Energy efficiency and conservation: Is solid state lighting a bright idea?

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Keywords

lighting; solid state lighting; time value of money; implicit discount rates.

Abstract

Because lighting constitutes 20 % of total US electricity consumption, and many current lighting technologies are highly inefficient, improved technologies for lighting hold great potential for energy savings and for reducing associated greenhouse gas (GHG) emissions. Solid-state lighting (SSL) is a technology that shows great promise as a source of efficient, affordable, color-balanced white light in the near future. Indeed, under a pure engineering-economic analysis, SSL already performs better than incandescent bulbs it is expected that commercial available LEDs to surpass fluorescents within the next decade. However, a large literature indicates that individual household decision-makers (and to a lesser extent commercial decision makers) do not make their decisions using pure engineering-economic evaluations. An analysis for commercial decision-makers and for individual households has been made to compare the cost, electricity consumption, carbon emissions and cost-effectiveness of incandescent lamps, fluorescent lamps (compact and tubes) and SSL. The analysis includes a parametric evaluation of the levelized annual cost (LAC) of providing an illumination service for households or commercial consumers similar to the one in place today by replacing incandescent or fluorescent bulbs with SSL bulbs as a function of the changes in electricity consumption, incremental cost and incremental lifetime of the new technology. The analysis accounts for the expected evolution of the main characteristics of SSL between 2007 and 2015. Also, this work has identified a number of fundamental methodological limitations in the adoption and diffusion of new technology clearly deserve more attention in the future.

Objectives and Motivation

Electricity is used everyday in our houses and in the commercial buildings. Because lighting constitutes 20 % of total US electricity consumption, and many current lighting technologies are highly inefficient, improved technology for lighting holds great potential for energy, emissions and cost savings. This research aims to answer two questions: (i) What are the costs of investing in the current lighting technologies and how are they likely to evolve over time? (ii) Which policies will enhance energy and GHG emissions savings through the adoption of more efficient lighting technologies?

Energy Efficiency and Conservation: Setting the Context for SSL

Global climate change is becoming an increasingly important problem and an enormous amount of effort has been devoted to understanding its main implications. California is adopting significant constraints on emissions of GHG, and seven Northeastern states are now organizing a cap and trade system for GHG emissions under the Regional Greenhouse Gas Initiative RGGI. Moreover, there is a broad acceptance from the power industry that carbon regulation will occur at the Federal level within the next two decades. In this carbon constraint new world, there is growing attention to energy efficiency and conservation.

A large literature has attempted to evaluate the cost-effectiveness of GHG mitigation through the use of energy efficient

Table 1 – Main characteristics of lamps in the US market (DOE, 2002; Color Kinetic, Inc., 2003, IEA, 2006. Cree Inc. website, 2006, Phillips-Novaled, 2006).

Lamp	Type	Power (W)	Efficacy (lumen/W)	Lifetime (h)	CCT (K)	CRI
INC	-	3-150	4-18	1k	2,400-3,100	98-100
Halogen	-		15-33	2k-6k	3,000 – 3,100	98-100
HID	-	40-400	14-140	6k-28k	2,900 – 5,700	15-62
FL	LPNa	26-180	70-200	7.5k-30k	1,700-7,500	75-95
	T12	14-90	60-105	7k-20k	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	5k-15k	3,000-6,500	75-90
CFL	external ballasts	40-95	60-80	10k-20k	2,700–6,500	80-85
White SSL	LED	1-20	160 (lab), 20-55	20k-40k	5,000-6,000	70-80
	OLED	1-20	<25	<10k	3,000-6,000	~80

Notes: INC = Incandescent; HID = High Intensity Discharge; FL = Fluorescent Lamps; LP Na = Low Pressure Sodium; CFL = Compact Fluorescent Lamps; SSL = Solid Date Light; LED = Light Emitting Diodes; OLED = Organic Light Emitting Diodes; CRI = Color Rendering Index. CCT = Correlated Color Temperature; Sources for data: IEA (2006), Tsao, (2002), DOE (2006).

technologies (IWG, 1997 and 2000; Gellings, 2005; Meier, 1982). Most emphasize the importance of more efficient end-use technologies in commercial and residential buildings. This attention is more than justified, since households and the commercial sector represent 37 % and 35 % of the US total electricity consumption (DOE, 2006). Although those studies provide useful insight on the potential reductions and cost-effectiveness, the estimates are usually conservative and do not take into account consumer behavior. However, when addressing demand side policies it is important to link the technological potential with consumers' decision making and with government policies strategy (Dyner, 2004). Jaffe and Stavins (1994) argue that an energy-efficiency gap exists between expected future energy use and optimal future energy use, and suggest that the magnitude of this gap depends mainly on how the *optimal behavior* is defined. Smil (2002) argues that the provision of illumination is one of the most promising areas for future improvement, suggesting that by the middle of the 21-century the world's average lighting efficiency could be 50 % above todays. The role of lighting technologies in U.S. energy policy agenda is also emphasized in the 2005 Energy Policy Act (EPACT, 2005), which contains a directive to carry out a *Next Generation Lighting Initiative* that will support R&D to accelerate the rate of improvement in white SSL.

Micro Analysis: SSL Technology and the Cost of Light

LIGHTING TECHNOLOGIES

Lighting systems are made up of lamps, luminaries and supporting systems such as power supplies and ballasts. For the purpose of this study we consider the following definitions associated with lighting technologies characteristics: *Efficacy* is the ratio of the light output to the input power and it is measured in unit of lumens per watt (lm/W); *Lumen-depreciation* is the fact that for some technologies, the light output decreases over the lifespan of the lamp (0 % - 40 %); *Correlated color temperature* (CCT), which is a metric of intensity of light across different parts of the visible light spectrum. It describes the color appearance of the lamp itself, it is measured in Kelvin and corresponds to the chromaticity that matches that of a black body heated at the same temperature; *Color rendering index* (CRI), which describes the color appearance of the surfaces being illuminated by the lamp (IEA, 2006). Table 1 presents the main characteristics of lamps in the US market for residential and commercial applications.

Altough we refer to CRI for SSL, the CRI is probably not the appropriate way for describing LEDs. White SSL is an emerging lighting technology, which uses inorganic or organic light emitting diodes (LEDs and OLEDs). A LED device is composed by two semiconductors, where the atomic arrangement determines the light color. AlInGaP LEDs lead to red and yellow

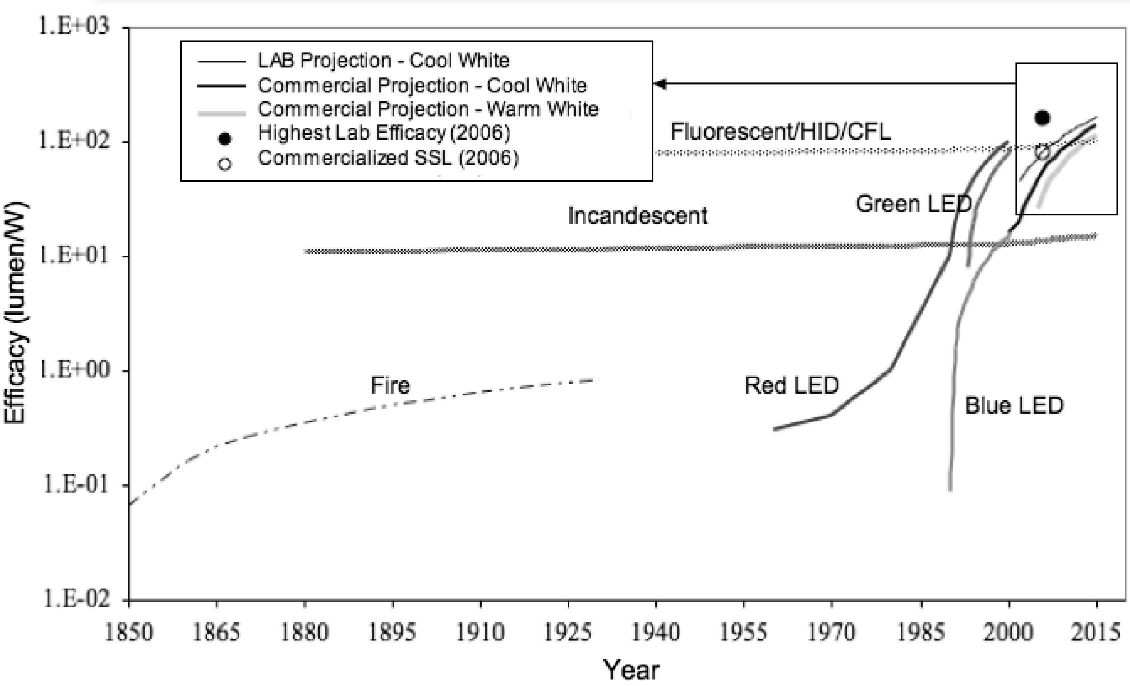

Figure 1 – Maximum commercialized efficacies of selected lighting technologies between 1850 and 2006. Achieved efficacies for white LED-SSL (laboratory and commercial, for 2006) and projections up to 2015 are also presented. (Data adapted from Tsao, 2004; DOE, 2006). Red and Green LEDs already have higher efficacies than fluorescent tubes/HID/CFLs. Commercialized white SSLs sre expected to reach those levels in the next couple of years. Note that the efficacies are function of the wattage, and that dimension is not shown the figure.

light whereas AlInGaN LEDs generate blue and green light. Monochromatic LEDs have already high efficacy, as illustrated by Figure 1. The challenge with LED for general illumination is to obtain high quality white light, for which two solutions are currently used. The first is to use three RGB monochromatic LED devices. The limitations of this approach are that the overall efficacy of the device is limited by the efficacy of each color and, since the spectral widths are narrow, color control is difficult. This approach has the advantage that there are no down-conversion losses. The current alternative is to use UV/violet or blue LED with the photons then down converted into a distribution of color using down-conversion materials.

Because the technology is rapidly evolving, projections of SSL efficacy, cost and lifetime are frequently updated. In 2002, OIDA expectations for the 2007 technology were an efficacy of 75 lm/W, a theoretical lifetime of 20,000 hours and an upfront cost of 20 $/klm. Today, in the laboratory, SSLs have reached efficacies of 160 lm/W (Cree, 2006). Commercialized SSLs have efficacies of 20-56 lm/W, last 30,000-50,000 hours and cost 47 $/klm (DOE, 2006). In our simulations, we assume the most up to date projections for white LED efficacy and up front costs targets from DOE (2006), for cold white SSL lihgintg available at commercial level.

According to DOE (2006), the lifetime of commercial cold white lamps is expected to increase linearly from 30,000 to 50,000 hours between 2005 and 2008, and remain at 50,000 hours thereafter. The prices and efficacies mentioned above assume that white LED devices are operating at a correlated color temperature (CCT) of approximately 5,000-6,000 K and a color rendering index (CRI) of 70-80 or higher.

Many argue that LED lighting systems will not be competitive with traditional lighting technologies until the initial cost per kilolumen is comparable to other technologies. However, a different theory proposes that some consumers look at the life-cycle costs, in a pure financial perspective (DOE, 2006). There are several metrics available that could be used to estimate the cost of light supplied by the different available technologies. DOE (2006) and participants in the SSL program mostly refer to the upfront cost ($/klumen) and to thefollowing metric for the cost of light:

$$\textit{Cost of light} =$$

$$\left(\frac{10}{\textit{lamp lumens}}\right)\times\left(\frac{\textit{lamp cost}+\textit{labor cost}}{\textit{lifetime}}+\textit{energy use}\times\textit{energy cost}\right)$$

Where the *cost of light* is in $/Mlumen, the *lamp lumens* represents the light output of the lamp (lumens), *lamp cost* is the initial cost of the lamp (cents$/lamp), *labor cost* is the labor cost necessary to replace the lamp (cents$/lamp), *lifetime* is the theoretical lifetime of the lamp (1,000 h), *energy use* is the power consumption of the lamp (W/lamp), and *energy cost* is the cost of electricity (cents$/kWh).

According to this metric, today's SSL is already cheaper (20 $/Mlmh) than incandescent (27 $/Mlmh) or halogen lamps (23 $/Mlmh). The cost of fluorescent lamps is estimated to be 7 $/Mlmh (Color Kinetics, 2003; DOE, 2006). However, this metric is inadequate because it does not consider the hours of operation or the time value of money.

Thus, in addressing the cost of different lighting technologies, one needs to choose among several decision criteria which are available to evaluate the best choice among a set of alternatives. Mishan (1972) and (Rubin, 2001) provide descriptions of the different decision options and the appropriate discount

Table 2 – Average implicit discount rates in energy-efficiency investments.

End-use	Implicit discount rate
Air conditioners	17% - 20% (Hausman, 1979)
Heaters	102% (Ruderman et al., 1987) 25% (Berkovec et al, 1983)
Freezers	138% (Ruderman et al., 1987)
Refrigerators	45% - 300% for refrigerators (Gately, 1980) 61-108% (Cole and Fuller, 1980) 34%-58% (Meier and Whittier, 1983)
Thermal shell measure	32% (Arthur D. Little, 1984) 26% (Cole and Fuller, 1980)
Cooking and water heating by fuel type	36% (Goett, 1983)
Electric water heaters	243% (Ruderman et al., 1987

rates to use under different circumstances. In a standard approach, the discount rate depends on the alternative opportunities open to the decision maker for the use of her funds. While the explanation provided by Mishan is appropriate for investment choices by economically rational actors, it does not explain why decision makers at the commercial and residential level do not voluntarily adopt energy efficient products such as CFLs. Therefore, the question that arises is what are the appropriate models to use to compare energy efficient investments in a behaviorally realistic way, when it has been shown that individuals have very high implicit discount rates.

Sanstad *et al*. (1994) and Frederick, Lowenstein and O'Donoghue (2002) refer several studies that have estimated implicit discount rates by examining consumers' choices among different models of an end-use technology, presenting purchasers with a tradeoff between the immediate purchase price and the long-term costs of running the appliance. Those implicit discount rates vastly exceeded the market interest rates and differed substantially across product categories as shown is Table 2. Hausman (1979) found that the implicit discount rate varied markedly with income. In contrast, a study by Houston (1983) that presented individuals with a decision of whether to purchase a hypothetical *energy-saving* device, found that income *played no statistically significant role in explaining the level of discount rate* (Frederick *et al*, 2002). Although the aspect of income as function of the implicit discount rate seems important, it is not going to be explored in this paper.

To date there is no consensus on the use of implicit discount rates since those might be embedding several market barriers, including: (i) a lack of information about the available technologies and cost savings among consumers; (ii) a disbelief among consumers that the cost savings will be as great as promised; (iii) a lack of expertise in translating available information into economically efficient decisions; (iv) the hidden costs of the more efficient appliances, such as reduced convenience or reliability (i-iv, Frederick et al, 2002); (v) the availability heuristic when an earlier attempt by the consumer or others to use the technology did not fulfill the expectations; (vi) the role of marketing and advertisement in promoting different technologies; (vii) dominance of retail sales staff and issues of product selection and promotion (Anderson et al. 1982); (viii) lack of information concerning electricity prices and hours of use of the technology. As Socolow (1985) 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" (Smil, 2003). When Samuelson first developed the discounted utility (DU) model he had clear concerns about its descriptive realism. Frederick et al. (2002) argue that there is little empirical behavioural support for using the DU model, although it continues to be widely used by economists. Similarly, Sanstad et al. (1994) argue that the mathematical formalism of economic rationality provides the basis for economic models of consumer behaviour but are generally not subjected to empirical testing. The main argument for DU theory, comes from Friedman (1953), which states that people may not actually solve complicated problems of utility maximization: they just behave as if they do so – so that the models provide a good description of observed behaviour. Goett (1988) uses this argument to explain the use of life-cycle calculations in modelling 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".

Regarding SSL, the experts in a NRC (2005) study, expected that to overcome market barriers for technology adoption SSL

Table 3 – Metrics to evaluate the cost and efficiency of lighting technologies.

Real Discount Rate	(i) Should the new technology be adopted?	(ii) How cost-effective is the technology likely to be?
d=[3% - 300%] for households* d=[3% - 30%] for commercial decision makers.** d=[2.5% - 10%] for regulatory agencies***	Levelized annual cost (LAC)	Cost of conserved energy (CCE) Cost of conserved carbon (CCC)†

Notes: d = discount rate; * = based on the review of implicit discount rates for energy efficient investments in end-use technologies (see Table 2) and discount rates in Rubin (2001); ** = based on Rubin (2001) corporate interest rates; *** = based on Rubin (2001) expenditure of public funds rates of return and in OMB Circular No A-94, revised in January 2006. † = cost effectiveness metric in this context only makes sense for desicion making in regulatory agencies.

Table 4 – Metrics for the cost and efficiency of lighting technologies.

Metric	Expression	Notation
LAC ($/year)	$LAC = I\dfrac{d}{(1-(1+d)^{-n})} + O\,\&\,M$	LAC = Levelized annual cost ($) I = investment ($) d = discount rate n = # of years that the technology lasts O&M = operation and maintenance costs ($)
CCE ($/kWh-year) or CCC ($/tonCO$_2$-year)	$CCE = \dfrac{LAC_{new\ tech} - LAC_{old\ tech}}{E_{old\ tech} - E_{new\ tech}}$ $CCC = \dfrac{LAC_{new\ tech} - LAC_{old\ tech}}{C_{old\ tech} - C_{new\ tech}}$	CCE= cost of conserved electricity ($/kWh-year) CCC= cost of conserved GHG emissions ($/tonCO$_2$eq.-year) LAC $_i$ = levelized annual cost of the technology i ($/year) E $_i$ = annual electricity consumption the technology i (kWh/year) C $_i$ = annual indirect equivalent GHG emissions of technology i (tonCO$_2$eq/ year) Old tech might refer to incandescent bulbs or fluorescent bulbs, depending on the scenario.

would need to reach: (i) an upfront cost of $ 33/klumen, (which DOE (2006) expects by 2007-2008); lifetimes of 50,000 h; a 70 % of lumen output by the end of life and a Color Rendering Index (CRI) between 80 and 100. Also, the experts from the NRC (2005) panel referred the need of having building and lighting infrastructures available for installation, known standardized equipment specifications, information available to the lighting industry and information to support interior design needs.

Finally the discussion on the metrics for the cost of light might be enlarged when one considers efficient lighting technologies adoption from an institutional perspective, in a context of regulatory agencies planning, R&D and societal outcomes of different technology investments. In that context, efficient lighting technologies play a major role not only as a tool for reducing overall electricity consumption reduction, but also for peak load management and GHG emissions reduction. In the context of cost-effectiveness literature on energy efficiency, usually the *cost of conserved energy* (CCE) is determined (Meier, 1982, Sathaye and Murtishaw, 2004). However, Sathaye *et al* (2004) point out that earlier analysis of energy-efficiency options typically ignored effects as changes in labour, material, and other resource requirements that are often monetized. The authors agree with Worrell *et al.* (2004), which does include these other costs and monetized benefits.

Also, note that Jaffe and Stavins (1994) identify distinct notions of optimality in the context of the energy efficiency-gap: the economists' economic potential, the technologists' economic potential, the hypothetical potential, the narrow social optimum and true social optimum, and argue that each of these has associated with it a corresponding definition of the energy-efficiency gap. In summary, to be behaviorally realistic studies of efficient lighting technologies need to distinguish between the different relevant actors: (i) residential consumers (household); (ii) commercial consumers and (iii) regulatory agencies. Concerning what do the metrics related to the cost of light aim to present, the following categories should be considered: (i) when does the new technology become cheaper then the current one and when would a residential/commercial consumer be likely to switch to the new technology? (ii) How cost-effective is the new technology likely to be? Table 3 and Table 4 describe what are the appropriate criteria to use for lighting technologies comparisons.

Numerical Examples for the Cost of Light

In this section we provide a comparison on the cost of investing in the different lighting technologies between 2007 and 2015 for some illustrative scenarios. The decision is whether to remain with the *status quo* technology, switch to/remain with fluorescent bulbs or to SSL. We assume that the illumination level remains constant so that wattage is the free variable. DOE (2006) targets for LED lighting are used. We assume that incandescent and fluorescent technologies are mature and will not change in the next nine years. We assume the lamp mix, wattage and hours of operation proposed by DOE (2002) for the residential and commercial sector. The analysis is performed on a one-bulb basis. A partly probabilistic and partly parametric model in Analytica® with a analysis for the main inputs of the model was developed as well as a fully parametric matrix-based model in MatLab, mapping the levelized annual cost of the technology and the cost of conserved electricity for each technology.

PURE ENGINEERING ECONOMICS ANALYSIS – EXAMPLE OF A COMMERCIAL BUILDING

Considering a pure engineering economics analysis for a commercial building, we assume a daily operation of 10 h/day, which is the average in US commercial buildings (DOE, 2002) and a 5 % market discount rate. The LAC of an SSL investment is less than half that of an incandescent and will reach CFLs and fluorescent tubes between 2008-2013 (Figure 2).

Note that in this case, even assuming discount rates as high as 20 %, SSL has a lower LAC than incandescent lamps, and reaches the LAC of fluorescent lamps by 2013. If the commercial consumer only perceives the upfront cost, a switch to SSL is not going to be made in the near future, since SSL bulbs only reach CFL levels by 2013.

We conclude from this analysis that in a pure engineering economic perspective, the actors in the commercial sector should be thinking about switching their incandescent bulbs to SSL right now. Given that most of the illumination in the commercial sector is provided by fluorescent technology, and assuming that DOE expected developments for the SSL technology are fulfiled, commercial building owners should think about switching to SSL in the near future.

EFFECT OF HIGH IMPLICIT DISCOUNT RATES – EXAMPLE OF A TYPICAL US HOUSEHOLD

Considering now an average household analysis, we assumed an illustrative discount rate of 20 % to incorporate the body of literature on implicit discount rates discussed above. We conclude that considering high implicit discount rates, and a small daily usage of 2 hours, SSL will perform better than incandescent lamp by 2008 and better than CFLs by 2013 (Figure 3). Thus, in the next 5 years, residential consumers should think about switching to SSL.

SENSITIVITY ANALYSIS

Despite the promising results for SSL levelized annual cost, there is a large uncertainty on the actual lamp mix, wattage, operation hours, future electricity prices, consumer adoption behaviour, and on how SSL performance and cost will evolve over time. Taking those considerations into account, a sensitivity analysis was performed for the LAC and the difference between the LAC among the different technologies. The inputs considered were the luminous efficacy of different lamp types, lifetime, lamp cost, electricity price, discount rate, and the number of hour of operation. Figure 4 shows the sensitivity of the LAC of SSL in 2010 and the difference between the LAC of a SSL and incandescent investments. Note that a negative value on the LAC difference corresponds to a win-win situation for the consumer, since the LAC of switching to the new technology is lower then an investment in the current tech-

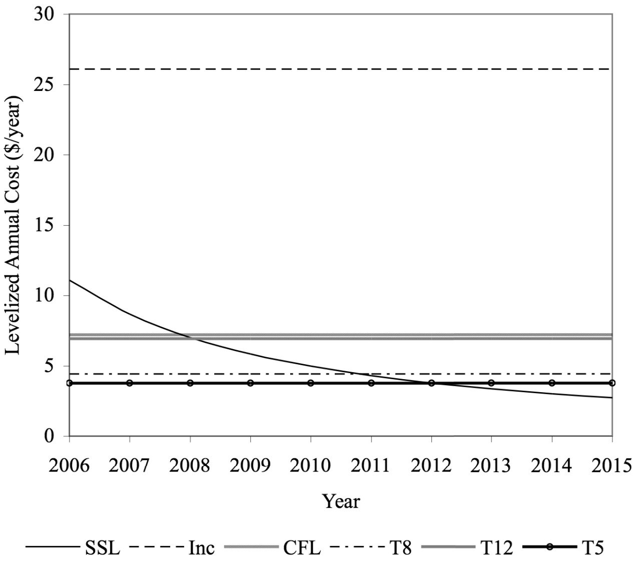

Figure 2 – LAC for each technology. Here we assume an electricity price of 0.10 $/kWh, a discount rate of 5 % and that the lamps are used 10 h/day, 365 days/year. SSL development in terms of efficacy, upfront cost and lifetime are assumed to follow DOE (2006) targets; incandescent, CFL, T5, T8 and T12 bulbs are assumed to not evolve significantly during the next 9 years; it is assumed that when comparing the bulbs, the same illumination level and number of bulbs are required. The wattage of the bulbs is the free variable. Incandescent bulbs characteristics: efficacy = 14 lumen/W; lifetime = 1,000 h; lamp cost = 0.5 $/lamp; CFL characteristics: efficacy = 69 lumen/W; lifetime = 10,000 h; lamp cost = 4 $/lamp; T5 characterisitcs: efficacy = 104 lumen/W; lifetime=20,000 h; lamp cost = 2 $/lamp; T8 characteristics: efficacy = 92 lumen/W; lifetime = 12,000 h; lamp cost = 2 $/lamp; T12 characteristics: efficacy = 69 lumen/W; lifetime = 5,000 h; lamp cost = 2 $/lamp; Sources for lamp typical characteristics: Color Kinetics (2004), DOE (2006), Tsao (2002, 2004), www.bulbs.com. Values for lamps charateristic are approximate.

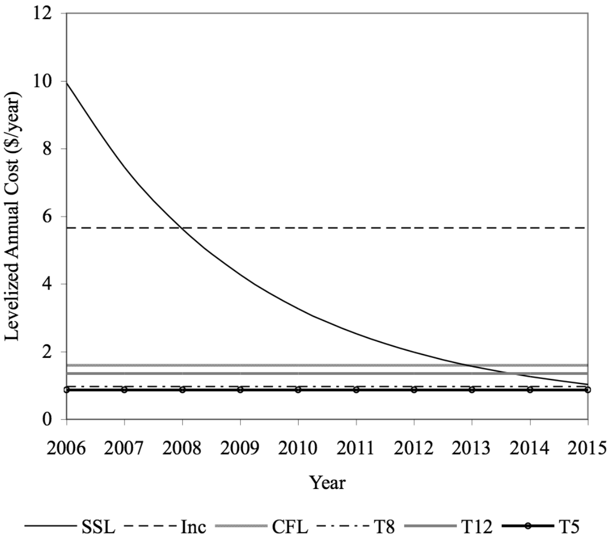

Figure 3 – LAC of lighting technologies over time ($). Here we assume a discount rate of 20 % and a daily usage of the bulbs of 2/day (365 days/year). For the remaining parameters, the same assumptions as in Figure 2 apply.

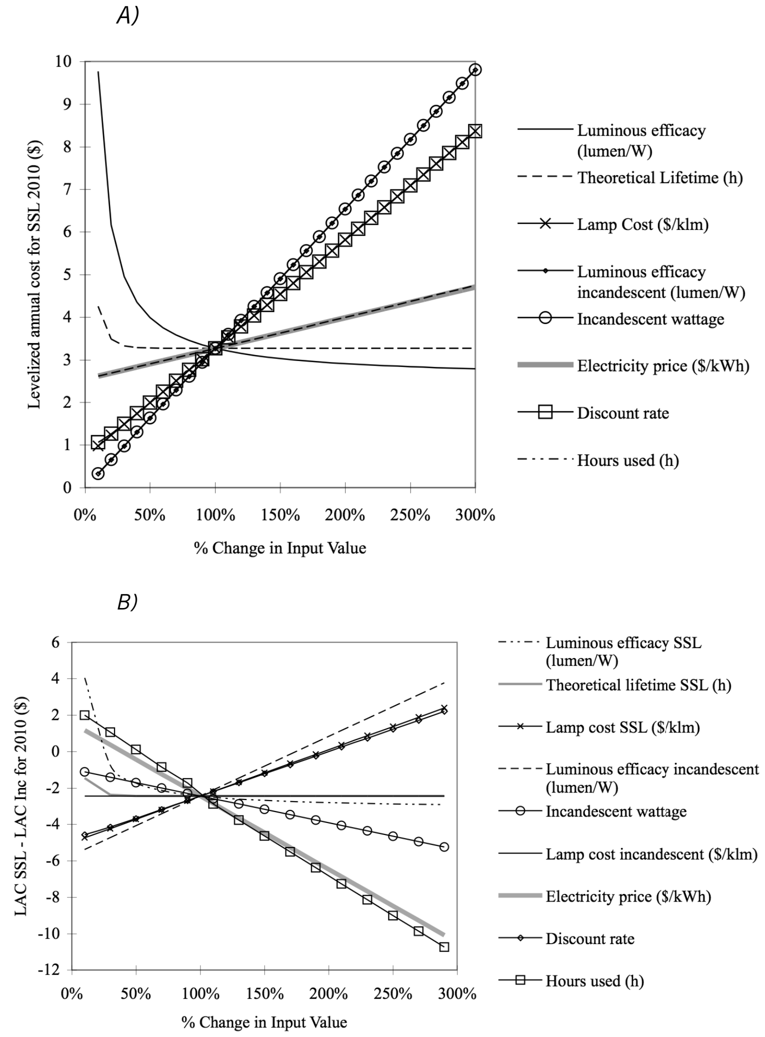

Figure 4 A and B – A) Sensitivity Analysis: Levelized annual cost from investing in SSL in 2010; B) Sensitivity Analysis: Difference between the LAC of SSL and incandescent in 2010. For the inputs, we have: the electricity price (100 %=0.10 $/kWh), the number of hours used (100 %=2 h/day), the discount rate (100 %=0.20), the luminous efficacy (100 %=92 lumen/W), the lifetime of SSL (100 %=50,000 hours) which vary from vary from 0 % to 300 %. Similar analysis was performed assuming different initial values for the inputs; #bulbs=1.

nology. According to our simulations, by 2010, SSL is a better investment than incandescent lamps even assuming a high discount rate (d = 20 %) and only using a lamp 3 h/day. The assumptions concerning the incandescent bulb characteristics are determinant to the LAC of SSL, since we assumed the illumination level to remain constant no matter the technology chosen. However, the luminous efficacy of incandescent lamps is not likely to evolve much in the next nine years, given the maturity of the technology. The LAC of SSL is very sensitive to the luminous efficacy achieved by SSL for values lower than approx. 46 lumen/W, but changes less than a dollar after reaching that efficacy which was already surpassed in 2006 (White light SSL efficacies in 2006 were approx. 55 lumen/W). Also, after SSL reaches a lifetime corresponding to 12,000 hours, the LAC becomes quite insensitive to the theoretical lifetime of SSL. Again, that lifetime threshold was already reached in 2002. It is noteworthy to say that one of the features that remain critical to achieve a competitive level for SSL is the initial upfront cost.

Some might argue that only SSL should be subjected to high implicit discount rates, since other technologies are well established in the market. Such a simulation found that if SSL is subjected to discounts rates as high as 30 % and the remaining technologies having discount rates as low as 3 %, the choice of SSL occurs with a lag of at most 2 years compared to the previous scenario, so that if a lamps is only used 2 h/day (providing thus a sort of worst case scenario for SSL competitiveness), the LAC of SSL is lower than incandescent by 2009 and reaching CFL and fluorescent levels by 2015.

Daily Lighting Electricity Consumption Load Shapes

Assuming low and high household lighting estimates found in the literature as well as our own estimates, and the normalized hourly lighting profiles from the Buildings Technologies Program, average household hourly lighting profiles are obtained (Figure 5). Then, assuming average bulb wattages from DOE (2002), we were able to obtain an estimate of the profile of the number of bulbs that are on by each hour of the day on the residential average U.S. household. This leads to 2 to 6 bulbs being used between 6 am and 8 am, and between 2 and 13 bulbs being used during the evening lighting peak, between 4 pm and 23 pm. Since there is already a large uncertainty on the number of bulbs being used, seasonality was not taken included in this analysis. We assume that the bulbs are incrementally added when the lighting load demand is increasing, and incrementally switched off when the lighting load is decreasing. Focusing only on the evening peak, so as to not double count the lamps, we estimate that there are 8 lamps being used for more than 3 hours a day. At 3 hours a day usage, and using a 10 % discount rate, the LAC of SSL is already lower than incandescent bulbs, so in a LAC base, consumers could switch those bulbs to SSL in 2007. However, SSL lamps only become as competitive as CFL or other fluorescent technologies by 2010-2014 (depending on the fluorescent technology considered).

Finally, the perspective of a regulatory agency in terms of decision making would be to understand the costs of promoting alternative illumination technologies per kWh not consumed, or per ton of carbon dioxide avoided. In Figure 6, we show our estimates of the cost-effectiveness, measure in terms of cost per electricity conserved. The grey area represented the range of levelized annual cost for different generating capcity for electricity production (the highest values corresponding to photovoltaics and the lower to coal power plants). We conclude that by 2010 the cost-effectiveness of SSL makes it a better strategy than investing in generating capacity, even if the base case for estimating the cost-effectiveness is an already efficient technology as CFL.

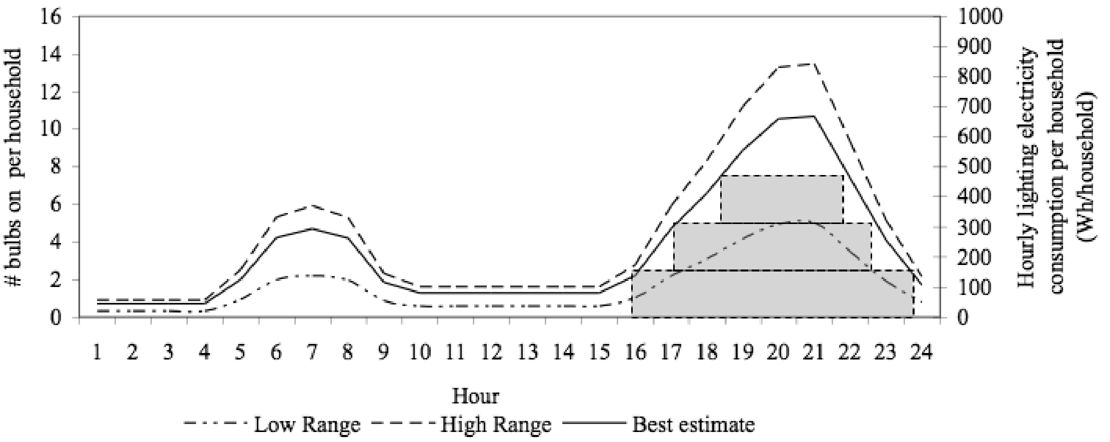

Figure 5 – Hourly lighting electricity consumption and bulbs usage of an US average household. Typical profile based on normalized lighting profiles of Building America (2006); the low range profile is obtained using Vorsatz, Koomey et al., (1997), the high range profile is obtained using Manclark et al. (1992) and Nelson (1992); the best estimates are obtained using our estimates for 2005 lighting consumption, based on DOE (2002) figures. The curves on the figure can be read both in terms of the number of bulbs that are turned on (left axis) and the hourly electricity consumption from the household (on the right axis).

Conclusions, Policy Recommendations and Future Work

Improving the energy efficiency of lighting technologies will lead to reduced energy use and associated emissions of CO_2 and conventional pollutants. However, a variety of behavioral factors can limit the rate of adoption of new and efficient lighting technologies, as experienced with CFLs in the past. According to our analysis, SSL will be competitive compared to most of the lighting technologies before 2015. SSL investments might make sense right now for large costumers, but the successful adoption of this technology will depend on the economical, institutional and regulatory context.

The upfront cost of SSL is the main barrier that needs to be addressed by the industry when pursuing the target of high market penetration. R&D efforts should focus on bringing the upfront costs down, since other important features, such as color balance, power supply, and controls are rapidly evolving and are not likely to be barriers to adoption.

Given the high upfront cost of the technology, different product standards for the commercial and residential sector should be considered. Residential consumers might not benefit much from further increase in the lifetime of the SSL bulbs, since lamps lifetimes might already be beyond the time a household remains in the same housing unit. Thus, product standards for residential lighting application could require product lifetimes of 30,000 hours, but requiring higher lighting quality and lower upfront costs. Commercial decision makers might benefit from expected future SSL 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 SSL or other competing technologies. For example, Wal-Mart recently initiated a vigorous marketing strategy for CFL, with the aim to sell 100million CFL bulbs in 2007. This strategy is likely to lead to significant electricity savings for the residential consumers. However, that strategy will also lead to an increase in the time of the stock turn over, and thus lagging the adoption of SSL. On the other hand, there might be positive spillover effects in terms of information on potential energy savings from lighting to consumers, and SSL adoption might benefit from that . Note that particularly for residential customers a gradual transition from incandescent to SSL through CFL might be an effective cost strategy, as it would offer customers opportunity to benefit from rapid advances in SSL technology, rather than locking into current state for long period due to the long life expectancy of the SSL bulbs.

There are other policy options (e.g. strategies that allow consumers to perceive the levelized cost of lighting;), which warrant future analysis. There are several aspects of SSL adoption that were not covered in this work, such as the implications of SSL adoption on air conditioning and heating demand, potential to flatten peak demand loads, and accordingly the marginal electricity price, which deserve future attention. Also, there are certainly other technical options (smart sensors, OLEDs, greater use of sunlight) that should be analyzed as this work goes forward. Finally, this work has identified a number of fundamental methodological limitations in the adoption and diffusion of new technologies that clearly deserve more attention in the future.

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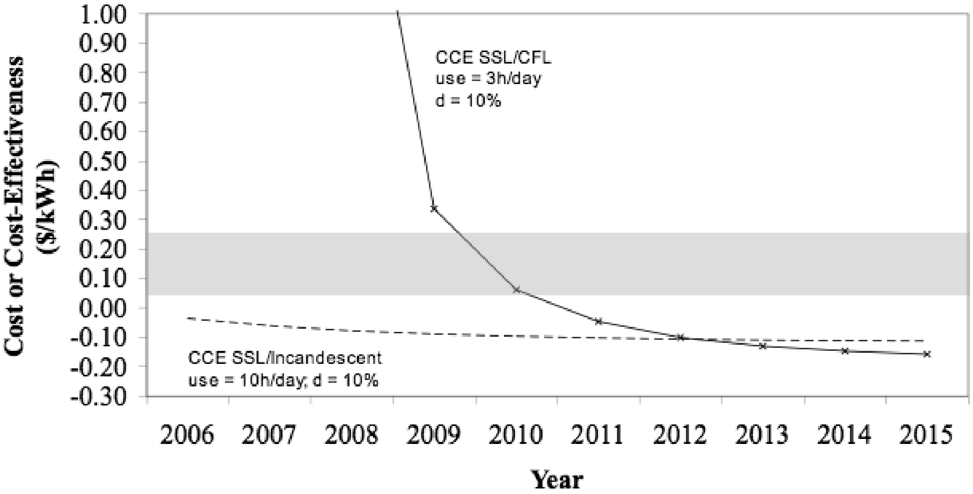

Figure 6 – Cost-effectiveness of SSL versus Incandescent lamps ($/kWh) and versus fluorescent lamps ($/kWh). Discount rate=10 %. The range of levelized annual cost for the different generation technologies was adapted from Bergerson (2005) and from the CA Energy Commission (http://www.energy.ca.gov/electricity/levelized_cost.html). The figure shows that an SSL investment is already better an incandescent lamp investment. SSL is already a better investment than new generation capacity if incandescent bulbs are taken as base case and by 2009, investing in SSL becomes a better strategy than new generation capacity if the base case is CFL. Note that there is a uncertainty on how SSL technology is going to evolve. Here, only the bulb costs are considered.

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