THE CASE FOR A NATIONAL RESEARCH PROGRAM ON SEMICONDUCTOR LIGHTING[1,2]

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EXECUTIVE SUMMARY

Dramatic changes are unfolding in lighting technology. Semiconductor light emitting diodes (LEDs), until recently used mainly as simple indicator lamps in electronics and toys, have become as bright and efficient as incandescent bulbs, at nearly all visible wavelengths. They have already begun to displace incandescent bulbs in many applications, particularly those requiring durability, compactness, cool operation and/or directionality (e.g., traffic, automotive, display, and architectural/directed-area lighting).

Further major improvements in this technology are believed achievable. Recently, external electrical-to-optical energy conversion efficiencies exceeding 50% have been achieved in infrared light emitting devices. If similar efficiencies are achieved in the visible, the result would be the holy grail of lighting: a 200*lm/W* white light source two times more efficient than fluorescent lamps, and ten times more efficient than incandescent lamps.

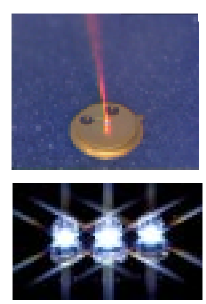
This new white light source would change the way we live, and the way we consume energy. The worldwide amount of electricity consumed by lighting would decrease by more than 50%, and total worldwide consumption of electricity would decrease by more than 10%. The global savings would be more than 1,000*TWh/yr* of electricity at a value of about US$100B/year, along with the approximately 200 million tons of carbon emissions created during the generation of that electricity. Moreover, more than 125*GW* of electricity generating capacity would be freed for other uses or would not need to be created, a savings of over US$50B of construction cost.

Bringing about such revolutionary improvements in performance will require a concerted national effort, of the order $0.5B over ten years, tackling a broad set of issues in semiconductor lighting technology. The effort would also require harnessing the most advanced high-technology companies, the best national laboratory resources, and the most creative university researchers in this area.

Fire

Candles and Lamps

Bulbs and Tubes



Semiconductors

[1] This white paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999.

[2] Revision B:03/30/1999

1 INTRODUCTION

Energy is the lifeblood of our economy, and a critical building block for global peace and security. Its generation incurs huge costs: both direct economic costs as well as indirect environmental costs (smog and particulate emissions, acid rain, global warming, waste disposal, etc). And, the direct economic costs will only increase as concern heightens over how to reduce the indirect environmental costs.[3] As a consequence, there is great benefit to enhancing the efficiency with which energy is used -- virtually all major energy consumers from transportation to heating to the various users of electricity are constantly being examined for energy saving opportunities.

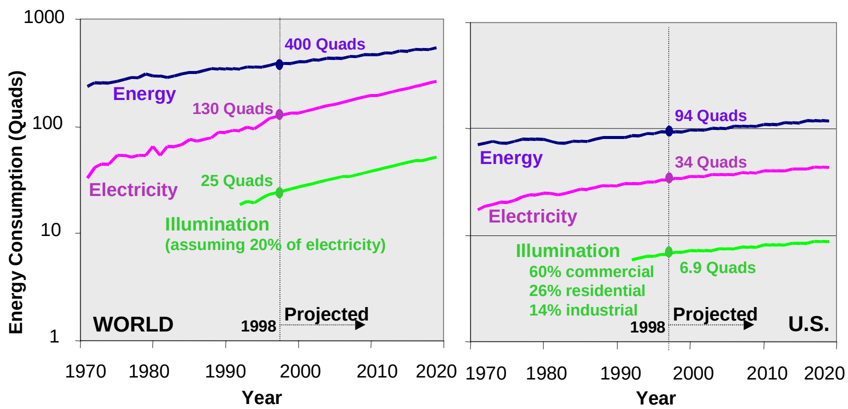


Figure 1. World (left) and U.S. (right) consumption of energy for use in all forms (blue), for use in electricity generation (pink), and for use in illumination (green).[4] One Quad (one quadrillion BTUs) of primary energy consumed is roughly equivalent, after energy conversion and transmission losses, to 92TWh of electricity at the wall plug.

Among the most widespread, important, and *growing* uses of energy is the electricity used for lighting. As illustrated in Figure 1, in the U.S., about 20% of all electricity consumed,[5] and about 7.2% of all energy consumed, can be estimated to be used for lighting. In 1998, the cost was about 6.9 quads of primary fuel energy (with an associated 112 million tons of carbon emissions), and about 637*TWh* of actual electricity consumed at a cost of about US$63B. Worldwide, about 3.4% of all energy consumed can be estimated to be used for lighting, a percentage that is expected to increase with standard of living. In 1998, the worldwide cost was about 25 quads of primary fuel energy (with an associated 410 million tons of carbon emissions), and about 2,350*TWh* of actual electricity consumed at a cost of about US$230B.

Because of this large contribution of lighting to worldwide energy consumption, it is no wonder that the lighting industry receives its fair share of inquiries regarding energy reduction. In 1995, the three major US lighting manufacturers – GE Lighting, Osram/Sylvania and North American Philips

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[3] In the Kyoto Protocol of 1997, e.g., the developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. The United States agreed to reduce emissions from 1990 levels by 7% during the period 2008 to 2012.

[4] World data taken from the International Energy Agency (http://www.iea.org), and assuming projected energy, electricity and illumination growth rates of 1.6%, 3.5% and 3.5%. U.S. data taken from the Energy Information Administration (http://www.eia.doe.gov), and assuming projected energy, electricity and illumination growth rates of 1.2%. We acknowledge Gerald Hendrickson and Arnold Baker at Sandia National Laboratories for assistance interpreting the data.

[5] According to a recent EPRI report (TR-106196), the four top electricity-consuming applications in the U.S. in 1995 were: electric motors (24%), cooling/refrigeration (18%), lighting (17%), and space/water heating (16%). These percentages include the three major market segments -- residential, commercial and industrial -- but not street lights, traffic signals, nor the use of electricity to remove the heat generated by lighting in air-conditioned buildings. The Industrial Lighting handbook estimates that it takes 1 kW of electricity in the air-conditioning system to remove 3 kW of heat generated by lighting. After including the above omissions, it is safe to say that, in the U.S., lighting consumes at least 20% of electricity and ranks a close second to the 24% consumed by electric motors.

– sponsored a three-day workshop to identify promising research areas for improving the efficiency of white light sources. This workshop confirmed that "lighting consumes about 20% of the electric power production of the nation." One of the most revealing figures in the resulting EPRI report[6] is a graph of luminous efficiency vs. time for the major "true" white light sources: incandescent, halogen, and fluorescent lamps. As illustrated in Figure 2, none of these workhorse technologies has shown any significant efficiency improvements during the preceding 20 years!

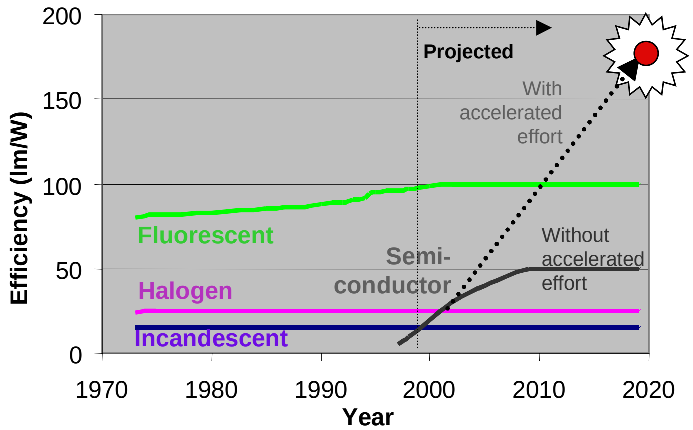

Figure 2. Condensed history and projection of efficiencies (in lm/W) of vacuum tube (incandescent, halogen and fluorescent) and semiconductor (LED) white lighting technologies.

There is, however, one striking exception. Light emitting diodes (LEDs), a 40-year-old semiconductor technology, have steadily improved their efficiencies and power levels to the point where they are knocking incandescent and halogen lamps out of such traditional monochrome lighting applications sockets as traffic lights and automotive tail lights. And, a recent breakthrough in the green and blue makes LEDs a serious contender for conventional white lighting.

It is the purpose of this white paper to call attention to this new lighting technology and to the potential impact of a concerted national effort to advance it further. Such an effort would fill a need identified by the U.S. Department of Energy for research in advanced lighting technologies.[7] And, such an effort would target the technology we believe has the highest potential to create an ideal lighting source, both in quality and in cost. LEDs and their semiconductor variants are visually appealing, convenient and environmentally friendly, and it is our assessment that they have a realistic shot at reaching the industry nirvana of an efficiency of 200*lm/W*.

If semiconductor lighting can achieve this goal through a concerted national effort, the lighting industry would be revolutionized. An efficiency of 200*lm/W* would be more than 2x better than that of fluorescent lamps (80*lm/W*), and more than 10x better than that of incandescent lamps (15*lm/W*). If current lighting, with an aggregate efficiency of roughly 50*lm/W* (in between the efficiencies of fluorescent and incandescent lamps), were replaced by semiconductor lighting with an aggregate efficiency of 150*lm/W* (somewhat less than the target), then the electricity currently used for illumination would decrease by a factor of three, from 2,350*TWh* to 780*TWh*. This would represent a decrease in global electricity use of about 13%, and a decrease in global energy use and associated carbon emissions of 2.3%.

In some ways such a revolution in lighting could be compared to the revolution in electronics that began 50 years ago and is only now reaching maturity. Just as for electronics, glass bulbs and tubes would give way to semiconductors. And, just as for electronics, the increased integrability, density, performance, and mass manufacturability of semiconductors may drive an explosion of additional, not-yet-thought-of uses for lighting. One can even speculate on visionary concepts in

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[6] The workshop is summarized in EPRI report TR-106022.

[7] This need has been identified in the Department of Energy's ongoing "Vision 2020" lighting technology roadmapping activity. It has also been identified separately by the Department of Energy's Office of Building Technology, State and Community Programs, whose program plan consists of three overall goals: (1) Accelerate the introduction of highly efficient technologies and practices through research and development; (2) Increase minimum efficiency of buildings/equipment through codes, standards and guidelines; and (3) Encourage use of energy efficient technology through technology transfer and financial assistance.

which information and illumination technologies combine to create ultra-fast wireless local-area networks that are mediated through building lights!

We begin this white paper in Section 2 with a brief history of LED technology, and compare its current and projected performance and cost with those of conventional technology. In Section 3, we discuss its penetration (and replacement of conventional technology) in signaling and lighting applications. We expect LED penetration into signaling applications, currently dominated by inefficient filtered incandescent lamps, to be rapid, and to drive continued improvements in performance and cost. These improvements will, in turn, enable gradual penetration of LEDs into lighting applications, currently dominated by a mix of incandescent and fluorescent lamps. Although the penetration will be gradual, its global impact will already be very significant, since lighting represents such a large fraction of global energy consumption. In Section 4, we describe an economic model for that global impact.

We believe much more dramatic improvements to be possible. In Section 5 we discuss such improvements, the resulting acceleration of the penetration of semiconductor lamps into lighting applications, and the resulting huge impact on global energy consumption. Finally, in Section 6 we discuss in general terms the daunting technical challenges, and the magnitude and nature of a national research program that might enable these challenges to be overcome.

2 History and Projection of LED Performance and Comparison with Conventional Lamps

LEDs have had a "colorful" history, alternately pushed by technology advances and pulled by key applications. The first demonstration was in 1962 by General Electric. The first products were introduced in 1968: indicator lamps by Monsanto and the first truly electronic display (a successor to the awkward Nixie tube) by Hewlett-Packard. The initial performance of these products was poor, around 1*mlm* at 20*mA*, and the only color available was a deep red.[8] Steady progress in efficiency made LEDs viewable in bright ambient light, even in sunlight, and the color range was extended to orange, yellow and yellow/green. Within a few years, LEDs replaced incandescent bulbs for indicator lamps, and LED displays killed the Nixie tube.

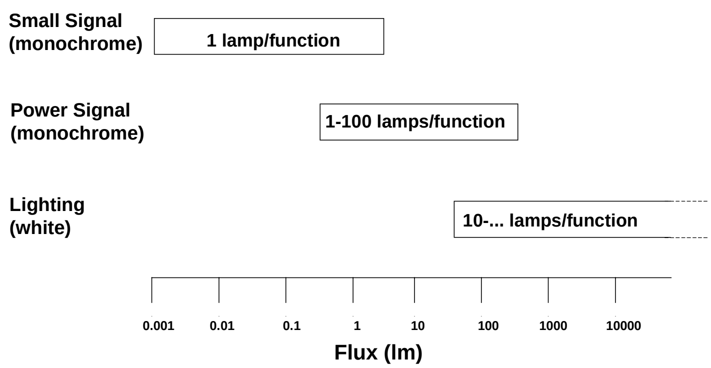

Figure 3. Flux and numbers of lamps required for various classes of LED applications: low-medium-flux "signaling" applications, in which lamps are viewed directly, and medium-high-flux "lighting" applications, in which lamps are used to illuminate objects. Current LED lamps emit 0.01-10lm of light.

Until 1985, LEDs were limited to small-signal applications requiring less than 100*mlm* of flux per indicator function or display pixel. Around 1985, LEDs started to step beyond these low-flux small signal applications and to enter the medium-flux power signaling applications with flux requirements of 1-100*lm* (see Figure 3). The first application was the newly required center high-mount stop light (CHMSL) in automobiles. The first solutions were crude and brute-force: 75 indicator lamps in a row or in a two-dimensional array. It did not take long to realize that more powerful lamps could reduce the lamp count, a significant cost advantage. *This was the first situation where efficiency became an*

[8] For comparison, a 60*W* incandescent lamp emits 6 orders of magnitude higher light flux (about 900*lm*).

issue and for which the market was willing to pay a premium.[9] So, in the late 1980's, we saw the first horse race for efficiency improvements. By 1990, efficiencies reached 10*lm/W* in the GaAlAs materials system, for the first time exceeding that of equivalent red filtered incandescent lamps. Nevertheless, even higher efficiencies were desired to continue to decrease the number of lamps required per vehicle. Plus, the GaAlAs system was limited in color to a deep red, above 640*nm*.

This horse race triggered the exploration of new materials system with still higher efficiency and a wider color range. First emerged GaAlInP materials, covering the range of red to yellow/green and quickly exceeded 20*lm/W* in the 620*nm* red/orange part of the spectrum. In 1995, Hewlett-Packard projected a room-temperature efficiency of 50*lm/W* by the Year 2000, with a theoretically possible efficiency of 150*lm/W* that could challenge that of even the most efficient conventional light source, the yellow low-pressure sodium lamp. This projection spawned a joint venture with Philips, and accelerated the use of LEDs in power signaling applications.

In 1993, there was another breakthrough in LED technology. Based on work at several universities, both in the US and Japan, Nichia Chemical Corporation in Japan announced a fairly efficient blue material, GaN. Efficiency improvements followed quickly, together with an extension of the color range from blue to green (430-530*nm*). Now, LEDs could cover practically the entire visible spectrum, enabling their entry into additional power signaling applications such as traffic lights.

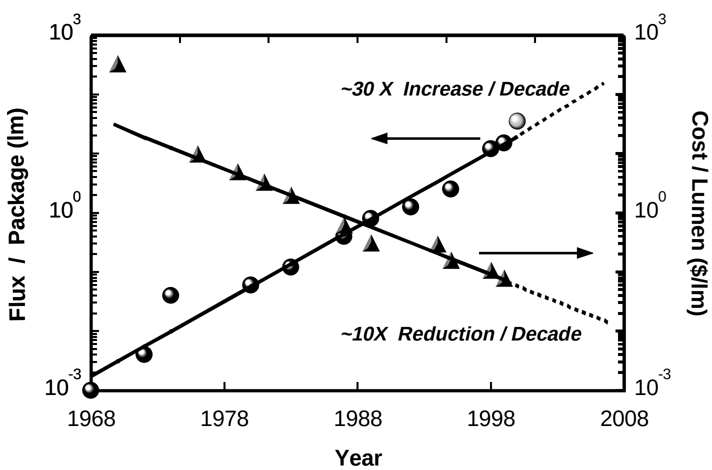

Figure 4. Historical and projected evolution of the performance (lm/package) and cost ($/lm) for commercially available red LEDs. This data was compiled by R. Haitz from HP historical records.

Before going on, we want to emphasize here the importance of the power signaling market on LED evolution. The penetration of LEDs into this market depended (and continues to depend) critically on performance and cost. Solutions based on large numbers of small-signal lamps are too expensive, thus demanding the development of higher-power LEDs. This evolution is illustrated in Figure 4 covering the period from first LED sales in 1968, projected to 2008. In a Moore's-law-like fashion, flux per unit has been increasing 30x per decade, and crossed the 10*lm* level in 1998. Similarly, the cost per unit flux – the price charged by the LED supplier to OEM manufacturers – has been decreasing 10x per decade and will reach 6*cents/lm* in 2000. At this price, the LEDs in a typical 20-30-lm CHMSL contribute only $1.50 to the cost of the complete unit![10] In other words, the power signaling market drove, and continues to drive, improvements in the design and manufacturing infrastructure of the compound semiconductor materials and devices on which LEDs are based.

These improvements have led to the LED efficiencies summarized in Figure 5 for the visible wavelength range 450-650*nm*. Because the efficiencies vary with temperature, the data shown refer

[9] Back in the small signal days where one lamp was used per function, a 2x improvement in efficiency did not allow customers to use half a lamp. And, to reduce the drive current of an indicator lamp from 20*mA* to 10*mA* did not matter very much in an instrument that used 10-100*W* for other electronic functions.

[10] Although this cost is higher than that of an incandescent light bulb, it is low enough that other factors, such as compactness, styling freedom and absence of warranty cost, easily make up the difference.

to a junction temperature of 85°C. For the GaAlInP material system (red to yellow), we show efficiency data for: (a) the expected Year 2000 production capability of the industry, (b) the expected Year 2005 production capability, and (c) the best results reported as of 1999, shown to substantiate our confidence in the Year 2005 forecast. For the GaInN material system (green to blue), we show efficiency data for: (a) current average production performance of the industry leader, Nichia, and (b) a curve that is 50% higher. According to Nichia, their best results seem to be 50% above their average, and we assume that these best results will become average industry production within five-six years (by the Year 2005).

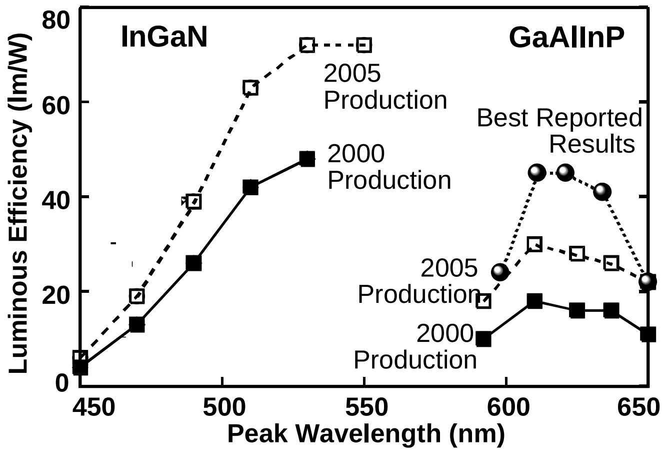

Figure 5. LED efficiency at an 85°C junction temperature as a function of wavelength. For the two dominant materials systems (GaAlInP and GaInN) we show current production data and our best estimate for Year 2005 production.

At this point, LEDs of reasonable efficiency span virtually the entire visible wavelength range (with the exception of a narrow window in the yellow-green), and it is possible to create white light sources. One approach, which gives white light sources with excellent color rendering properties, involves combining 3-6 LEDs of different colors. Another approach involves combining a blue LED with down-conversion phosphors in a relatively inexpensive package. Both of these approaches involve some losses (color mixing in the former and photon down-conversion in the latter), but nevertheless can achieve good overall efficiencies. In fact, assuming the efficiencies of Figure 5, and a color mixing loss of 15%, semiconductor white light sources made with red, yellow, green and blue LEDs will already exceed that of standard 60-100*W* incandescent lamps in the Year 2000.

Lamp Type	Power (W)	Efficiency (lm/W)	Lifetime (hrs)
Standard Incandescent	15	8	1,000
Standard Incandescent	100	15	1,000
Long Life Incandescent	135	12	5,000
Halogen	20	12	3,000
Halogen	300	24	3,000
Compact Halogen	50	12	2,500
Compact Fluorescent	11	50	10,000
Standard Fluorescent	30	80	20,000
White LED 2000	Any	20	100,000
White LED 2002	Any	30	100,000
White LED 2005	Any	40	100,000
White LED 2010	Any	50	100,000

Table 1. Efficiencies and lifetimes of various conventional and semiconductor white light sources. Similar to Figure 5, the semiconductor white light sources refer to a junction temperature of 85°C.

This is illustrated in Table 1, which compares current and projected efficiencies of white LED-based lamps with those of the most widely used conventional white light lamps. The most popular incandescent lamps with a power rating of 60-100*W* have an efficiency of around 15*lm/W* and a rated life of 1,000 hours. The efficiency of incandescent lamps drops off at lower power ratings or for lamps with a longer 3,000-6,000 hour rated life. Halogen lamps show a similar pattern covering the range of 12-24*lm/W*. Fluorescent lamps at 80*lm/W* are the most efficient white light sources and dominate commercial and industrial lighting applications.

In comparison, using the projections shown in Figure 5, LED-based white light sources will have efficiencies of 20*lm/W* in the Year 2000, should reach 40*lm/W* in the Year 2005, eventually leveling off in the 40-60*lm/W* range by the Year 2010. These efficiencies exceed significantly those of standard 60-100*W* incandescent lamps.

Moreover, the comparison between LED and incandescent lamp efficiencies favors LEDs even more in the case of monochrome applications. For these applications, there are no color-mixing losses for the LEDs, but there are additional filtering losses for incandescent lamps. [11] As shown in Table 2, LED efficiencies exceed those of filtered incandescent lamps by a large margin over the entire visible wavelength range except for yellow, where the two technologies are close to parity.

Color	Filtered Long-Life Incandescent Efficiency (lm/W)	Year 2000 LED Production (lm/W)
Red	1-6	16
Yellow	4-8	10
Green	3-10	48
Blue	1-4	13
White	12	20

Table 2. Current (Year 2000) LED efficiencies in broad color ranges as compared to those of filtered long-life incandescent lamps. The LED efficiencies refer to a junction temperature of 85°C.

3 LED PENETRATION INTO POWER SIGNALING AND LIGHTING APPLICATIONS

The penetration of LEDs into the signaling and lighting markets is a complex issue. Like in any new technology, in the early years LED solutions will be considerably more expensive than conventional solutions. To justify their selection, the higher initial cost has to be compensated with lower operating costs or other tangible benefits.

With the dramatic progress that has been made in LED performance and cost over the past decades, however, LEDs have already begun to penetrate a number of monochrome signaling applications. We describe several of these applications in Appendix A, which include traffic and automotive lights, and large-screen outdoor TVs. Energy savings are the driving force for traffic lights; ruggedness, long life and styling are important factors in automotive tail lights; and lamp density and integrability are the key factors in TV screens with 3,000,000 pixels over an area of $600m^2$.

The penetration of LEDs into white light applications will be much more difficult. A comparison between Table 2 (monochrome efficiencies) and Table 1 (white light efficiencies) shows why. At Year 2000-2005 performance levels, an LED-based red traffic light consumes 10x less power than its filtered incandescent alternative, while an LED-based white light consumes only 2x less power than its standard incandescent alternative, and about 2-3x *more* power than its fluorescent alternative.

As a consequence, in the very near term, the white light applications that can realistically be attacked will be lower-flux "specialty" lighting applications in the 50-500*lm* range, currently dominated by incandescent and compact halogen lamps with relatively modest efficiencies in the range of 8-12*lm/W*. We describe several of these applications in Appendix A, which include accent and landscape lights, and flashlights.

General lighting of residential, office, retail or industrial buildings, which consumes much more total energy than either signaling or specialty white lighting, will be much more difficult to penetrate

[11] Note that this comparison does require some caution, due to the variability in efficiency of the filters used to produce various colors. For instance, the filter used in a red traffic light absorbs 90% of the white light and results in a deep red color. The red filter of an automobile taillight has a wider transmission band and yields an orange-red color. Yellow and green filters are fairly efficient and transmit a large fraction of the white spectrum. Blue filters are comparable to the transmission of red filters. Nevertheless, filtered incandescent color sources will always be less efficient than unfiltered white sources, while LEDs are inherently monochrome and do not suffer filtering losses.

for several reasons, the foremost being cost. Lamp cost: a 100 W incandescent lamp delivering a flux of 1.5*klm* costs only \$0.50, or \$0.33/*klm*, while a comparable LED-based light source would cost over \$150, or roughly \$100/*klm*. Efficiency: Incandescent lamps with a rating of 60-150*W* have an efficiency of 14-16*lm/W*. To recover the initial difference in lamp cost in a reasonable time, today's white LED efficiency of 20*lm/W* is insufficient. White LEDs will not cross the critical threshold of 30*lm/W* before 2002. Maintenance labor cost: The majority of incandescent lamps are used in residential buildings where the cost of maintenance labor is not an issue.

Penetration into these higher-flux general lighting markets thus depends on continued efficiency improvements to the point where the energy savings pay back the initial cost penalty in a reasonable time, i.e. in six years or less. To quantify this, we define a "breakeven" time, which is the period over which energy savings equal the difference in initial lamp costs. A simple calculation of breakeven times is given in Appendix B for a standard 100 W incandescent lamp and an LED lamp of equivalent flux. For example, in the Year 2002, when LED lamp retail prices are expected to be of the order 100\$/*klm* with an efficiency of 30*lm/W*, the breakeven time for a daily operating time of 12 hours is just about six years. This is a marginal payback situation and penetration will be quite limited. But continued improvements in LED cost and efficiency should gradually expand the penetration.

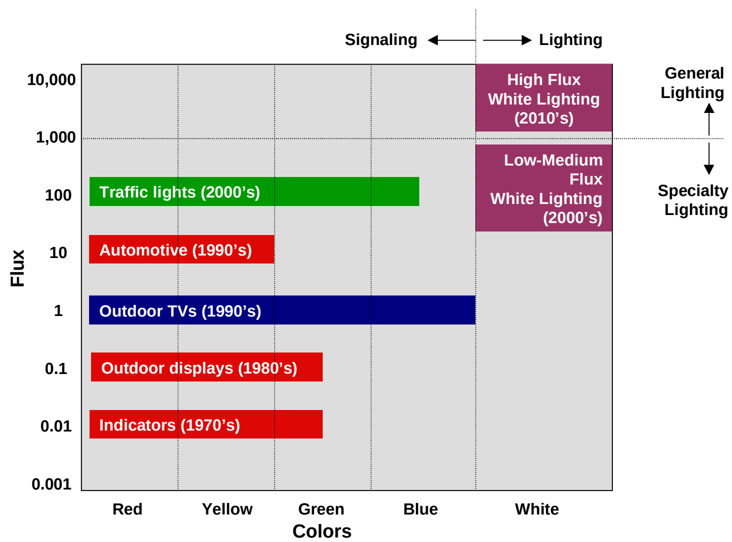

Figure 6: The stepping stones from LED indicators to LED illumination over half a century from 1970 to 2020. Signaling applications are mostly monochrome; lighting applications are mostly white. Specialty lighting includes monochrome and low/medium flux white lighting and is dominated by incandescent lamps. General lighting includes high flux white lighting and is dominated by a combination of incandescent and fluorescent lamps.

It is helpful at this point to remind ourselves that these improvements will almost certainly continue at a rapid rate, due to the pressure that has been, and will continue to be, supplied by the power signaling market. To emphasize this, we show in Figure 6 the key stepping stones in the cost evolution of LEDs. Large outdoor displays with thousands of LED lamps made sense only after the growing volume for indicator lamps had reached hundreds of millions of units per month at a price of 10 cents or less per unit. LEDs in automotive rear combination lamps will not make economic sense until the cost/lumen approaches 5*cents/lm*. Replacing a red traffic light with 12-18 LEDs has created LED power packages that can handle a heat dissipation of several Watts at a reasonable cost. In turn, such a capability is needed for the front turn indicators which are mounted close to the head lamps of the car. The cost sensitive and potentially huge automotive market will force the industry along a steep cost learning curve. And, it is this cost pressure that will enable white LEDs to cross the critical threshold of 100\$/*klm* and 30*lm/W* that we estimate will be achieved in the Year 2002.

When this critical threshold is achieved, LED-based white lamps will begin to replace incandescent and compact halogen lamps in the following situations:

Highly directional lamps: Our prototype work with Philips has shown that LED-based lamps are far more effective in distributing light to where it is needed rather than trapping light within the luminaire or sending part of it into undesirable directions ("light pollution"). In one particular example that we studied extensively, the difference was 2x over a conventional light source. If this advantage can be realized in many applications, then a 25*W* LED lamp with an efficiency of 30*lm*/*W* can do the job of a 100W incandescent lamp with its 15*lm*/*W* efficiency. In this case the break-even point for a daily operation of 12 hours is a respectable two years!

High Maintenance Cost: In all commercial applications the cost of maintenance labor is real. A regular incandescent lamp with 750-1000 hours operating life has to be replaced 25 times over 5 years if it is operated 12 hours/day. Depending on the situation, the maintenance cost could be comparable to the initial cost of an LED based lamp. Some applications have very high maintenance cost, i.e., street and tunnel lights, and swimming pool lights. To shut down a tunnel or to partially drain a swimming pool is both a nuisance and expensive.

Long Life: Lamps with an extended life rating of 3000-6000 hours or lamps that are designed for a shock and vibration environment have a reduced efficiency in the range of 8-12*lm*/*W* increasing the energy consumption by 25-100% over a regular incandescent lamp. The breakeven time is reduced correspondingly.

Dimmability: Most dimmable lamp applications use incandescent lamps. Dimming an incandescent lamp reduces its filament temperature slightly and dramatically kills the efficiency. The result is a much reduced flux at nearly the same energy consumption. In contrast, an LED based lamp can be dimmed with practically no loss in efficiency. Also, a dimmed incandescent lamp changes its color temperature and subsequently its color rendering properties while an LED lamp maintains its color temperature.

Year	LED Efficiency *(lm/W)*	Cost *($/klm)*	Breakeven time at Equal flux *(Years)*	Half flux *(Years)*
2002	30	100	6.1	2.1
2005	40	75	3.8	1.5
2010	50	47	2.2	0.9

Table 3. Summary of breakeven times at which LED lamps operated 12 hrs/day become economical over standard 100W incandescent lamps with 15lm/W efficiencies. The equal-flux and half-flux breakeven times assume LED flux equal to, and half, that of the incandescent lamp flux., respectively.

Beyond this critical threshold (100$/*klm* and 30*lm*/*W*), penetration will increase as LED technology continues to improve. As indicated in Table 1, we expect the 85°C efficiencies to increase to 40*lm*/*W* in 2005 and to 50*lm*/*W* in 2010. In parallel, we expect white LED cost to drop by at least 10% per year, reaching $75/*klm* in 2005 and less than $50/*klm* in 2010. With these improvements, the breakeven times will be substantially reduced, as shown in Table 3. A strong replacement of incandescent lamps in commercial and industrial applications should start in 2005, and should reach residential applications well before 2010.

Note that we do not expect that, at efficiencies of 50*lm*/*W* or less, LEDs will penetrate that part of the general lighting market currently served by fluorescent lamps, either compact or large tubes. Only in applications where fluorescent lamps lead to large, undesired light spillage or to significant losses within the luminaire could LED-based lamps "break-even" over fluorescent lamps by the Year 2010. Therefore, for the analysis described in the next Section, we do not count on any LED penetration into the fluorescent lamp market.

4 Impact on Energy Consumption

As discussed in the previous Section, in the Year 2002 we expect LED-based white lamps with an efficiency of 30*lm*/*W* to start to replace incandescent lamps with an efficiency of 12*lm*/*W*. What will be the global economic and energy impact of the penetration of LED lamps into these general lighting applications? To answer this question requires creating an economic model for the evolution of lighting usage and LED penetration. We discuss a simple such economic model in Appendix C.

The model depends on a multitude of assumptions, some of which characterize lighting and electricity usage generally, and others of which characterize LED cost, performance and market penetration. The assumptions we have made are described in detail in Appendix C. They are somewhat conservative, but because lighting is such a large market, they nonetheless imply very significant global economic and energy savings. The total worldwide electricity used for lighting in the Year 2000, e.g., is expected to be over 2,000*TWh*, at a cost of approximately US$200B!

Table 4 summarizes the projected savings. The key assumption is that LED penetration begins, as expected from the above breakeven analysis, in the Year 2002, gradually increases through the Year 2020, where it saturates at roughly 10%. The saturation occurs when LEDs reach an efficiency plateau of 50*lm/W*, which is sufficient for significant penetration into that part of the general lighting market currently served by incandescent lamps, but not sufficient for penetration into that part of the general lighting market currently served by fluorescent lamps.

	Year	2005	2010	2015	2020	2025
LED Penetration	%	0.05	0.5	4	9	10
Energy Savings per year	TWh/yr	1	18	150	370	440
Energy Cost Savings per year	M$/yr	100	1,800	15,000	37,000	44,000
Energy Generating Capacity Savings	GW	0.1	2	17	42	50

Table 4. Projected global savings in energy, energy cost, and energy generating capacity due to LED penetration into specialty lighting markets, assuming LED efficiencies level off at 50lm/W in 2010.

The projected savings are obviously very significant. The $44B savings in 2025 corresponds to 15% of the $300B conventional lighting would have cost. According to this model we have replaced 10% of the least efficient installed flux base and saved 18% of the electricity used in lighting, or 440*TWh*. That also represents a 15% reduction in the carbon emissions associated with electricity, or 88 million tons. These are of course ongoing savings in electricity usage every year. There is also a savings in the electricity generation capacity that would be freed for other uses or that would not need to be created. That savings is 50*GW*, the equivalent of 37 large 1.35*GW* power plants, which would require more than $20B to construct.[12]

5 EFFICIENCY BREAKTHROUGH!

The above analysis is based on evolutionary improvements in the efficiency of white LED based light sources. Based on our 30 years of LED leadership and on the experimental data that we have seen so far we are quite confident that the 50*lm/W* goal for 2010 can be achieved without counting on any breakthrough. But 50*lm/W* corresponds to an energy conversion from electricity to light of only 12%. Is this the end? How far can we push the technology? In this section we will develop the arguments for a very bold scenario that could revolutionize the entire lighting industry.

In 1997, Sandia reported a conversion efficiency exceeding 50% for a vertical cavity surface emitting laser (VCSEL) at a wavelength of 980*nm*. This VCSEL generated 2*mW* of light at a drive current of 2*mA* and a drive voltage of 2*V*. Such a VCSEL takes up only a 10μm diameter circle. Replicating these VCSELs with a 40μm spacing yields 500 VCSELs in a 1mm^2 chip. Each VCSEL has a reasonable large series resistance allowing a massive parallel operation from a single current source. Driving the array with 1*A* at 2*V* should result in a 1*W* optical source with a 50% conversion efficiency. Nobody has built such a 1*W* source yet, but 300*mW* prototype arrays have demonstrated the feasibility of this concept.

[12] The cost per GW is approximately $400M for combined-cycle natural gas plants, and is higher for other types of power plants (coal, oil, nuclear).

Now comes a leap of faith: Let us assume that a major national R&D program involving National Labs, universities and industry can replicate the projected infrared result at any wavelength in the visible spectrum: 1W of optical flux with a conversion efficiency of 50% in a 1mm² chip anywhere from blue to red. As a next step, imagine that we could build a white lamp consisting of six chips with a 30*nm* wavelength spacing between 470*nm* and 620*nm*. This 12*W* lamp would generate an optical flux of 6*W* or 2,400*lm* and have a superior color rendering index approaching 100. With an efficiency of 200*lm/W*[13], it would beat incandescent lamps by more than an order of magnitude and the most efficient fluorescent lamps by more than 2x. But that is not all. The VCSELs have well-defined beams – the photons are trained while they are young! - and light distribution is quite straight forward. A large fraction of "light pollution" and internal losses can be avoided. This feature is worth another factor of 2x in many lighting applications. Such a lamp would truly revolutionize the industry!

Back to reality! The best reported efficiency of red VCSELs is in the 12% range and no one has yet succeeded making any yellow, green or blue VCSELs. The problem is enormous! There are many arguments suggesting a "Mission Impossible". But since the concept does not violate any laws of physics and since the infrared results are so compelling, a large national research project for the "Wonder Bulb" can be justified (see below).

There are two other approaches worth exploring. Can we develop blue or UV power lasers with 50% conversion efficiency? Those lasers could pump a phosphor. The conversion process results in a down-conversion related energy loss, and 200*lm/W* would not be possible, but we still could beat all other light sources, including the LED.

The second approach is LED based. Why should LEDs be limited to a 12% conversion efficiency (50*lm/W*)? In the red GaAlInP system, Hewlett-Packard recently reported a quantum efficiency of 53% corresponding to an energy conversion efficiency of 45%. How far can we push the GaInN system? Is the 30-50% range a realistic target and worth a major research project?

Suppose we are successful in creating such a light source. What will be the global economic and energy impact of the penetration of semiconductor lamps into not only that part of the lighting market served by incandescent lamps, but into that part of the lighting market served by fluorescent lamps ? To answer this question requires creating an economic model for the evolution of lighting usage similar to that described previously. The model is described in detail in Appendix C. The overall projected savings are summarized in Table 5. The key modified assumptions from the previous model are:

- Semiconductor lamp penetration is accelerated from 2005 on, reaching 2% in 2010. And, instead of flattening out at 10%, the penetration continues to rise and reaches 55% in 2025 (see Table C2 in Appendix C).
- The cost per *klm* of flux is assumed to be the same as in the previous model, because the cost forecast is already quite aggressive.
- Since this more efficient lamp can attack the fluorescent lamp installations, the efficiency of the replaced lamps keeps rising to 65*lm/W* in 2025. Similarly the average efficiency of the new lamps keeps rising and reaches 150*lm/W* in 2025. This value is less than the 200*lm/W* mentioned above. The difference is due to the fact that we need a broad family of lamps and not all lamps will be at 200*lm/W*.

[13] 200*lm/W* would be the efficiency of a white light source made up of six LEDs spaced evenly by 30*nm* from 470*nm* to 620*nm* and which convert electrical to optical power with 50% efficiency at each wavelength.

	Year	2005	2010	2015	2020	2025
LED Penetration	%	0.05	2	12	30	55
Energy Savings per year	TWh/yr	2	67	330	720	1100
Energy Cost Savings per year	M$/yr	200	6,700	33,000	72,000	110,000
Energy Generating Capacity Savings	GW	0.2	8	38	82	125

Table 5. Projected global savings in energy, energy cost, and energy generating capacity due to semiconductor lighting penetration into specialty and general lighting markets, assuming semiconductor lighting efficiencies increase to 150lm/W and beyond.

To put the above into perspective: The $110B saving in 2025 corresponds to 37% of the $300B conventional lighting would have cost. That also represents a 37% reduction in the carbon emissions associated with electricity, or 220 million tons. These are ongoing savings in electricity usage every year. The savings in the electricity generation capacity that would be freed for other uses or that would not need to be created is 125*GW*, the equivalent of 93 large 1.35*GW* power plants, which would require approximately $50B to construct.

6 Magnitude and Nature of a National Lighting Research Program

The benefits of the efficiency breakthrough discussed in the previous section and summarized in Table 5 are very large indeed, both for the U.S. and for the world. However, a set of enormous technical problems has to be tackled, and the breakthroughs that are required are not likely to be achieved without a concerted, coordinated national effort. In this section, we discuss the nature, size and possible structure of such an effort.

A Technical Areas

As mentioned in the preceding section, a set of enormous technical problems has to be tackled. To increase the probability of success and to accelerate the LED penetration in the early years the following three technical areas have to be addressed:

1 Cost Reduction of the LED Lamp. III-V materials and processes are a far cry from the processes used in the silicon industry. The wafers are small and fragile, processes are complex and have practically no margin for error (narrow process windows). Yields are variable and the device parameters vary all over the map. The development of robust manufacturing equipment and processes with substantially improved controls is one of the most important elements of this program.

The manufacturing infrastructure technologies developed would also have substantial spin-off benefit to a wide range of compound semiconductor device types. These include optoelectronic (LEDs, diode lasers, VCSELs, modulators, and photodetectors), electronic (both discrete transistors as well as analog and digital integrated circuits), sensor, and solar cell devices. The market for these devices and chips is expected to grow from approximately $6B in 1997 to over $10B in 2002. It is composed of chips and applications ranging from high-speed lasers and integrated circuits for optical fiber and RF/microwave wireless communications to high-efficiency photovoltaic cells for satellites to short-wavelength lasers for digital videodisk (DVD) players/recorders.

2 Breakthrough in LED Efficiency. As mentioned earlier, the best reported LED efficiencies are around 45% for red. How far can we push yellow GaAlInP, and the blue and green GaInN, materials? We must reduce the resistive losses in the wide bandgap GaInN material. Can we reduce the temperature sensitivity of GaAlInP such that operation at 85°C does not cut the efficiency by 2x relative to room temperature? Can we avoid the efficiency drop in GaInN with increasing current

density? Will a reduction in dislocation density improve the efficiency of GaInN? All of these questions are critical to improving LED efficiency.

It is also not just sufficient to have high quality material. Even after light has been created within an LED structure, its extraction presents considerable difficulty, as there are numerous parasitic channels by which light can be trapped and absorbed within the structure. Clever and innovative design and chip design integrated with materials advances may be key here. The development of advanced and comprehensive electrical transport and optical models for testing new ideas will also be important.

3 Lasers. This technical area would be aimed at creating efficient lasers at all colors. Ideally, these would be vertical-cavity surface-emitting lasers (VCSELs), as these appear to be the most amenable to batch manufacturing. However, VCSELs are perhaps the toughest solution. Innovative, breakthrough thinking and a large number of potential options would have to be explored. A dozen universities with some of our most brilliant scientists should participate. An especially important breakthrough would be efficient blue or UV lasers. This approach could be based on Fabry-Perot lasers or VCSELs. Fabry-Perot lasers with reasonable product life have been reported at 410*nm*. The efficiency is still low and improvements are expected. However, this technology must achieve a 50% conversion efficiency in the blue or UV to be attractive. The subsequent conversion to longer wavelength light includes a down-conversion shift and, therefore, an additional conversion loss. Resonant-cavity LEDs may also play a role here.

We note that these technical areas complement and build upon ongoing fundamental research in semiconductor materials and devices at universities. As illustrated in Figure 7, these research programs have a much longer time horizon of 8-16 years, and are much more broadly targeted at fundamental III-V semiconductor materials and device research. Likewise, these technical areas complement and build upon ongoing evolutionary development activities at industrial laboratories. These development activities have a much shorter time horizon of 0-8 years, and are very narrowly targeted at improving current devices. *The program we envision would fill this gap, with an intermediate time horizon of 4-12 years. It would be aimed directly at semiconductor lighting, but would not be confined to evolutionary, low-risk improvements of current devices.*

We also note that these technical areas would complement separate efforts aimed at developing building and lighting architectures that could, at a system level, exploit best the unique characteristics of semiconductor lighting while still appealing at a consumer level to human ergonomics. Many of these efforts are already ongoing (e.g., the RPI lighting institute, Lawrence Berkeley's lighting research center, and other efforts connected to the U.S. Department of Energy's Office of Building Technology, State and Community Programs), and could be expanded to include a forward-looking component on semiconductor lighting.

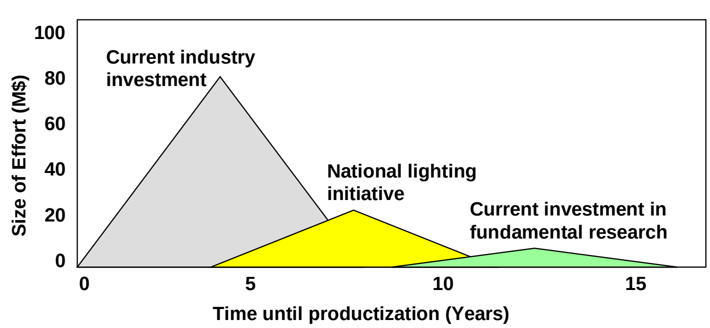

Figure 7. Current and proposed R&D investments in the area of semiconductor lighting.

B Organization

Of the above technical areas, the manufacturing technologies addressed in area 1 have to be tackled by industry with important help from national laboratories. Universities can participate in exploring some subtasks. In the remaining technical areas 2 and 3, universities can and must play an important role. We envision that clusters of universities, similar to the existing DARPA centers, jointly attack a series of well defined research tasks followed by a technology transfer to the industrial partners.

We further envision that one or more of the national laboratories could coordinate the overall project, along with the university programs. These non-profit national laboratories can be the recipient of proprietary information from various companies, and hence can help facilitate work that would require access to such information and that would also benefit the larger consortium.

In principle, there may be more than one consortium. In the major consortium that we envision, industry participation should include and be limited to the 2-3 major players in this area: HP/Philips, Emcore/WiTech/GE and, possibly, Cree/Osram/Sylvania. The 2-3 groups mentioned above are all established lighting suppliers and are all partnering with the leading North American and European technology companies in compound semiconductors. A consortium with these nearly equal partners should ensure a fairly effective cooperation since all partners have comparable opportunities to exploit the technology. With smaller competitors in the consortium, we fear that the openness of the cooperation would suffer -- the smaller partners would demand an equal share in the technology for a very small contribution to the overall program. If smaller companies would like to participate in some way, then we suggest that they do so through separate consortia.

C Size

How much DOE support is required to achieve critical mass and to assure a credible opportunity to succeed with a significant breakthrough? Let us start with an estimate of what the lighting industry (the 3 above partnerships) will spend on short-term development of monochrome and white power LEDs, not including the development of small signal LED indicators and displays: $60-80M in 2000, $100-120M in 2005 and $120-150M in 2010. This spending chain will sum to $1B over 11 years.

This total frames the magnitude of the investment, but is dwarfed by the magnitude of the potential cost savings indicated in Table 4. It is an upper bound to the DOE support required for the initiative we propose, but should not be far off the mark. An enormous set of technical problems has to be tackled, and the breakthroughs that are required are not likely to be achieved without a similar critical mass. Hence, we believe a DOE supported program should be of a comparable magnitude, i.e., $500M for the period from 2000 to 2010. We would propose to start with $30M in 2000, $40M in 2001 and $50M for 2002 and thereafter. This program represents a smaller investment, appropriate for a higher-risk program with longer-term impact, but the pay-off is even more profound, as indicated in Table 5.

How should these funds be distributed? Our initial proposal is in the range of 30/30/40% to 25/25/50% for universities/national laboratory/industry. There should be an additional condition on the funds going to industry: 3:1 matching. The industry should not receive more than 1$ for every $3 of its own R&D spending in semiconductor-based lighting. This degree of industry cost-sharing for a program this forward-looking and of this magnitude is unprecedented, and is an indication of our seriousness.

D Risk Exposure

Some people will quickly raise the question: If this is such a great deal, why doesn't the industry pay for it out of their profits? The answer is quite simple: The profits aren't there, at least not in the next six years.

Between now and the middle of the next decade, the power signaling and lighting segments of the LED industry will be losing money. The calculation behind this statement is quite simple. In 1999, Strategies Unlimited estimates that the power signaling market represents $400M of the $2,100M LED market. At a growth rate of 20%, it will grow to $1,200M in 2005. In 1999, and, most likely, also in 2005, approximately half of this market will be controlled by Asian companies.

The illumination market will grow from nothing today to $200M in 2005 bringing the combined power signaling and lighting markets to $1,400M or $700M for the non-Asian participants.

Because of the potential size of the illumination market beyond 2005, we estimate the R&D spending of the U.S. and European power LED industry will be very large: $60-80M in 2000 and $100-120M in 2005. In 2000, this R&D spending represents 30-40% of revenue dropping to 14-17% by 2005. With cost of goods sold typically in the 60-70% range, and selling and administrative expenses of 10-15%, simple arithmetic shows that in 2000, the industry will be in the red to the tune of 10-20% of revenue and, with some luck, might break even in 2005. The only way out of this dilemma is a drastic reduction in R&D spending. If the industry chooses this option, then the critical threshold of 30*lm/W* and $100/*klm* for penetration of white lighting moves out, well beyond 2005. The energy savings discussed in Appendix C and Table 4 will shift correspondingly to later years.

The only way to achieve the energy savings of Table 4 and, subsequently, of Table 5, is through a government-industry partnership, where the industry commits to the LED program (and its financial losses in the early years), and the government commits to an LED or laser based breakthrough attempt of comparable magnitude.

There are benefits for both sides that justify this risk exposure. We create a new segment of the lighting industry that is LED based. The value of this segment is substantially enhanced by the government's funding of the breakthrough attempt. If the attempt is successful, the industry's return off-sets the losses in the early years and the taxpayer obtains a substantial reduction in electricity bills, year after year for a long time to come.

E Intellectual Property

Intellectual property and how to deal with it are issues that always arise with technology research and development partnerships. Among the issues that would have to be resolved: Licensing terms for university-generated IP, sharing of national-laboratory-generated IP, ownership and licensing terms for industry-generated IP supported by DOE funds.

Resolving these issues will require some discussions between the parties involved, but we do not believe they are a deal killer. Sematech, the consortium of semiconductor manufacturing equipment suppliers, had to solve a similar problem several years ago. The Department of Commerce's Advanced Technology Program also has a great deal of experience with this. Indeed, we would expect to borrow ideas from other successful government-industry-university partnerships in intermediate time-horizon technologies. These technologies are forward-looking enough that sharing the risk and the rewards is reasonable even for the largest companies, while important enough that the nation cannot afford not to invest.

7 CONCLUSIONS

In summary, we have presented a case for a national research program on semiconductor lighting. Enough progress has been made since the first products in the 1960's to know that this technology is real and that it has the potential to alter significantly the economics of energy usage.

We have also identified an investment gap that, if closed, could revolutionize the development and ultimate application of this technology. We believe this gap represents a unique opportunity to engage our nation's best scientists and engineers in a university/national lab/industry research program whose success would truly change the way we live.

APPENDIX A: EXAMPLES OF POWER SIGNALING AND LOW-FLUX WHITE LIGHTING APPLICATIONS

In this Appendix, we describe some examples of specialty lighting applications for which LEDs, with current and projected performance and cost, can compete effectively with incandescent solutions. Note that, as with any relatively immature technology, in the early years LED solutions will be more expensive than incandescent solutions. To justify their selection, the higher initial cost has to be compensated by a combination of benefits such as energy savings over the product life, switching speed, ruggedness, operating life, etc.

Monochrome Applications

Traffic Lights: A 12 inch traffic light in the US usually uses a 135*W* long-life light bulb in combination with a red, yellow or green filter. The most advanced red LED solution uses 12-18 lamps per traffic light and consumes a total of 14*W* including power-supply losses. A single LED traffic light sells for $110 compared with a $30 cost of an incandescent solution. The operating cost for electricity is approximately $10 per year for the LED compared with $90 for the incandescent model. The long operating life of the LED further reduces maintenance and emergency repair costs. The payback period for the higher LED investment is significantly less than one year. There are 10M red/yellow/green traffic lights in the USA consuming approximately 400*MW* of power. Red lights are lit on an average 65% of the time, 90% in the case of red arrows. Just converting all red lights to LEDs would reduce the US electricity consumption by approximately 250*MW*.

Safety/Emergency Lights: All large buildings with public access must have lighted emergency signs assisting the evacuation during a power failure. These "Exit" signs are designed with two incandescent or compact fluorescent lamps consuming 15-30*W*. A solution using approximately 100 cheap LEDs is comparable in cost to the conventional solution but uses only 5*W*. An LED solution not only saves $10 to $25 in annual electricity cost per sign, it also reduces the size and cost of the stand-by battery.

Decorative Lighting: For many years the trademark of the Ford Thunderbird was a taillight that covered the entire width of the car. When the car designers lowered the trunk lid all the way to the bumper for easier access, the wide tail light had to go. Slamming the lid when the tail light switched on would have broken the filaments of any incandescent lamp. So, for a few years in the late 80's the T-bird was built without its trade-mark tail light. For the 1992 model year, HP designed an LED based taillight that could survive repeated slamming of the trunk lid at night.

Another decorative lighting application emerged recently. The Australian branch of the McDonald's restaurant chain started to outline the roof lines of its buildings with a chain of red LED's. LED's are significantly more energy efficient than the competing neon technology. Red LED's are already at cost parity with neon and we expect similar cost parity for yellow, green and blue in 2-3 years. There are three major groups of commercial enterprises that are interested in decorative lighting: fast food chains, gas stations and hotels. All three groups wish to be noticed by people driving at night.

Automobile Tail Lights: As mentioned earlier, LEDs started on the tail end of cars shortly after the CHMSL was made a mandatory feature in the USA in 1982. As of 1999, LED's have reached a penetration of 30-40% of those cars equipped with a CHMSL. In the model Year 2000, the first rear combination lights (tail light, brake light and turn indicator) will emerge on high-end models in the US and Europe. Other functions such as side markers and front turn indicators will follow in the early years of the next decade. The reasons for choosing LED's are: shallow design that does not protrude into the trunk, styling freedom, reduced warranty cost, reduced power consumption (smaller alternator), etc. The red tail lights will convert from incandescent to LEDs quite rapidly, while the yellow front beam indicators will start converting in a few years and eventually the white back-up and license plate lights will follow. In total, the average car will contain 1000*lm* of LED flux: 300 red, 300 yellow and 400 white. Operating these LED chips at $100 A/cm^2$ will require about $20mm^2$ of LED material per car. The conversion of the passenger car market is quite sensitive to the cost differential between LEDs and incandescent solutions. The rapid decline of the cost per unit of flux for LEDs will lead to an LED penetration of > 50% by the end of the decade. The truck and bus market is less cost sensitive and failed tail lights require an immediate repair. As a result, the US truck market made a quick and nearly complete conversion to LEDs several years ago.

Outdoor Displays: Outdoor large video screens and changeable displays for advertising are target applications for LEDs. For instance, a $600 m^2$ video screen uses 3M 5*mm* LEDs. The LEDs are arranged in end-stackable tiles. The LED density is 1 lamp per $2cm^2$ of board space. The 5*mm* lamp itself has a cross section of $0.2 cm^2$, thus leaving 90% of the space empty. The LED flux is sufficient to fill the $2 cm^2$ space and achieve an average brightness of several hundred nits, good enough for outdoor viewing. As a matter of fact, the LED is the technology of choice for large video screens: it is the technology with the lowest cost of the empty space between the pixels, the cost of a two-sided printed circuit board. This is far cheaper than any glass based display technology! And since the LEDs are directly viewed and unfiltered, the power consumption is far lower than for any other competing display technology.

Low Flux White Light Applications

There are many lighting applications that are served by low power incandescent or halogen lamps. For instance, a 15*W* incandescent bulb generates 120*lm*, while a 50*W* compact halogen lamp generates 600*lm*. In this low-flux range from 100-600*lm* incandescent and halogen lamps are relatively inefficient and the energy savings from LED's can be significant, especially for applications with 12-24 hours of operation per day.

Shelf Lighting: In many retail outlets the merchandise is illuminated by lamps mounted on the underside of shelves. Incandescent and halogen lamps are quite hot and protective surfaces make the lamp fixture quite bulky. Fluorescent lamps require protection against the high operating voltage. LED based solutions are nearly ideal: cold, compact, efficient, dimmable, long operating life, low voltage, etc.

Theater/Stair Lighting: Low power lights are often used to illuminate stair steps in darkened theaters or to illuminate flights of stairs or gangways. The lights can either be mounted into the stair steps or they can be wall mounted. Very often, wall mounted units require a very directional beams wasting a large fraction of the light from an incandescent light bulb. The superior directionality of an LED based design should lead to significant energy savings.

Accent Lights: Accent lights are used in retail shops to highlight merchandise. In the residential market the main application is decorative ceiling lighting or highlighting artwork. The majority of the applications use incandescent or compact halogen lamps. LED based solutions will contribute to energy savings, lower maintenance cost and reduced fire hazards. Since most accent lights require a highly directional beam, LEDs should have a substantial power advantage over incandescent lamps.

Landscape Path Lights: These lights are used to provide orientation in public places such as parks, gardens, office grounds, etc. Most lights use low voltage, inefficient incandescent lamps and LEDs could make a contribution to energy savings. Also, low voltage operation should reduce installation cost.

Flashlights: Incandescent lamps in flashlights have chronically poor shock resistance. Many flashlights are thrown away when the incandescent filament breaks during a drop. The 40-60*lm* that are needed can easily be provided by an LED source. At \$0.05/*lm* the LED adds \$2.50 to the cost which is quickly made up by extended battery life.

APPENDIX B: BREAK-EVEN ANALYSIS FOR LED REPLACEMENT OF INCANDESCENT LAMPS

In this Appendix, we give a simple calculation of the breakeven time over which the energy savings due to LED replacement of an incandescent lamp equals the difference in initial lamp costs. The results are shown in Figure B1 for a standard 100*W* incandescent lamp and an LED lamp of equivalent flux. The assumptions we have made for incandescent lamp and LED cost, lifetime and efficiency are listed in Table 1 and in the inset to Figure B1. We do not expect significant improvements over time for the incandescent lamp technology, but do expect significant improvements for LED technology. In particular, we anticipate that the 85°C LED efficiency will start at 30*lm*/*W* in 2002, increase to 40*lm*/*W* in 2005 and level off at 50*lm*/*W* in 2010.

Note that the breakeven time is a strong function of the duty cycle, i.e., the fraction of time the light is on during a day. The longer the average daily burn time, the shorter the interval between incandescent lamp replacement, while with 100,000-hour lifetimes LEDs never need to be replaced on the time scale of this calculation. Therefore, the longer the average daily burn time, the higher the relative cost of the incandescent lamp solution, and the shorter the breakeven time. If the LED lamp has a useful service life significantly exceeding the breakeven time, then the additional energy savings are a bonus.

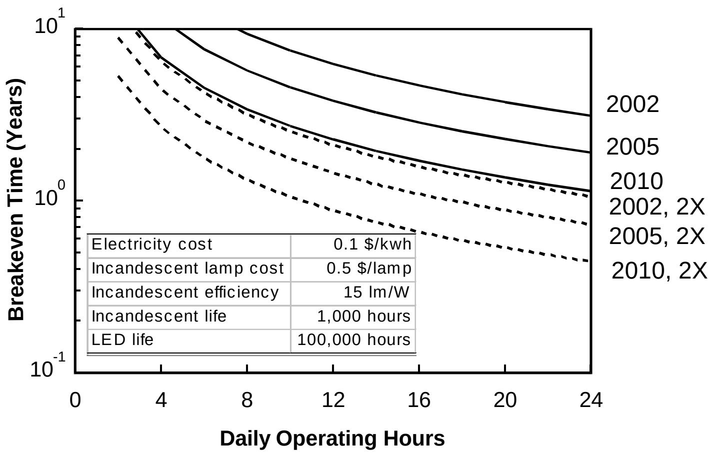

Figure B1. Breakeven time for LED lamps as a function of daily operating hours, for the projected efficiencies in the Years 2002, 2005 and 1010. The solid upper curves are based on LED fluxes equal to incandescent lamp fluxes. The dashed lower curves represent applications where the LED solution substantially reduces light spillage and thus requires only 50% of the flux of an incandescent lamp.

The solid lines refer to LED lamps with the indicated projected efficiencies for the Years 2002, 2005 and 2010. For instance, in 2002, for a lamp with an average operating time of 12 hours, a retail price of 100$/*klm* and an efficiency of 30*lm*/*W*, the breakeven time is 6.1 years. This is a marginal payback situation and penetration would be quite limited. Moreover, although such long average daily operating times are not that uncommon in industrial or commercial applications, they are rare in residential applications.[14] By 2010, however, improvements in efficiency and reductions in cost should reduce the daily operating time for a 5-year breakeven time to 5 hours. Now LED lamps make economic sense in many residential applications.

In addition, in many applications conventional lamps waste a significant fraction of the light. Inexpensive luminaires trap light or send it into unwanted directions ("light pollution"). 50% waste or losses are quite common. LED lamps are far superior in this respect and our studies have shown that a 750*lm* LED lamp can substitute for a 1500*lm* incandescent lamp in many applications. Since the initial LED cost is proportional to the flux rating of the lamp, this effect cuts the purchase cost and the energy consumption in half.

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[14] It should be noted that this analysis does not include any maintenance labor to exchange the burnt-out incandescent lamps. The break-even picture improves in favor of the LED when maintenance labor costs are significant.

With these assumptions, the breakeven time is substantially reduced, as shown in the dashed lines of Figure B1. For a daily operation of 8 hours the breakeven time is less than 3 years in 2002 and less than eighteen months in 2010. Now the cost of an LED lamp is practically equivalent to the electricity cost during the life of 3-4 incandescent lamps. This argument should be compelling to budget-conscious households.

APPENDIX C: ECONOMIC MODEL OF LED PENETRATION INTO WHITE LIGHTING

In this Appendix, we describe a simple economic model for the impact of LED penetration into specialty and general lighting markets. The model depends on a number of assumptions, some of which characterize lighting and electricity usage generally, and others of which characterize LED cost, performance and market penetration.

The assumptions that characterize lighting and electricity usage generally are listed in Table C1. According to DOE report DOE/EIA-0219(93), global electricity consumption in 1993 was 10,800*TWh*. With an estimated growth rate of 2% per year, the consumption in the Year 2000 will grow to 12,400*TWh*. Assuming that 20% is used for lighting and dividing by the number of hours per year, we compute an electricity consumption of 280*GW*. Further assuming that some of the energy is used to remove the lighting related heat, and in ballasts and drive electronics, we estimate that 200*GW* are used in the light generating process itself.

To estimate the amount of light that is actually generated, we must estimate the efficiency of the average light source. The spectrum of lamp efficiencies ranges from a few *lm/W* for low end incandescent lamps to 120*lm/W* for low pressure sodium lamps. The bulk is fluorescent at 80*lm/W* and incandescent/halogen at 15*lm/W*. Mercury lamps at 50*lm/W* are in between. If we assume that 50*lm/W* is the average efficiency for all lamp types, then the 200*GW* of electricity generates 10*Tlm* of flux at every instant in the Year 2000. Not every lamp is lit at any moment. We estimate an average lamp use of 30%. Then the installed lamp capacity is 10*Tlm*/30% = 33*Tlm*. For subsequent years, we assume a 2% growth rate.

Global electricity consumption in 2000:	10,000 TW-hours	Average lamp efficiency	50 lm/W
Growth rate:	2 %/year	Average light flux from lamps	10 Tlm
Electricity for lighting:	2,000 TW-hours	Average lamp duty cycle	30%
Cost of electricity per unit:	0.1 $/kW-hour	Installed flux capacity	33 Tlm
Cost of electricity for lighting:	200 G$/year	Growth rate of light flux	2 %/year
		Lamp mark-up in retail channel from OEM price	100%

Table C1. Assumptions on lighting and electricity usage used in the economic models shown in Tables C2 and C3.

The assumptions that characterize LED cost, performance and market penetration are entered directly into the spread-sheets shown in Tables C2 and C3. In terms of cost, we assume the retail price of LED lamps will start at 100$/*klm* in 2002 and decrease 10% per year between 2002 and 2015, reaching $75/*klm* in 2005 and less than $50/*klm* in 2010. Then, beyond 2015, we assume that it will drop 5%/year.

In terms of performance, we use two different sets of assumptions for the spreadsheets in Tables C2 and C3. For Table C2, we assume that LED efficiency saturates at 50*lm/W* in 2010, limiting penetration to specialty lighting applications dominated by incandescent lamps. For Table C3, we assume that LED efficiency continues to improve to 200*lm/W*, enabling penetration of general lighting applications dominated by fluorescent lamps.

LED penetration into incandescent white lighting market (low-investment model)

Let us start first with Table C2, which assumes an LED efficiency saturating at 50*lm/W*. Based on the break-even analysis of Section 3, we concluded that LEDs start to make economic sense in the Year 2002. The break-even point over 5 years is at a daily operation of 16 hours, even without considering maintenance cost or reduced light losses/spillage in LED lamps relative to incandescent lamps. So, we set the 2002 LED penetration flux as a percentage of the total flux at an arbitrarily low level of 0.001%. By 2005, both LED performance improves and costs are reduced. By 2010, LEDs can compete effectively against halogen lamps and the penetration reaches 0.5%. Over the next decade, the penetration keeps increasing and levels off in 2021 at 10%. This is not very scientific, but we have to make some assumptions.

Semiconductor Lighting: Low Investment Model

Assumptions:	Cost/kWh ($)	**0.1**	Price Decline/Year	**10%**	**Investment 2000-2010**		File:roland\ssl1b.xls
	Avge. Duty Cycle	**30%**	Hours/Year	8760	**Industry**	**1000M$**	
	SSL Lamp Life (Y)	**10**	Retail Mark-up	**100%**	**DOE**		

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Act. Flux Usage	TLm	**10.0**	**10.2**	**10.4**	**10.6**	**10.8**	**11.0**	**11.2**	**11.4**	**11.6**	**11.8**	**12.0**	**12.2**	**12.4**
Installed Capacity	TLm	33	34	35	35	36	37	37	38	39	39	40	41	41
SSL Penetration	%			**0.001**	**0.01**	**0.02**	**0.03**	**0.05**	**0.10**	**0.15**	**0.30**	**0.50**	**1.00**	**1.50**
SSL Installed Capacity	TLm			0.0003	0.004	0.01	0.01	0.02	0.04	0.06	0.12	0.20	0.41	0.62
Ann.Conversion Rate	TLm			0.0003	0.003	0.00	0.00	0.01	0.02	0.02	0.06	0.08	0.21	0.21
Ann.Replacem't Rate	TLm													
Ann. Convers. + Replacem't	TLm			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2
Retail Price	$/kLm			**100**	91	83	75	68	62	56	51	47	42	39
Retail Value	G$			0.0	0.3	0.3	0.3	0.5	1.2	1.1	3.1	3.8	8.8	8.2
OEM Value White	G$			0.0	0.1	0.2	0.1	0.3	0.6	0.6	1.5	1.9	4.4	4.1
Efficiency Old Lamp	Lm/W	**12**	**12**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**18**	**18**	**18**	**18**
Efficiency SSL Lamp	Lm/W	**20**	**25**	**30**	**32**	**35**	**38**	**40**	**41**	**42**	**43**	**44**	**45**	**45**
Energy Saving New Inst.	G$			0.00	0.04	0.04	0.04	0.08	0.17	0.17	0.51	0.71	1.81	1.87
Energy Sav. Prev. Inst.	G$				0.00	0.04	0.08	0.12	0.20	0.37	0.54	1.05	1.76	3.57
Total Energy Savings	G$			0.00	0.04	0.08	0.12	0.20	0.37	0.54	1.05	1.76	3.57	5.44

		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Act. Flux Usage	TLm	**12.6**	**12.8**	**13.0**	**13.2**	**13.4**	**13.6**	**13.8**	**14.0**	**14.2**	**14.4**	**14.6**	**14.8**	**15**
Installed Capacity	TLm	42	43	43	44	45	45	46	47	47	48	49	49	50
SSL Penetration	%	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**10**	**10**	**10**	**10**
SSL Installed Capacity	TLm	0.84	1.28	1.73	2.20	2.68	3.17	3.68	4.20	4.73	4.80	4.87	4.93	5.00
Ann.Conversion Rate	TLm	0.22	0.44	0.45	0.47	0.48	0.49	0.51	0.52	0.53	0.07	0.07	0.07	0.07
Ann.Replacem't Rate	TLm		0.00	0.00	0.01	0.02	0.02	0.06	0.08	0.21	0.21	0.22	0.44	0.45
Ann. Convers. + Replacem't	TLm	0.2	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.3	0.3	0.5	0.5
Retail Price	$/kLm	35	32	29	28	26	25	24	23	22	21	20	19	18
Retail Value	G$	7.7	14.1	13.2	13.1	13.1	12.8	13.5	13.7	16.0	5.8	5.6	9.5	9.2
OEM Value White	G$	3.9	7.1	6.6	6.5	6.6	6.4	6.8	6.8	8.0	2.9	2.8	4.7	4.6
Efficiency Old Lamp	Lm/W	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Efficiency SSL Lamp	Lm/W	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**
Energy Saving New Inst.	G$	1.93	3.85	3.97	4.09	4.20	4.32	4.44	4.56	4.67	0.58	0.58	0.58	0.58
Energy Sav. Prev. Inst.	G$	5.44	7.36	11.22	15.19	19.28	23.48	27.80	32.24	36.80	41.47	42.05	42.64	43.22
Total Energy Savings	G$	7.36	11.22	15.19	19.28	23.48	27.80	32.24	36.80	41.47	42.05	42.64	43.22	43.81

Table C2. Economic model of LED penetration into global power signaling and incandescent white lighting markets, assuming best production LED efficiencies at 85°C of 30lm/W in 2002 and 50lm/W in 2010.

With these assumptions on LED performance and penetration, we can proceed to calculate the energy savings associated with increased efficiencies of LEDs as compared to incandescent lamps. These savings depend, of course, on the difference between the efficiencies of the lamp replaced and the new LED lamp, and so we must make some assumptions on the efficiency of the lamp being replaced. We assume that these lamps are at first low/medium flux incandescent lamps, with efficiencies of 12*lm/W* in 2002. With time this average will shift up to 18*lm/W* as more efficient and lower cost LEDs start to replace halogen lamps. Since for Table C2, LEDs will not replace fluorescent lamps the replaced lamp average will level off at 18*lm/W*.

Let us discuss the key assumption of 10% penetration around 2020. With an average LED efficiency of around 45*lm/W* from 2010-2020, LEDs will be more efficient than incandescent and halogen lamps by 3x and 2x, respectively, so there will be a strong incentive for replacement. An upper bound on the penetration would then be the percentage of lighting that is either incandescent or halogen -- approximately 20-30%. That upper bound could be approached if LED lamp costs could be reduced even further than the 20-25$/*klm* assumed in this analysis, and if the industry can design a family of LED lamps that can be screwed into existing incandescent sockets. However, if LED lamps require new light fixtures then the conversion could be significantly slower. So, we believe our 10% penetration assumption to be reasonable, neither overly optimistic nor overly pessimistic.

Another cross-check of the model is a comparison of LED industry revenue with energy savings. Since to the consumer the trade-off is the price of the lamp versus the cost of operating the lamp, these two should at first be roughly comparable. The line labeled "OEM Value White" represents the revenue of the LED lamp industry -- it reaches $100M in 2005, $1,900M in 2010, and $6,800M in 2020. The line labeled "Total Energy Savings" represents the energy savings associated with the accumulated conversions of less-efficient incandescent lamps with more-efficient LED lamps. In 2005, LED lamp revenue and energy savings are balanced and in the range of $100M. There is a similar balance in 2010 at $1.8-1.9G. In the 2010-2015 period, the pace of installations is picking up to a lamp revenue level of $7G, but savings from the installed base exceed $15G. By 2020, conversion is saturating, but energy savings have reached $37G/year and continue at this level indefinitely.

We have chosen the scenario of Table C2 because we believe that the industry is likely to make these investments, especially if governments provide some financial or tax incentives. Another argument is based on the magnitude of the market that is created by this new lighting technology. Table C2 in Appendix C shows a $6-8B market from 2014 to 2021 compared with today's total light bulb market of around $20B. And the biggest incentive for the industry to make these investments over the next 5-7 years is the opportunity that it creates: Go for a real breakthrough in semiconductor lighting efficiency and revolutionize the entire lighting industry!

LED penetration into incandescent and fluorescent white lighting market (high investment model)

Let us now discuss Table C3, which assumes a semiconductor lamp efficiency that continues to increase beyond 50*lm/W*, to the 200*lm/W* level. In other words, we assume here that there will be a research breakthrough that will keep the efficiency of semiconductor light sources rising after 2010 to a top performance of 200*lm/W* by 2015. There is also a corresponding rise in the performance of the replaced lamps by attacking compact fluorescent and, eventually, regular fluorescent, lamps.

The results of these assumptions are shown in the spreadsheet of Table C3. The semiconductor penetration rate by 2025 is somewhat speculative. If the SSL technology is really superior (2x against fluorescent and 10x against incandescent/halogen), then we should have a lighting revolution at hand. The rate of penetration, however, depends on a number of factors that are difficult to predict today. Can we build a cost-effective lamp that screws into an incandescent lamp socket? Such a lamp could result in a rapid penetration. But, it is unlikely that semiconductor lamps would go into the sockets of fluorescent tubes. For this market segment, the conversion would be slow. On the other hand, building code changes for new construction or remodeling could have an accelerating effect.

Also note that the caveats of Table C2 regarding our assumptions apply here in spades. A significant breakthrough in efficiency is anything but certain. A 50% penetration between 2015 and 2025 against the well entrenched and fairly efficient fluorescent technology is also quite uncertain. But if the industry can deliver the efficiency, then the energy savings are huge and real and conservation arguments will amplify the economic arguments. A 40% reduction of electricity used in lighting translates into an 8% reduction of total electricity consumption. Such large savings in the second largest energy sector will be difficult to find elsewhere, especially at the fairly modest level of the proposed government incentives.

Semiconductor Lighting: High Investment Model

Assumptions:	Cost/kWh ($)	**0.1**	Price Decline/Year	**10%**	**Investment 2000-2010**		File:roland\ssl1a.xls
	Avge. Duty Cycle	**30%**	Hours/Year	8760	**Industry**	**1000M$**	
	SSL Lamp Life (Y)	**10**	Retail Mark-up	**100%**	**DOE**	**500 M$**	

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Act. Flux Usage	TLm	**10.0**	**10.2**	**10.4**	**10.6**	**10.8**	**11.0**	**11.2**	**11.4**	**11.6**	**11.8**	**12.0**	**12.2**	**12.4**
Installed Capacity	TLm	33	34	35	35	36	37	37	38	39	39	40	41	41
SSL Penetration	%			**0.001**	**0.01**	**0.02**	**0.05**	**0.10**	**0.20**	**0.50**	**1.00**	**2.00**	**4**	**6**
SSL Installed Capacity	TLm			0.0003	0.004	0.01	0.02	0.04	0.08	0.19	0.39	0.80	1.63	2.48
Ann.Conversion Rate	TLm			0.0003	0.003	0.00	0.01	0.02	0.04	0.12	0.20	0.41	0.83	0.85
Ann.Replacem't Rate	TLm													
Ann. Convers. + Replacem't	TLm			0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.8	0.9
Retail Price	$/kLm			**100**	91	83	75	68	62	56	51	47	42	39
Retail Value	G$			0.0	0.3	0.3	0.8	1.3	2.4	6.6	10.3	19.0	35.1	32.9
OEM Value White	G$			0.0	0.1	0.2	0.4	0.6	1.2	3.3	5.1	9.5	17.5	16.4
Efficiency Old Lamp	Lm/W	**12**	**12**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**22**	**24**
Efficiency SSL Lamp	Lm/W	**20**	**25**	**30**	**33**	**36**	**40**	**42**	**44**	**46**	**48**	**50**	**55**	**60**
Energy Saving New Inst.	G$			0.00	0.04	0.04	0.12	0.19	0.37	1.04	1.67	3.21	5.92	5.61
Energy Sav. Prev. Inst.	G$				0.00	0.04	0.09	0.21	0.40	0.77	1.81	3.48	6.69	12.61
Total Energy Savings	G$			0.00	0.04	0.09	0.21	0.40	0.77	1.81	3.48	6.69	12.61	18.22

		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Act. Flux Usage	TLm	**12.6**	**12.8**	**13.0**	**13.2**	**13.4**	**13.6**	**13.8**	**14.0**	**14.2**	**14.4**	**14.6**	**14.8**	**15**
Installed Capacity	TLm	42	43	43	44	45	45	46	47	47	48	49	49	50
SSL Penetration	%	**8**	**10**	**12**	**15**	**18**	**22**	**26**	**30**	**35**	**40**	**45**	**50**	**55**
SSL Installed Capacity	TLm	3.36	4.27	5.20	6.60	8.04	9.97	11.96	14.00	16.57	19.20	21.90	24.67	27.50
Ann.Conversion Rate	TLm	0.88	0.91	0.93	1.40	1.44	1.93	1.99	2.04	2.57	2.63	2.70	2.77	2.83
Ann.Replacem't Rate	TLm		0.00	0.01	0.02	0.04	0.12	0.20	0.41	0.83	0.85	0.88	0.91	0.93
Ann. Convers. + Replacem't	TLm	0.9	0.9	0.9	1.4	1.5	2.1	2.2	2.4	3.4	3.5	3.6	3.7	3.8
Retail Price	$/kLm	35	32	29	28	26	25	24	23	22	21	20	19	18
Retail Value	G$	30.8	29.0	27.4	39.1	38.8	51.3	52.1	55.5	73.3	71.8	70.2	68.6	67.0
OEM Value White	G$	15.4	14.5	13.7	19.6	19.4	25.7	26.1	27.8	36.7	35.9	35.1	34.3	33.5
Efficiency Old Lamp	Lm/W	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**	**45**	**50**	**55**	**60**	**65**
Efficiency SSL Lamp	Lm/W	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**110**	**120**	**130**	**140**	**150**
Energy Saving New Inst.	G$	5.34	5.11	4.91	6.90	6.68	8.47	8.24	8.04	8.86	8.07	7.44	6.92	6.49
Energy Sav. Prev. Inst.	G$	18.22	23.56	28.66	33.57	40.47	47.14	55.61	63.86	71.90	80.75	88.83	96.27	103.20
Total Energy Savings	G$	23.56	28.66	33.57	40.47	47.14	55.61	63.86	71.90	80.75	88.83	96.27	103.20	109.69

Table C3. Economic model of semiconductor light source penetration into power signaling and incandescent/fluorescent white lighting markets, assuming substantially improved best production efficiencies of 150-200lm/W in 2015.