Other authors [52] argue that there is little empirical behavioral support for using the discounted utility model, although it continues to be widely used by economists. Similarly, Sanstad and Howarth [53], [54] argue that the mathematical formalism of economic rationality provides the basis for economic models of consumer behavior but is generally not subjected to empirical testing. The main argument for discounted utility theory comes from Friedman [55], who states that people may not actually solve complicated problems of utility maximization; they just behave *as if they do*. Thus, it is argued that the models provide a good description of observed behavior. Goett [56] uses this argument to explain the use of the leveled annual cost calculations in modeling consumer decisions regarding energy efficiency by stating that implicit discount rates “do not simply reflect a conscious, mental calculation of the cost tradeoffs among alternative technologies. Rather, they summarize an amalgam of market forces that determine consumers’ actual choices.”

In the analysis that follows, we separately assess private and societal costs. Additional considerations must be added when selecting lighting from a societal perspective, where important factors include reducing emissions of conventional pollution and CO₂, reducing need for new construction and reducing dependence on imported fuels. From behavioral studies on consumer choice, it is possible to infer the effective discount rates employed.

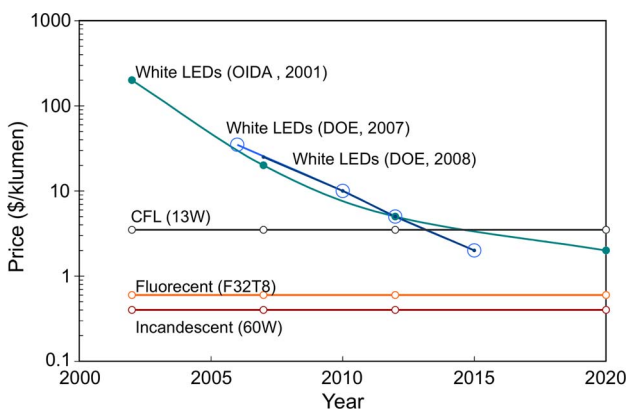


Fig. 13. White light LED OEM price targets for commercial applications. DOE efficacy and cost projections assume a CRI between 70 and 80, a CCT between 5000 and 6000 K, and a 350 ma drive current. Results are for devices alone (driver and luminaire costs are not included). (Data adapted from [29], [30], and [44].)

Table 2 Average Implicit Discount Rates Adopted by Consumers for Energy-Efficiency Investments (Adapted From [52] and [53])

End-use	Implicit discount rate
Air conditioners	17 % - 20 % [59]
Heaters	102 % [60]; 25 % [61]
Freezers	138 % [60]
Refrigerators	from 45 % to 300 % [62]; from 61% to 108 % [63]; from 34 % to 58 % [64]
Thermal shell measure	32 % [65]; 26 % [63]

These implicit rates are typically *much* higher than market rates: as high as 300% for residential consumers and up to 30% for commercial consumers (Table 2). In contrast, decisions made by government in the public interest typically employ a discount rate that ranges between 2.5% and 10% [57].

There is mixed evidence on the influence of income on discount rates. Hausman [58] found implicit discount rates that varied markedly with income. However, in another study, Houston [65] presented individuals with a decision of whether to purchase a hypothetical *energy-saving* device, and *no statistically significant role of income* was observed [52].

Implicit discount rates embody a variety of factors, including:

- lack of knowledge by consumers about available technologies and the cost savings that could be achieved [52];
- disbelief among consumers that the cost savings will be as great as promised [52];
- lack of expertise in translating available information into economically efficient decisions [52];
- hidden costs of the more efficient appliances, such as reduced convenience or reliability [52];
- the role of the availability heuristic [66] when an earlier attempt by the consumer or others to use the technology did not fulfill expectations;
- the role of marketing and advertisement in promoting different technologies;
- dominance of retail sales staff and issues of product selection and promotion [67];
- the tendency of many architects, designers and builders to only use products and processes with which they are already familiar;
- lack of information concerning electricity prices and hours of use of the technology.

As Socolow [68] complained, “we still know pitifully little about the determinants of durability of hardware and even less about the determinants of durability of attitudes and behavior” [16].

A recent NRC study [69] concluded that requirements for solid-state lighting to overcome market barriers include the following.

- An upfront cost of < 33 \$/klm—which according to DOE [29] should be reached in 2008; lifetimes of 50 000 hours—which, again, according to DOE [29], should be reached by 2008; a 70% lumen output by the end of life and a CRI between 80 and 100.
- “Building and lighting infrastructures available for installation, known standardized equipment specifications, information available to the lighting industry and information to support interior design needs” [69].

In addition to their different time preferences, residential consumers typically use much of their illumination only a few hours a day, while commercial consumers average 10 h/day. Since the different illumination technologies considered have substantially different lifetimes, we compare them using levelized annual cost rather than net present value. We define *levelized annual cost* [33], or LAC as

$$\text{LAC} = I \frac{d}{(1 - (1 + d)^{-n})} + O\&M$$

where I is the initial capital investment in the lighting system in dollars, d is the discount rate, n is the number of years that the technology lasts, and $O\&M$ is the expected annualized cost of operation and maintenance in dollars.

VI. THE COST OF LIGHT

Given the expected performance of different lighting technologies over the period from 2008 to 2015, the choice of lighting technologies by rational economic actors will depend on conversion efficacy, upfront cost, lamp lifetime, and lamp usage. We assume DOE [29], [30] values for future white LED system efficacy, original equipment manufacturer (OEM) upfront costs, and lifetimes. Assumptions about alternative lighting technologies are shown in Table 3. We also assume that all technologies will be chosen so as to provide the same illumination level no matter the choice of the technology. Incandescent and fluorescent technologies are taken as mature and are not changed over the course of the analysis.

Lifetime depends on the amount of usage. For example, we assume that an incandescent lamp with a theoretical lifetime of 1000 h that is used 2 h/day will last roughly one year and four months. In this calculation, we also assume that the consumer replaces all old lamps with new lamps of the same kind.

Table 3 Assumptions of Key Characteristics of Mature Lighting Technologies Used in the Analysis in Section VI

		Efficacy (lm/W)	Lifetime (h)	Lumen Output (lm)	Power (W/lamp)	Service Cost (\$/thousand lm)	Lamp Cost (\$/lamp)
Incandescent		14	1 000	926	65	0.5	0.5
Compact fluorescent lamp (CFL)		69	8 000	926	13	4.3	4
Fluorescent tube (T12)		69	5 000	926	13	2	2
Fluorescent tube (T8)		92	12 000	926	10	2	2
Fluorescent tube (T5)		104	20 000	926	9	2	2
Solid-State Lighting (System Level, Warm White)	Targets from DOE for 2008	47 (cool) 27 (warm)	50 000	926	13	25	23
	Targets from DOE for 2015	137 (cool) 117 (warm)	50 000	926	7	3	3

Sources for lamp typical characteristics from [29], [30], [43], [44], and [48]. For solid-state lighting, we used OEM prices for the lamp retail costs. “Cool” and “warm” mean “cool white” and “warm white” as defined by DOE [29], [30].

In doing engineering-economic analysis from the perspective of a consumer driver, costs should be included and OEM prices should be marked up to reflect retail prices. However, the DOE OEM cost trends already appear to match full system retail LED prices (including driver and luminaire). Thus, we use the DOE projections as an estimate of future retail LED system prices. In the sensitivity analysis that follows, we explore how additional markup prices as high as 30% on top of DOE’s projected OEM prices would delay consumers’ decisions to adopt white LEDs.

A. Rational Economic Actor

We start by looking at the engineering-economic analysis for lighting technology choice for a commercial building owner. For this case, we assume a daily operation of 10 h/day and a 5% market discount rate (Fig. 14).

The results show that the levelized annual cost of a cool white solid-state lighting investment today is less than half that of an incandescent and is about to reach that of CFLs and fluorescent tubes. The levelized annual cost for warm white light solid-state lighting is also substantially lower than incandescent lamps. Both cool and warm solid-state lighting is likely to reach the cost of the most competitive fluorescent technologies before 2015.

Note that even assuming discount rates as high as 20%, solid-state lighting has a lower levelized annual cost than incandescent lamps, and is the same as the levelized annual cost of fluorescent lamps by 2009. However, if the commercial consumer only considers upfront costs (in either \$/klm or \$/lamp—assuming the lamps will provide the same total lumens), a switch to solid-state lighting will not be made in the near future, since the cost of solid-state lighting luminaries is only projected to reach that of fluorescent lamps by 2013 (Fig. 15).

We conclude from this analysis that rational economic actors in the commercial sector now using incandescent bulbs would find it cost-effective to switch to solid-state lighting today. Given that most of the illumination in the commercial sector is provided by fluorescent technology, commercial building owners should begin to think about switching to solid-state lighting in just the next few years.

B. Effect of High Implicit Discount Rates

In performing a similar analysis for an average household, we assume a discount rate of 20% in recognition of the body of literature on implicit discount rates discussed in Section V (see Fig. 16). We conclude that considering high implicit discount rates, and a daily

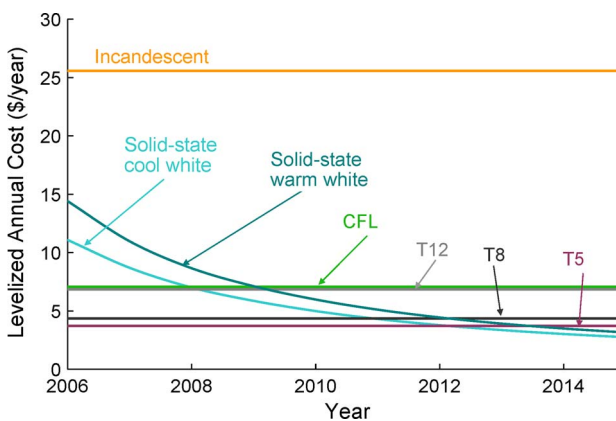


Fig. 14. Levelized annual cost for different lighting technologies (incandescent, CFLs, T12, T8, T5, and cool and warm white solid-state lighting). We assume an electricity retail price of 0.10 \$/kWh, lamps used 10 h/day, and a discount rate of 5%.

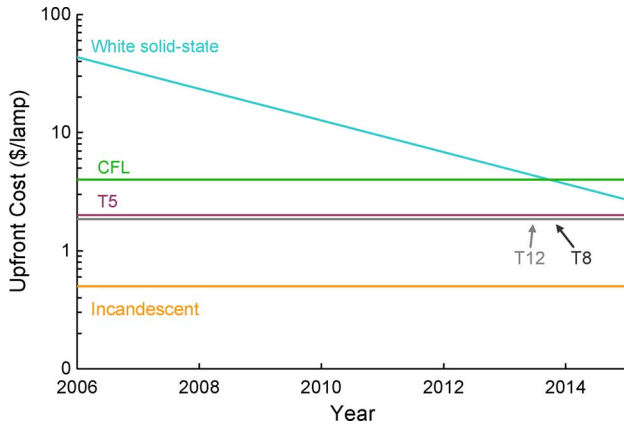


Fig. 15. Upfront cost for different lighting technologies (incandescent, CFLs, T12, T8, T5, and cool and warm white solid-state lighting).

usage of 2 h, solid-state lighting will have a lower levelized annual costs than incandescent lamps this year and lower than CFLs by 2012 if they can be purchased at DOE’s projected prices (stated as OEM, but today closer to retail). Retail markups above these prices will delay these times by a few years, as indicated in the sensitivity analysis that follows. We conclude that, in less than a decade, residential consumers should begin to think about switching to solid-state lighting.

C. Sensitivity Analysis

There is large uncertainty about the likely future mix of luminaires, their wattage, hours of operation, future electricity prices, consumer adoption behavior, and how solid-state lighting cost and performance will evolve over time. Fig. 17 reports the sensitivity of the levelized annual cost of white LEDs in 2010 to variations in luminous

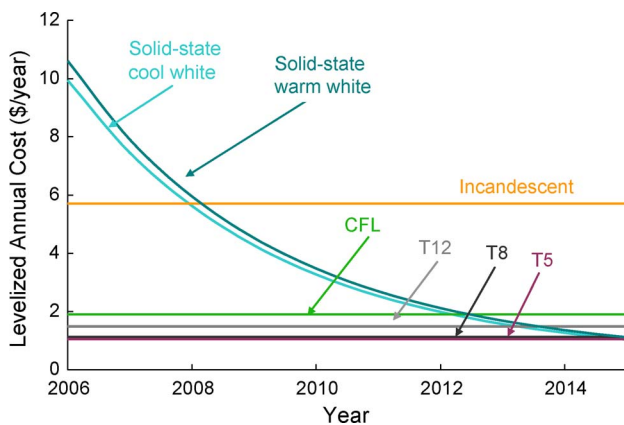


Fig. 16. Levelized annual cost for different lighting technologies (incandescent, CFLs, T12, T8, T5, and cool and warm white solid-state lighting). We assume an electricity retail price of 0.10 \$/kWh, a discount rate of 20%, and a daily usage of 2 h/day.

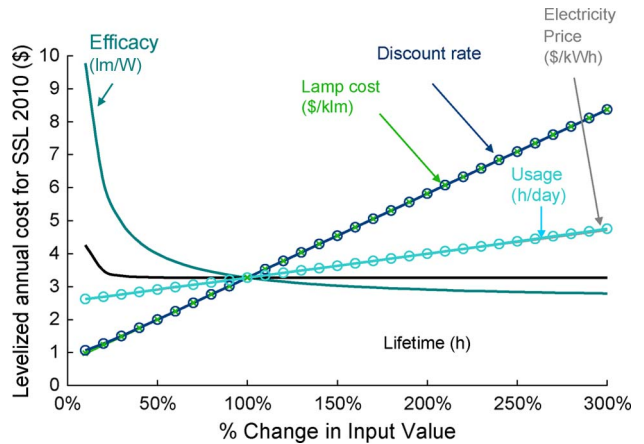


Fig. 17. Sensitivity analysis for the main parameters of the engineering-economic simulation of the levelized annual cost of cool white solid-state lighting in 2010. The 100% values correspond to an electricity price of 0.10 \$/kWh, operation of 2 h/day, a 20% discount rate, a luminous efficacy of 92 lm/W and, and a theoretical solid-state lighting lifetime of 50 000 hours.

efficacy, lifetime, cost, electricity price, discount rate, and number of hours of operation. Across the same range of values, Fig. 18 reports the difference between the levelized annual cost of white LEDs and incandescent lamps. A negative levelized annual cost corresponds to a lower cost for, and less energy use by, the consumer, since the levelized annual cost of switching to the new technology is lower than an investment in the current technology.

These results indicate that, across this wide range of assumptions, by 2010 solid-state light is a better investment

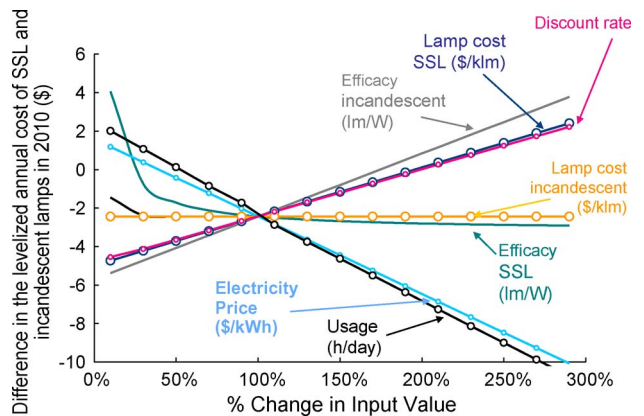


Fig. 18. Sensitivity analysis for the main parameters of the engineering-economic simulation of the difference between the levelized annual cost of cool white solid-state light and incandescent light in 2010. The 100% values correspond to an electricity price of 0.10 \$/kWh, operation of 2 h/day, a 20% discount rate, a luminous efficacy of 92 lm/W, and a theoretical solid-state lighting lifetime of 50 000 hours.

than incandescent lamps even assuming a high discount rate (20%) and using a lamp only 3 h/day. The levelized annual cost of solid-state lighting is very sensitive to the luminous efficacy achieved by solid-state lighting for values lower than ~ 46 lm/W but changes less than a dollar after reaching that efficacy, a level already exceeded in 2006. Above a lifetime of 12 000 hours, the levelized annual cost becomes quite insensitive to the theoretical lifetime of solid-state lighting. Again, this threshold was reached in 2002. The feature that remains most critical to achieving a competitive level for solid-state lighting is the initial cost. Even assuming a markup as high as 50% on top of the projected price, by 2010 solid-state lighting is a better option than incandescent lamps (see Fig. 18).

Some might argue that only solid-state lighting should be subjected to high implicit discount rates, since other technologies are well established in the market. In a simulation with this assumption, we found that if solid-state lighting is subjected to discount rates as high as 30% with choices about the remaining technologies based on discount rates as low as 3%, the choices about solid-state lighting occur with a lag of at most two years compared to the previous scenario. This result is largely due to the high upfront cost and the rapid rate at which the technology is evolving. For example, if a lamp is only used 2 h/day, with a discount rate of 30% on just the new technology, the LAC of solid-state lighting is lower than that of incandescent by 2009 and reaches CFL and fluorescent levels by 2015.

Despite DOE targets [29], [30], there is considerable uncertainty about how commercial solid-state lighting technology will perform over time. For this reason, we have performed a parametric analysis of the levelized annual costs for solid-state lighting technologies for different values of inputs using a matrix model, as illustrated in Fig. 19.

The advantage of the full parametric model is that it can account for new and unexpected pathways in the evolution of the technology and its economic performance. Given a set of initial inputs, the model provides a contour plot of the levelized annual cost (Fig. 20), providing a very effective way to determine the implications of changes in the solid-state lighting technology performance in key characteristics.

In Fig. 20 we present the levelized annual cost for solid-state lighting under different assumptions for efficacy (lm/W), theoretical lifetime (h), discount rate (%), and usage (h/day). Upper plots correspond to levelized annual cost surfaces and lower plots are the respective contour plots.

In (a), we present the levelized annual cost for a 926 lm solid-state lighting bulb (typical light output of a 60 W incandescent bulb) as a function of efficacy (lm/W) and theoretical lifetime (h). For that case, we assumed that the upfront cost of solid-state lighting remains at 14 \$/klm. In (b), we present the levelized annual cost for one solid-state lighting bulb with an illumination service of 926 lm as a function of efficacy (lm/W) and upfront cost (\$/klm) for a theoretical lifetime of 30 000 h. The joint results of

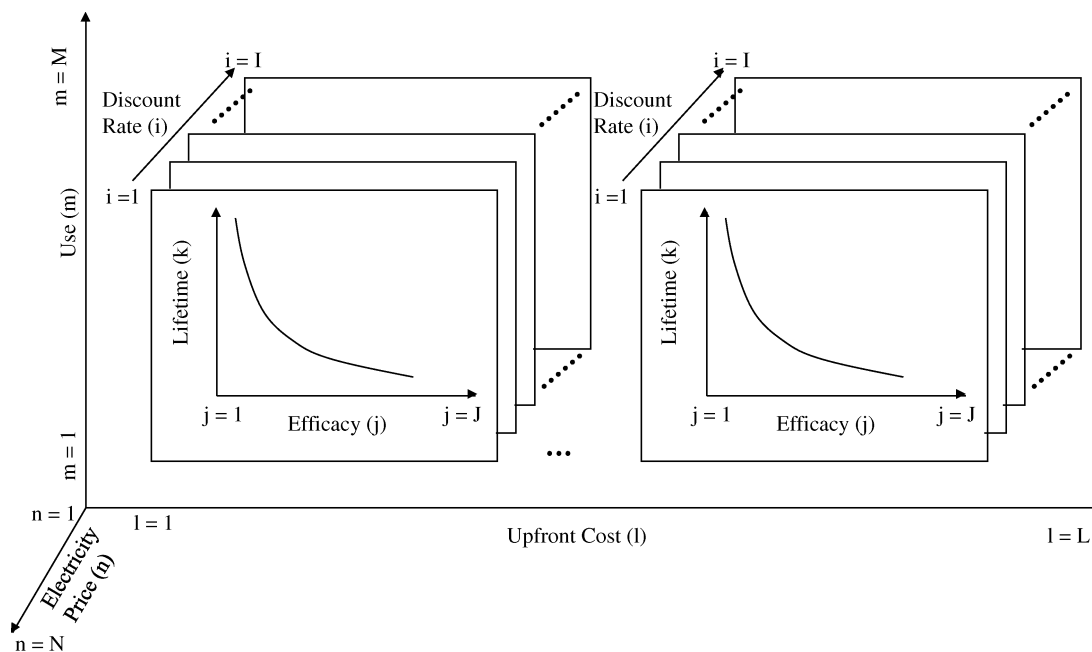


Fig. 19. Representation of the dimensions of the parametric model for levelized annual costs of solid-state lighting, which was designed based on matrices assuming a plausible range of values for electricity price, upfront cost, efficacy, lifetime, discount rate, and hours of use. The curves correspond to levelized annual cost.

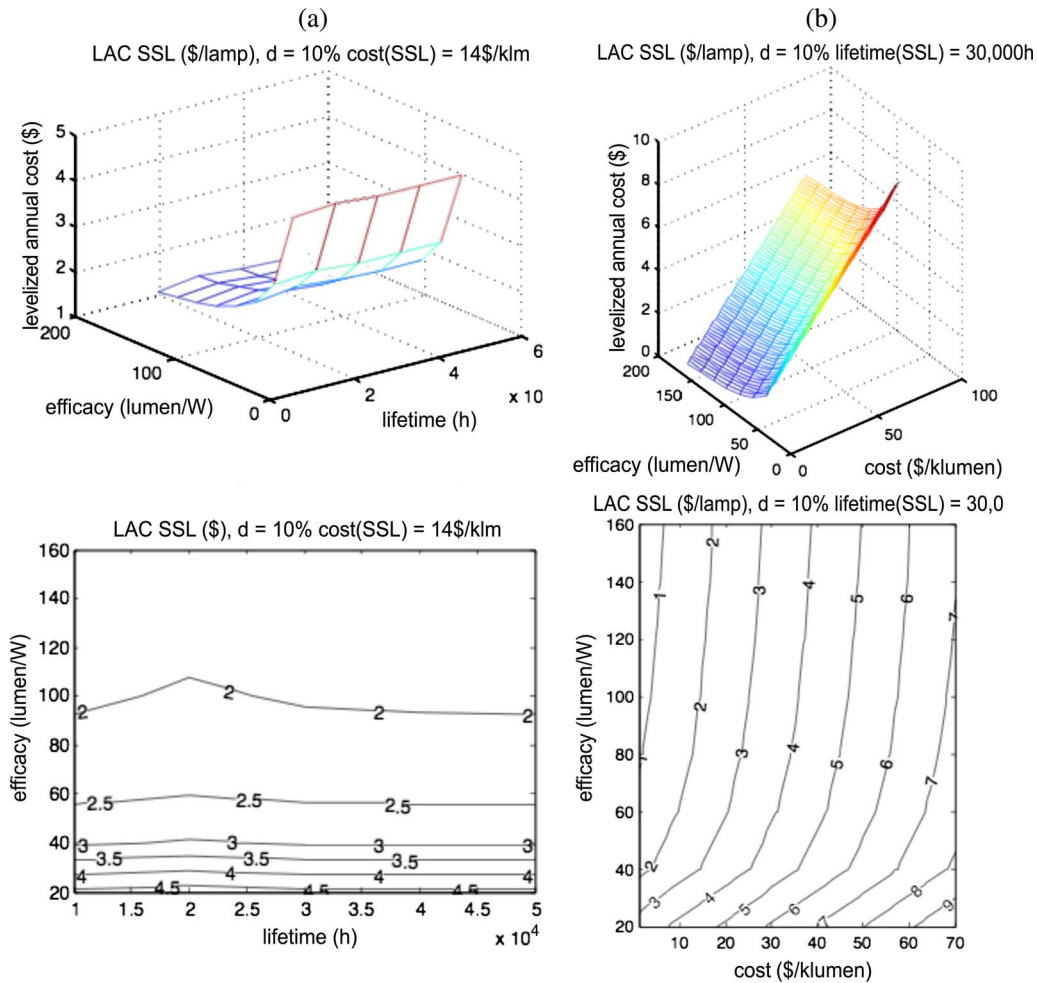


Fig. 20. Levelized annual cost for solid-state lighting under different assumptions for efficacy (lm/W), theoretical lifetime (h), discount rate (%), and usage (h/day). The upper plots correspond to levelized annual cost surfaces. The lower plots are the respective contour plots. In (a), we present the levelized annual cost for one solid-state lighting bulb with an illumination service of 926 lm as a function of efficacy (lm/W) and theoretical lifetime (h). We assume that the upfront cost of solid-state lighting remains at 14 \$/klm. In (b), we present the levelized annual cost for one solid-state lighting bulb with an illumination service of 926 lm as a function of efficacy (lm/W) and upfront cost (\$/klumen) for a theoretical lifetime of 30 000 h. We assume an electricity price of 0.10 \$/kWh, usage of 2 h/day, and a discount rate of 10%.

(a) and (b) suggest that from the perspective of consumer adoption, increases in efficacy performance from solid-state lighting are likely to be more important than increases in lifetime. Moreover, after reaching efficacies of 40 lm/W, reductions in cost are likely to be more important for reducing the levelized annual cost than increases in efficacy. We have assumed an electricity price of 0.10 \$/kWh, a usage of 2 h/day, and a discount rate of 10%.

D. Daily Lighting Electricity Consumption Load Shapes

Assuming the low and high household lighting estimates found in the literature as well as our own estimates (Section VIII), and the normalized hourly lighting profiles from the Building America program [70], average household hourly lighting profiles were constructed (Fig. 21).

Assuming average bulb wattages from [1], we then estimate a profile of the number of bulbs that are operating during each hour of the day. This leads to two to six bulbs' being used between 06:00 and 08:00, and between two and 13 bulbs' being used during the evening lighting peak, between 16:00 and 23:00.^{5,6} Focusing only on the evening peak, so as to not to double count the lamps, we estimate that there are eight lamps being used for more than 3 h/day. As shown in the previous section, at a usage rate of 3 h/day and using a 10% discount rate,

⁵Since there is already a large uncertainty in the number of bulbs being used, seasonality was not included in this analysis.

⁶We assume that the bulbs are incrementally added when the lighting load demand is increasing, and incrementally switched off when the lighting load is decreasing.

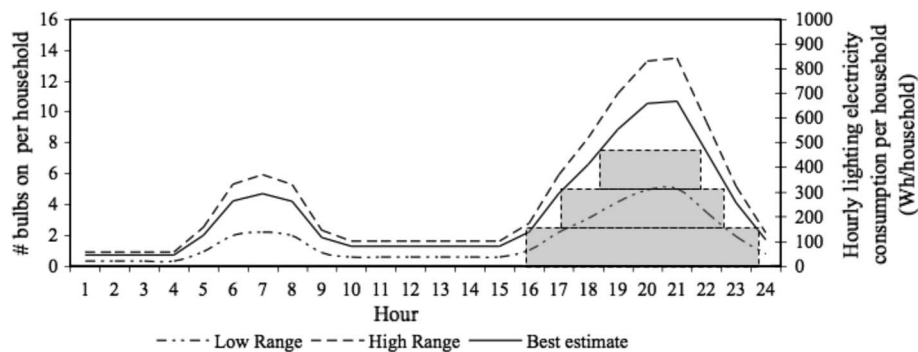


Fig. 21. Hourly lighting electricity consumption and bulbs usage of an average U.S. household. The typical household light use profile is based on normalized lighting profiles from [70], “Low range” profile is estimated using Vorsatz et al. [71] and the “high range” profile is obtained using Mandark and Nelson [72]. “Best estimate” is obtained using our estimates for 2005 lighting consumption based on [1]. The curves on the figure can be read in terms of both the number of bulbs that are turned on (left axis) and the hourly electricity consumption from the household (on the right axis).

the LAC of solid-state lighting is already lower than incandescent bulbs. On the basis of LAC, economically rational consumers would find it cost-effective to switch those bulbs to solid-state lighting today. However, solid-state lighting lamps only become as competitive as CFL or other fluorescent technologies by 2010.

VII. SOCIAL COST-EFFECTIVENESS OF WHITE LEDS

For a given lighting service, individuals largely make choices on the basis of cost. However, from a societal perspective, other considerations also enter into account. For example, if the focus is on reducing emissions of greenhouse gases while providing a similar energy service, then a cost-effectiveness measure such as cost per kilogram of CO₂ avoided is appropriate. In the literature on energy efficiency, it is common to use the *cost of conserved energy* (CCE) [4]–[12]. Sathaye and Murtishaw [13] point out that earlier analysis of energy-efficiency options typically ignored effects such as changes in labor, material, and other requirements, which can be monetized. Subsequently, Worrell [73] included these other costs and monetized benefits. In an analysis of the cost-effectiveness of several carbon mitigation strategies for the residential sector, Brown [4] accounted for effects that could shift either the carbon savings potential or the cost effectiveness. This is sometimes called a take-back effect. Jaffe and Stavins [74] identified distinct notions of optimality in the context of different “energy efficiency-gaps” (the economists’ economic potential, the technologists’ economic potential, the hypothetical potential, the narrow social optimum, and the true social optimum) and argue that each corresponds to a different definition of the energy efficiency.

We evaluate the cost-effectiveness of a program that invests in solid-state lighting and explicitly compare the

provision of the illumination service accounting for energy efficiency with the cost of additional generating capacity. The following definition is used for the CCE:

$$\text{CCE} = \frac{\text{LAC}_{\text{newtech}} - \text{LAC}_{\text{oldtech}}}{E_{\text{oldtech}} - E_{\text{newtech}}},$$

where CCE is the cost of conserved energy (\$/kWh), LAC_{*i*} is the levelized annual cost of technology *i*, E_{*i*} is the annual electricity consumption from technology *i*, and CCC is the cost of conserved greenhouse gas emissions (\$/tonCO₂ eq).

An energy service, such as lighting, heating, or cooling, can be provided through either greater energy consumption or improved efficiency. In the case of lighting, one can either use incandescent bulbs, which are energy intensive, or solid-state lighting to provide the same service (illumination) while using less energy. Thus, it makes sense to compare the cost-effectiveness of a technology change (e.g., changing from incandescent to a solid-state lighting technology) with the levelized cost of providing electricity. In Fig. 22, we compare the cost-effectiveness of changing from a mature technology (incandescent lamps or CFLs) to cool white solid-state lighting with the levelized cost of several electricity generation plants. In terms of cost-effectiveness for reducing energy consumption, solid-state lighting investments are already better than incandescent lamp investments. Improvements in solid-state lighting technology will make it more cost-effective than CFL lamps by 2010.

Investing in solid-state lighting becomes a better strategy than new generation capacity before 2010, even if the base case is already efficient CFLs. The implication is that solid-state lighting should be considered a key component of any policy to address climate change in a cost-effective way.

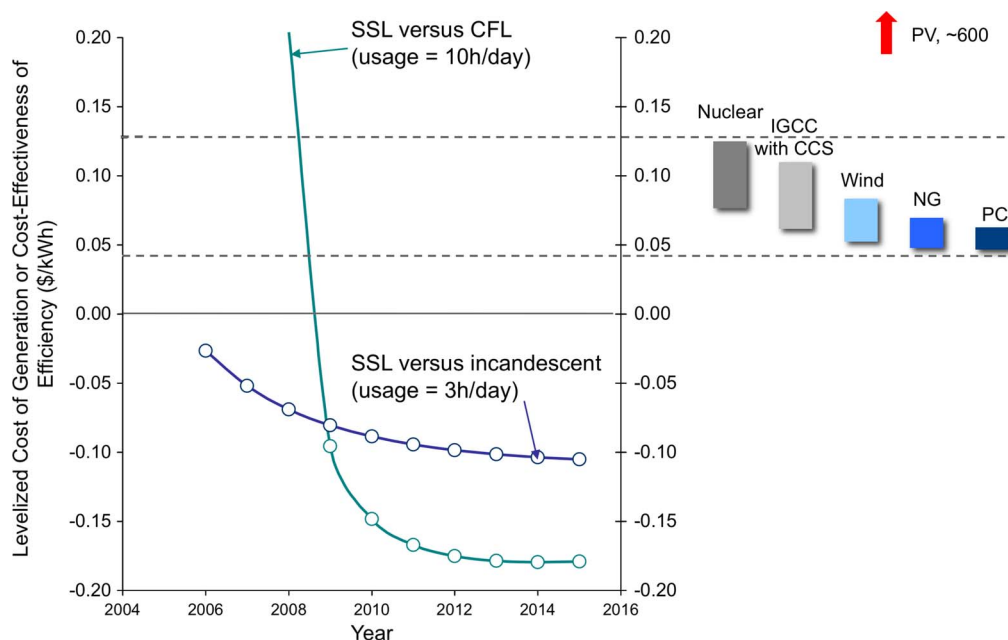


Fig. 22. Cost-effectiveness of solid-state lighting versus incandescent lamps (green line) and versus fluorescent lamps (blue line) (\$/kWh). A discount rate of 10% is assumed. The green curve assumed the bulbs are used 3 h/day all year. The blue curve assumes that the lamps are used 10 h/day all year. The bars represent ranges of levelized cost from different electricity power plant types. (Ranges of values from [75]–[79].) IGCC with CCS: integrated gasification with combined cycle and with carbon capture and sequestration. NG: natural gas power plants. PC: pulverized coal power plants.

VIII. SOLID-STATE LIGHTING POTENTIAL FOR ENERGY AND GHG EMISSIONS SAVINGS

Having shown that solid-state lighting investment is a more cost-effective strategy to achieve a certain demand level than an investment in new generation technologies, we next estimate the current and future lighting electricity and carbon savings consumption in the U.S. residential and commercial sector between 2007 and 2015 under several scenarios. We define a status quo scenario, where solid-state lighting fails to penetrate the general illumination market by 2015. We then simulate the likely savings for a voluntary and market-driven adoption of solid-state lighting under various rates of technology adoption. Next we simulate the impacts of lighting standards applied in all new construction. Lastly, we perform an analysis of a rebate or analogous subsidy policy to enhance adoption of solid-state lighting lamps.

A. U.S. Lighting Electricity Consumption

Only a few studies have estimated the level of U.S. lighting electricity consumption by different economic sectors, and consistent time series data are lacking (Fig. 23). EIA estimated that residential and commercial lighting electricity consumption were, respectively, 94 and 340 TWh in 1995 [80], [81], whereas Vorsatz *et al.* [71] estimated use as 135 and 280 TWh. The large range of

estimated values reflects the urgent need for a better accounting of electricity consumption for lighting nationwide. Also, Mills [82] notes that while campaigns to promote efficiency and conservation usually target lighting, there is a substantial lack of systematic data on lighting energy consumption.

In order to account for uncertainty concerning lighting electricity consumption in the United States, we use the ranges of estimates from previous studies (Figs. 23 and 24) to forecast electricity consumption for lighting in the residential and commercial sector up to 2015 under different sets of assumptions (Figs. 25 and 26). We estimate the annual lighting electricity consumption in 2007 to be between 96 and 257 TWh in the residential sector and between 415 and 488 TWh in the commercial sector. Thus, residential lighting accounts for between 7% and 19% of residential electricity consumption, and commercial lighting accounts for between 31% and 36% of commercial electricity consumption. We estimate that lighting only in the residential sector accounts for yearly revenue for utilities of more than \$20 billion.

B. Lighting Contribution to Greenhouse Gases Emissions

If we assume that lighting is responsible for 8% to 20% of residential and 27% to 39% of commercial electricity consumption and thus CO₂ emissions (Table 4), then the

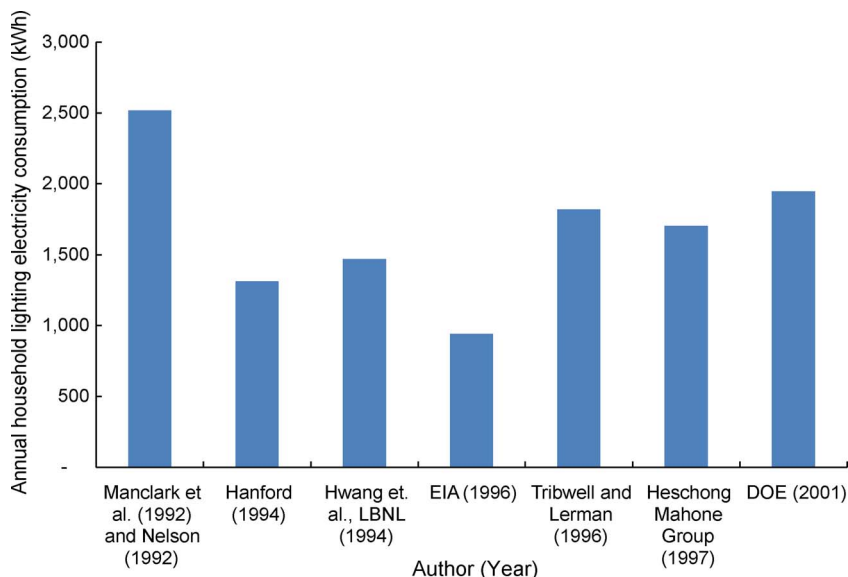


Fig. 23. Estimates of annual average household lighting electricity consumption (kWh) from previous studies. The year of publication is in brackets. While some of these are national and some regional, clearly there is great uncertainty even when regional factors are excluded [83]–[87].

CO₂ emissions due to lighting correspond to between 17% and 23% of total CO₂ emissions from electricity generation. CO₂ emissions due to lighting correspond to between 5% and 14% of the total CO₂ emissions of the residential sector and 27% to 30% of the commercial sector. Carbon dioxide emissions due to lighting in the three sectors account for 7% to 9% of total U.S. CO₂ emissions.

These estimates of carbon emissions due to electric lighting assume average national values for carbon intensity of electricity generation. They could be refined with a more detailed consideration of the time of day when consumption occurs, regional differences in the electricity generation mix, and regional differences in illumination

needs, but given the large uncertainty in the basic use data, such refinements would change little.

C. Policy Designs for Enhancing Energy Efficient Lighting

1) *Impact of Adoption of Solid-State Lighting on U.S. Electricity Consumption:* The NRC recently developed a method for the DOE to perform a prospective evaluation of their applied energy research programs [69]. DOE’s Energy Efficiency and Renewable Energy lighting program was selected to test the methodology, and the DOE’s National Energy Modeling System (NEMS) was used to estimate solid-state lighting penetration in the market. The panel notes that “a simpler model [than NEMS] could have done much the same and given the panel the opportunity to run parametric analysis.” Given that, we have developed a simple model that allows a parametric assessment of solid-state lighting penetration between now and 2015 as a function of the rate of penetration in the residential and commercial sectors.

In the technology diffusion literature, four different models (the *epidemic model*, the *probit model*, the *legitimation and competition model*, and the *information cascades model*) are commonly used to explain the market penetration of a technology [91]. We have adopted the most widely used model, a standard epidemic model as provided by Griliches [96]. We assume that the diffusion of solid-state lighting will follow the typical pattern of a logistic curve as follows:

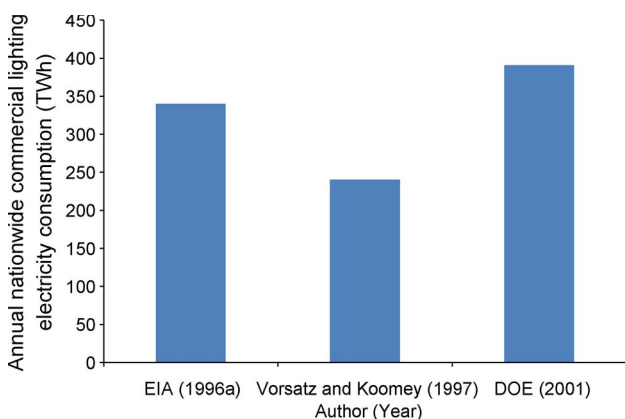


Fig. 24. Estimates of annual nationwide commercial lighting electricity consumption (TWh) from previous studies. The year of publication is in brackets [87].

$$P_i(t) = \frac{P_i^*}{1 + e^{(-\eta_i - \phi_i t)}}$$

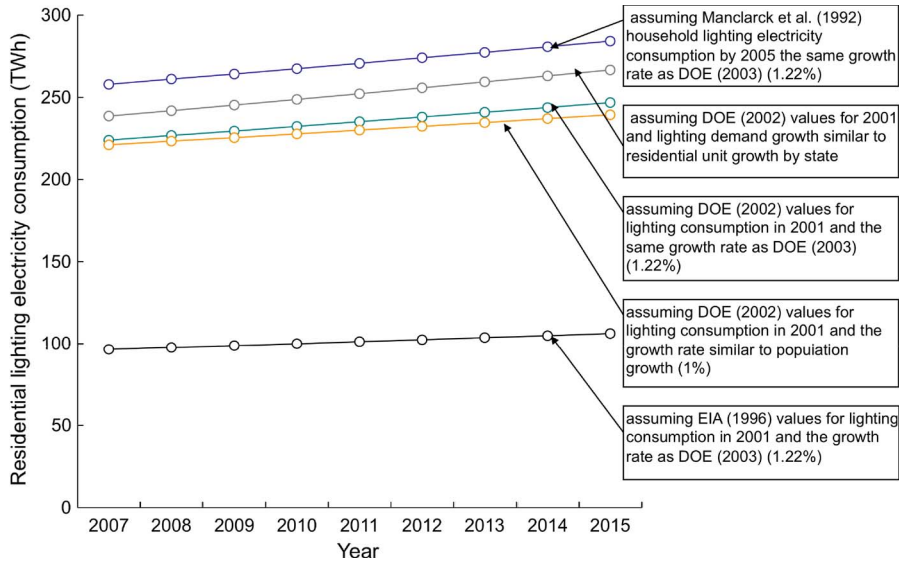


Fig. 25. Estimates of residential annual lighting electricity consumption between 2007 and 2015 under different assumptions. Upper curve assumes that household annual lighting electricity consumption in 2005 is as in [72] and residential lighting growth rate as in [81]. The three following curves assume DOE [1] values and annual growth rates on residential lighting electricity consumption similar to the historical state residential housing units growth rates (estimated using census division data from 2001 to 2005) of 1.22% (as in [81]) and 1% (similar to population growth), respectively. The lower curve assumes the estimate for household annual average lighting electricity consumption from [80] and a growth rate of 1.22% [81].

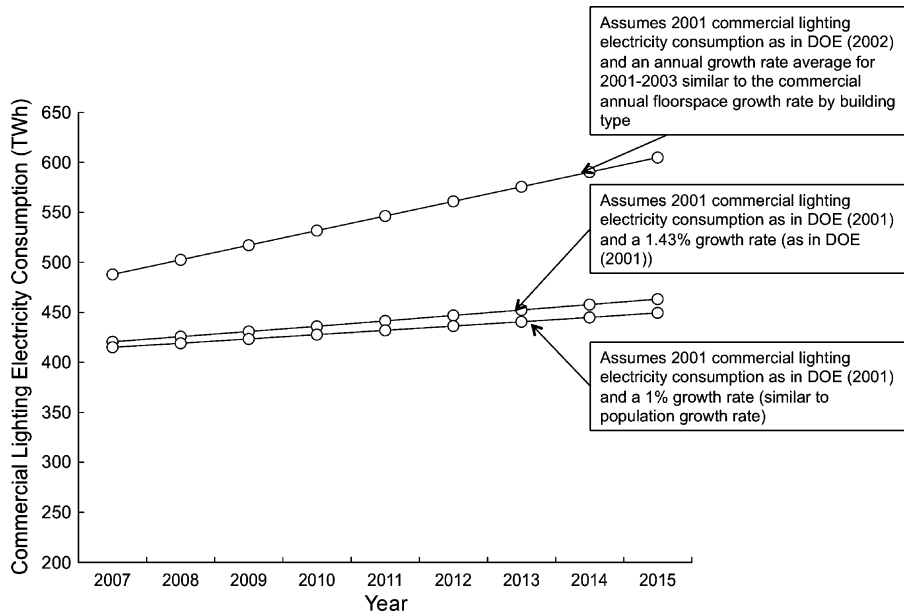


Fig. 26. Estimates of commercial annual lighting electricity consumption between 2007 and 2015 under different assumptions. Upper curve assumes values from [1] for 2001 DOE lighting consumption and a commercial lighting demand growth rate similar to the annual floorspace stock growth rate by building type as in 2001-2003. The two lower curves assume initial values from [1] and a commercial lighting demand growth annual increase similar to [81] (1.43%) and U.S. population increase (1%).

where P_i^* is the asymptotic level of use, η_i locates the diffusion curve on the horizontal axis, and ϕ_i is a measure of the speed of diffusion. We define the potential market as

illumination in the residential and commercial sectors and model annual Tlm-h provided. We use the model in a prescriptive form, assuming that in 2007 only 1% of the

Table 4 Estimates of 2005 Carbon Emissions Due to Lighting Use in the Residential and Commercial Sectors in Annual Metric Tons of Carbon. The Values in Brackets Correspond to the Upper and Lower Estimates Using Upper and Lower Electricity Consumption Estimates From Figs. 23 and 24. We Assumed the National Average Carbon Factor of 0.63 kg CO₂/kWh [88]

GHG Emissions from:	Residential (MMTC/year)	Commercial (MMTC/year)
Lighting	38 (16 – 43)	71 (70 - 80)
Electricity	212	203
Total Emissions	312	264

Assuming U.S. electricity generation emissions of 600 million metric tons of carbon (MMTC) per year [89] and total U.S. emissions of 1579 MMTC per year [90].

illumination energy service is provided by solid-state lighting, and consider three scenarios for solid-state lighting market penetration in 2015: 5%, 50%, and 99% (see Figs. 27 and 28).

In the residential sector, 90% of the wattage (and 64% of the lumens) is provided by incandescent lamps. Thus, the turnover of the lamps is less than once per year, even considering an usage of 2 h/day. In the commercial sector, 32% of the wattage is incandescent, 56% fluorescent, and 12% HID. We assumed that the stock turnover is similar to that of the fluorescent bulbs with lights operating for an average 10 h/day. Assuming that bulbs have theoretical lifetimes of 10 000 h, this roughly corresponds to a turnover of three years. Each year, the model assumes the prior cumulative adoption of the technology and takes into account solid-state lighting efficacy projections from DOE [30].

A solid-state lighting adoption of 5%, 50%, and 99% in terms of lumen demand would provide cumulative savings between 2007 and 2015 from 20 to 50 TWh, from 125 to 340 TWh, and from 385 to 1030 TWh for the residential sector; and from 25 to 30 TWh, from 90 to 110 TWh, and from 430 to 525 TWh for the commercial sector, depending on the assumptions made about future lighting demand.

A 99% adoption by 2015 (2018 in the case of the commercial sector) is unlikely to be achieved. However, a

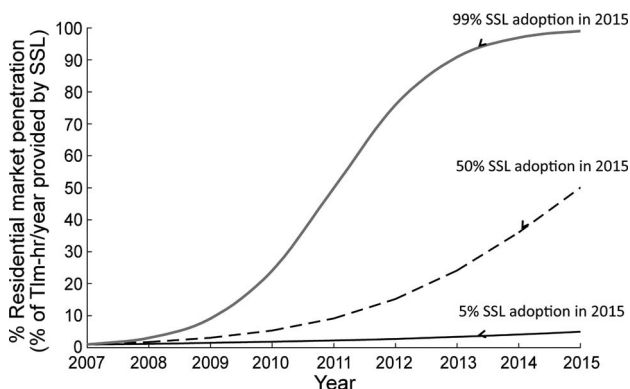


Fig. 27. Percent of residential market penetration of solid-state lighting measured as illumination service provided (Tlm-h/y), assuming a share of the illumination service from solid-state lighting of 5%, 50%, or 99% by 2015. Similar curves were simulated for the commercial sector but lagged by three years to account for the turnover of the fluorescent stock. A 1% penetration of solid-state lighting in 2007 was assumed.

50% penetration in the residential and commercial sectors (by 2015 and 2018, respectively) could be possible and would have significant impact on the overall U.S. electricity consumption and CO₂ emissions. DOE [87] estimated that within all economic sectors, solid-state lighting could save between 500 and 1850 TWh (for scenarios of moderate and accelerated investment, accordingly), cumulatively between 2010 and 2025. Our figures are in agreement with DOE findings but are more optimistic in the early penetration of solid-state lighting in the market.

2) *Nationwide Adoption of California’s Title 24 Standards:* As it often has in the past, today California is leading the nation in the development of energy efficiency standards. The 2005 Title 24 standards [17] that went into effect in October 2005 specify an allowed lighting power for commercial buildings and establish minimum efficacies for the luminaries in residential settings. According to Title 24, three methods can be used to estimate the allowed lighting power in a building: i) the complete

Table 5 Assumptions for Lamp Mix and Usage for Household Fluorescent and Incandescent Bulbs

Input	Incandescent	Fluorescent	Notes
# of lamps by household	Triangular (0, 37,80)	Triangular (0, 6,15)	Based on data from the 2001 Residential Energy Consumption Survey (RECS) [98] and [1]
Wattage (W)	Triangular (40, 67, 100)	Triangular (5,38,100)	Based on data from the DOE [1]
Hours use (h)	Parametric: [0.5h, 2h, 4h, 8h]	Parametric: [0.5h, 2h, 4h, 8h]	Since the model was highly sensitive to the number of hours the lamps were used, it was modeled parametrically
Efficacy (lumens/W)	Uniform (13,16)	Uniform (48,96)	Typical efficacy ranges for each technology

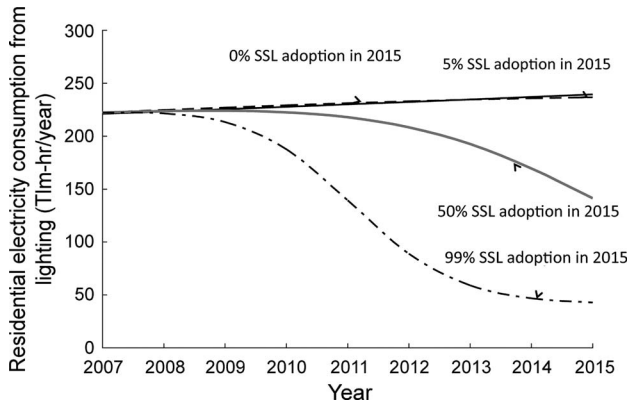


Fig. 28. Lighting electricity consumption in the residential sector between 2007 and 2015 assuming of the illumination service provided by solid-state lighting a share of 0%, 5%, 50%, and 99% in 2015. An initial 1% solid-state lighting penetration for 2007 was assumed.

building method (see Table 4); ii) the area category method; or iii) the tailored method.

We estimate the impact that the standards would have if they were applied nationwide using the complete building method for the commercial sector and the minimum efficacies that comply with Title 24 with the residential sector.

However, a note of caution should be made with respect to the implementation of standards in the residential sector. Effectively, the design of standards of illumination will matter in terms of the potential energy savings that can be achieved. For example, in the case of Title 24 standards for the residential sector, all residential projects that apply for a building permit are required to have high efficiency luminaires or be controlled by sensors. The minimum requirements for what is considered a high efficacy

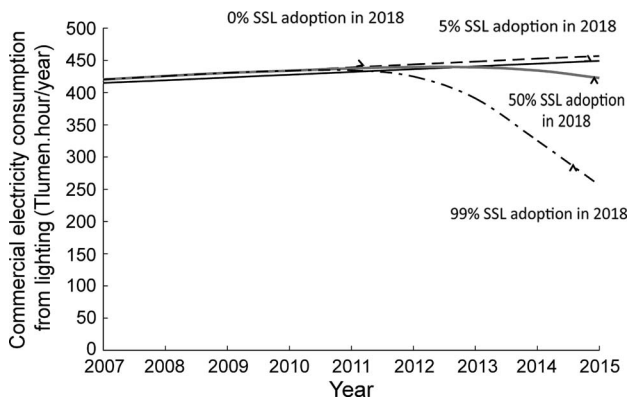


Fig. 29. Lighting electricity consumption in the commercial sector between 2007 and 2015 assuming that 0%, 5%, 50%, and 99% of the illumination service is provided by solid-state lighting by 2018. An initial 1% solid-state lighting penetration for 2007 was assumed. Here, the 0% penetration in 2015 assumes lighting demand from [B] in Fig. 12.

luminaire is presented in Fig. 30. The average power of incandescent lamps in the U.S. residential sector is roughly 65 W with an efficacy of 18 lm/W. This is presented as an “X” in Fig. 30. Now, note that the standards impose a minimum efficacy on the lighting system but do not set maximum wattage limits. Accordingly, under this standard an improvement in the efficiency of the lighting system may not result in large energy savings.

In Fig. 30, an illustrative *isolumen* line corresponding to constant levels of light service is provided for the point marked “X.” Assuming an energy service that provides at least the same illumination as today, energy saving only occurs if the old luminaire is replaced by one that has lower wattage and lies to the right of the *isolumen* line. Only solid-state lighting, CFL, and T6 will satisfy the minimum requirements, so it is likely that those technologies will prevail in new construction. The standards should be augmented with additional requirements that either i) include power maximum allowances or ii) require that illumination (total lumens) provided by the technology would be in the same lumen isoquant as those already in place in the current construction stock. These different additional standard requirements are likely to lead to different outcomes in terms of technology mix, energy consumption, and illumination levels in the buildings, but they guarantee two things: that the lighting system efficiency will increase and that energy savings compared to a situation without standards are going to occur.

We use the 2005 residential housing unit stock by state from U.S. Census Bureau data [98] and a distribution of annual construction change up to 2015 using a triangular distribution, where the minimum, maximum, and average construction annual changes for the period 2000–2005 are assumed to apply over the period of the forecast. Cumulative distribution functions for the construction rates in five states are presented in Fig. 30.

In order to see the effects of applying the policy nationwide, the potential energy savings up to 2015 for each U.S. state for the residential sector and by building type for the commercial sector were modeled, assuming that the standards began to be applied in 2007. The key modeling assumptions are presented in Table 6. Household lighting electricity consumption is then expressed by

$$\begin{aligned} \text{Household Lighting Cons}[\text{kWh/year}] &= \sum_{j=1}^n \left(\#Lamps_j \times \text{Wattage}_j[\text{W}] \right. \\ &\quad \left. \times \text{Usage}[\text{h/day}] \times 365/10^3 \right) \end{aligned}$$

where j denotes a lamp type.

For simplicity and because of the lack of regional data, interstate differences in household lighting electricity

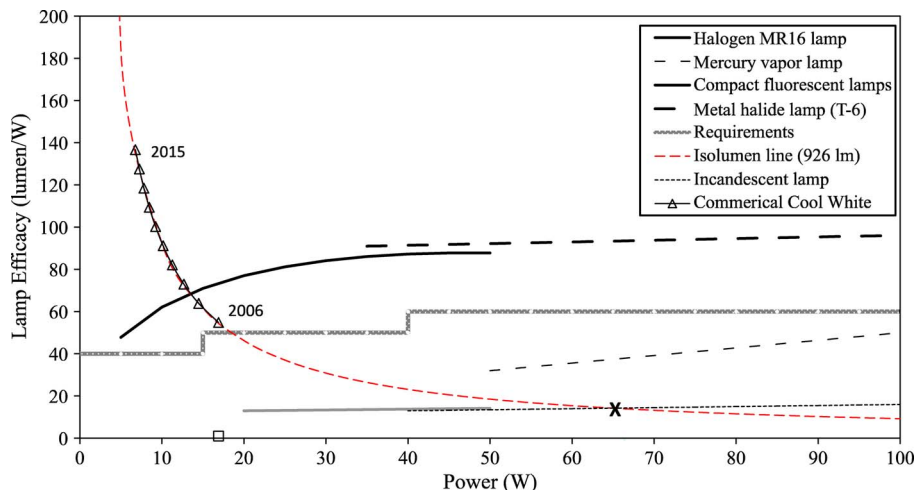


Fig. 30. Lamp efficacy in lm/W and wattage in W for current lighting technologies (halogen MR16, mercury vapor, CFL, metal halide, and incandescent lamps), adapted from Title 24 standards in California [17]. The dashed line corresponds to a lumen isoquant for a 65 W incandescent bulb with an efficacy of 18 lm/W. “Commercial cool white” corresponds to white solid-state lighting range of expected efficacies is also presented as projected by [29]. In new construction and retrofits, the luminaires are required to have efficacies above the requirements (gray line tick).

consumption were not considered. Lighting demand increase by state was considered to be similar to the house unit annual change. Housing stock over time in each state was modeled as

$$\text{Housing unit stock}_{t+1} = \text{Housing unit stock}_t \times (1 + \text{annual change}).$$

Under those assumptions, a projection of the mean housing units up to 2015 is obtained. The total state residential consumption in lighting in state i for year t is estimated as

$$\begin{aligned} &\text{Residential Lighting Electricity} \\ &\text{Consumption}_{i,t} [\text{kWh/year}] \\ &= \text{Annual Household Lighting Electricity} \\ &\text{Consumption} [\text{kWh/year.household}] \\ &\times (\text{Unit Housing}_{i,t}). \end{aligned}$$

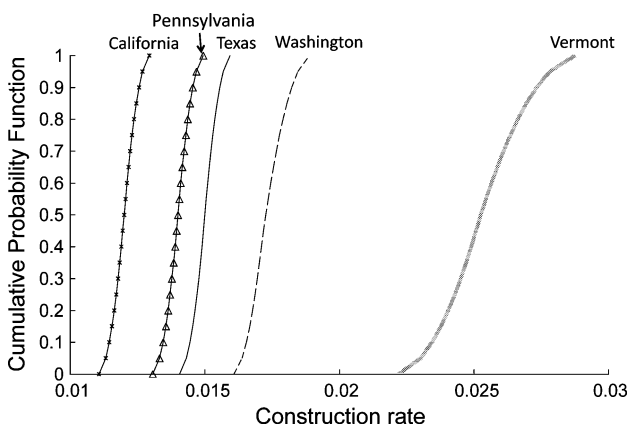


Fig. 31. Cumulative probability function of residential construction’s annual changes for California, Pennsylvania, Texas, Vermont, and Washington. We assumed the 2005 residential housing unit stock by state from the U.S. Census Bureau data [98] and a distribution of annual construction change for the period up to 2015 using a triangular distribution where the minimum, maximum, and average construction annual changes were considered to be the minimum, maximum, and average observable annual changes in each state during the 2000–2005 period.

In order to model the effect of the standards, we assume that the illumination in lumens remains the same as under a *no standards* scenario but that more efficient lighting is used in the new construction. The new residential construction is assumed to have luminaires with efficacies uniformly distributed between 60–100 lm/W, thus complying with the Title 24 residential standards. The simulated mean lighting electricity consumption over time, with and without standards, is presented in Fig. 32 for some illustrative states and for average total U.S. annual electricity savings up to 2015. Fig. 33 provides a sensitivity plot for the average hours of lighting use by households.

For the simulations of lighting electricity consumption without standards in the commercial sector, we assumed the wattage per square foot in 2001 values from [1]. With the implementation of standards, new buildings’ wattage per square foot would follow the values from Title 24 standards (see Table 6). We assume the annual change in building stock by building type until 2015 would be similar to the average annual change in building stock for

Table 6 Power Allowed by Building Type According to the Complete Building Method in Title 24 Standards [17]

Type of Use	Allowed Lighting Power (W/sq ft)	Type of Use	Allowed Lighting Power (W/sq ft)
Auditoriums	1.5	Office buildings	1.1
Convention centers	1.3	Parking garages	0.4
Financial institutions	1.1	Religious facilities	1.6
General commercial and industrial work buildings	1.1 (high bay) 1.0 (low bay)	Retail and wholesale stores	1.5
Grocery stores	1.5	Restaurants	1.2
Hotel	1.4	School	1.2
Industrial and commercial storage buildings	0.7	Theaters	1.3
Medical buildings and clinics	1.1	All others	0.6

2001–2003 estimated using the Commercial Energy Building Consumption Survey data from 2001 and 2003 [99]. We used the average hours of operation by building type from [1]. We consider the square footage and number of building for each category as in [1].

The annual lighting electricity consumption in the commercial sector for each building type was estimated by

$$\begin{aligned} \text{Lighting electricity consumption}_{i,t} &= \# \text{buildings}_{i,t} \times \text{hours of operation}_i [\text{h/y}] \\ &\quad \times \text{power per area}_i [\text{W/sqft}] \times \text{area}_i [\text{sqft}] \end{aligned}$$

for each building type i and each year t . The estimated electricity savings between 2007 and 2015, by building type for some illustrative building types, are presented in Fig. 34.

We conclude that given the current U.S. generation mix, the nationwide adoption of California’s Title 24

illumination standards could lead by 2015 to cumulative savings of roughly 113 TWh for the residential sector and 232 TWh for the commercial sector, or a cumulative total of 217 million metric tons of CO₂ by 2015.

3) *Rebates or Other Subsidies as a Policy to Enhance Solid-State Lighting Adoption*: A number of rebate programs are in place for CFLs, supported by state governments, nongovernmental organizations, major retailers, and utilities that face capacity constraints. The design of a rebate program will influence its cost and effectiveness. Here we conduct a simulation to estimate the level of rebate (or other equivalent subsidy) for two rebate designs: i) the difference between the levelized annual cost of solid-state lighting and another lighting technology (incandescent bulbs or CFLs) and ii) the difference between the upfront cost of solid-state lighting and another lighting technology (incandescent bulbs or CFLs). We present the simulations of the rebate amount over time accounting for the expected evolution of white LEDs (Fig. 35). If we assume

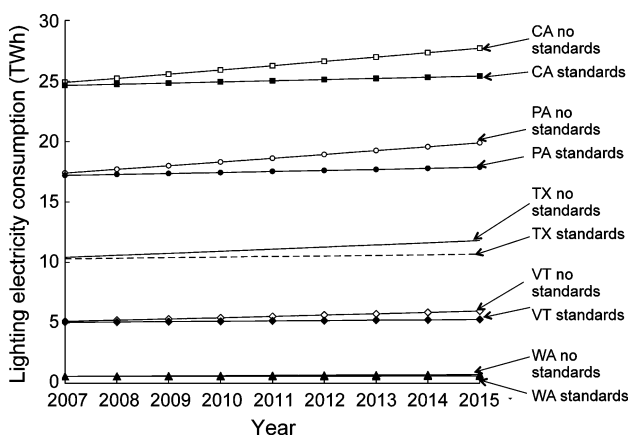


Fig. 32. Simulation of mean annual lighting electricity consumption in the residential sector for some illustrative states, with and without Title 24 standards, and assuming an average usage of 2 h/day.

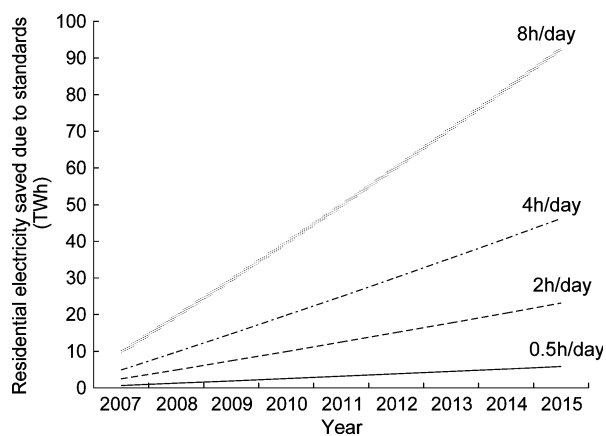


Fig. 33. Simulation of the electricity saved from the implementation of Title 24 lighting standards nationwide for the residential sector up to 2015. Sensitivity for different assumptions concerning the average operation hours of the bulbs: 0.5, 2, 4, or 8 h/day.

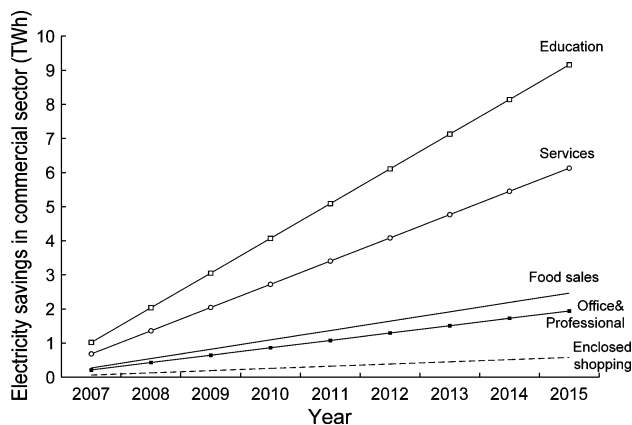


Fig. 34. Potential electricity savings in the commercial sector between 2007 and 2015 for various building types.

that the mental decision-making process from consumers is based just on the comparison of the upfront cost of two illumination technologies that provide the same energy service, then a rebate of more than \$20 per lamp would be needed today for a consumer to choose solid-state lighting over an incandescent bulb. However, if we assume that the mental decision process is based on the levelized annual cost, today's solid-state lighting bulbs would already be cheaper than incandescent lamps and no rebate would be necessary. Also, if a consumer's mental process only includes upfront costs, a rebate of \$20 per lamp would be needed for the consumer to be indifferent between a solid-state lighting and CFL. However, if we consider levelized annual cost, no rebate would be needed if the lamps were to be used more than 2 h/day.

A rebate or subsidy to set the LAC for solid-state lighting equal to that of incandescent lamps will only be required if the usage is less than 2 h/day and consumers have implicit discount rates higher than 20%. Comparing with CFL, rebates of roughly 5\$/lamp would be required if

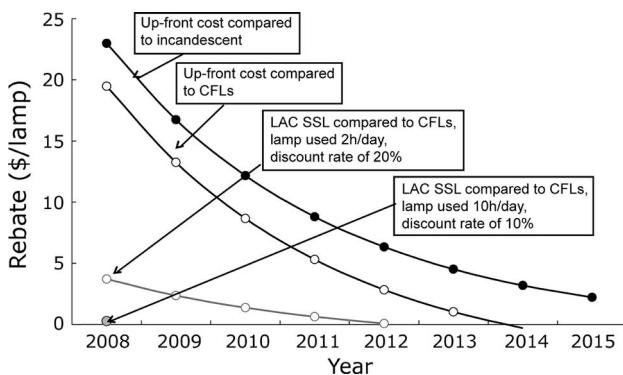


Fig. 35. Estimate of the rebate needed to make solid-state lighting LAC similar to incandescent or fluorescent bulbs, assuming 2 and 10 h/day usage and discount rates of 5% and 20%.

consumers are expected to discount solid-state lighting at 20%. Assuming a 10% discount rate, a rebate of less than 2.5 \$/luminaire would be needed starting in 2007, and would decrease over time, as solid-state lighting technology improves. By 2012, basing the rebate scheme only on the levelized annual cost, no rebate would be needed.

4) *Utility Cost-Effectiveness*: Using the preceding results, we can ask what CO₂ permit price or tax is necessary for a utility to prefer to invest in efficient lighting than to pay the permit price or tax. In this calculation, we assume the utility would pay the full cost of the lighting technology. Thus, the utility cost-effectiveness is the ratio of the levelized annual cost of each lighting technology and the amount of carbon dioxide emissions it would avoid. We compare each lighting technology with an incandescent bulb. Figs. 36 and 37 present the estimates of cost-effectiveness assuming two extreme usages (2 and 10 h/day).

For comparison, we also present the cost-effectiveness of several other carbon mitigation strategies. The cost-effectiveness of carbon capture and sequestration for new power plants is estimated to range from 13 to 80 \$/ton CO₂ avoided [75] depending on the type of plant and fuel (Fig. 36). These estimates do not account for transportation and storage.

Similarly, the levelized cost-effectiveness for today's solar photovoltaics is roughly 980 \$/ton CO₂ and is estimated to range from 95 to 380 \$/ton CO₂ avoided in the

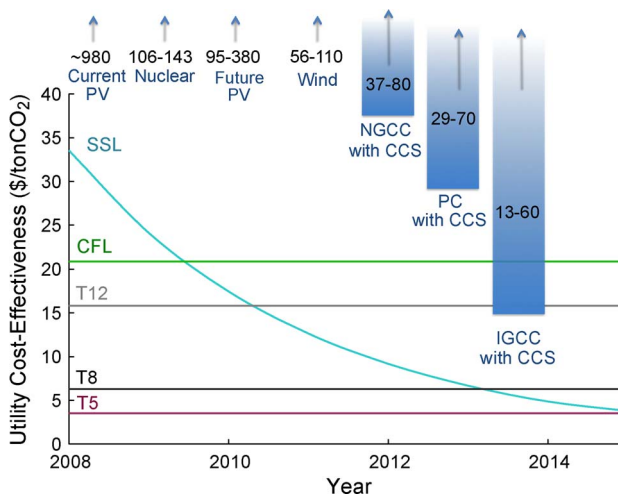


Fig. 36. Utility cost-effectiveness in \$/ton CO₂ for solid-state lighting, CFL, T12, T8, and T5 lamps assuming the same illumination service is provided. The amount of carbon dioxide emissions avoided is estimated by comparing each lighting technology with an incandescent bulb. We assume a usage of 10 h/day and a discount rate of 10%. We include the cost-effectiveness of other mitigation strategies [current photovoltaics (PV), nuclear, future PV, wind, new natural gas combined cycle power plant with carbon capture and sequestration (NGCC with CCS), new pulverized coal power plant with carbon capture and sequestration (PC with CCS), and new integrated gasification combined cycle with capture and new gasification (IGCC with CCS)].

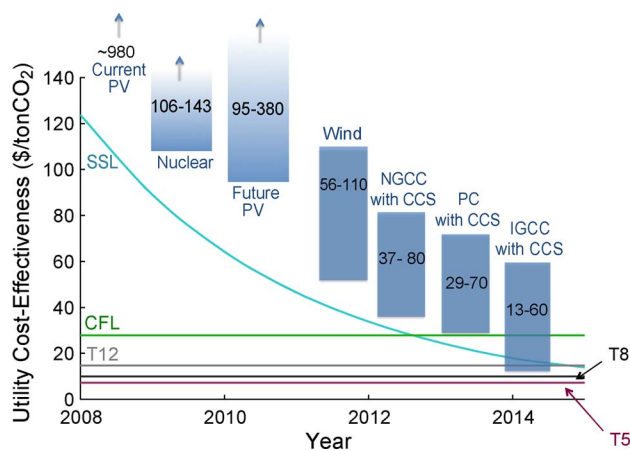


Fig. 37. Utility cost-effectiveness in \$/ton CO₂ for solid-state lighting, CFL, T12, T8, and T5 lamps assuming the same illumination service is provided. The amount of carbon dioxide emissions avoided is estimated by comparing each lighting technology with an incandescent bulb. We assume a usage of 2 h/day and a discount rate of 10%. We include the cost-effectiveness of other mitigation strategies (current PV, nuclear, future PV, wind, new NGCC with CCS, new PC with CCS, and new IGCC with CCS).

near future.⁷ Wind power cost-effectiveness ranges from 56 to 110 \$/ton CO₂ avoided.⁸ Also, nuclear estimated cost-effectiveness ranges from 106 to 143 \$/ton CO₂ avoided.⁹

According to our simulations, the cost-effectiveness of mature lighting technologies ranges from 4 to 28 \$/ton CO₂. Assuming a 10% discount rate, solid-state lighting cost-effectiveness for a utility ranges from 34 to 134 \$/ton CO₂ in 2008 and from 4 to 14 \$/ton CO₂ in 2015, making it among the more attractive investments available for large CO₂ abatement by the electricity sector. The cost-effectiveness of current incandescent bulbs will be highly depended on how much the lamps are used. Clearly, mature lighting technologies today and solid-state lighting in the near future provide a competitive alternative to carbon capture and sequestration or other carbon mitigation strategies and should be included in any future national climate change mitigation plan.

IX. CONCLUSIONS AND POLICY RECOMMENDATIONS

Improving the energy efficiency of lighting technologies will lead to reduced energy use and associated emissions of CO₂ and conventional pollutants. However, as experience with CFLs clearly demonstrates, a variety of behavioral factors can limit the rate of adoption of new and efficient lighting technologies. Our analysis suggests that solid-state

lighting will be competitive with conventional lighting technologies before 2015. White light solid-state lighting investments for general illumination may make sense right now for large customers, but the successful adoption of this technology will depend on the economic, institutional, and regulatory context.

The upfront cost of solid-state lighting is the main barrier to high market penetration. R&D efforts should focus on bringing the upfront costs down, since other important features, such as efficiency, color balance, power supply, and controls, are rapidly evolving and are not likely to be barriers to adoption.

Different product standards for the commercial and residential sector should be considered. Residential consumers might not benefit much from a further increase in the lifetime of the solid-state lighting bulbs, since lamps' lifetimes are already longer than the time the average household remains in the same housing unit. Thus, if product standards are to be developed for residential lighting, they might only require product lifetimes of 30 000 h but require higher lighting quality and lower upfront costs. Commercial decision makers might benefit from expected future solid-state lighting lifetimes, so a different product standard for commercial applications would be appropriate.

The marketing and information strategies of large retailers for different lighting technologies should be considered when addressing the adoption of solid-state lighting or other competing technologies. For example, Wal-Mart recently initiated a vigorous marketing strategy for CFL, with the aim to sell 100 million CFL bulbs in 2007. This strategy is likely to lead to significant electricity savings for residential consumers. While the strategy will increase the length of the stock turnover, perhaps slightly delaying some solid-state lighting adoption, the impact will probably be small. On the other hand, in addition to the energy savings achieved, there may also be positive spillover effects in terms of information on potential energy savings from lighting to consumers, from which solid-state lighting may benefit. A gradual transition from incandescent to solid-state lighting through CFL might be an effective cost strategy, as it would offer customers the opportunity to benefit from rapid advances in solid-state lighting technology rather than locking them in to current technology with the very long life expectancy of solid-state lighting luminaires.

Our analysis of the California Title 24 standard demonstrates that nationwide illumination standards for new residential and commercial construction would lead to large cumulative electricity savings if illumination service level remains constant. However, if lighting standards are to be implemented nationwide in new construction and retrofits, we recommend a residential standard that is based on power per area or that adds the requirement of providing new lighting systems that lie in the same *isolumen* line as the illumination service provided today.

There are other policy options such as rebates or subsidies, strategies that allow consumers to perceive the

⁷Estimated using levelized annual costs from [76] and the national average carbon factor (0.63 kg CO₂/kWh).

⁸Estimated using levelized annual costs from [77] and [78] and the national average carbon factor (0.63 kg CO₂/kWh).

⁹Estimated using levelized annual costs from [78] and [79] and the national average carbon factor (0.63 kg CO₂/kWh).

levelized cost of lighting, or product standards, which warrant future analysis. There are several aspects of solid-state lighting adoption that were not covered in this paper, such as the implications of solid-state lighting adoption on air conditioning and heating demand, potential to flatten peak loads and, accordingly, lower the marginal electricity price. Also, there are other technical options (*smart sensors*, OLEDs, greater use of sunlight) that should be analyzed as the country considers strategies to improve lighting efficiency.

Finally, this analysis has identified a number of fundamental methodological limitations in current methods for analyzing the adoption and diffusion of new technologies. Improved methods would be valuable to a wide range of analyses of future energy use technologies. ■

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REFERENCES

- [1] U.S. Lighting Market Characterization, vol. 1, *National Lighting Inventory and Energy Consumption Estimates*. Washington, D.C.: U.S. Department of Energy, 2002, Navigant Consulting, Inc. [Online]. Available: http://www.eere.energy.gov/buildings/info/documents/pdfs/lmc_vol1_final.pdf
- [2] Energy Information Administration, *Historical electricity retail sales tables*, U.S. Department of Energy. [Online]. Available: http://www.eia.doe.gov/cneaf/electricity/page/at_a_glance/sales_tabs.html
- [3] International Energy Agency, "Light's labours lost: Policies for energy-efficient lighting, in support of the G8 plan of action," 2006, p. 558.
- [4] R. E. Brown, "Estimates of the achievable potential for electricity efficiency in U.S. residences," M.A. thesis, Energy and Resources Group, Univ. of California, Berkeley, 1993.
- [5] Interlaboratory Working Group, "Scenarios of U.S. carbon reductions: Potential impacts of energy-efficient and low-carbon technologies by 2010 and beyond," Oak Ridge National Lab./Lawrence Berkeley National Lab., ORNL-444/LBNL-40533, 1997.
- [6] Interlaboratory Working Group, "Scenarios for a clean energy future," Oak Ridge National Lab./Lawrence Berkeley National Lab., ORNL/CON-476/LBNL-44029, 2000.
- [7] C. E. Gellings and K. Parmenter, *Draft of CRC Handbook Contribution*, private communication, 2005.
- [8] A. Meier, "Supply curves of conserved energy," Lawrence Berkeley National Lab., Berkeley, CA, LBL-14686, 1982.
- [9] A. H. Rosenfeld, C. Atkinson, J. Koomey, A. Meier, R. Mowris, and L. Price, "A compilation of supply curves of conserved energy for U.S. buildings," Lawrence Berkeley National Lab., Berkeley, CA, LBL-31700, 1991.
- [10] A. H. Rosenfeld, C. Atkinson, J. Koomey, A. Meier, R. J. Mowris, and L. Price, "Conserved energy supply curves for U.S. buildings," *Contemp. Policy Issues*, vol. 11, pp. 45–68, 1993.
- [11] A. H. Rosenfeld, "The art of energy efficiency: Protecting the environment with better technology," *Annu. Rev. Energy Environ.*, vol. 24, pp. 33–82, 1999.
- [12] E. S. Rubin, N. R. Cooper, R. A. Frosch, T. H. Lee, G. Marland, A. H. Rosenfeld, and D. D. Stine, "Realistic mitigation options for global warming," *Science*, vol. 257, pp. 148–149, Jul. 10, 1992, pp. 261–266.
- [13] J. Sathaye and S. Murtishaw, "Market Failures, consumer preferences, and transaction costs in energy efficiency purchase decisions," Lawrence Berkeley National Lab., Berkeley, CA, 2004, prepared for the California Energy Commission Public Interest Energy Research Program.
- [14] Energy Information Agency, "Net generation by energy sources: Total (All Sectors), U.S. Department of Energy, 2007 Values." [Online]. Available: http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html
- [15] EU Directorate-General of Energy and Transportation, "Energy & transport: Figures and main facts—Statistical pocket book 2006 & 2007." [Online]. Available: http://ec.europa.eu/dgs/energy_transport/figures/pocketbook/2006_en.htm
- [16] V. Smil, *Energy at the Crossroads—Global Perspectives and Uncertainties*. Cambridge, MA: MIT Press, 2003.
- [17] California Energy Commission, Title 24 of the California Code of Regulations: California's energy efficiency standards for residential and nonresidential buildings, part 6. [Online]. Available: <http://www.energy.ca.gov/title24/>
- [18] U.S. Department of Energy, "Energy Policy Act (EPAct)," 2005. [Online]. Available: <http://www.energy.gov/about/EPAct.htm>
- [19] U.S. Department of Energy, "Energy Independence and Security Act," 2007. [Online]. Available: <http://thomas.loc.gov/cgi-bin/query/D?c110:12::/temp/~c110IPZX0W>
- [20] R. Friedel, P. Israel, and B. S. Finn, *Edison's Electric Light: Biography of an Invention*. New Brunswick, NJ: Rutgers Univ. Press, 1986, p. 263.
- [21] W. E. Bijker, *Of Bicycles, Bakalites and Bulbs: Toward Theory of Sociotechnical Change*. Cambridge, MA: MIT Press, 1999, p. 379.
- [22] H. J. Round, "A Note on carborundum," *Electr. World*, vol. 49, p. 308, 1907.
- [23] O. V. Losev, "Luminous carborundum detector and detection with crystals," *Telegrafiya i Telefoniya bez Provodov*, vol. 44, pp. 485–494, 1927.
- [24] E. E. Loebner, "Subhistories of the light emitting diodes," *IEEE Trans. Electron Devices*, vol. ED-23, pp. 675–699, 1976.
- [25] K. Lehovc, C. A. Accardo, and E. Jamgochian, "Injected light emission of silicon carbide crystals," *Phys. Rev.*, vol. 83, pp. 603–607, 1951.
- [26] R. Braunstein, "Radiative transitions in semiconductors," *Phys. Rev.*, vol. 99, pp. 1892–1893, 1955.
- [27] C. J. Humphreys, "Solid-state lighting," *MRS Bull. (Special Issue on Harnessing Materials for Energy)*, vol. 33, 2008.
- [28] S. Nakamura and G. Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers*. Berlin, Germany: Springer-Verlag, 1997.
- [29] Solid-state lighting research and development portfolio: Multi-year program plan FY07-FY12, Navigant Consulting, Inc., 2006, prepared for Lighting Research and Development Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Dept. of Energy.
- [30] Solid-state lighting research and development portfolio: Multi-year program plan FY07-FY12, Navigant Consulting, Inc., 2008, prepared for Lighting Research and Development Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Dept. of Energy.
- [31] U.S. Department of Energy, Energy efficiency and renewable technology, building technologies program, solid-state lighting, lumen depreciation. [Online]. Available: http://www.netl.doe.gov/SSL/usingLeds/general_illumination_life_depreciation.htm
- [32] U.S. Department of Energy, "Energy efficiency and renewable technology, building technologies program, DOE solid-state lighting CALIPER program: Summary of results—Round 5 of product testing," May 2008.
- [33] *The IESNA Lighting Handbook*, 9th ed., Illuminating Engineering Society of North America, 2000.
- [34] J. M. Phillips, M. E. Coltrin, M. H. Crawford, A. J. Fisher, M. R. Krames, R. Mueller-Mach, G. O. Mueller, Y. Ohno, L. E. S. Rohwer, J. A. Simmons, and J. Y. Tsao, "Research challenges to ultra-efficient inorganic solid-state lighting," *Laser Photon*, no. 4, pp. 307–333, 2007, Rev. 1.
- [35] E. F. Schubert, *Light-Emitting Diodes*. Cambridge: 2003, p. 313.
- [36] Commission Internationale de l'Éclairage, Commission Internationale de l'Éclairage proceedings, Cambridge Univ. Press, Cambridge, U.K., 1978.
- [37] E. F. Schubert, *Light-Emitting Diodes*. Cambridge, U.K.: Cambridge Univ. Press, 2006, Fig. 20.6. [Online]. Available: <http://www.ecse.rpi.edu/%7Eeschubert/Light-Emitting-Diodes-dot-org/chap20/chap20.htm>
- [38] *Proc. Commission Internationale de l'Éclairage*, Cambridge, U.K., 1931.
- [39] National Institute of Standards and Technology, Physics Laboratory, Optical Technology Division, Color rendering of light sources. [Online]. Available: <http://physics.nist.gov/Divisions/Div844/facilities/vision/color.html>
- [40] Philips Lumileds Application Brief AB21, Luxeon product binning and labeling, 2007. [Online]. Available: <http://www.lumileds.com/pdfs/AB21.pdf>
- [41] Energy Information Administration, "Energy Star requirements for solid-state lighting luminaires, ver. 1.0," U.S. Dept. of Energy, Sep. 2007.
- [42] M. S. Rea, A. R. Robertson, and W. M. Petrusic, "Color rendering of skin under fluorescent lamp illumination," *Color Res. Applicat.*, vol. 15, no. 2, pp. 80–92, 2007.
- [43] J. Y. Tsao, "Solid-state lighting: Lamps, chips and materials for tomorrow," *IEEE Circuits Devices*, vol. 20, no. 3, pp. 28–37, 2002.
- [44] J. Y. Tsao, "Lighting emitting diodes for general illumination—An OIDA Technology Roadmap update," 2002. Prepared for the

- Optoelectronics Industry Development Association.
- [45] *Information Technology Equipment—Radio Disturbance Characteristics—Limits and Methods of Measurement*, Internal Harmonized Standard EN55022, 2006. [Online]. Available: <http://www.global.ihs.com/>
- [46] M. S. Rea, Ed., *IESNA Lighting Handbook*, 9th ed. New York: Illuminating Engineering Society, 2000.
- [47] R. Haitz, R. Kish, F. Tsoo, and J. Nelson, "The case for a national research program on semiconductor lighting," presented at the 1999 Optoelectronics Industry Development Association Forum, Washington, D.C., Oct. 6, 1999.
- [48] K. Dowling, "The cost of light, color kinetics whitepaper," 2003. [Online]. Available: <http://www.colorkinetics.com/whitepapers/CostofLight.pdf>
- [49] E. J. Mishan, *Elements of Cost-Benefit Analysis*. London, U.K.: George Allen and Unwin, 1972.
- [50] E. S. Rubin and C. I. Davidson, *Introduction to Engineering and the Environment*. New York: McGraw-Hill, 2001.
- [51] P. Samuelson, "A note on measurement of utility," *Rev. Econ. Studies*, vol. 4, pp. 155–161, 1937.
- [52] S. Frederick, G. Lowenstein, and T. O'Donoghue, "Individual discounting and time preference: A critical review," *J. Econ. Lit.*, vol. XL, p. 10, 2002.
- [53] A. H. Sanstad and R. B. Howarth, "Consumer rationality and energy efficiency," in *Proc. ACEEE 1994 Summer Study Energy Efficiency Build.*, 1994.
- [54] R. B. Howarth and A. H. Sanstad, "Discount rates and energy efficiency," *Contemp. Econ. Policy J.*, vol. 13, p. 8, 1995.
- [55] M. Friedman, "The methodology of positive economics," in *Essays in Positive Economics*. Chicago, IL: Univ. of Chicago Press, 1953.
- [56] A. Goett, "Appliance fuel choice: An application of discrete multivariate analysis," Ph.D. dissertation, Dept. of Economics, Univ. of California, Davis, 1983.
- [57] Office of Management and Budget, "Guidelines and discount rates for benefit-cost analysis of federal programs," Circular A-94, 1992.
- [58] J. Hausman, "Individual discount rates and the purchase and utilization of energy-using durables," *Bell J. Econ.*, vol. 10, p. 21, 1979.
- [59] H. Ruderman, M. L. Levine, and J. E. MacMahon, "The behavior of the market of energy efficiency in residential appliances including heating and cooling equipment," *Energy J.*, vol. 8, p. 23, 1987.
- [60] J. Berkoved, J. Hausman, and J. Rust, "Heating systems and appliance choice," MIT Energy Lab., Cambridge, MA, Rep. MIY-EL 83-004WP, 1983.
- [61] D. Gately, "Individual discount rates and the purchase and utilization of energy-using durable: Comment," *Bell J. Econ.*, vol. 11, no. 1, 1980.
- [62] H. Cole and R. Fuller, Hittman Associates, Inc., "Residential energy decision-making: An overview with emphasis on individual discount rates and responsiveness to household income and prices," Columbia, MD, 1980.
- [63] A. Meier and J. Whittier, "Consumer discount rates implied by purchases of energy-efficient refrigerators," *Energy*, vol. 8, no. 12, pp. 957–962, 1983.
- [64] Arthur D Little, Inc., "Measuring the impact of residential conservation programs: An econometric analysis of utility data," Electric Power Research Institute, Final Rep. RP1587, 1984, vol. III.
- [65] D. A. Houston, "Implicit discount rates and the purchases of untried, energy-saving durable goods," *J. Consum. Res.*, vol. 10, pp. 236–246, 1983.
- [66] D. Kahneman, P. Slovic, and A. Tversky, *Judgment Under Uncertainty: Heuristics and Biases*. Cambridge, U.K.: Cambridge Univ. Press, 1982, 551 pp.
- [67] C. D. Anderson and J. D. Claxton, "Barriers to consumer choice of energy efficient products," *J. Consum. Res.*, vol. 9, p. 7, 1982.
- [68] H. R. Socolow, "The physicist's role in using energy efficiently: Reflections on the 1974 American Physical Society summer study and on the task ahead," in *Energy Sources: Conservation and Renewables*, vol. 17, D. Hafemeister, H. Kelly, and B. Levi, Eds. New York: American Institute of Physics Press, 1985.
- [69] National Research Council, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One)—A First Look Forward*. Washington, D.C.: National Academies Press, 2005.
- [70] "Building technologies program, energy efficiency and renewable energy," U.S. Department of Energy. [Online]. Available: http://www.eere.energy.gov/buildings/building_america/for_builders.html
- [71] D. Vorsatz, L. Shown, J. G. Koomey, M. Moezzi, A. Denver, and B. Atkinson, "Lighting market sourcebook," Lawrence Berkeley National Lab., LBNL-39102, Dec. 1997.
- [72] B. Manclark and M. Nelson, *The Grays Harbor PUD Compact Fluorescent Maximization Study*. Eugene, OR: Delta-T, 1992.
- [73] E. Worrell, L. Price, and C. Galitsky, "Emerging energy-efficient technologies in industry: Technology characterizations for energy modeling," Lawrence Berkeley National Lab., Berkeley, CA, LBNL-54828, 2004, prepared for the National Commission on Energy Policy.
- [74] A. B. Jaffe and R. N. Stavins, "The energy-efficiency gap—What does it mean?" *Energy Policy*, vol. 22, no. 10, pp. 804–810, 1994.
- [75] E. S. Rubin, C. Chen, and A. B. Rao, "Cost and performance of fossil fuel power plants with CO₂ capture and storage," *Energy Policy*, vol. 35, pp. 4444–4454, 2007.
- [76] A. E. Curchright, M. G. Morgan, and D. W. Keith, "Expert assessments of future photovoltaic technologies," submitted for publication.
- [77] R. Wiser and M. Bolinger, *Annual report on U.S. wind power installation, cost, and performance trends: 2006*, DOE/GO-102007-2433, 2007. [Online]. Available: www.nrel.gov/docs/fy07osti/41435.pdf
- [78] J. Harding, "Economics of nuclear power and proliferation risks in a carbon-constrained world," *Electricity J.*, vol. 30, pp. 65–76, 2007.
- [79] J. Deutch and E. Moniz, "The future of nuclear power." [Online]. Available: <http://web.mit.edu/nuclearpower/>
- [80] Energy Information Administration, "Residential lighting: Use and potential savings," U.S. Department of Energy, EIA DOE/EIA-0555(96)/2, 1996.
- [81] Energy Information Administration, "Annual energy outlook, with projections to 2015," U.S. Department of Energy, DOE/EIA-0383(96), 1996.
- [82] E. Mills, "The \$230-billion global lighting energy bill," in *Proc. 5th Int. Conf. Energy-Efficient Light.*, Nice, France, May 2002.
- [83] J. W. Handford, J. Koomey, L. E. Stewart, M. E. Lecar, R. E. Brown, F. X. Johnson, R. J. Hwang, and L. Price, "Baseline data for the residential sector and development of a residential forecasting database," Lawrence Berkeley National Lab., Berkeley, CA, 1994.
- [84] Heschong Mahone Group, "Lighting efficiency technology report," Sacramento, CA, CEC Contract 400-95-012, May 30, 1997, vol. I, prepared for the California Energy Commission.
- [85] R. J. Hwang, F. X. Johnson, R. E. Brown, J. W. Hanford, and J. G. Koomey, "Residential appliance data, assumptions and methodology for end-use forecasting with EPRI-REEPS 2.1," Energy and Environment Division, Lawrence Berkeley National Lab., Berkeley, California, LBL-34046, May 1994.
- [86] L. S. Tribwell and C. J. Campbell, "Perceptions of compact fluorescent lamps in the residential market," Macro Consulting, 1992, prepared for the Electric Power Research Institute.
- [87] Navigant Consulting, Inc., "Energy savings potential of solid-state lighting in general illumination applications," U.S. Dept. of Energy, 2003, prepared for Buildings Technology Program, Office of Energy Efficiency and Renewable Energy.
- [88] Environmental Protection Agency, "Inventory of U.S. greenhouse gas emissions and sinks: 1990-2004," Washington, D.C., EPA 430-R-06-002, 2006.
- [89] G. Morgan, J. Apt, and L. Lave, "The U.S. electric power sector and climate change mitigation," Pew Center on Global Climate Change, Carnegie-Mellon University, Pittsburgh, PA, 2005.
- [90] M. Brown, F. Southworth, and T. Stovall, "Towards a climate-friendly built environment," Pew Center on Global Climate Change, Oak Ridge National Lab.
- [91] P. A. Geroski, "Models of technology diffusion," *Res. Policy*, vol. 29, p. 12, 2000.
- [92] P. Stoneman, *The Economics of Technological Diffusion*. Oxford, U.K.: Blackwell, 2002.
- [93] F. Bass, "A new product growth model for consumer durables," *Manage. Sci.*, vol. 15, p. 12, 1969.
- [94] P. David, "A Contribution to the Theory of Diffusion," Center for Research in Economic Growth, Res. Memo. 71, 1969.
- [95] S. Davies, *The Diffusion of Process Innovations*. Cambridge, U.K.: Cambridge Univ. Press, 1979.
- [96] Z. Griliches, "Hybrid corn: An exploration in the economics of technological change," *Econometrics*, vol. 48, p. 11, 1957.
- [97] U.S. Department of Energy, 2001 Residential energy consumption survey, micro-data files. [Online]. Available: <http://www.eia.doe.gov/emeu/recs/contents.html>
- [98] U.S. Census Bureau, Annual Estimates of housing units for the United States and States: April 1, 2000 to July 1, 2005, 2HU-EST2005-01. [Online]. Available: <http://www.census.gov/popest/housing/HU-EST2005.htm>
- [99] U.S. Department of Energy, 2003 commercial buildings energy consumption survey, micro-data files. [Online]. Available: <http://www.eia.doe.gov/emeu/cbecs/contents.html>

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