Strategies for the Future of Lighting

by

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Abstract

The motivation behind this thesis came from years of work in the solid-state lighting industry at Color Kinetics. My role there was mostly technical, but a bit of market understanding was involved. I wanted to gain a better understanding of the market forces at work, yet develop this understanding within a strong technical framework.

The goal of this thesis is to address the adoption of Light Emitting Diodes (LEDs) into the lighting market. Lighting consumes an enormous amount of energy, and LEDs have the potential to dramatically reduce energy dependence.

The approach utilized for this thesis involved first analyzing the projected performance improvements for LEDs, as these metrics are key factors to customer adoption. In addition, some of the more amorphous issues are discussed for both the market needs and the technical solutions available. Finally, a system dynamics model is developed which utilizes the data for the projected performance of LEDs and looks at how their adoption in different market segments may unfold. Variations are analyzed, and conclusions about the important factors for adoption are discussed.

Thesis Supervisor: James Utterback

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Chapter 1: Introduction

This chapter will look at both the historical and projected performance of Light Emitting Diodes (LEDs). This information is vital to determining the adoption of LEDs. Organic LEDs will also be discussed, as well as the incumbent lighting technologies that LEDs are competing with. All of the information presented in the first four chapters builds towards the system dynamics model detailed in the fifth chapter.

The Case for LEDs in Lighting

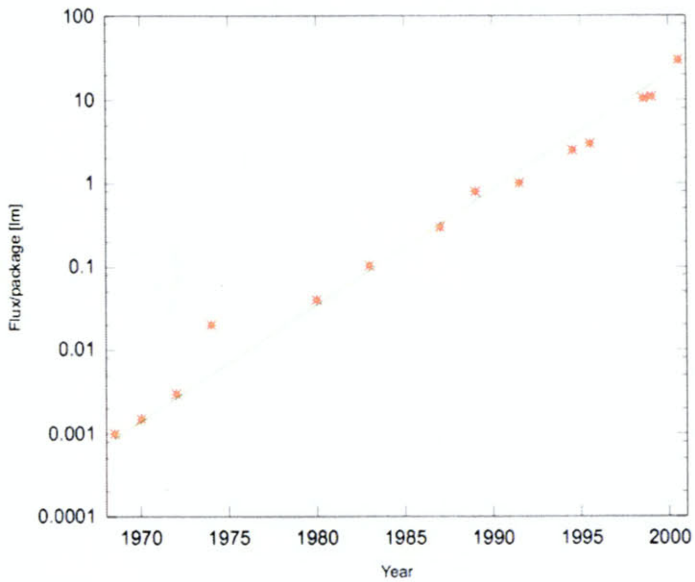
For generations, the main source of light has been the incandescent lamp. This basic technology of simply heating a thin piece of metal until it produces light has been around for over a century. While newer technologies have evolved to replace the incandescent lamp, it remains the predominant source of illumination for many applications around the world.

Light Emitting Diodes are a relatively new phenomenon, with the first white light solid-state source emerging in the 1990s. Despite their relatively short existence, LED performance has grown at an incredible rate. Efficiency has improved and prices have dropped, and these trends look to continue for the foreseeable future. LEDs are valuable in lighting as their efficiency and lifetime far surpass that of incandescent lamps, and are on par with many of the more advanced lighting technologies available today. There is extensive literature available describing the history and benefits of LEDs.

LED Performance - Inorganic

As with most new technologies, the performance is generally poor upon introduction, and steadily increases over time. Moore's law projected the increase in performance of microprocessors, and Haitz law dictates a similar performance increase for LEDs.

Figure 1: Improvement in red Light Emitting Diodes over time

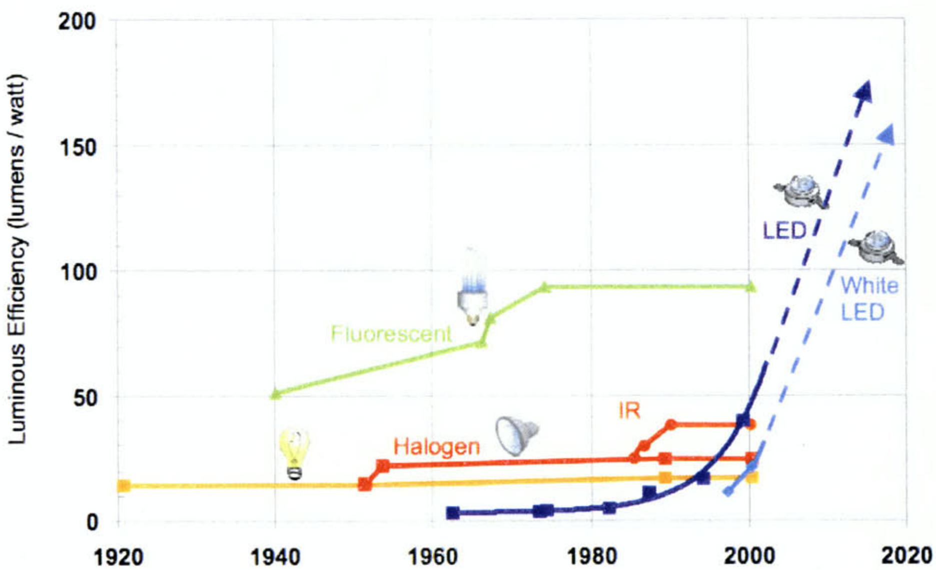


Haitz Law, Wikipedia.com [i]

The diagram above shows the performance of red LEDs, which were the first LEDs produced. The data points line up well with the solid line, which defines the trend predicted by Haitz Law. The units are in lumen per package, or single device. To produce white light two different approaches can be utilized. The combination of red, green and blue LEDs can produce white light, or a combination of phosphor(s) excited by blue LEDs will also produce white light. Blue LEDs were not introduced until the mid 90's, so this is why the first white light LED products were not available until this time as both white light approaches depend on blue LEDs.

The following diagram compares the increase in efficiency for LEDs versus other lighting technologies. As you can see, LEDs are rapidly approaching the luminous efficacy of fluorescent sources, and will soon surpass them.

Figure 2: Historical and projected performance of LEDs versus traditional light sources



Department of Energy [ii]

There is a maximum limit to the efficacy of LEDs. Depending on wavelength the maximum theoretical efficiency varies anywhere from ~200 lumens/W to almost 700 lumens/W.[iii] The issue with the higher end of this range is that it is defined for a light source having a narrow (saturated) 555nm output, which conforms perfectly with the eye response curve. This is not white light, but a strong, green source. A typical white light source has a wide range of wavelengths present typically spanning the entire visible region, and at the extreme edges of the eye response the efficiency (lumens/optical watt) is in the single digits.[iv] The bottom line is that even if no heat is produced and all of the electrical energy going into an LED is converted into optical energy (100% wallplug efficiency), there is a theoretical limit to the efficacy of an LED source. This theoretical limit is shown in the chart below.

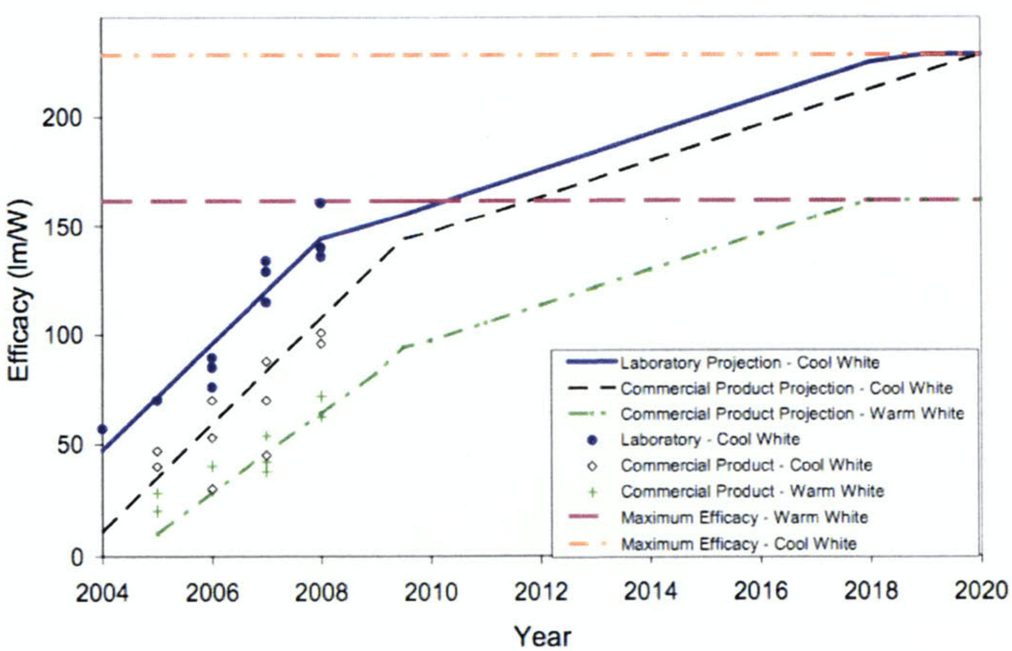
Figure 3: Maximum theoretical efficiency of LEDs

Maximum Efficacy (lm/W)		
CCT	75 CRI	90 CRI
3000K	182	162
4100K	220	193
6500K	228	186

Department of Energy [v]

The left column is the Correlated Color Temperature of the light source, and CRI defines the quality of light. For most indoor lighting applications a color temperature of 3000K (warm white) and a CRI of 90 is preferred. Below is a chart detailing the historical and projected efficacy of LED sources. This takes into account the maximum theoretical efficiency shown above.

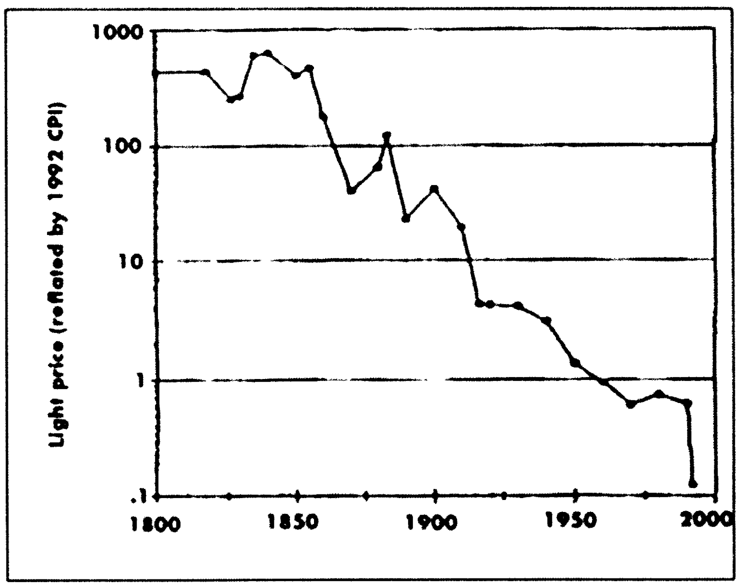
Figure 4: Historical and projected performance of LEDs versus theoretical limits



Department of Energy [vi]

Efficacy is only half the discussion. Price must be considered. Even if the theoretical limit of efficacy is reached for LEDs, if the price of LEDs stay prohibitively high LEDs will never be adopted in large numbers. Dollars per lumen (or sometimes kilolumen) is a standard metric used to describe the initial cost of a light source. A historical chart outlining this trend is shown below.

Figure 5: Historical price reductions for illumination

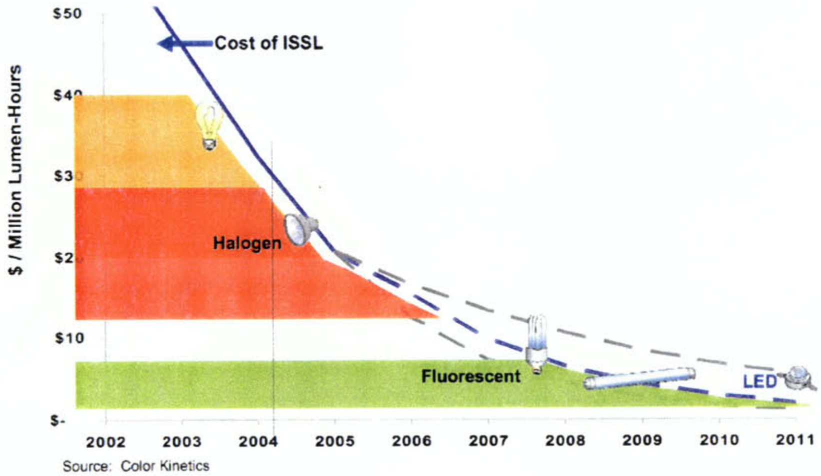


The cost of light as a service is shown in dollars per lumen for the last 200 years. (From Nordhaus)

Color Kinetics, Cost of Light [vii]

While initial cost is important, the lifetime cost of a lamp is also vital when discussing the adoption of advanced light sources. Dollars per million lumen-hours is the metric typically used to describe the lifetime cost of a lamp. This takes into account both the initial cost and the energy use of a lamp. The chart below shows the trend for the cost of Solid State Lighting (SSL) sources in contrast to the cost of other lighting technologies.

Figure 6: Projected price reduction for solid state lighting versus traditional lighting



Color Kinetics, Cost of Light [viii]

The Department of Energy has accumulated data for the expected growth in the performance of LEDs by speaking with industry experts. This takes into account both the projected increase in efficiency and the projected decrease in initial cost. This data is shown in the following chart.

Figure 7: Summary of projected price and performance improvements for LEDs

Metric	2008	2010	2012	2015
Efficacy- Lab (lm/W)	144	160	176	200
Efficacy- Commercial Cool White (lm/W)	108	147	164	188
Efficacy- Commercial Warm White (lm/W)	64	97	114	138
OEM Lamp ($/klm)	169	101	61	28

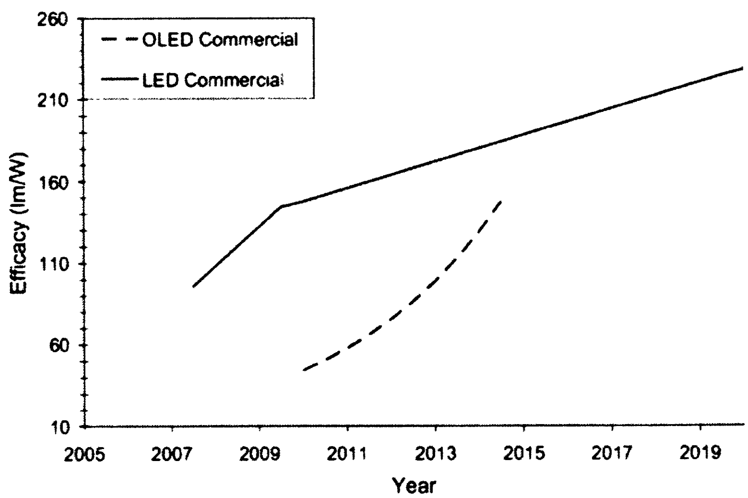
Department of Energy [ix]

This data sums of the projected performance of LEDs, and is critical to their adoption. The system dynamics model in the later sections will utilize this data to project the adoption rate of LEDs in different market segments.

Organic LEDs

While inorganic LEDs have made the greatest inroads in the lighting market, organic LEDs are mostly still in the R&D phase. However, in many ways organic LEDs are better suited for the lighting market. Their soft, diffuse, low luminance output mimics many conventional lighting fixtures/sources. The chart below shows the lag in performance for OLEDs versus inorganic LEDs.

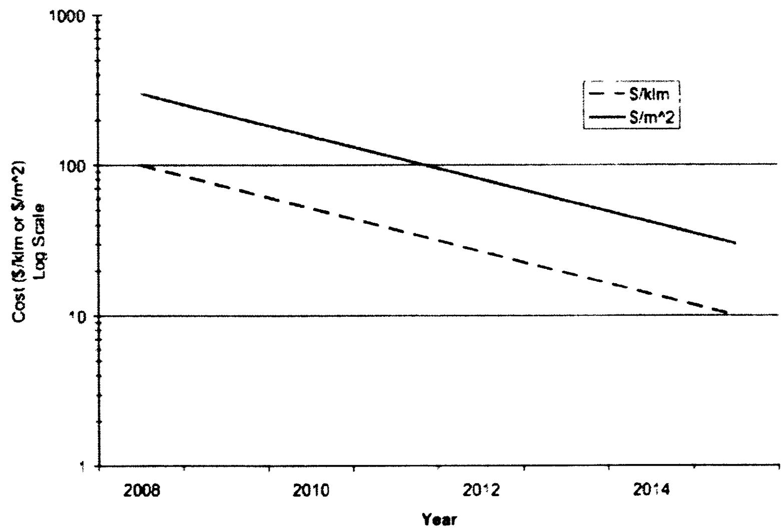
Figure 8: OLED performance versus inorganic LED performance



Department of Energy [x]

Despite the fact that OLEDs are not as efficient as inorganic LEDs, their efficacy is already superior to that of incandescent bulbs, and is projected to grow quickly. The biggest issue with OLEDs currently is that they are expensive to manufacture, and the manufacturing yield is low. Below is the projected decrease in cost (both dollars per kilolumen and dollar per square meter) for OLEDs. Note the logarithmic scale.

Figure 9: Projected decrease in cost for OLEDs



Department of Energy, [xi]

Competition

While LEDs have the potential to displace existing lighting technologies, the current technologies have a strong foothold in the market. Incandescent lamps have been around for over a century. Halogen, which has slightly better performance then incandescent lamps are used for many projection light sources like MR16 lamps and spotlights. Compact Fluorescent Lamps (CFLs) are continuing to replace incandescent bulbs in many installations. Fluorescent tubes dominate the commercial market. High Intensity Discharge (HID) lamps are used in many industrial applications. Low and high-pressure sodium are used in exterior applications. There are a number of other technologies that have a small market share in many niche applications. Therefore LEDs are not simply competing with incandescent lamps as the incumbent technology. Each application and market must be analyzed by first looking at the incumbent technology(ies) and comparing LED's existing and project performance to determine LED adoption. The system dynamics model in the later sections compares and contrasts LEDs versus many of these incumbent technologies. It is vital to understand the performance and limitations of these existing technologies when making the case for utilizing LEDs in lighting.

Chapter 2: System Definitions for Lighting

This chapter will look at the efficiency of LED systems. It is vital to look at all levels of an LED system to determine the overall system efficiency, and break down the system appropriately. There are four main levels; the system level, room level, fixture level and component level. This chapter builds on the efficacy noted in the previous chapter, and how the projected numbers fit within the overall lighting system.

System Level Efficiency

The system level efficiency of each lighting application must be analyzed to determine the usefulness of LEDs. Day lighting may be utilized in some applications, which limits the need for electrically powered lighting. Power supplies, electrical wiring, controls, etc can all factor into the system efficiency.

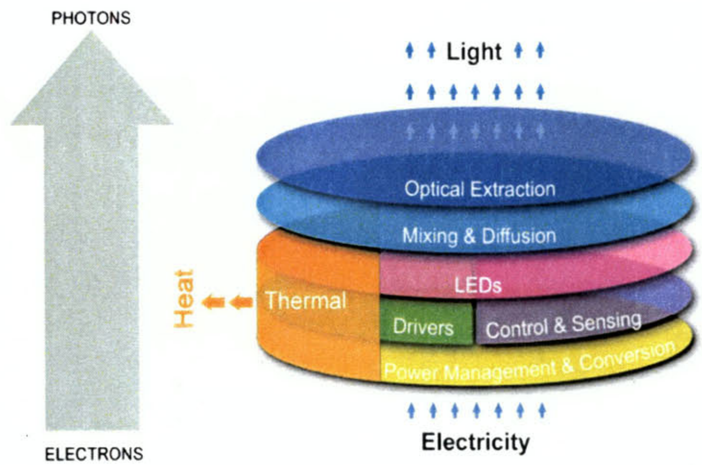
Room Level Lighting Efficiency

Moving down one step from the system level efficiency of a lighting system, the room level efficacy must be determined. Where is light needed within the room? Does it need to be aimed at a particular location, or simply flood the entire room? Is up lighting used so ceiling/wall reflections are important, or is the room lit primarily by downlights, where the emitted light is directed at the vital surfaces? This same logic can be used for exterior applications as well. Is the goal simply to light a surface of a building, or is an exact illumination pattern on a roadway for driver safety the goal?

Fixture Level Efficiency

The fixture level efficiency of a lighting system is critical to proper performance. Historically, the fixture level efficiency has been defined by the ratio of the amount of light coming out of a bulb versus the amount of light that comes out of the fixture. There can also be losses due to the electrical efficiency of the power supply that drives the bulb. The use of LEDs changes the standard view of fixtures. LEDs are typically not meant to be replaced, so discussing the fixture efficiency in typical terms is not accurate. The fixture IS the bulb, so from a customer standpoint it is one complete unit. The diagram below defines the system losses within an LED fixture.

Figure 10: System diagram of energy use in an LED system



Department of Energy SSL report [xii]

While LED replacement bulbs are coming into the market, there are sacrifices made in terms of system efficiency, as these LED bulbs typically use the existing low efficiency fixtures, which are not optimized for LEDs.

Component Level Efficiency

The base level for efficiency is the component level. The data presented in Chapter 1 is generally for the component level. In addition, power supplies can also be considered a component if they are integrated into the fixture, and any power loss can be factored into the overall fixture efficiency.

Analyzing the System Efficiency

It is vital to break down a lighting system into its component parts when determining how to optimize for efficiency. While you might have Energy Star ratings at the fixture level, LEED certification is done at the building level. The system dynamics model will generally break down systems to the fixture level to determine adoption rates.

However, it is important to be able to move easily up or down a level, as this understanding is also vital to the supply chain for a company. It is also important to realize that as you move up from the component level the efficiency will always drop, as the system can never become more efficient as you add additional layers of loss into the system.

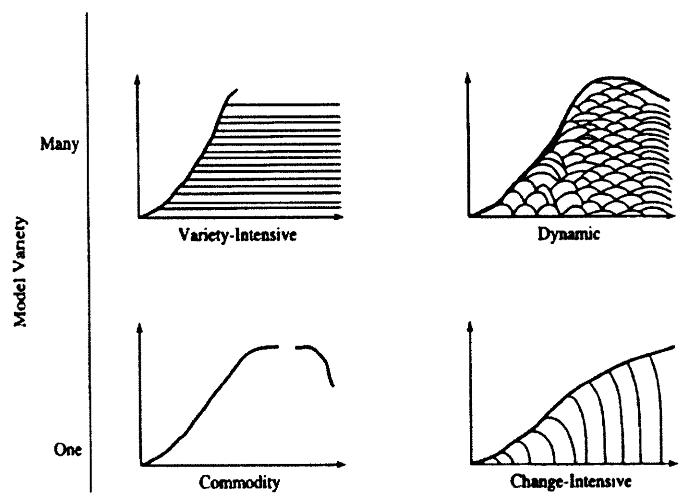
Chapter 3: Market Analysis

This chapter will look at the appropriate segmentation of the lighting market. In addition, the different types of replacement will be evaluated, as well as the needs of lighting customers. The system dynamics model looks at different slices of the lighting market as defined by the market segmentation scheme discussed here.

Market Segmentation

An important component of evaluating any market is clearly determining the type of market you are looking to enter. Looking at the four different frameworks presented by Susan Walsh Sanderson we can get a better idea of the market types. Her basic framework is shown below.

Figure 11: Market frameworks



Susan Walsh Sanderson [xiii]

The mobile market is an example of a dynamic market. Handsets are generally replaced at two-year intervals, so lifetime is not a major factor. The display market is similar to a change-intensive market like microprocessors. Once a new technology has entered a market all the major players adopt it quickly. The general illumination market is a bit different then the mobile or display markets. It is a variety-intensive market. There are many little niches within the lighting market, and each one of those needs to be addressed individually. While the standard A lamp architecture may seem to be a commodity, the A lamp is installed in thousands of different fixtures. As long as the adoption of LEDs is promoted towards different fixtures and not standard replacement lamps then the variety-intensive framework still applies. Even within the A lamp architecture there are different wattages, some of which LEDs cannot currently replace. In addition, the adoption of CFLs has brought about a number of different color temperatures, further adding to the variety-intensive approach. The system dynamics model splits the whole lighting market into distinct layers. In this way, the model can be tuned to analyze each market layer. This leads to more accurate results then trying to construct a singular model that encompasses the entire lighting market.

Continuous Innovation versus Discontinuous Innovation

Continuous innovation is what most companies strive for, as it requires no change in customer behavior. It is simply an improvement to an existing product that enhances the performance for the customer. That being said, some disruptive technology customers would prefer a discontinuous innovation if their product simplifies the life of the customer. These terms come from Geoffrey Moore's book entitled, "Crossing the Chasm." The difficulty in applying this framework to LEDs as a disruptive technology is the market segmentation scheme that is applied. Utilizing the market types discussed above if the entire lighting market is viewed as one, singular market, then the crossing the chasm rules would apply. I believe that this is not the case, as the layered market approach introduces multiple, smaller markets, each with a small chasm to be crossed. It is much easier to "cross the chasm" if the chasm is smaller due to being part of a smaller market segment. This is because the effort can be focused on the value proposition that carries the most weight in that particular market segment. In addition, the success of a smaller market can be utilized to educate the next market segment, which aids in the adoption of LEDs.

New Construction versus Retrofit versus Replacement

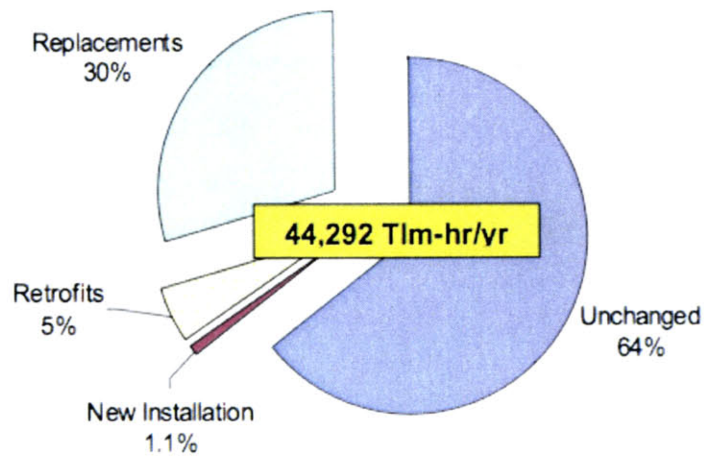
There are three distinct ways for the lighting market to adopt LED lighting products. The most basic is new construction. If a new building is constructed then an LED product can be specified and installed. This is generally considered the slowest evolving type of adoption, as either new buildings need to be constructed in new locations, or old buildings need to be torn down to make room for new buildings. The advantage to this type of installation is the number of fixtures necessary for a particular installation can be quite high, and therefore the volume per installation is quite attractive.

The retrofit market bridges the gap between the new construction market and the replacement market. When a retrofit takes place it is generally done on the fixture level. A building owner may decide to improve/remodel their building and new LED fixtures can be specified at this time. The interface is important for this market, as there is an existing infrastructure that needs to be considered. A typical retrofit requires replacing the existing fixtures. This can be a labor-intensive process, which can significantly add to the cost of an installation. There are also many factors that can limit the adoption of LED fixtures. For example, simply putting LED downlights into a ceiling packed with insulation can severely degrade the performance and lifetime of the LED downlights. The existing infrastructure of each installation must be carefully analyzed before embarking on an LED retrofit.

The replacement market is the fastest moving and most interesting market for the LED lighting industry, but it has many drawbacks. The most critical drawback is the strong reliance on the existing interfaces, whether it is a 120V Edison socket, an existing fixture that requires a particular bulb "envelope" or an application which requires an exact CCT or light quality. In addition, the Edison socket was never intended to dissipate conducted heat, which is a problem for LEDs. While there are new interfaces being researched, it will be difficult to replace the existing infrastructure of 5 billion Edison sockets.[xiv]

The following chart is from the Department of Energy's energy savings report on lumen turnover in 2010. Units are in tera lumen hours per year, which is simply a different way to define the size of the lighting market. The most important aspect of this chart is the percentage breakdown of the lighting market, as this points directly at the types of installation that LED lighting companies should focus on.

Figure 12: Lumen Turnover for 2010



Department of Energy [xv]

As you can see, the replacement market is the fastest moving market, followed by the retrofit and new installation markets. Therefore despite the drawbacks of the replacement market for LEDs, it is a valuable market to target due to the high turnover. The system dynamics model will focus on the replacement market, as this is the most relevant market for rapid LED adoption.

Business versus Consumer

This is a relatively straightforward market segmentation choice. The typical consumer makes their purchases at a local hardware store for a bulb for their existing lamp. They are purchasing only a few bulbs at a time and are extremely cost sensitive.

The typical business customer is purchasing a large quantity of bulbs for their building/company, and in many cases is involved in the specification of lighting fixtures for new construction and retrofits.

The system dynamics model will analyze both the business and consumer markets. Each values different factors, so variables within the model are weighted to reflect this difference.

Customer Needs

When a customer makes the purchase of a light source, there are a number of factors that they may consider. It is valuable to analyze each market segment with respect to the following factors.

1. Light output
2. Cost
3. Interface
4. Color Temperature
5. Color Quality
6. Efficiency
7. Lifetime
8. Time to full brightness
9. Dimmable?
10. Shape

Light output

Light output is typically the most important metric that a lamp is judged by. In the residential market light output is typically defined as a "100-watt equivalent," referring to the light output by a typical incandescent lamp. This form of comparative labeling was seen as vital to the adoption of CFLs in the residential market, as consumers could quickly determine how the replacement technology compared to the old technology. Light output can be also be defined by the beam pattern. Lighting can generally be categorized into two main groups; focused and diffuse. Focused lighting can also be considered projection lighting. A spotlight is a great example of a focused light, as it is made to light a specific area from some distance away. Diffuse lighting is the more common type of lighting. Most lamps and fluorescent ceiling fixtures fall into this group. The specification grade (commercial) market has a better understanding of light output and uses lumens, beam angle, etc to define the required light output.

LEDs are well suited to focused lighting. Their very high luminance allows for tight, controlled beam patterns. The downside of LEDs is their high luminance makes soft, diffuse lighting more difficult. While high luminance may be acceptable in shielded, lamp style fixtures it is problematic for open ceiling fixtures that are typically found in office spaces. To achieve the low luminance preferred for these applications diffusion must be utilized, which lowers the efficiency of the fixture.

OLEDs and HLEDs (which utilize quantum dots) promise to be low-luminance, high efficiency light sources. While these are not well suited to projection illumination, they are perfect for low-luminance, diffuse lighting.

In many cases the LED source is replacing a traditional light source, so a direct comparison may be utilized to ensure the light output is consistent.

Cost

The upfront cost is obviously an important factor for any purchase, and is relatively straightforward for the consumer to understand. Rebates or other offers may be used to reduce the initial cost of a light source. These options will be analyzed using the system dynamics model.

Interface

The interface is a simple, and usually easy question to answer. The lamp may have an Edison socket, bi-pin connector, GU10 plug, fluorescent pins, etc. This is typically a yes/no question. There are other factors to consider, however. The weight of the new fixture may be greater then the existing interface is able to handle. The electrical input may be a different voltage. There are a number of different dimming standards, and it may be difficult to produce an LED power supply to work with all of them. In the system dynamics model these issues are grouped together and called standards. The relative weight of this factor defines the difficulty that LEDs may have fitting within the market segment's existing standards.

Color Temperature

Color temperature has not historically been a concern to the residential market, thought its importance has been growing. Incandescent lamps are typically only offered in one color temperature, so the typical consumer has had little exposure to this factor.

The introduction of "daylight" and "neutral" CFLs have broadened the color temperature options available to the consumer and LED replacement lamps will only continue this trend.

Color Quality

Color quality is a very amorphous factor. The Color Rendering Index (CRI) was developed in the middle of the 20th century as a way to numerically evaluate this factor.[xvi] While CRI can be a reasonable metric for some light sources, it is not very effective at evaluating the color quality of LED based lamps. The Color Quality Scale (CQS) is being developed by NIST as a new, more accurate way of quantifying color quality.[xvii] In some applications the desired color quality is of little importance, and in others (surgical lighting for example) the color quality is vital. Sources may vary from a negative CRI for a low-pressure sodium lamp to 100 CRI for halogen sources.

Efficiency

Efficiency is one of the vital metrics by which LEDs aim to compete. Lumens per watt is the standard term used within the industry, but this is not well understood by the general public. In addition, efficiency can drop precipitously once a lamp is installed into a fixture, which is rarely considered. Efficiency should also be viewed by the lifetime cost. This make it easier to compare the lifetime cost to the upfront cost and to calculate the payback period. In the previous sections the Department of Energy data on efficiency was presented. This data will be a key input to the system dynamics model.

LEDs do not exhibit the same efficiency at all color temperatures; they are generally less efficient at low CCTs. Most white LEDs use a blue LED and a mix of yellow and red phosphors to produce white light. Stokes shift occurs when high-energy light (blue) is absorbed and re-emitted as lower energy light (yellow/red.) This inherent energy loss reduces the overall efficiency of the LED source. It is therefore important to determine the relative efficiency at a specific color temperature when comparing technologies.

Lifetime

Lifetime is an important factor for LED adoption, especially for installations where replacement is difficult. One distinct difference in lifetime for an incandescent lamp versus an LED is that the incandescent lamp's end of life is a "hard fail," as the filament breaks and no more light comes out of the lamp. For most LED lamps the end of life is a "soft fail," as the lamp continues to slowly dim over its lifetime. Therefore metrics that looks at the level that an LED lamp has dimmed to are used to define the lifetime. Lifetime is used as an input to the system dynamics model, and is especially important for markets where replacement is difficult and costly, for example street lighting.

Time to full brightness

Time to full brightness is defined by how long it takes a bulb to produce its full intensity after being turned on. Incandescent and LED bulbs are virtually instantaneous, whereas some HID bulbs can take many minutes to produce full brightness. In addition, if HIDs are turned off they need a few minutes before they can be re-striked, or turned back on. This is one of the major factors which limited the adoption of HID lamps in the residential market, as consumers want instant light when they flip the switch.

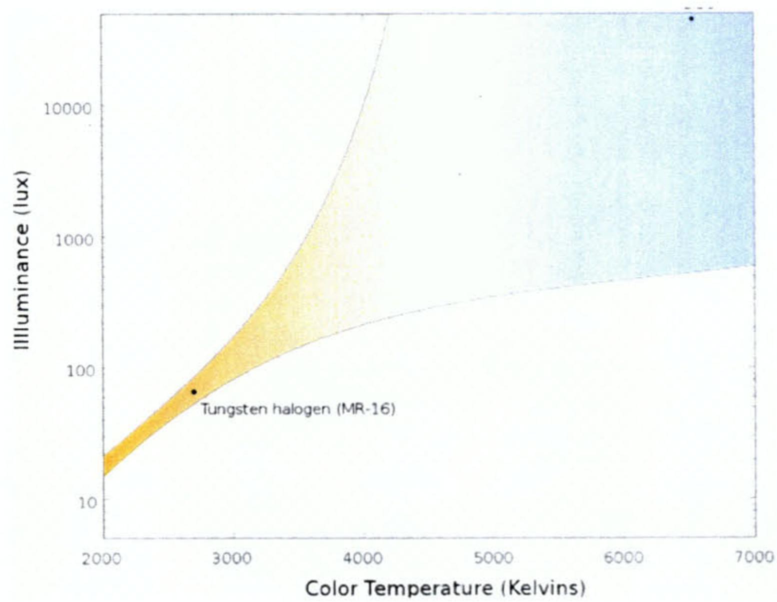
Dimmable

Dimmable describes the ability of a light source to be dimmed. There are a number of different dimming interfaces, and not all bulbs work with all types.

For hospitality and home markets, incandescent bulbs are the preferred light source. The color quality and "dim-to-warm" capability are important. One of the major issues with LEDs is the poor quality of light at low color temperatures and the inability to "dim-to-warm." Dim-to-warm describes the behavior of an incandescent bulb; as the intensity is reduced the color temperature goes down.

The Kruithof curve[xviii] shows the human preference for low color temperatures at low illuminance levels.

Figure 13: The Kruithof Curve



Wikipedia, Kruithof Curve [xix]

This visual preference is important when designing halogen and incandescent replacements. Halogen and incandescent bulbs have an inherent advantage as their color temperature becomes warmer and more reddish in appearance as they are dimmed. Their inherent disadvantage is that their efficiency drops as well, making a dimmed incandescent incredibly inefficient.

Not all markets prefer "dim-to-warm." One lighting designer stated that only 50% of the markets that desire dimming want "dim-to-warm". In the other markets (conference rooms for example) simply lowering the illumination level is sufficient, and in many cases no color temperature shift is preferable.

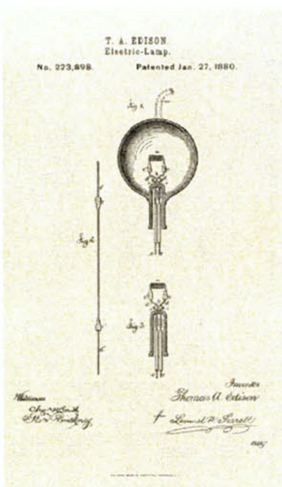
In some applications, daylight sensors will determine the level of illumination provided by daylight, and then increase or decrease the level of electric illumination to provide a sufficient illumination level at a minimum electrical usage. Therefore dimming is going to become more important as consumers look to reduce energy use, and fluorescent lamps relative inability to be dimmed will limit their appeal to these markets.

Shape

Shape is also a vital component, but its effect can by analyzed many different ways. The visual appearance of a bulb can be an important factor in some markets.

The incandescent bulb has been around for over a century, and the basic shape and look has not changed very much. Below are images of Thomas Edison's original patent and a modern A lamp.

Figure 14: The classic A lamp



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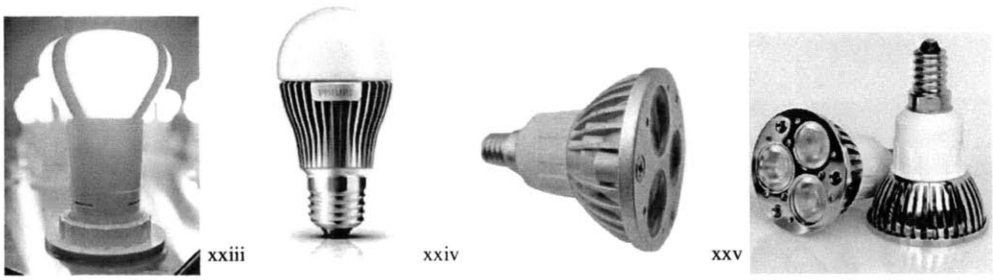
xxi

Edison Patent, Philips

LED replacement lamps have a challenge ahead of them. CFLs initially had a difficult time with consumer acceptance, and many believe that one of the reasons behind this is the spiral shape, which is not familiar or well liked by regular consumers. With respect to other LED products, "'It's taken them a long time to get traction, and part of it is because they didn't have that A-line shape,' said Phil Rioux, general manager of Osram Sylvania's LED retrofit product line. 'The A-line shape is kind of like apple pie. American consumers are familiar' with it, he said.'"[xxii] How much will the consumer change? While the upcoming ban on incandescent bulbs will certainly push consumers to alternate technologies, they still have to overcome the look of the bulb. Below are a few images of LED replacement lamps.

Figure 15: Current LED replacement lamp designs



xxiii xxiv xxv xxvi

Philips

While the first image (Philip's official L prize submission) has some of the same appeal as an A lamp, it is still far from a "visual" drop in replacement. The LED sources shown differ dramatically from their existing traditional counterparts, and this difference could hinder adoption.

Even though LED lamps do not look identical to incandescent lamps, all is not lost. CFLs look quite different from incandescent lamps, and yet their adoption is continuing. The look of an LED lamp may inhibit early adoption, but in time it should not limit the long-term adoption. Lamp performance is typically of greater importance then the visual appearance.

In addition, there are specific physical volume requirements for particular classes of lamps. Some fixtures are designed for a very streamlined fit to a bulb type, so any deviation from this shape will prevent their use in particular installations. This could also be considered a physical interface.

Using the List

So what is the goal of this list? A market segment can be systematically analyzed by stepping through the list. The first task is to determine the market's preference in order of each factor. The next step is to compare the existing technology to LEDs. Let's give an example.

Let's look at a small niche market, say track lighting in a museum. The most vital factor is light output. It needs to be the right quantity, beam pattern, and uniformity to ensure the artwork is properly lit. Color quality and color temperature come next, as they both affect how the artwork looks. In addition, a source that lacks UV and infrared radiation is preferred, as both of these can lead to degradation of the artwork. Efficiency is certainly important, but it falls behind color quality. The interface needs to be evaluated, and it varies on the type of replacement. Shape is only important if the new product needs to fit into a particular fixture. In a well-designed museum, the lighting will rarely need to be dimmed, so this is less of a concern. However, in a museum that constantly rotates their displays dimming may be valuable to tailor the lighting to the art being displayed. Time to full brightness is not a concern, as museums can generally turn on the lighting well before customers enter the building, and leave it on the whole time.

The next step is to compare LEDs with the current market solution. In many museum applications, the existing track lighting is halogen. Halogen has a perfect color rendering, a preferred low color temperature, instant on, is dimmable and inexpensive. It is also inefficient leading to a high cost of ownership, emits both UV and infrared radiation and has a short lifetime. LEDs can therefore compete on the cost of ownership, and the lack of infrared and UV radiation, provided the color quality is sufficient.

Once a market is analyzed using this list, data can be fed into the system dynamics model. A market's preference for upfront cost versus lifetime cost can be factored in, and other variables which will be discussed later.

Chapter 4: A Changing Market

This chapter will look at the important emerging technologies in the lighting market. In addition, important "triggers" that may increase or hinder adoption are discussed. Segmentation on the supply side is also evaluated. This chapter looks at the opposite side of adoption as the previous chapter, because now we are analyzing the different options available to fit the market needs discussed previously.

Interfaces

Examining the system diagram shown earlier, one can see the important interfaces that need to be defined for an LED system. Optical interfaces are quite simple, as light only needs to pass from one surface to another. The electrical interfaces are a bit more complex, but certainly not something that has not been solved before. The greatest interface challenge for an LED system is the thermal interface. There are two main thermal interfaces that must be address: LED to board and board to fixture/housing. The LED to board interface is easily solvable, and this feature is incorporated into most LEDs in the form of a thermal pad for soldering. The board to fixture/housing interface is usually a custom interface, as each board and each housing are usually product specific. GE is one of the first companies to attempt to solve this problem, with their LED module.

Figure 16: GE's replacement LED module

GE Lighting [xxvii]

The goal of this module is to allow for a simple thermal and electrical interface and an upgradeable component, similar to a light bulb. According to GE's vice president of marketing and global product management with GE Consumer & Industrial's LED business, Lumination, LLC, "Leading lighting designers and architects are on the record with concerns about integrated LED fixture upgradeability and serviceability. Some won't specify an integrated LED fixture. This is GE's answer. It's future-proof and market-ready."[xxviii] Is this going to be the Edison socket for LEDs? It is difficult to know, but one must ask why individuals purchase LED luminaries. The typical response is to reduce power consumption (therefore pushing for a ROI) so upgradeability is usually not of importance. A well-designed LED fixture should rarely need replacing, so serviceability is not generally a concern. That being said, I believe the main driver for this module approach is to alleviate concerns with serviceability, as the average user of lighting fixtures has historically been concerned with bulb replacement, and it is difficult to change the consumer mindset about the need for serviceability.

Inorganic versus Organic

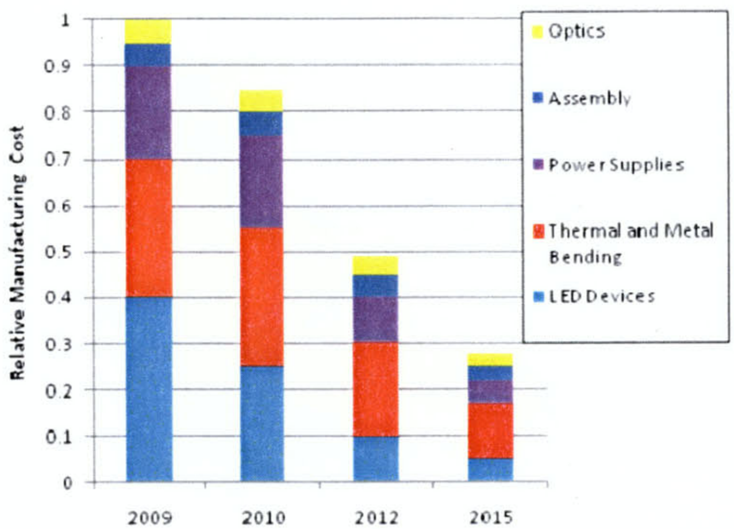
"The light bulb is ugly, that's why it's hidden behind the lampshade."[xxix]

The standard A lamp light bulb has been around for a century. While a few different form factors have come along through the years, they have a similar basic shape. Most of the variety within the lighting market is the fixture itself, not the source. Organic light-emitting materials have the ability to dramatically change the traditional form factor. Instead of putting a lamp inside a lampshade, imagine if the lampshade itself glowed. Instead of having deep recesses in ceilings for ugly fluorescent fixtures, imagine if the ceiling itself glowed. The standard fixture design no longer applies, and this opens up a wide variety of novel designs. That being said, the paradigm of the incandescent bulb inside a fixture will be hard to get over, despite the many potential improvements of these novel designs.

System Cost Trends

One of the greatest drivers towards LED adoption is the cost of the fixtures. Below is a figure from the Department of Energy outlining the projected reduction in fixture cost.

Figure 17: System cost trends for LED lamps



Department of Energy [xxx]

Of course, manufacturing cost is important, but profits are as well. A Mckinsey studied recently published in LEDs magazine paints a picture of the future of profits in the LED lighting industry, and compares this to the traditional lighting industry.

Figure 18: Current and projected profit for traditional and LED lighting

Traditional lighting share of profits	Today[1]	LED lighting share of profits	Today[1]	2020[2]	Rationale for change
Lamp	20%	Epi/chip[3]	10%	Lower	· One or two big players expected to dominate · Typical commoditization
Ballast/ optics	5%	Packaging	50%	Lower	· Commoditization will happen · Still significant share due to white light conversion
		Moduling	25%	Higher	· Increasing technical integration needs (e.g. chip on board)
Luminaire	70%	Driver/ optics	3%	Flat	· Growingly integrated into moduling part · Potential differentiation via including driver and optics in module step
		Luminaire[4]	10%	Slightly higher	· Exploding variety of applications and solutions · Threat of standardization
External controls	5%	External controls	3%	Slightly higher	· Standard component · However, more sophisticated controls needed
	Total = €3.5 billion		**Total = €0.1 billion**	**Total = €1.5 billion to €2.0 billion**	

[1] 2007, worldwide. Source: McKinsey.
[2] Includes LED applications for general illumination only. Source: Amadeus, Bloomberg, analyst reports, expert interviews, McKinsey.
[3] Margins for white high-brightness LEDs higher, but all current LED players need to have broader portfolios due to binning variation.
[4] Professional segment only.

Mckinsey in LEDs Magazine [xxxi]

This article goes into detail about where the expected profits will be in the future of the LED industry. Certainly LEDs will continue to become a commodity product. This process is already happening.

Are LEDs Becoming Commoditized?

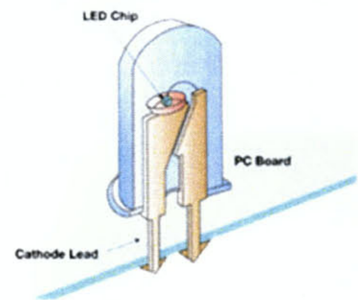
Before LEDs had sufficient power to be used for lighting they were introduced as indicator lights. The 5mm LED package became the industry standard. While there were other, more complicated designs developed the basic 5mm LED is the industry standard that is still in use today. Two images are shown below.

Figure 19: The first standard LED

5mm LED

xxxii

Cutaway of 5mm LED



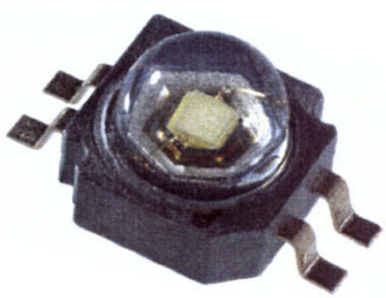
xxxiii

LED lights, Philips Lumileds

As you can see, the 5mm LED is a relatively simple device, and was not designed for high thermal loads. The only path for thermal transfer is through the leads, which is extremely inefficient. This was understood by LumiLeds, as their first power LED design, the Luxeon emitter solved the thermal issue.

Figure 20: Lumiled's Luxeon

Luxeon I



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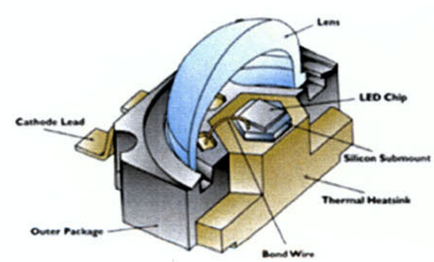
Cutaway of Luxeon I

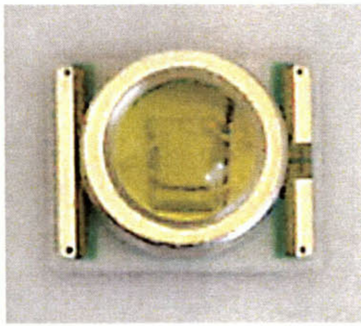


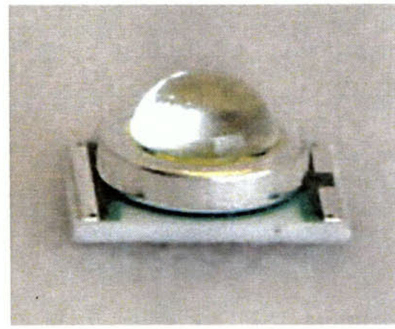
xxxv

Lumileds

The Luxeon was a revolutionary design aimed to effectively dissipate the heat generated by an LED. The heat generated by an LED is conducted and not radiated, so the beam stays "cool" while the LED itself gets hot. This is a distinct difference from an incandescent source (which simply radiates), so it is a challenging thermal problem.

Figure 21: Cree's 7090


xxxvi

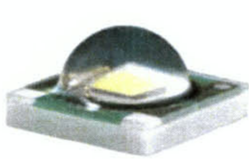

xxxvii

Cree

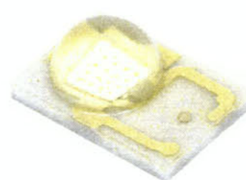
The Cree 7090 design simplified the design a bit, but there is still some unnecessary structure (and therefore cost) added to the product.

Figure 22: A dominant design?

Cree


xxxviii

LumiLeds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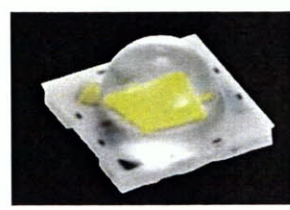
Nichia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Cree, LumiLeds, Nichia

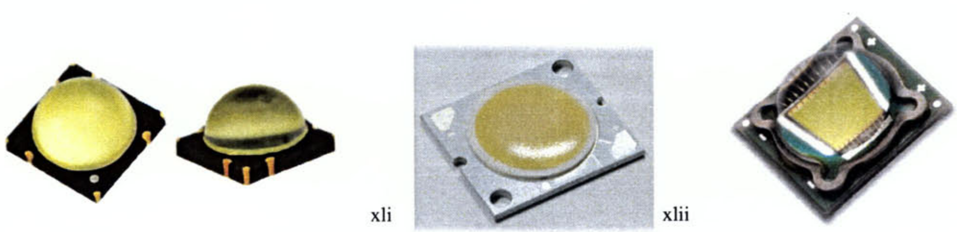
The three images above are of the new Cree XP-E, the Lumileds Rebel and the Nichia NCSW119. The three companies are rapidly converging on a dominant design, with a single 1mm square LED, dome encapsulant and ceramic board. The relatively arbitrary 1mm size LED chip has been the standard size produced by both Cree and Lumileds for quite some time. Nichia typically has avoided the 1mm chip size, but with the introduction of the NCSW119 is now going head to head with Cree and Lumileds. There are a few minor differences in the electrical interface for the three products, but they are minor differences. As these products continue their evolution and converge on a common design, it will be easier then ever for LED fixture manufacturers to use whichever LED they want.

A Different Approach

While I just wrote about LED becoming a commodity and the emergence of a dominant design, there are a few manufacturers taking a different approach. The driver behind this approach is the lumen limit of a single 1mm die. Many lighting applications calls for hundreds if not thousands of lumens per fixture, and this can be solved by either using multiple 1mm die or a single, larger source. LedEngin has been producing multi-chip custom LED assemblies for years. They seem to be attacking the market by providing custom solutions to fit particular market challenges. While they also offer products that are almost identical to the ones shown above, the multi-chip high-flux approach has its benefits. BridgeLux is taking this approach a step further, as they are both producing their own die and assembling them into custom products. Luminus, an MIT spin-off, is using their own custom large die to compete with the higher lumen level devices.

Figure 23: A different approach to LED sources

LedEngin BridgeLux Luminus



xli xlii xliii

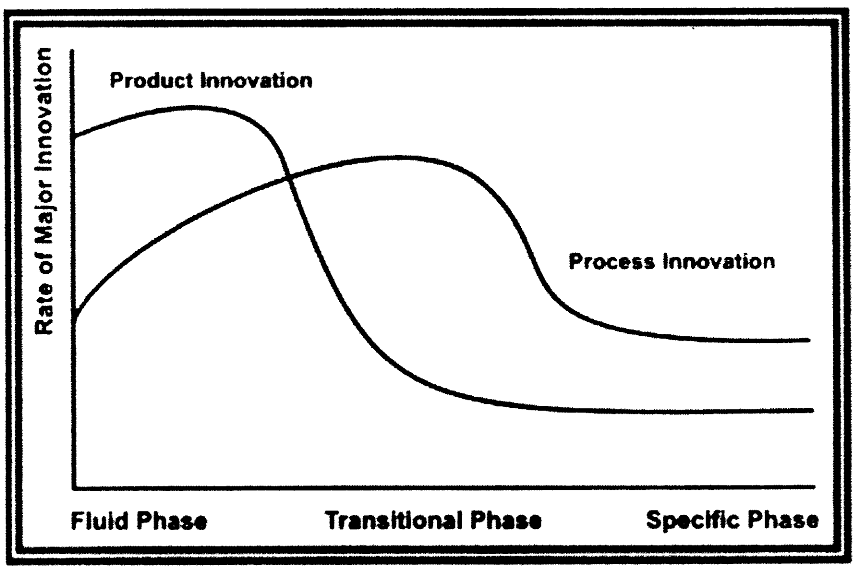
LedEngin, BridgeLux, Luminus

These approaches need to be carefully watched, as they have the potential to change the dollar per kilolumen pricing trend. This price difference is tied into the sensitivity analysis presented in the system dynamics section.

Dominant Design

The emergence of dominant design is a natural progression of any industry. According to the Utterback/Abernathy model of adoption, industries start with product innovation, and then transition into process innovation. A period of a "transitional phase" ushers in this change. Below is the chart of major innovation within an industry.

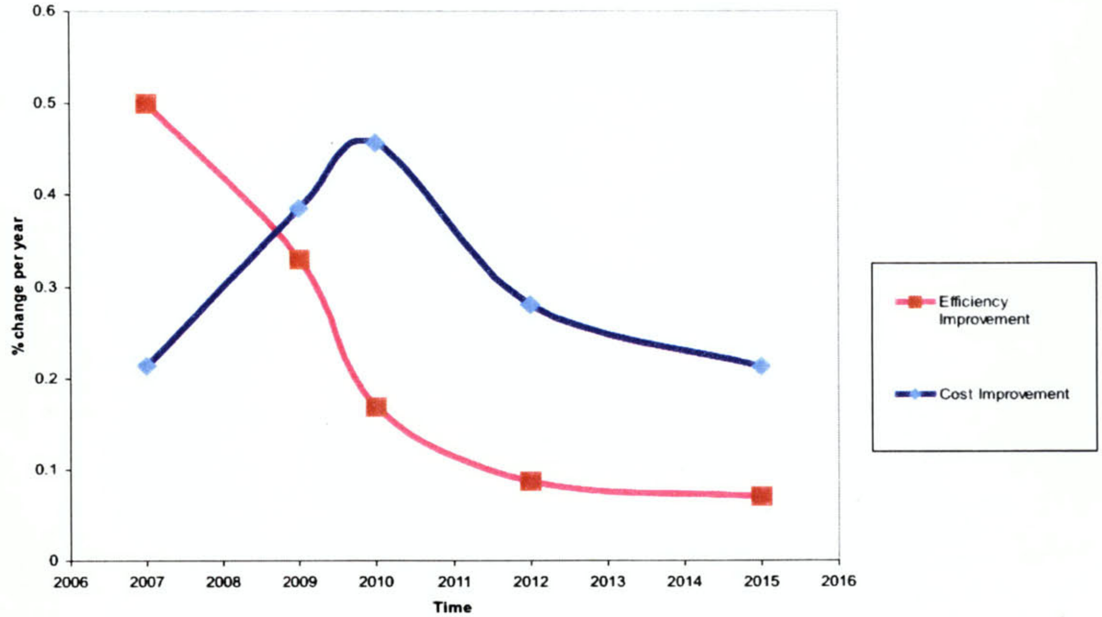
Figure 24: Utterback/Abernathy model of adoption



Mastering the Dynamics of Innovation, Utterback [xliv]

Below is a chart showing the performance improvement in the LED industry. This data is from both historical data and the Department of Energy's projection for performance improvement. The Y-axis is percentage change per year. Efficiency can be considered the product innovation, and cost can be considered the process innovation.

Figure 25: Percent change in efficacy and cost of inorganic LEDs over time



Modified Department of Energy Data

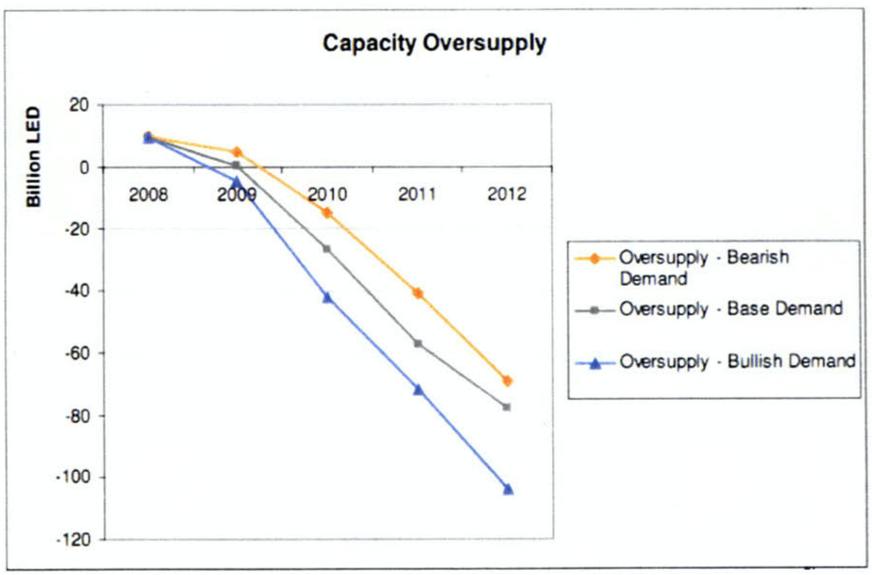
Therefore according to the Utterback/Abernathy model the LED industry is in the transitional phase. One of the significant characteristics of the transitional phase is that it generally has the greatest number of competitors. As an industry moves from the transitional phase to the specific phase the number of competitors drops as a dominant design emerges. The solid-state fixture/bulb industry, however, should lag the LED component industry as a dominant design has not yet emerged. This will be discussed further in the system dynamics model section.

As noted in the previous section about LEDs as a commodity (which is virtually synonymous with dominant design) the packaged LED industry is rapidly developing dominant designs, which correlates with the performance change shown above.

Pricing

The use of LEDs in our everyday lives has continued to grow at a rapid rate. Canaccord Adams views LEDs as having three cycles. The first cycle was the mobile phone market. LEDs are the dominant technology for backlighting keyboards and screens for mobile phones. The second cycle is the display market. While the most talked about segment of this market is large LCD displays, laptops and smaller displays are also significant. Apple first introduced an LED backlit display in 2007, and this architecture has continued to move throughout their product line. Other laptop manufacturers are following suit. In the larger LCD market, LED backlit LCDs are just now being introduced. Why is this important? Canaccord Adams is projecting a significant deficit in LED supply as LEDs continue to penetrate the LCD market.

Figure 26: Potential LED production capacity issue



Canaccord Adams, Jed Dorsheimer [xlv]

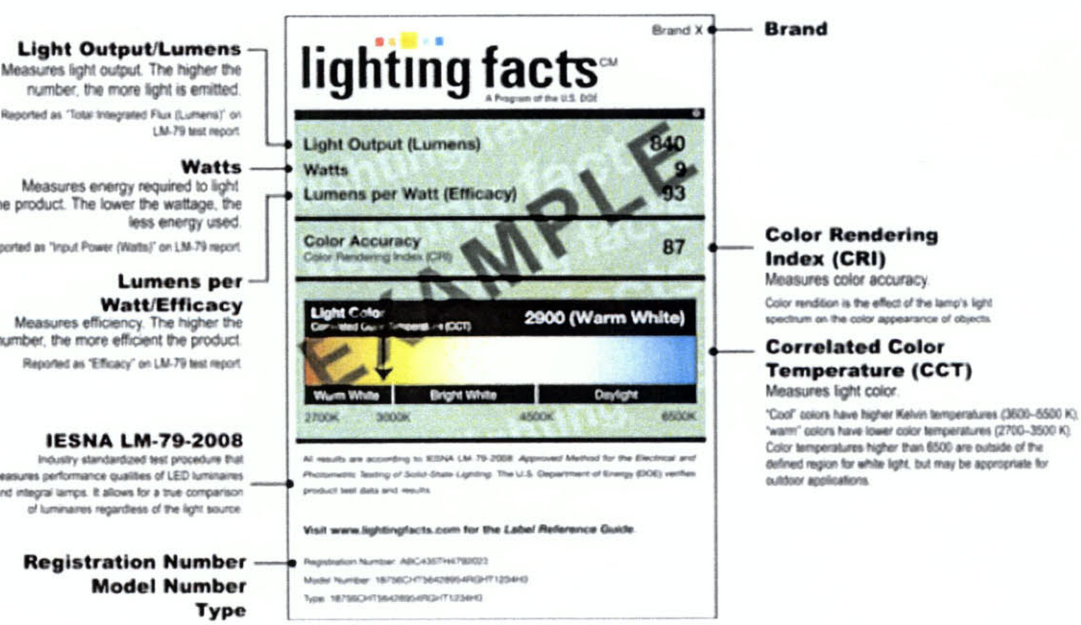
The short-term prospect of this demand spike is important, as pricing could rise in the immediate future despite the long-term trend in price reduction for LEDs. While this spike is not guaranteed to happen, pricing must be closely watched. In the system dynamics model section a sensitivity analysis will be performed, which presents alternative pricing scenarios similar to the one discussed here.

Perceived Quality versus Quality

"The rapid growth of LEDs has resulted in an increasing number of new products on the market, from desk lamps to outdoor lighting. While many of these products showcase the energy-savings potential and performance attributes of LED lighting, quite a few under-performing products are also appearing in the market. Since bad news travels fast, such products could discourage consumers from accepting this new technology. This is exactly what occurred in the early days of compact fluorescent lighting (CFL), which slowed the market acceptance of these products. DOE developed the Lighting Facts label to avoid this problem for solid-state lighting."[xlvi]

As LEDs continue to penetrate the lighting market, the perceived quality of these products is vital to their success. The Department of Energy and Energy Star are working together to provide a number of metrics for consumers. The Lighting Facts label has the potential to be a crucial initiative to promote LED adoption. The distinct difference between the Lighting Facts label and an Energy Star label is that the Lighting Facts label is ensuring the accuracy of the performance metrics, whereas the Energy Star label is ensuring that these metrics meet a minimum performance requirement.

Figure 27: The lighting facts label



lightingfacts.com [xlvii]

The effect of quality will be looked at in greater detail in the system dynamics model. As quoted above the introduction of poor quality products was an important factor that limited the early adoption of compact fluorescent bulbs. This factor was critical to properly tuning the system dynamics model when looking at the adoption of compact fluorescent lamps.

A relevant industry example might be useful when it comes to customer's perception of quality. For many years industry "experts" have stated that color quality and color temperature are irrelevant for exterior applications. A high-pressure sodium lamp (the yellow street and parking lot lights) has a negative CRI, and the output is almost purely yellow (2200K). Therefore it was assumed that any LED that was generally perceived as white was good enough. Many of the early LED streetlights used 6500K or higher CCT LEDs, as they are the most efficient in terms of lumens per watt. However, this output is perceived as very blue. In Seattle, the LED streetlights being tested were quickly labeled, "zombie lights."[xlviii] If you look at the chart of the Kruithof curve presented earlier, this issue quickly becomes apparent. In fact, it has been proposed that the bluish light of the LED street lights is perceived as daylight by humans, and could interfere with circadian rhythms, leading to high blood pressure and obesity. This is certainly not the reputation LEDs want to earn! In some of the test locations in Seattle the objections were so loud that they canceled the testing. Therefore it is important to not only ensure that the lifetime and performance of LEDs are as advertised but that customers do not find the color objectionable as the new products must meet ALL of the market needs. Quality is a broad term, but it must be analyzed at all levels and for all factors in a system.

Legislation

Legislation can have a powerful effect on market behavior. The ban on incandescent bulbs has already started in Europe, and is planned for the United States. Both Europe and the United States have started by banning the 100-watt incandescent bulb, and then moving down wattage by banning the 60-watt bulb and then 40-watt bulb within a few years.[xlix] While banning the highest power consumption lamp makes sense from an energy saving standpoint, the availability of other options for consumers is a challenge. While CFL replacements are available at the corresponding light output levels, LED replacements are costly, and none exist at the 100-watt incandescent equivalent. Therefore consumer choices are extremely limited, especially for replacing the 100W incandescent lamp, which will be the first to be banned. The effect of legislation will be explored with the system dynamics model. One of the greatest challenges when analyzing the effect of legislation is predicting consumer behavior. Hoarding, black markets, fighting the legislation and simply adapting are all reactions consumers may have to legislation. It is difficult to project how consumers will react in the lighting market.

Lighting Supplier Segmentation

LEDs have the potential to dramatically disrupt the usual supply chain in the lighting market. Currently, there are a few major companies who produce light bulbs, and a large number of small companies who produce lighting fixtures. LEDs will change this dynamic, as the ultimate LED solution is not a replacement bulb, but LEDs integrated into a fixture. In addition, the long lifetime of LEDs will eliminate the replacement market, and the traditional bulb makers are starting to see the writing on the wall. Therefore the power in the market is transferring from the bulb manufacturers to the fixture manufacturers. The challenge is that many of the current fixture manufacturers are not technically savvy, so it is difficult for them to produce LED fixtures. On the other side, the large companies who currently produce bulbs are trying to move up market to produce LED fixtures, as they realize the replacement bulb market is shrinking. What happens in the future? If you go to Home Depot right now, bulbs of all types are sold in one section, and fixtures are sold in another. Eventually, these will be one in the same. The system dynamics model will look at how the long lifetime of LEDs will shrink the volume of sales for lighting products while the overall value of the lighting market increases.

Industry Consolidation

As the lighting market continues to adopt LEDs, the industry structure is changing. Many of the major players are developing their own internal LED capabilities.

Philips has certainly been the leader, as they have purchased both Lumileds (an LED manufacturer) and Color Kinetics (an LED system integrator.) With the purchase of Genlyte Philips is now a vertically integrated company capable of sourcing almost every necessary component internally. The system dynamics model looks at the number of companies in the industry, which relates directly to the industry consolidation that is currently taking place.

The Mckinsey study discussed earlier claims that modularization will take over as the source of profits within the industry. This is a tenuous claim. As leading lighting manufacturers continue to vertically integrate themselves around LED lighting, there is little need for modularization. To fully optimize around both efficiency and cost each fixture is constructed with a customized LED board, not a modularized component. The thermal interface is critical for a successful LED design, and it is difficult to modularize a heat sink around every size of fixture. While the need for a highly optimized thermal design will be reduced as LED efficiency improves, it will continue to be an important issue for the foreseeable future.

There is a need for modularized LED components, but it is a niche market. There are a number of smaller lighting fixture manufacturers who are beginning to integrate LEDs into their designs. They do not have the LED competency in house, so they will need a simple, modularized reference design. However, these companies make up a small portion of the market, and the highly vertically integrated large-scale manufacturers have little need for modularization. The greatest value in modularization lies in the relatively high volume per SKU, which should lead to reduce cost.

If modularization takes place it will drive industry consolidation on the road to a dominant design. Therefore it is important to watch modularization as it may change the rate of exit for companies within the LED lighting market. On the other hand, the push for tightly integrated systems is already driving the consolidation of the industry, further leading to the case of the transitional phase.

Chapter 5: System Dynamics Model

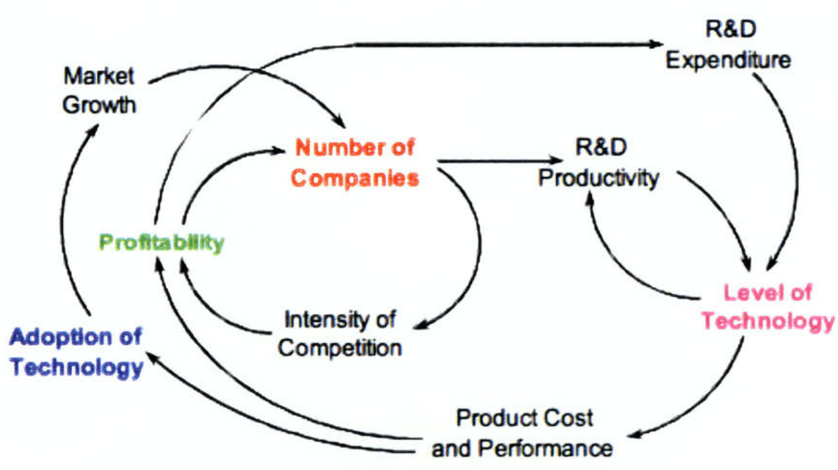
This chapter dives into a system dynamics model for adoption in the lighting market. Details of the vital feedback loops and important variables are discussed. In addition, a number of scenarios are run through the model and the results analyzed. Much of what is defined below is discussed in detail in the previous sections.

Background and Overview

The following system dynamics model builds on the work of James Utterback and Henry Weil. Their original model looked at how mp3s overtook CDs in the marketplace. It has also been modified to look at the adoption of digital cameras. An adaptation of their model to evaluate the lighting market is described here.

The following diagram highlights the high-level conceptual feedback loops from the original system dynamics model.

Figure 28: High-level system dynamics feedback loops

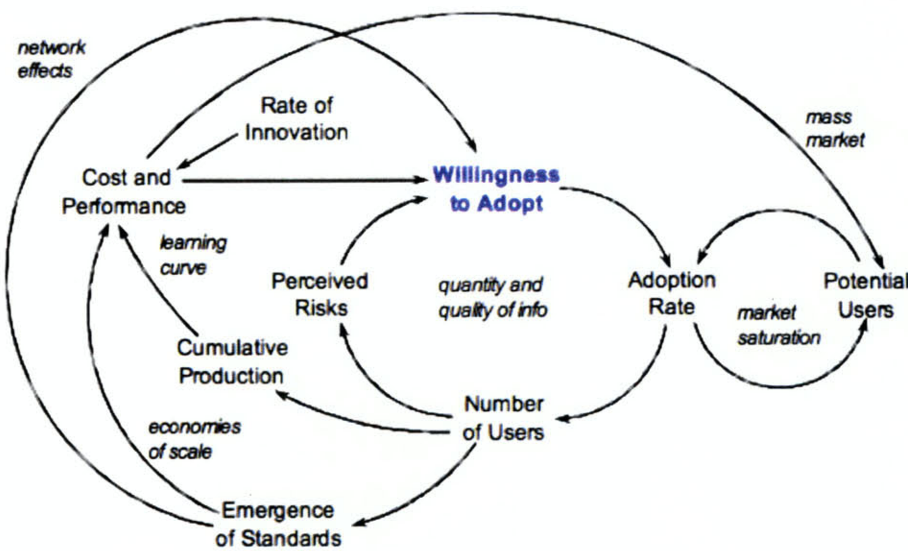


Henry Weil and James Utterback, "The Dynamics of Innovative Industries" [1]

The modified model discussed in the following section is a simpler version of this diagram. In the original model, the level of technology is calculated over time. In the modified model, the product cost and performance is defined exclusively by the Department of Energy data. While this eliminates some of the important feedback loops of the original model the data has been well vetted by the solid-state lighting industry. In addition, variations on this data can be evaluated to look at the model's (and therefore the market's) sensitivity to these inputs.

A customer's willingness to adopt a new product is vital to the success of that product. The following diagram describes the important feedback loops from the original model, all affecting "willingness to adopt."

Figure 29: "Willingness to adopt" feedback loops

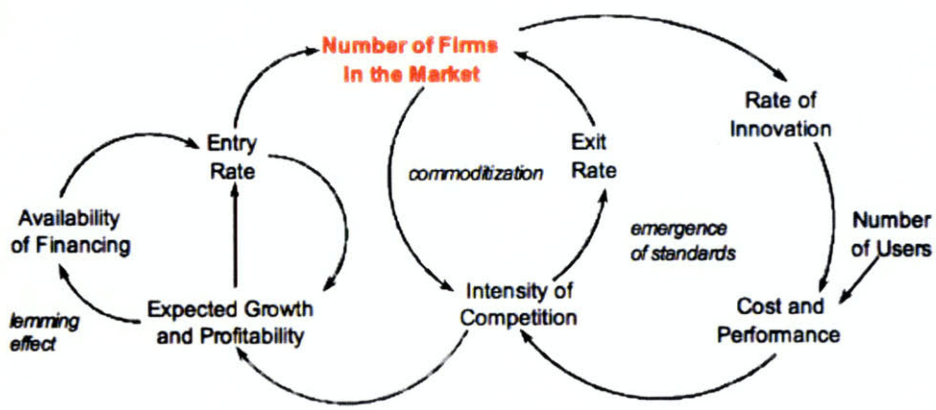


Henry Weil and James Utterback, "The Dynamics of Innovative Industries" [li]

The modified model uses most of the same concepts. Again, similar to the previous changes discussed the cost and performance are explicitly stated by the Department of Energy data.

The final important piece of the model is the number of firms in the industry. The different phases described by the Utterback/Abernathy model were discussed previously, and these can be evaluated in the context of the model by looking at the number of companies.

Figure 30: "Number of firms in the market" feedback loops



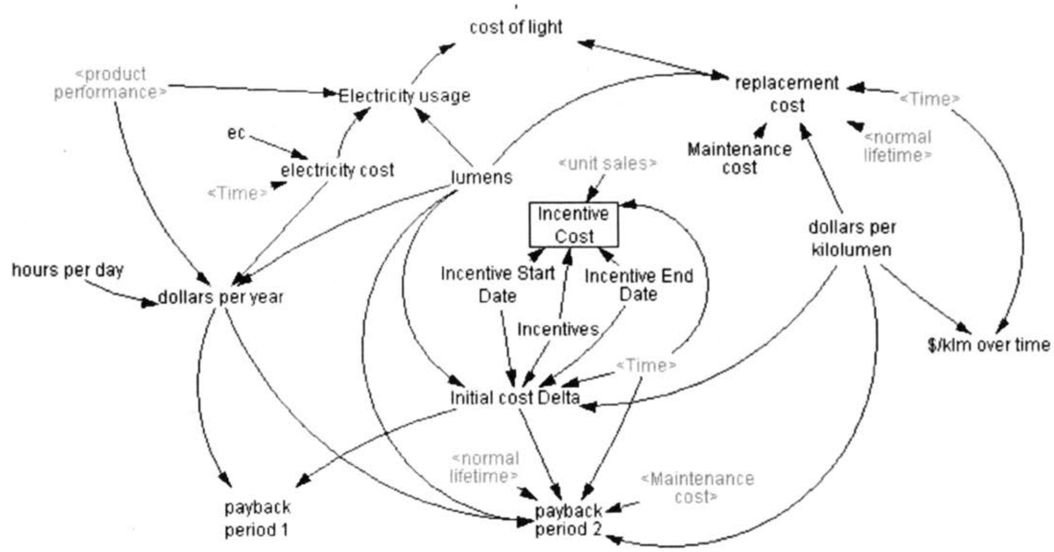
Henry Weil and James Utterback, "The Dynamics of Innovative Industries" [lii]

To modify the model for the lighting market these main concepts are changed slightly. The cost and performance is again an input to the model, but the trends follow the natural progression of the adoption model, as shown in the previous section. Many of the other dynamics feeding into the number of firms in the market were left alone, as they were very accurate in previous iterations of the model.

Cost of Light

The cost of light is an important metric when discussing advanced lighting solutions, whether it is CFLs, LEDs, or other technologies. Generally the initial cost is higher, but the cost of light is lower. The units for cost of light are in dollars per million lumen hours.

Figure 31: "Cost of light" feedback loops



Electricity usage is an important factor when determining the cost of light. This calculation involves the historical and projected electricity cost multiplied by the product's performance in units of lumens per watt. Lumens are used because the product performance is given in lumens per watt, and the electricity usage needs to be calculated per watt.

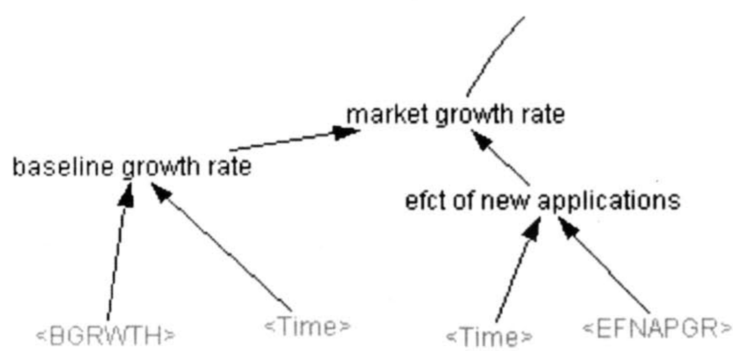
Replacement cost factors in both the initial cost of the bulb and the maintenance cost associated with replacing the bulb. For the home market the maintenance cost is essentially zero, but for many markets (traffic lights, high-bay, etc) the maintenance cost may even exceed the cost of the new bulb. The initial cost is calculated by using the lookup for dollars per kilolumen given by the Department of Energy data and the total lumens from the package.

The payback period is often viewed as a vital metric for consumers to make a decision. It is often referred to as the return on investment. In this model "payback period 1" simply incorporates the electricity savings versus initial cost to determine the payback period. Payback period 2 also factors in the maintenance cost and the replacement cost to the calculation. Units are in years.

Incentives can be utilized to jump-start a market. In fact, incentives were given by many utilities in the early days of the CFL market. This model calculates the total cost of incentives given the amount a bulb is discounted and the number of years incentives are offered.

Macroeconomic Effect

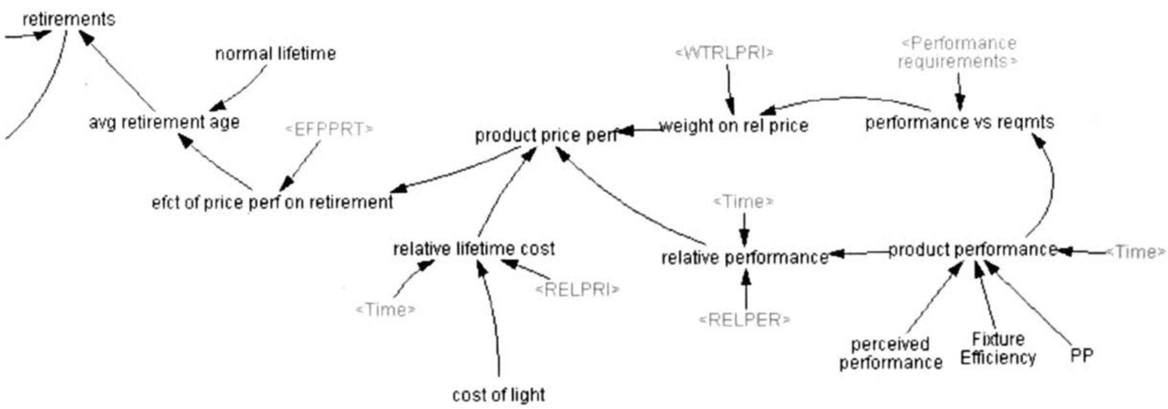
Figure 32: Macroeconomic Effect



Market growth takes into account both the baseline growth rate of the macroeconomic market and the effect of adding new applications to the market. Baseline growth data is simply the year over year GDP growth[liii]. The effect of new applications is generally small for most of the lighting market, but may be considered when looking at emerging markets (Africa, etc) where lighting is being added.

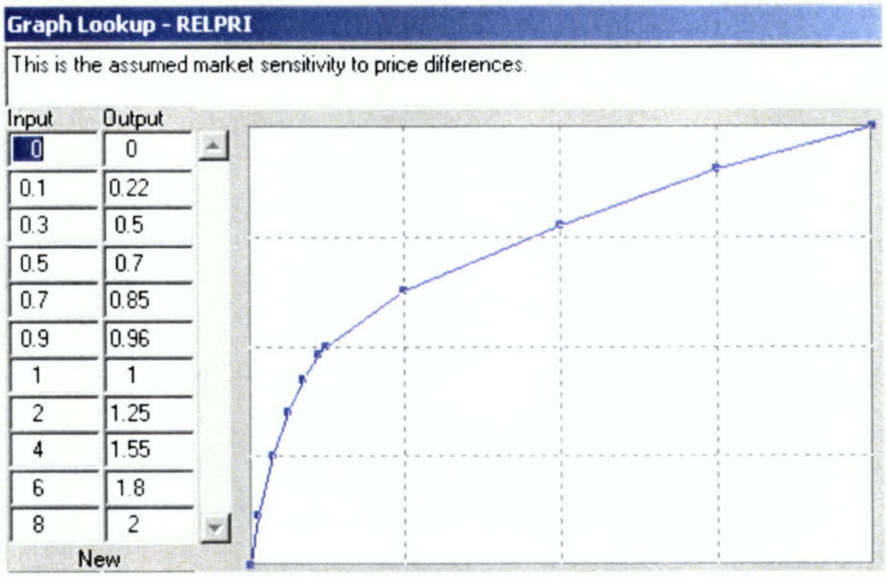
Retirement

Figure 33: Retirement



Product retirement is vital to the adoption of a new technology. If the old product is never retired, then the only possible adoption for a new technology is with market growth, which isn't always assured. The relative lifetime cost is factored into this calculation, which compares the cost of light for both the new and old technology.

Figure 34: Market sensitivity to pricing



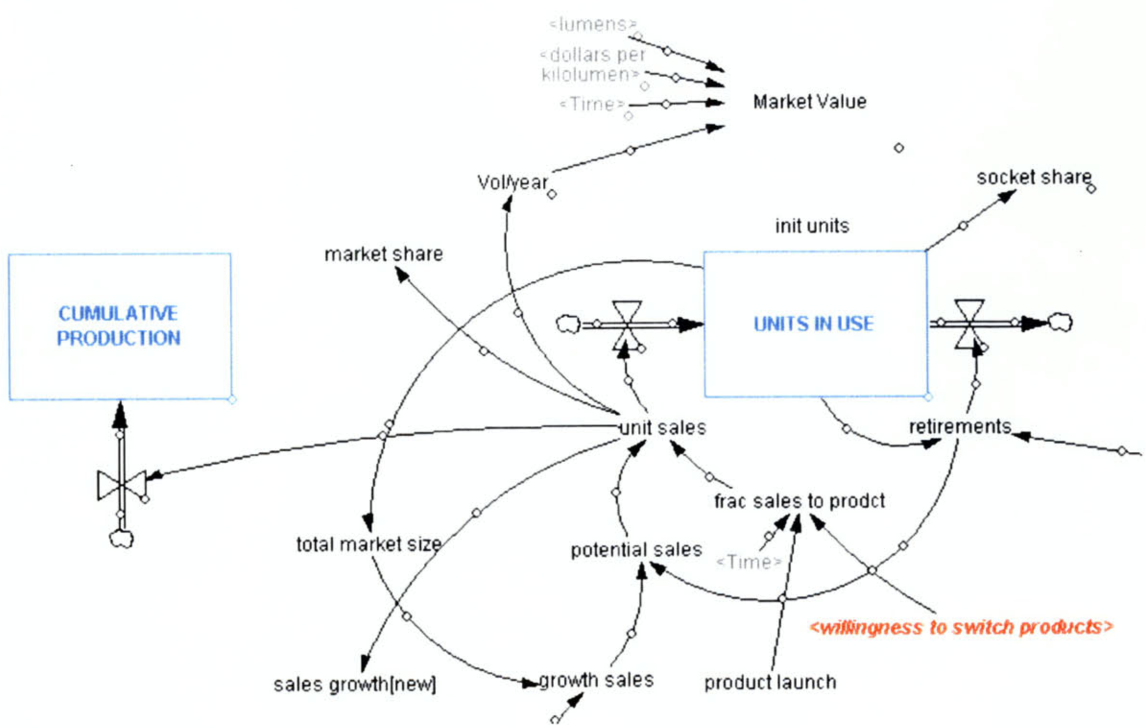
The lookup table for the relative lifetime cost factors in the market sensitivity to lifetime cost differences. This is not a linear relationship, because when the cost is extremely high, the market doesn't view the difference as to be as extreme as it actually is.

Performance versus requirements compares the actual product performance for each product versus the performance requirements of the market. This feeds into "weight on rel price." The weight on relative price depends on the extent to which a product meets customer requirements. If the established product meets/exceeds requirements, the new product's attractiveness depends on relative price, i.e., it must be cheaper to win converts. If the established product falls short of requirements then customers put increasing weight on relative performance.

Product price performance takes into account the weight on relative price, the product's performance and the product's price. This single combined metric can then be used to calculate the average retirement age of a product. In the case of lighting, an average lifetime is well established; a year or so for an incandescent bulb, a few years for a CFL, etc. However, if the price is low enough and the performance is high enough an individual will make the decision to retire the old product early in favor of the new product, rather then waiting for it to burn out. If the cost of using an old technology is high enough versus the cost of the new technology, the old will be removed and replaced with the new.

Units in Use

Figure 35: Units in use

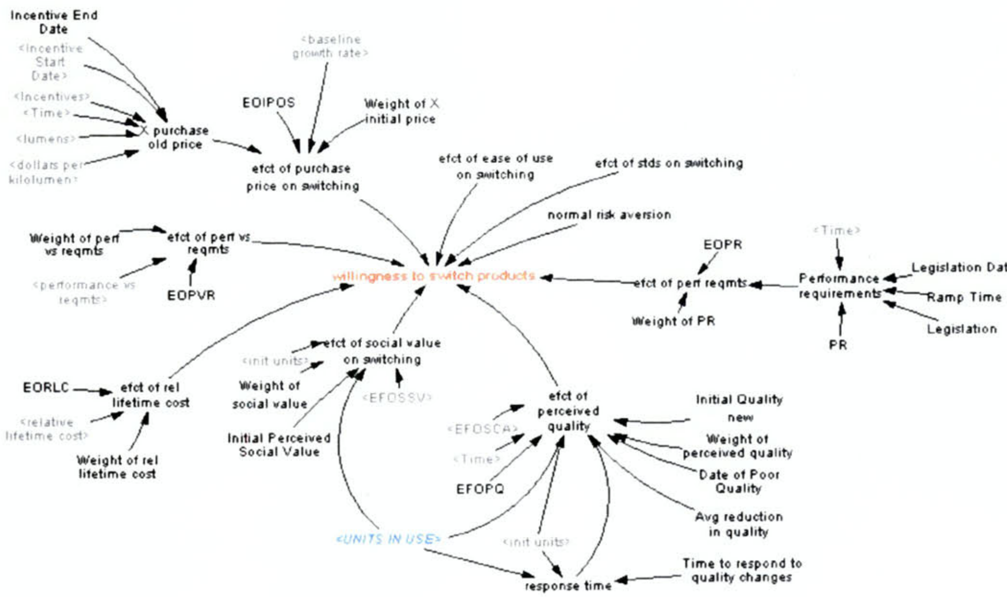


The image above gets into the heart of the model. In the middle is a stock describing the number of units in use for each product. Feeding into this stock is a metric for sales, and outgoing from this stock are retirements as discussed above. "Willingness to switch products " is a vital metric which will be discussed below. "Market value" describes the total value of a market. This is particularly important when discussing LED products, as the total volume year is projected to go down due to the long lifetime of LED products. That being said, the market value is going to increase due to the higher price of LED products.

Willingness to Switch

"Willingness to switch products" is vital to the model. There are many factors feeding into this. In general, the factors are calibrated into a 0.5-2 range. Therefore a value of 1 has no effect on the model, since the willingness to switch multiplies the inputs together. The image below encompasses all of the factors that feed into "willingness to switch." Each factor is split off and discussed separately below.

Figure 36: Willingness to switch products



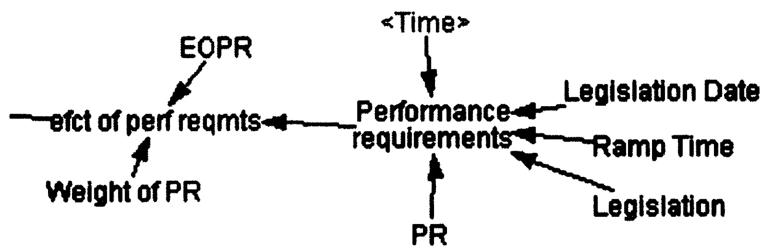
Starting at the 12:00 position, the first variable is "effect of ease of use on switching." This is simply a number on a 0-1 scale. This dictates how easy typical products within the market are to use.

Moving clockwise around the center, "Effect of standards on switching" defines the standards within a market. In the lighting market, this may be used define interface standards (Edison socket, bi-pin, etc) and other factors.

"Normal risk aversion" describes the risk aversion present within a market. In some markets the customers don't mind taking risks and purchasing an unknown product, where in other markets the customers are very conservative about their purchasing decisions.

The figure below defines the customer's demand in terms of performance requirements.

Figure 37: Performance Requirements

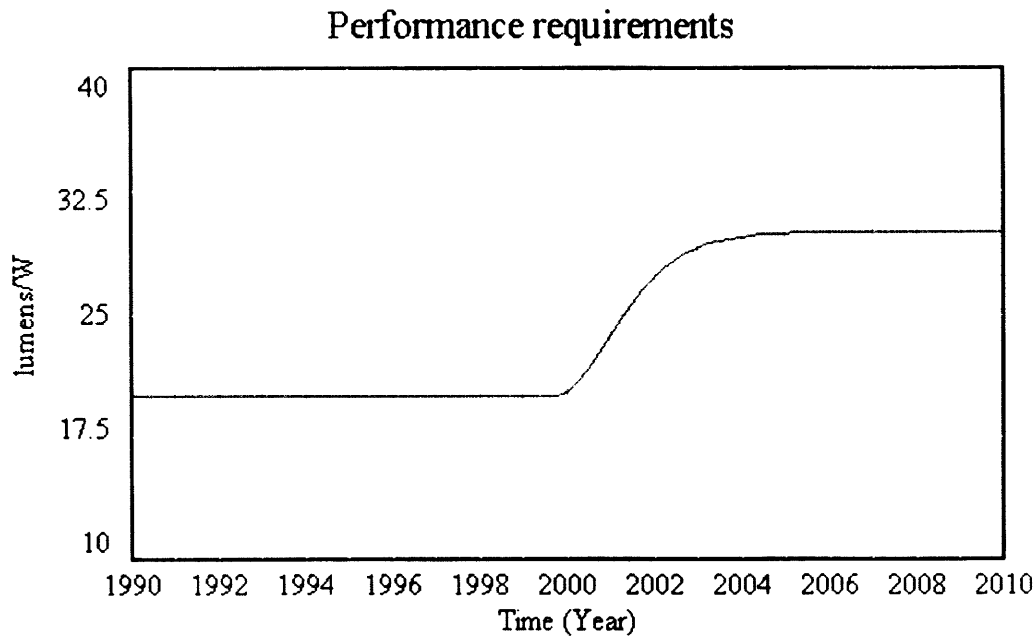


PR is a defined lookup for the normal performance requirements, which is generally a slowly increasing demand for product performance. In this case it is defined as lumens per watt, to match up with the units for product performance.

Legislation can be used to change the normal customer demand curve. In this model legislation is calculated using the "Legislation Date," "Legislation" which is defined in terms of lumens per watt and "ramp time," which is the number of years it takes for the performance requirements to meet the legislation. This is used because many of the legislation options currently being discussed or implemented are stepped, and not an instantaneous change. It is possible for the customer's demand to eventually overtake the legislation, so the maximum value of either is used.

The example shown below is the affect of legislation on performance requirements. In this basic example the customer demand is 20 lumens per watt, the legislation is 30 lumens per watt, the start date is the year 2000 and the ramp time is 3 years.

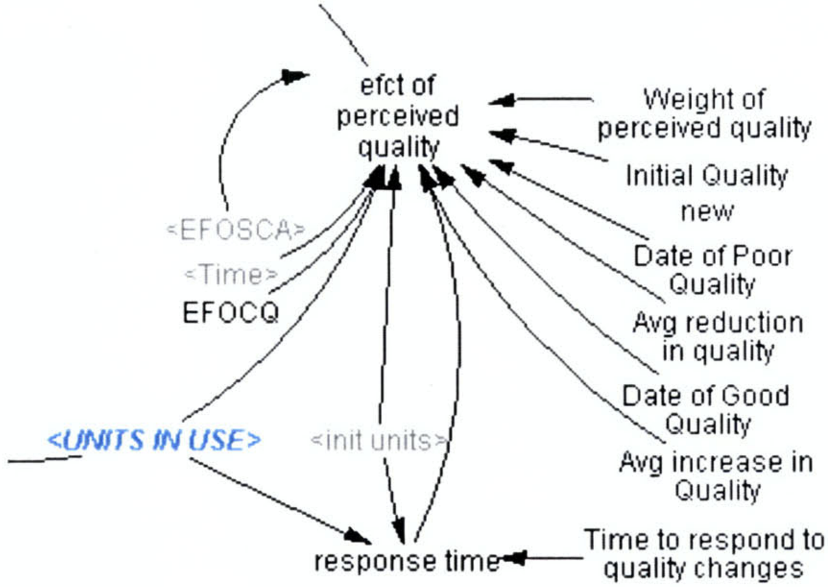
Figure 38: Legislation's effect on performance requirements



The output of performance requirements is fed into a lookup to bring it into the 0.5-2 range for "willingness to switch products." This performance curve has only a relatively mild affect on the "willingness to switch products." The reason is that this is only determining the customer's interest in looking for other products. If legislation takes place, then customers are more willing to look at new products. Once they decide to look at new products, then they will compare the performance versus the old product. This is calculated in a different portion of the model, but utilizes the performance requirements curve calculated in this portion. This input also has a weight assigned, to tailor the output to the interest of each market segment in performance requirements. For example, in the residential market individuals are rarely aware of performance requirements and their meaning, so this is weighted relatively low, say 0.3. On the other hand, a lighting designer who needs to design a commercial building to meet the latest LEED requirements for energy efficiency will look at every available technology in order to meet these requirements, and is very aware of the developments within the industry. In this case, the weight is relatively high, say 0.8.

The effect of quality on adoption is critical, as a product that is perceived to be of poor quality will rarely be adopted.

Figure 39: Effect of perceived quality



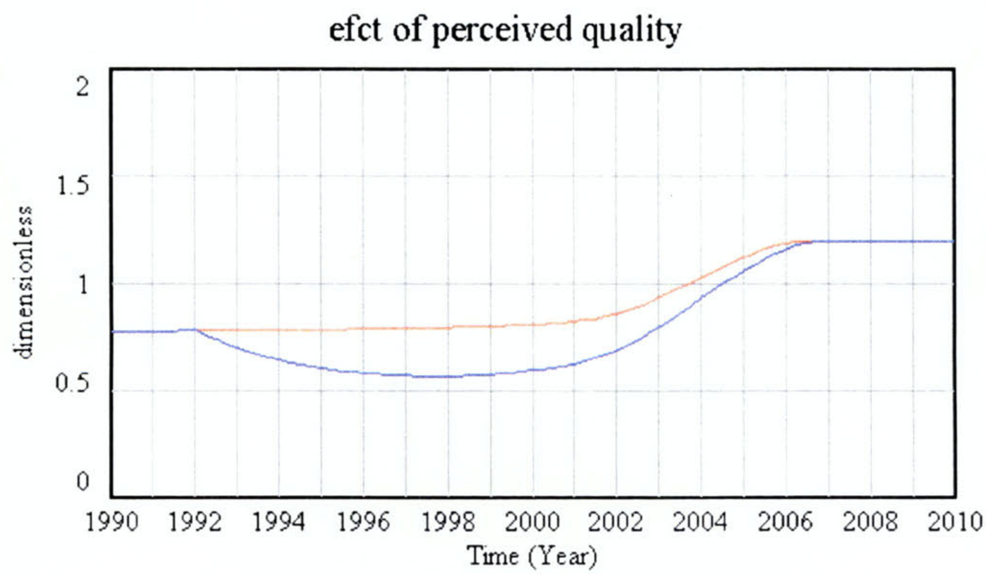
At a basic level, the effect of quality is calculated by utilizing a starting perceived quality, the importance of quality to the particular market (weight of perceived quality), and the number of units in use. In general, as the number of units of a particular product increases, the perceived quality increases as well. At a certain point (say 10% of a market) the perceived quality starts to flatten out, as there are sufficient units of a product in the market to be perceived to have good quality. This in essence "de-risks" the new technology to the consumers.

One fear in the minds of many solid-state lighting suppliers is that that LEDs will gain a poor reputation in the industry due to low-quality products being introduced. This happened in the early days of the CFL market, and delayed the adoption of CFLs by many years. This model can account for this issue, by utilizing an "average reduction in quality" variable. In addition, the "response time" of the market to changes is defined by how large a market share the new product has. A current example of this is Toyota. Toyota has a large percentage of the market, so when the issue of poor quality came to light the market's perception of Toyota's quality was reduced rather quickly. The high publicity of these problems contributed to the fast market response time.

The effect of perceived quality can also change due to a sudden increase in quality. This could be the implementation of more rigorous testing, increased public awareness through marketing, or other factors that could boost quality in the mind of the customer.

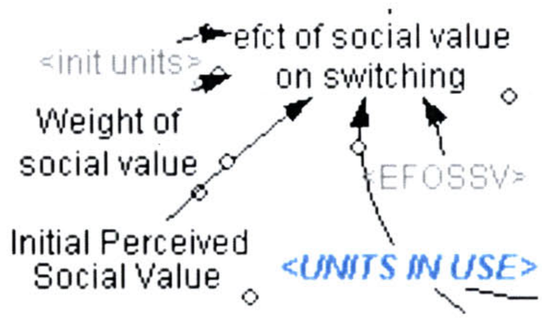
The example shown below compares an average reduction in quality starting in 1992 versus no reduction in quality. This reduction is 0.2, and the average market response time is 3 years. The adoption rate in this example is relatively low until 2000, when the market share increases. Therefore at this time the reduced quality curve rapidly approaches the curve without any quality issues, due to the decrease in response time of the market brought on by the increase in market share.

Figure 40: The effect of a decrease in quality



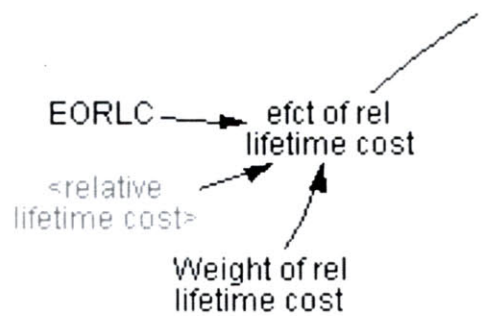
Social value can be an important adoption criteria for a new product. As the market share of a product increases the social value increases accordingly. This factor can also be weighted according to the market segment.

Figure 41: The effect of social value



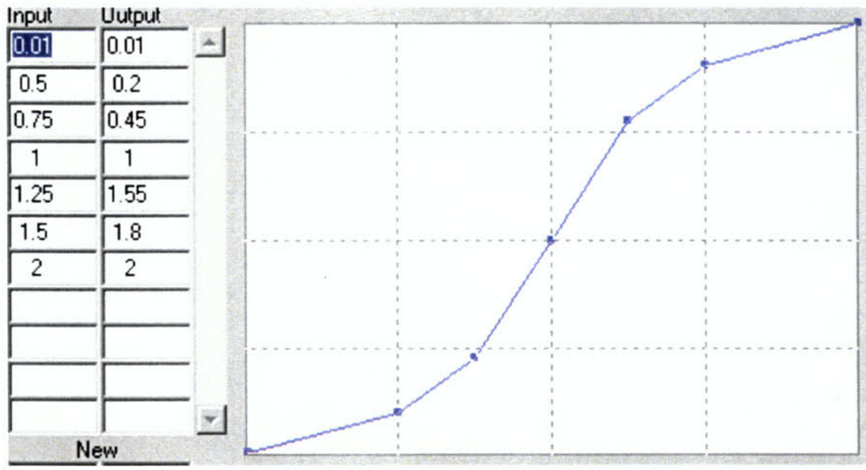
The relative lifetime cost of a product compares the lifetime cost of the new product versus the old product. In this calculation the relative lifetime cost (in $ per million lumen hours) is pulled from the earlier calculation and then a simple fraction is calculated.

Figure 42: The effect of relative lifetime cost



The EORLC lookup defines the market's view of this fraction. If the relative lifetime cost is either very large of very small the market's view is extreme, whereas if the relative lifetime cost is similar a small change can have a significant effect on the adoption. This lookup is shown below.

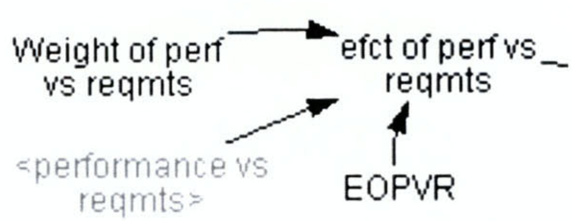
Figure 43: Lookup table for the effect of relative lifetime cost



This can also be weighted according to the market segment. This weighting is especially important when comparing market segments. For example, in the residential market individuals rarely look at the lifetime cost. It is buried in their electric bill, and it is difficult to see the change of adding an efficient product, especially if only a single bulb is changed at one time. In the commercial market, a building owner is very aware of the variable costs associated with running the building, and is more willing to invest the upfront cost of a more expensive lighting system if the lifetime cost will be reduced.

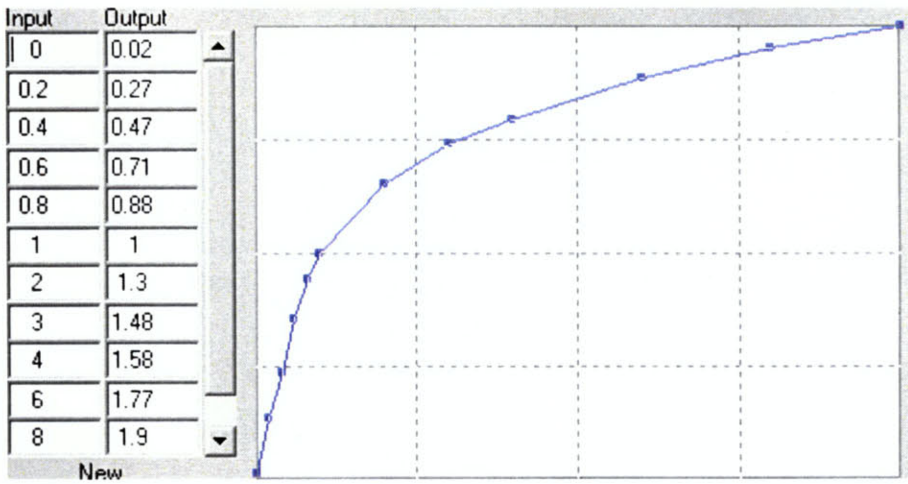
Performance versus requirements looks at the relative performance of each product (old and new) versus the performance requirements of the market segment.

Figure 44: Performance versus requirements



The calculation feeds each ratio into the lookup shown below, then takes the fraction.

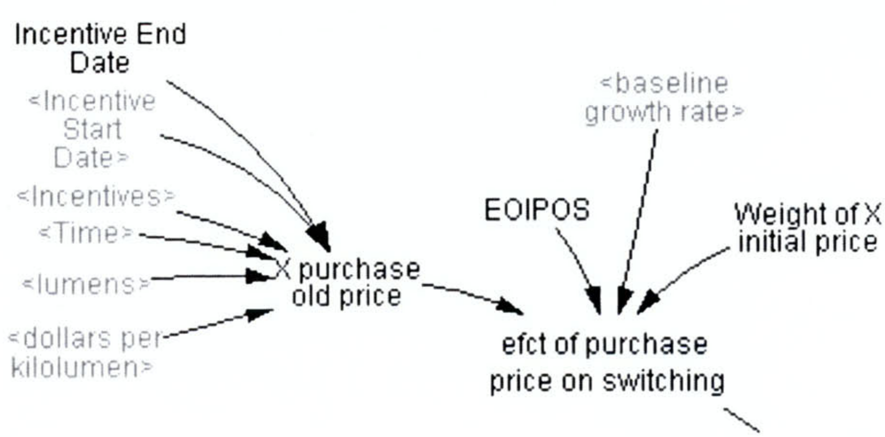
Figure 45: Lookup table for performance versus requirements



As you can see, the market's perception of performance versus requirements is not linear. For example, if a product's performance is 10 times better then the market demands, then the desire to purchase the product is only a 2.

The purchase price of a product is in many cases the most important variable which customers use to decide whether to purchase a new product or not. This is especially true in the residential market. In most cases a consumer wouldn't pay $100 for a light bulb, even if it used no electricity at all! This isn't the case for other markets, so again this input can be weighted accordingly.

Figure 46: The effect of purchase price on switching

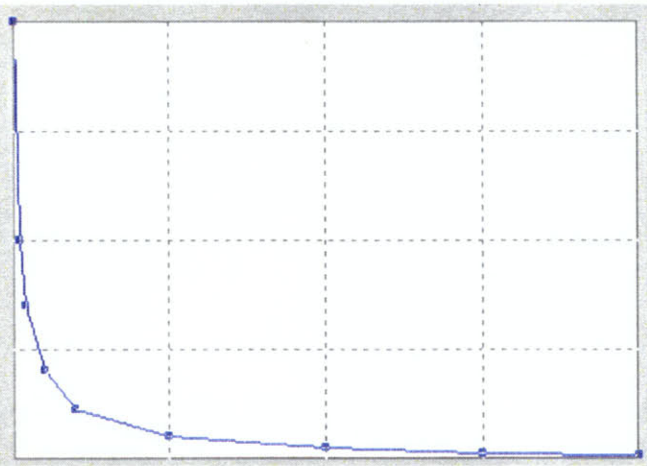


"X purchase old price" is simply a ratio of the new product's price versus the old product's price. In general for the lighting market the new technology is significantly more expensive, so this is the most appropriate way to look at the pricing. The baseline growth rate is also a variable fed into this factor. The reason for the use of this variable is that if the market is growing the customers have more money available, so they are more likely to pay the higher initial price for the new technology. On the other hand, in a recession customers are cutting costs wherever possible, so it is doubtful that they will pay for a more expensive lighting system even if they will see significant savings in the future.

The lookup for the effect of purchase price is shown below.

Figure 47: Lookup table for the effect of purchase price on switching

Input	Output
0.1	2
1	1
2	0.7
5	0.4
10	0.22
25	0.1
50	0.05
75	0.02
100	0.01

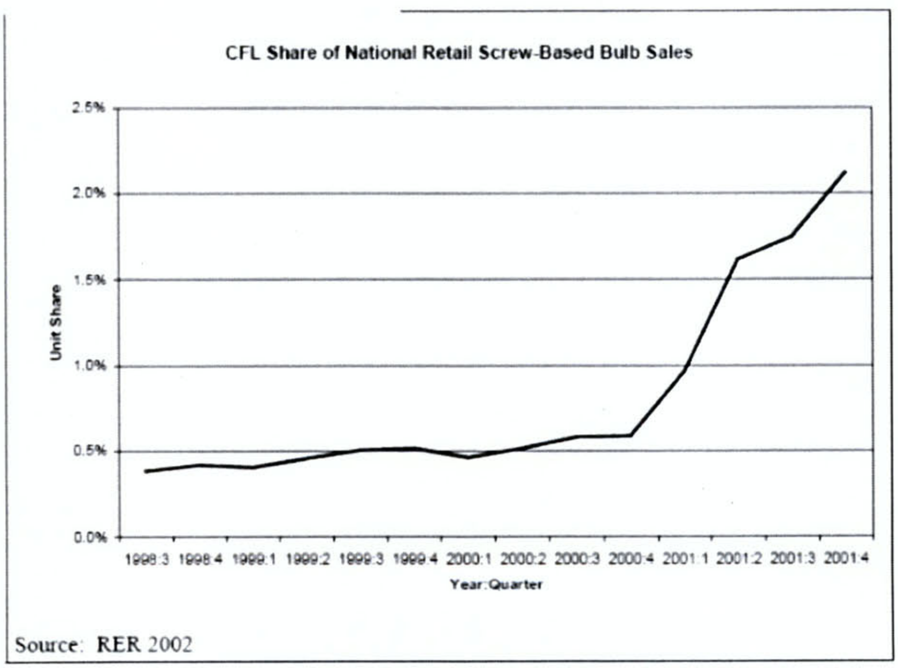


If the cost of a new technology is 100 times the cost of the old, only 1% of the customers are willing to purchase it. These could be considered the early adopters, where price is less of a concern. Once the price of the two technologies are equal, the output of the lookup is one, since the lack of a price difference means it has no effect on the purchase decision.

Tuning the Model - CFL Adoption

While it is important to construct a model that utilizes all of the important variables described above, the model needs to be tuned accurately to ensure the outputs are believable and useful. I utilized the historical CFL and incandescent shipping rates from the Department of Energy. There are two distinct periods of growth in the CFL market. The first was in the end of 2001, when sales jumped from ~0.5% of the market to 2% in one year. The main drivers discussed for this jump are incentives, improved quality, and the increase in electricity rates.

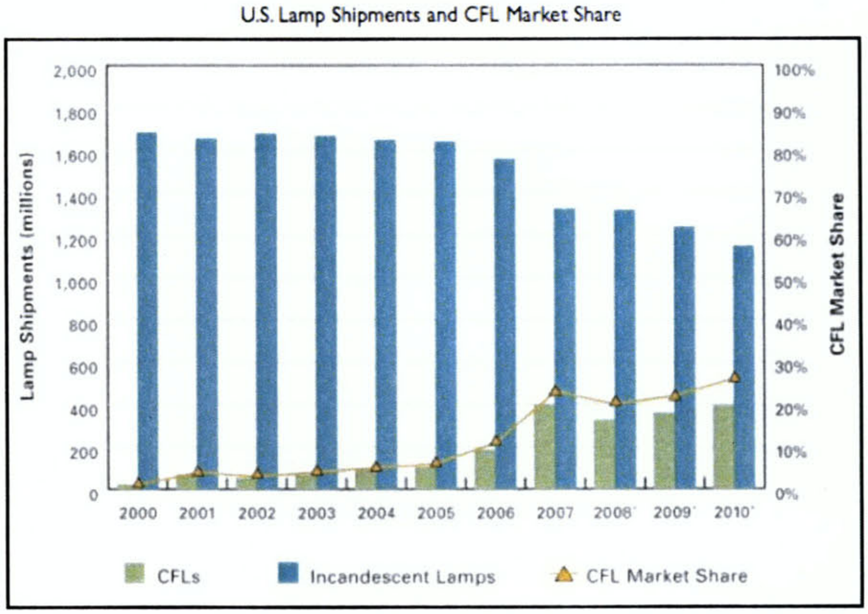
Figure 48: Early CFL market share



CFL lessons learned [liv]

The second significant jump in sales was in 2005. According to Canaccord Adams this is when the ROI period became less then one year. Sales increased by four times in the next two years.[lv]

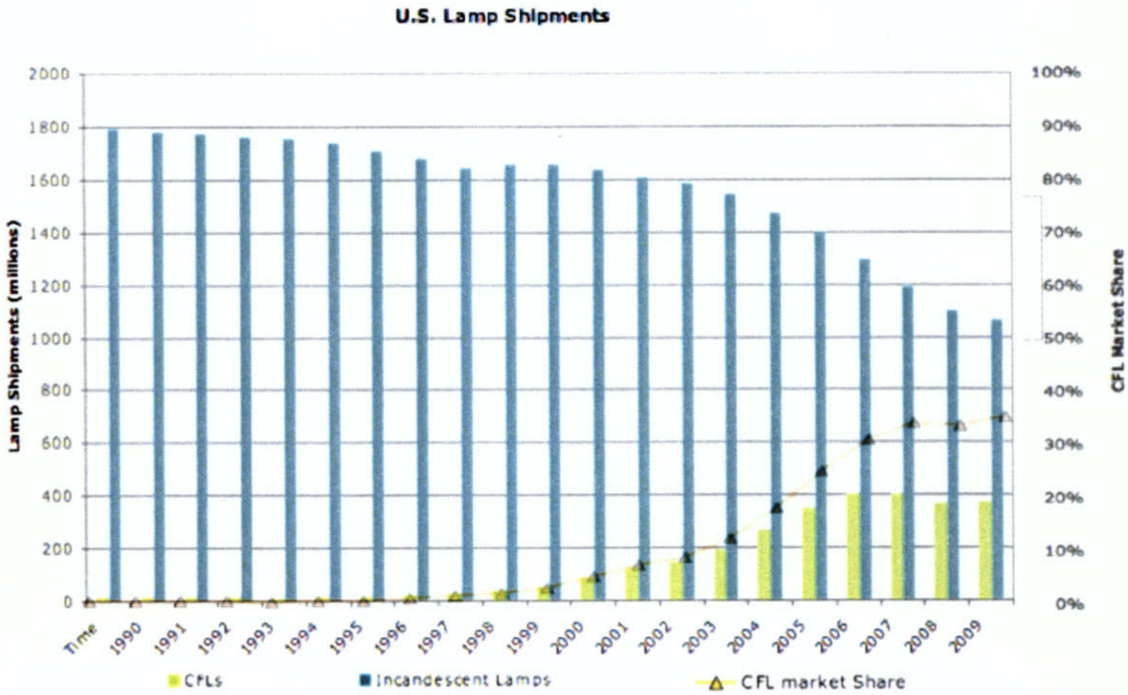
Figure 49: CFL versus incandescent lamp sales



Source: US Department of Energy, analysis by D&R international; CFL Shipments – US Department of Commerce; Incandescent Shipments – D&R, based on Navigant Lighting Study, RECS, DOC. lvi

The data shown below is from the system dynamics model. The important inputs are the historical CFL performance data, average lifetime, a decrease in quality around 1992 (when poor quality CFLs entered the market and gave CFLs a bad early reputation), an increase in quality around 2000 when increased testing weeded out the poor quality lamps, an incentive period around 2000 which decreased the selling price for a short period, the historical national electric utility rates and the historical change in GDP.

Figure 50: System dynamics model output for CFL and incandescent lamp sales

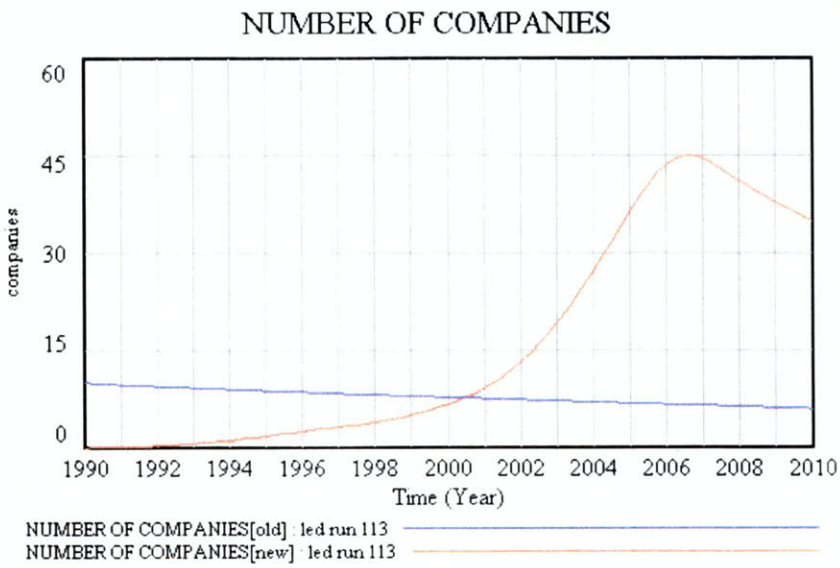


You can see that while this chart is similar to the historical data, there are a few variances from the actual data. First the scale is shown from 1990, the beginning of the simulation. This allows the chart to take into account both the 2001 increase in CFL sales and the 2005 increase. Overall, the model follows the real data rather well, and proves the validity of the model.

The CFL market had in essence two tipping points; in 2001 and in 2005. While these tipping points are important, they need to be viewed within the larger context of the lighting market. CFLs are predominantly used in home illumination. Twin-tube, T5, and other fluorescent bulb types are widely used outside of the home, and their market share in those market segments far surpasses CFLs market share for home illumination. In addition, there are other types of lighting where LEDs are trying to compete (low pressure sodium, HID, etc) so it is important to understand the entire lighting market when looking for a tipping point. This is why the model can be tuned to look at each niche, as it is difficult to evaluate the entire market as a whole in a single model.

According to the model the CFL market is in the transitional phase, as the number of companies is decreasing as the dominant design has arose. This makes sense, as every CFL looks almost identical and the price has dropped dramatically in the past few years. The trends for the number of both incandescent and CFL companies is shown below.

Figure 51: Number of CFL and incandescent companies

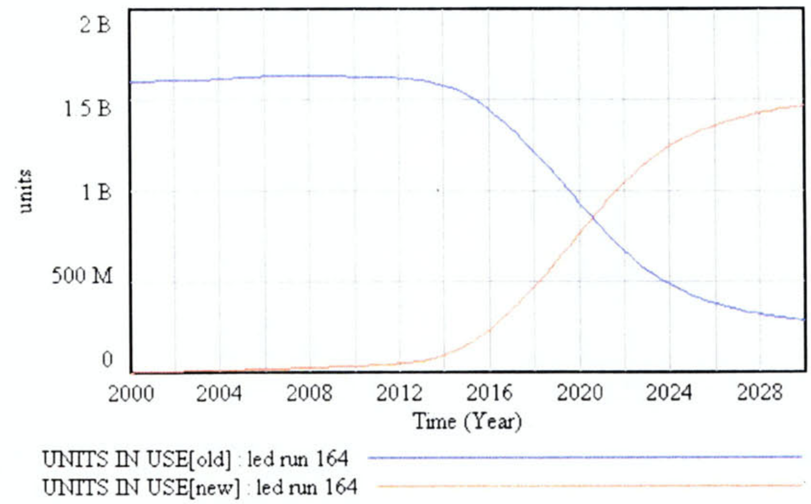


LED versus Incandescent

The first and simplest model to run is to look at how LEDs could overtake incandescent bulbs in the home illumination market. It is important to remember that this simply looks at LEDs versus incandescent lamps, and does not include CFLs. Therefore this is not a realistic environment, but it does tell us how quickly LEDs could be adopted in certain installations (dimming, narrow beam, etc) where CFLs cannot compete.

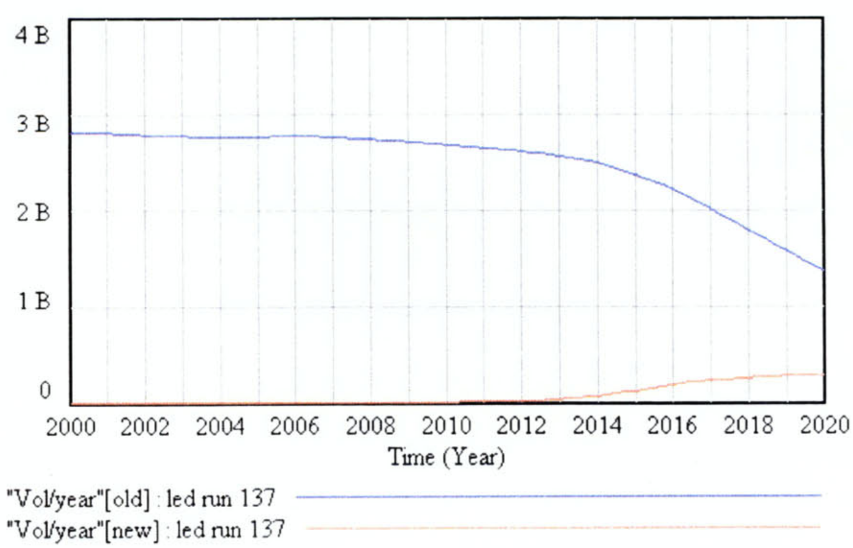
Below is an output graph showing how LEDs (red line) will overtake incandescent bulbs around the year 2021.

Figure 52: Units in use for LEDs versus incandescent lamps



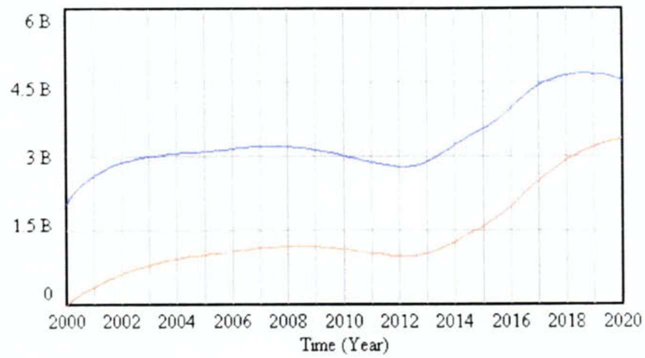
One important aspect of LEDs is a long lifetime. Compared to incandescent bulbs the volume/year of LED bulbs will be significantly lower, but the overall market value will remain high due to the increased purchase cost. The decrease in overall volume is shown below.

Figure 53: Volume per year of LED and incandescent lamps



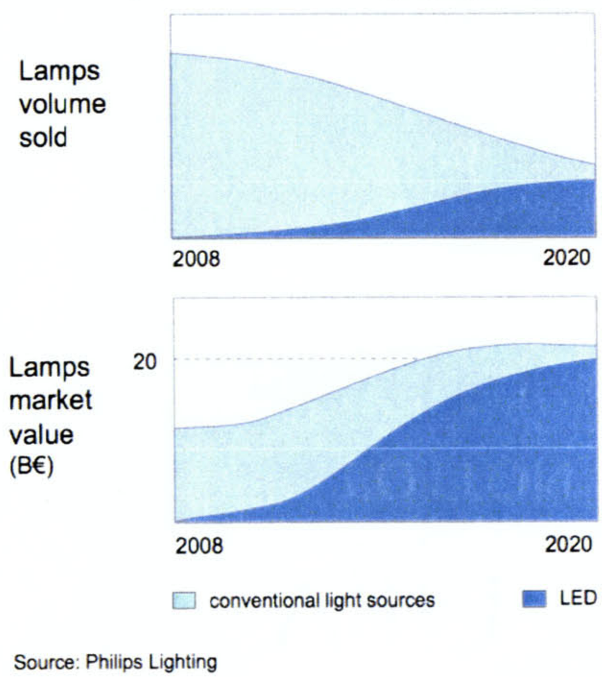
As was discussed above, the market value will increase. The red line is the LED market value, and the blue line is the conventional light source market.

Figure 54: Lighting market value



This trend is certainly one that has been discussed before. Rudy Provost of Philips Lighting presented Philip's view on this trend to investors in 2009. The pertinent charts are show below.

Figure 55: Philip's view of the changing lighting market value

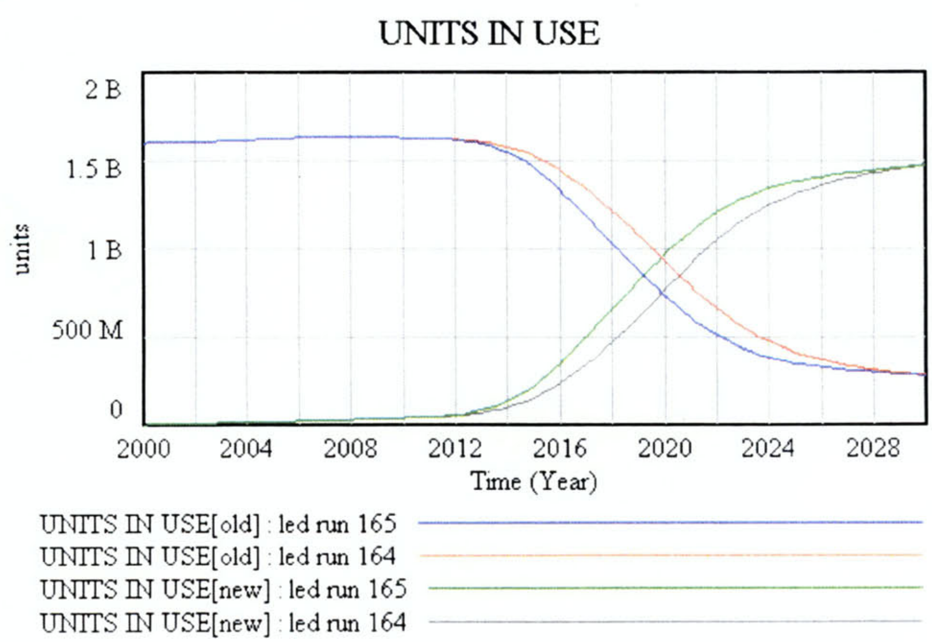


lvii

The model follows the trends well, but there are a few important differences. Philip's charts encompass the entire replacement lamp market, whereas the model is only looking at the incandescent market. Also, Philip's view is global, where the number of sockets used in the system dynamics model is for the US only. It is also important to note that both the model and the charts represent the lamp market. The replacement fixture market is not discussed here.

In the previous discussion of the system dynamics model in the previous chapters many different "levers" were discussed that may affect the adoption of LEDs. One important lever that is currently being implemented in Europe is the banning of the incandescent bulb. For modeling purposes a change in performance requirements was utilized. A jump in performance requirements to 60 lumens/W starting in 2012 with a one-year ramp was used. The results for units in use are shown below.

Figure 56: The effect of legislation on purchases of LED lamps

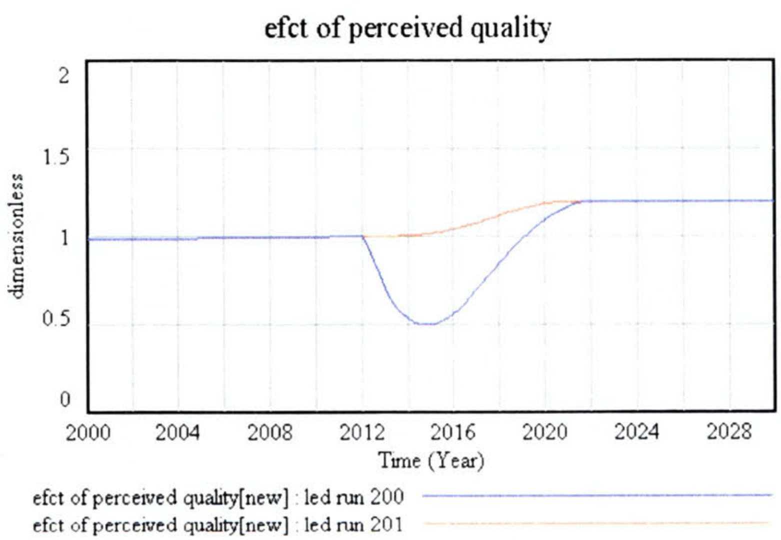


As you can see, the addition of legislation reduced the crossover point by roughly two years. Therefore legislation is an important lever for the lighting market. However, it is more appropriate to dictate a minimum performance rather then ban a technology, because selectively banning a technology stifles innovation.

Another potential trigger is the introduction of poor quality products. The Department of Energy is working hard to ensure that the Energy Star rating and Lighting Facts label are applied to LED products, but it will be difficult for consumers to avoid the flood of low quality LED lighting products currently being introduced.

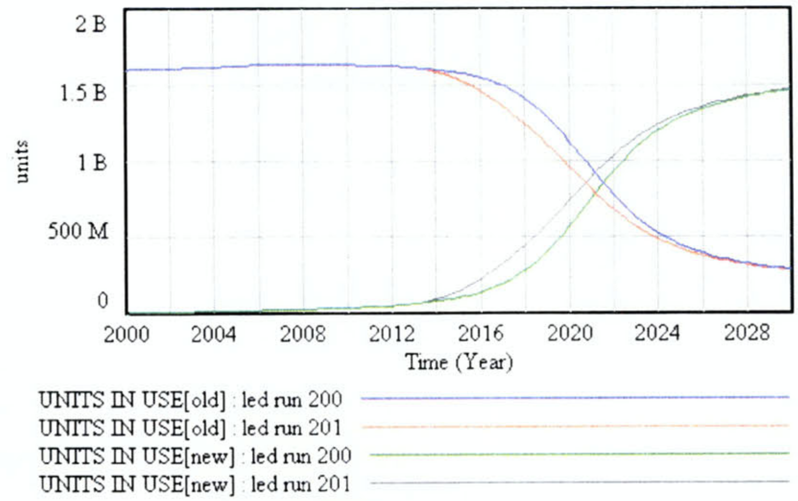
Let's say that the in 2012 the flood of low quality LED products reduces the average quality in the market by 50%. LEDs are currently perceived as having good quality, but that could change with this introduction. The change in consumer's perception of quality is shown below.

Figure 57: The effect of poor quality LED lamps



This inherently leads to a reduction in overall sales, delaying the crossover point as shown below.

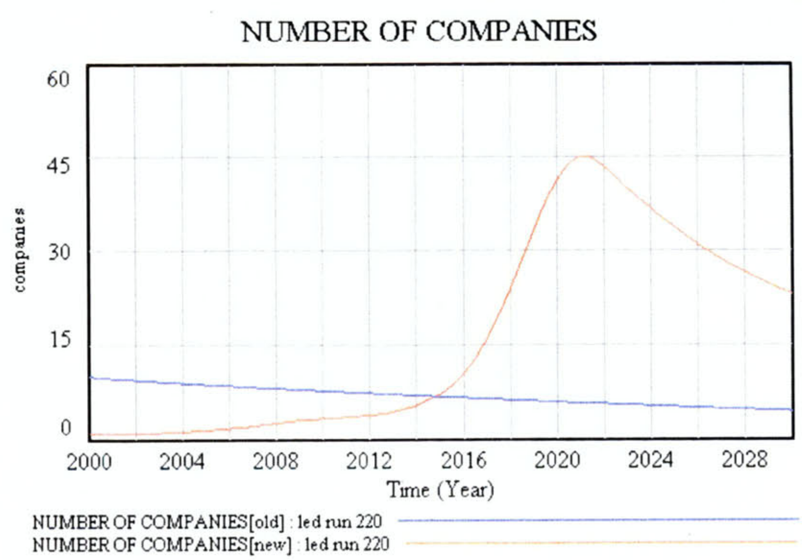
Figure 58: Reduction in sales due to poor quality LED lamps



This illustrates the need to be vigilant about the introduction of poor quality LED products. It is well documented that poor quality CFLs hurt their adoption, and delayed it for years.

In a previous section the Utterback/Abernathy model was discussed, and the idea of the transitional phase of the market. The Department of Energy data for LEDs showed that the LED industry is entering the transitional phase. However, the LED bulb/fixture stage lags the LED component stage by a few years at least, as the dominant design for LED bulbs/fixtures has not emerged. The model agrees with this time lag.

Figure 59: Number of LED lamp companies versus incandescent lamp companies

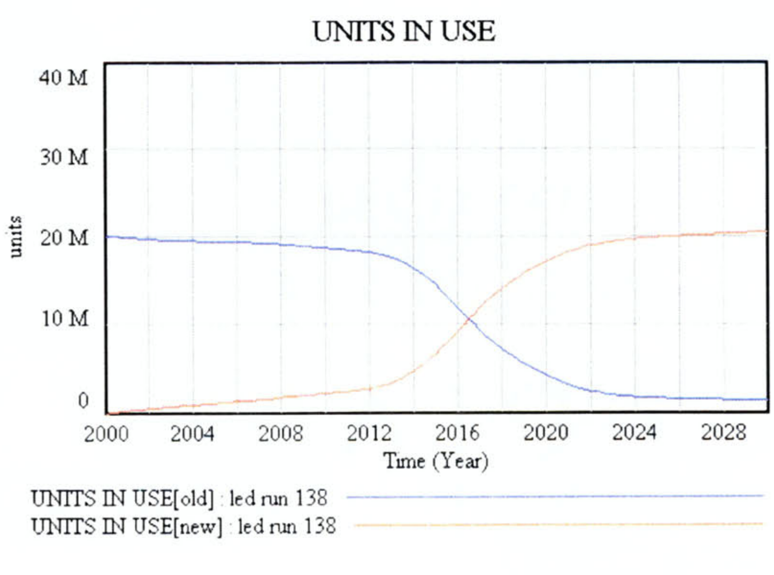


There are currently a large number of LED bulb/fixture manufacturers. This looks to continue for quite a while, as the industry consolidation will not happen until after 2020. It is important to note that the current lighting market is dominant by a few large players. Whether the small fixture manufacturers can make the transition into selling LED fixtures remains to be seen.

LED versus Colored Lighting

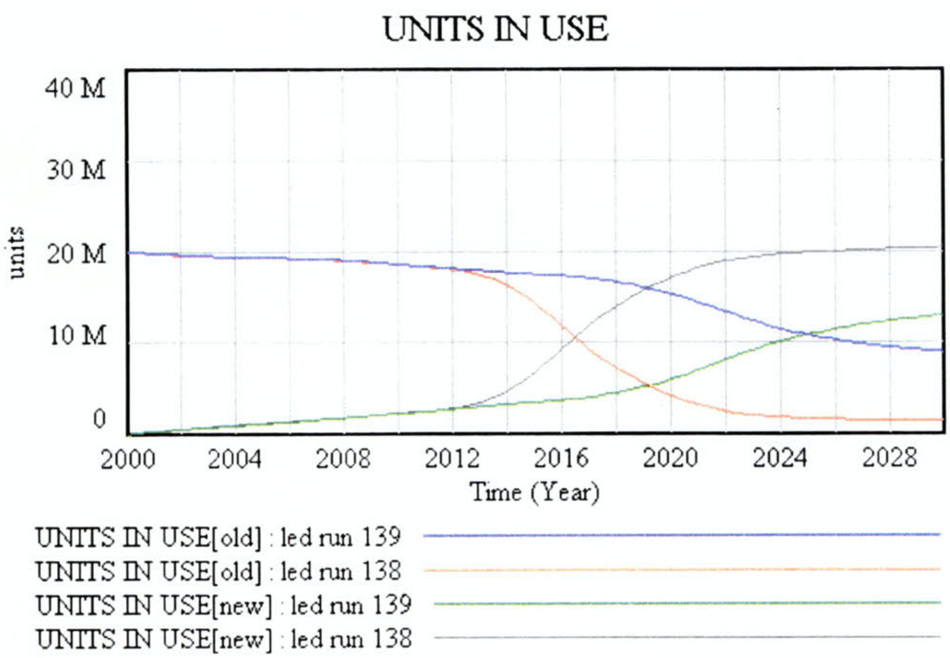
Another segment of the lighting market that is important to look at is colored lighting. Traditionally, the only way to make colored light from incandescent or halogen sources was to place a colored gel filter in front of the lens. This absorbs the unwanted wavelengths of light, but is extremely inefficient. LEDs are rapidly growing to dominant this market, as their inherent saturated color and the additive approach to color mixing leads to system efficiencies that far surpass that of traditional colored lighting. Below is a chart detailing the model's prediction for the adoption of LEDs into colored lighting applications. It is important to note that the major changes to the model are the drop in efficiency of incandescent sources, decrease in the initial number of units (smaller market), the increase in replacement cost and the increase in weighting for the effect of lifetime cost.

Figure 60: LED fixtures versus color incandescent sources



It is important to note that this variation uses 600 lumens as the source brightness. However, many colored lighting markets (theatrical for instance) require much higher lumen levels, on the order of 2000+ lumens. By simply changing the model to require a 2000 lumen source the crossover point changes dramatically.

Figure 61: High output colored incandescent versus LED

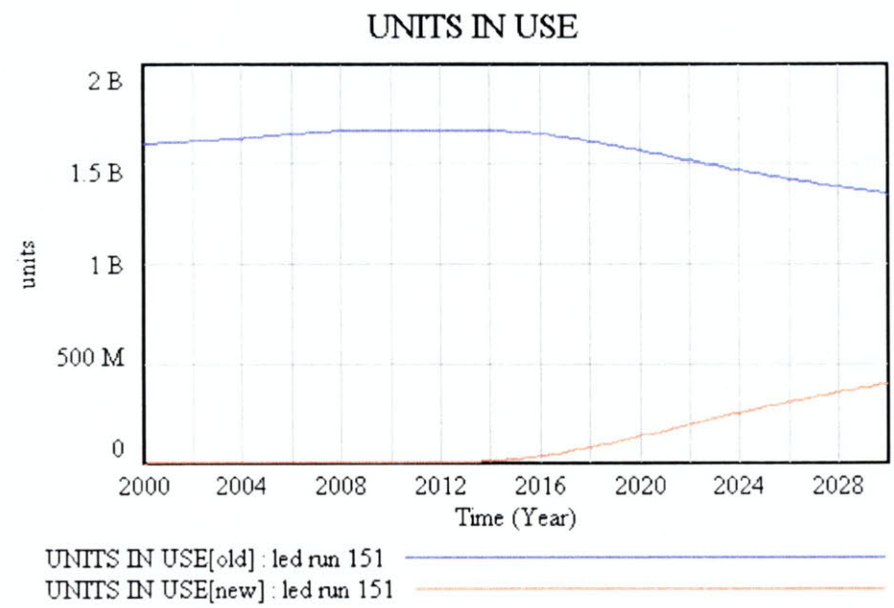


The driver behind this delay is the dramatic increase in up front cost. This is apparent in the current theatrical lighting market, as there are few installations of LED lighting products, and the few that have succeeded are in relatively low power installations. It is also important to realize that the model is not absolute. LEDs bring other important factors to the table. One is the ability to instantly change color therefore reducing gel cost, which can also lead to a reduction in the total number of fixtures required for a theater. This may lead to a faster adoption of LEDs in the theatrical lighting market then predicted by the model.

LED versus CFL

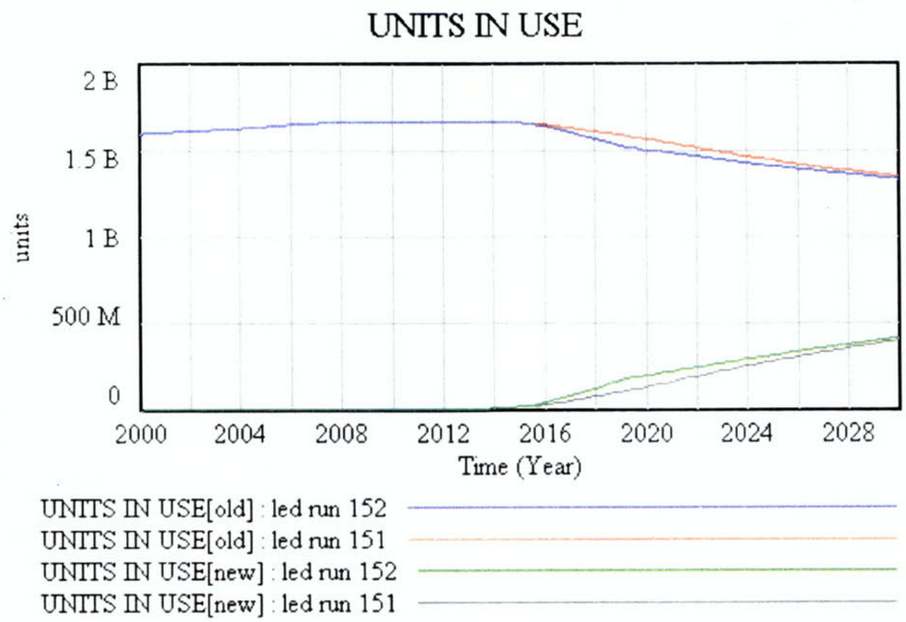
A natural competitive relationship to evaluate is the potential for LEDs to overtake CFLs in the lighting market. The greatest issue for adoption with this comparison is that the performance of CFLs far surpass that of incandescent lamps, and for many applications is greater then the current performance of LEDs. Below is a graph detailing the potential for LEDs to overtake CFLs in the residential market.

Figure 62: LED versus CFL for the residential market



As you can see, it will take quite a while for LEDs to replace CFLs in the residential market. However, a few things may take place to increase LED adoption. Incentives were discussed earlier as a potential lever that may be utilized. If a $5 incentive were offered on every LED bulb from 2014 to 2016 it would cost a little over $750 million. The effect is shown below.

Figure 63: The effect of incentives on adoption for the residential market

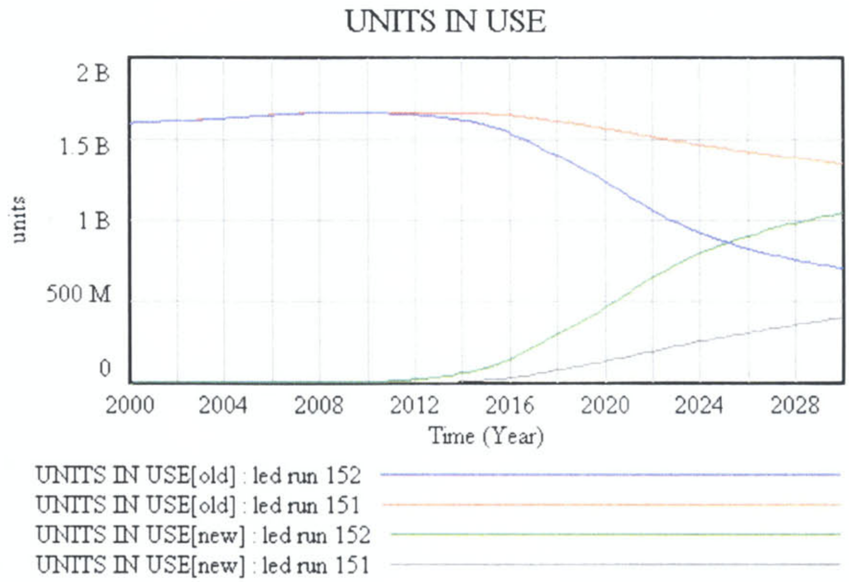


While incentives could increase adoption, they do not have a dramatic effect. However, incentives are another lever that could be utilized. They may also be more appropriate for markets where the tipping point is projected to happen sooner, as incentives are more effective in providing the final push towards a tipping point.

Commercial Fluorescent Market

The commercial lighting market is a significant portion of lighting sales. However, the commercial market is a less attractive market because fluorescents have a dominant position there. On the other hand, building owners are more likely to see the benefit of the reduced lifetime cost of CFLs, and therefore perceive the overall lifetime cost as more important then the initial cost. The following chart takes the same adoption curves shown above for the residential market and changes the weight of the relative lifetime cost and initial cost.

Figure 64: Residential versus commercial adoption rates for LEDs



As you can see, the commercial market is much more attractive then the residential market as the model predicts a much faster adoption. While the absolute numbers shown above are not accurate as this chart utilizes the absolute numbers for the residential market, the relatively adoption curves are important.

OLED versus Commercial Fluorescent

OLEDs have the potential to become a dominant lighting technology due to their inherent soft, diffuse output. The commercial market seems to be a market where OLEDs could be readily adopted, as OLEDs naturally mimic fluorescent fixtures, but with a thinner, cleaner profile. When the projected performance curves of OLEDs were put into the model, the crossover point was reached by 2017! This is much faster then LEDs, despite the fact the OLEDs are not currently selling into the lighting market in any significant volume. How can this be? Looking at the exact data revealed the answer.

Figure 65: Department of Energy projections for OLED performance

Metric	2008	2010	2012	2015
Efficacy- Lab (lm/W)	58	99	150	150
Efficacy- Commercial (lm/W)	N/A	44	76	150
OEM Device Price- ($/klm)	N/A	72	27	10
OEM Device Price- ($/m^2)	N/A	216	80	30
Device Life- Commercial Product (1000 hours)	N/A	11	25	50

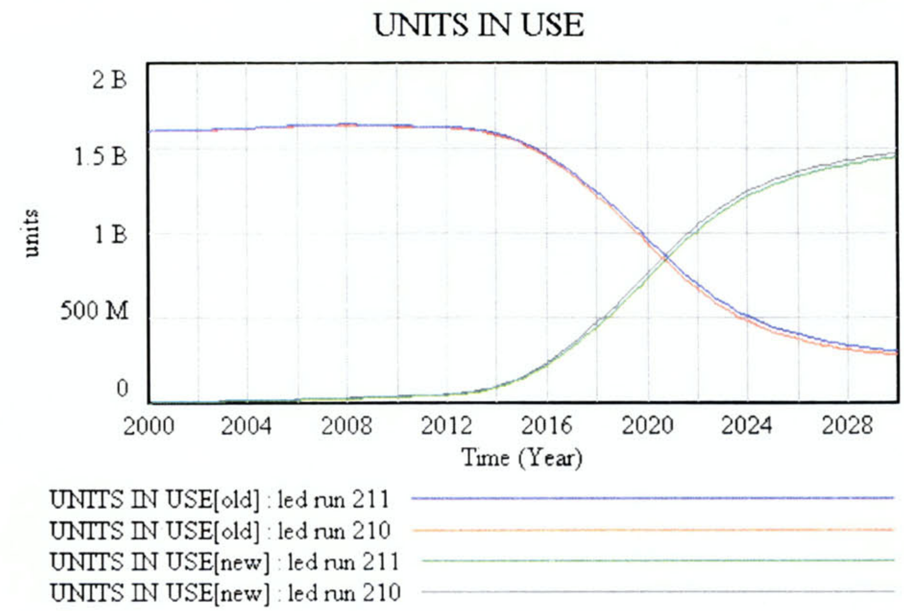
Department of Energy [lviii]

The projected OLED cost is extremely low, surpassing inorganic LEDs. In fact, currently the price of OLEDs should be only 72 dollars per kilolumen. The OSRAM Orbeos OLED panel can be purchased in sample quantities. It cost $375 and puts out 15 lumens, for a rating of 25,000 dollars per kilolumen.[lix] Even if production panels cost an order of magnitude less, their cost would be a far cry from the Department of Energy data. While OLEDs are a technology that will benefit from large-scale production, the current price projections are a bit aggressive.

Sensitivity Analysis

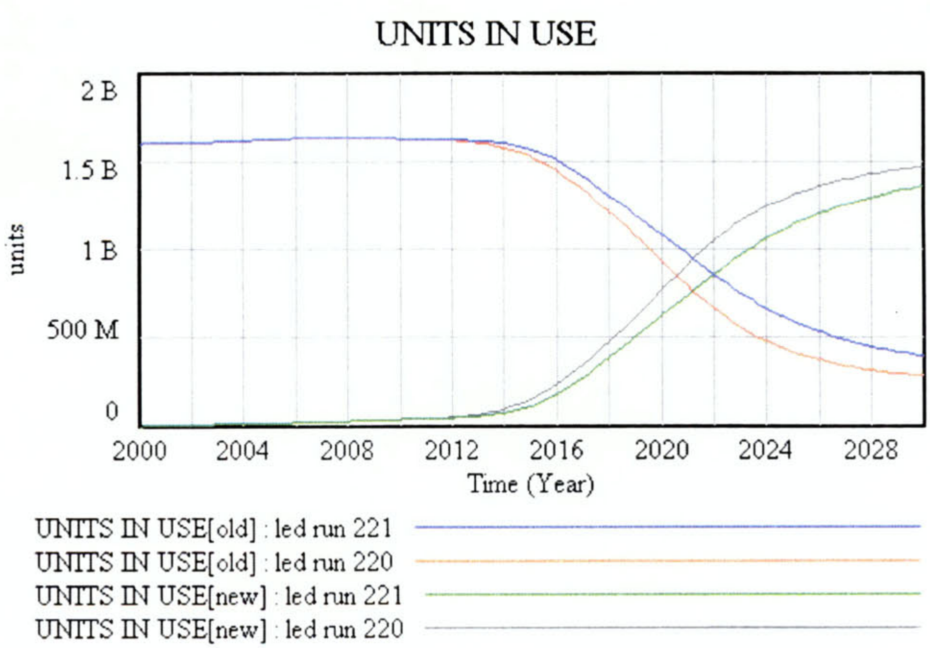
As noted in the previous section, we should not take the Department of Energy data as perfectly prescribing the future. A 20% reduction in the projected performance of LED fixtures does delay their adoption, but not dramatically.

Figure 66: Effect of a reduction in projected performance for LED adoption



However, due to the sensitivity of the consumer market towards price changes, a 20% increase in dollars per kilolumen significantly reduces the adoption rate of LEDs.

Figure 67: Effect of an increase in cost for LED adoption

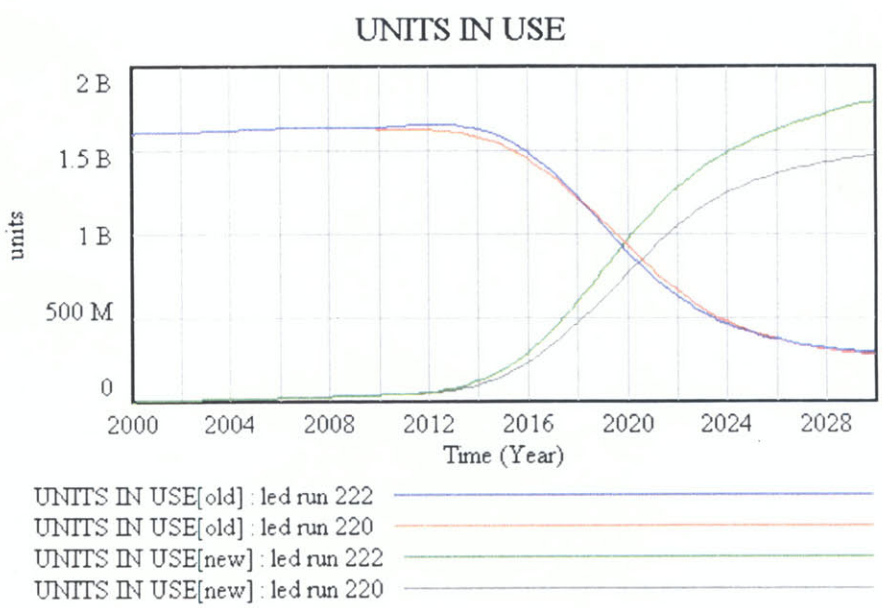


This reinforces the idea that price is the critical parameter for the consumer lighting market.

Macroeconomic Effects

While changes in the lighting market are important, stepping back even further we can look at how macroeconomic climate changes affect the lighting market. While the current recession is certainly hurting sales, the rate of overall market growth post recession could have a dramatic effect on LED adoption. An increase in market growth affects the model in two ways. First, the overall market size and therefore potential sales is increased. Second, the higher the market growth rate, the more likely consumers will be to pay a higher upfront cost for a product. Below is the output if the market growth rate post 2010 is increased from ~3% to ~10%.

Figure 68: Macroeconomic effect on LED adoption

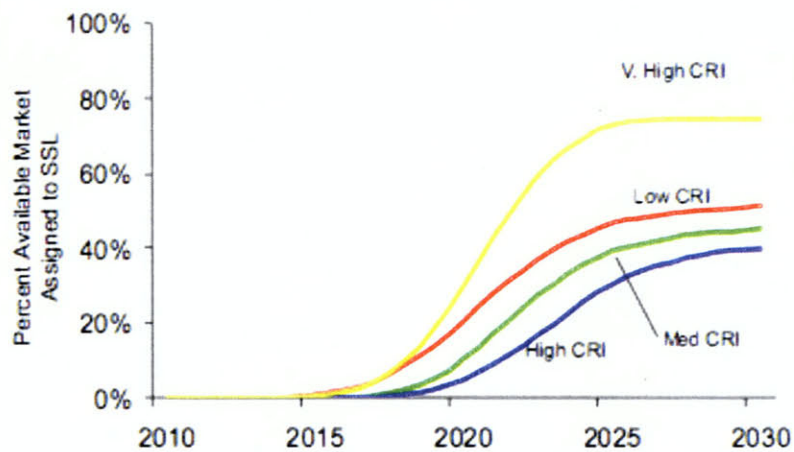


Initially, incandescent lamp sales increase because the overall market is larger. However, once LED product's price/performance reaches a tipping point that drives adoption the rate of decrease in incandescent lamps in the market actually speeds up, as consumers are more likely to switch if the market growth is higher.

Reference Models

Navigant Consulting, working with the Department of Energy developed one of the more interesting and publicly available models for LED adoption. However, it is difficult to perfectly correlate the two models as the Navigant consulting model splits the market by necessary CRI, which correlates to specific lamp types. The following chart shows the adoption of LEDs in the commercial market.

Figure 69: Department of Energy LED adoption model



Department of Energy [lx]

The low CRI curve compares well to the model presented here, which predicts a crossover point around 2025. Beyond this chart, however, it is difficult to correlate the two models. Most of the other models have been developed by consulting firms for their internal use, so it is difficult to find public data, other then a few charts representing overall lighting market adoption for LEDs.

Chapter 6: Conclusions

What have we learned from this discussion and model? There are a number of factors that will effect the adoption of LEDs, and some factors are more important then others.

The price of LEDs is a critical parameter for their adoption, especially in the residential market. Consumers are very sensitive to price, so LED companies need to focus their efforts on reducing cost.

The performance of LEDs is in many cases already good enough. The performance is reaching a point of diminishing returns in many markets, as the cost savings are already significant. This is especially true in markets where LEDs are competing with incandescent and other inefficient lighting technologies.

Incentives are a useful lever for the market, but not the most effective one. In addition, the use of incentives must be well timed to induce an increased adoption rate, but only at the point that the performance of LED products versus the incumbent technologies is good enough.

Legislation can have a powerful effect on market behavior. That being said, it needs to be carefully implemented by looking at the existing technologies, the market requirements, and the potential replacement technologies. It should also be done with respect to performance requirements (Energy Star for example) rather then technology types, as this may stifle innovation.

It is useful to slice the lighting market into small, easily analyzable segments. Each segment will care about different factors by varying extents. By ranking the different factors and the feeding them into the model each market segment can be analyzed for its attractiveness to LED products.

The LED component market is well into the transitional phase. Despite this, there are a number of large semiconductor companies entering the market, and it may be difficult for them to compete unless it is solely on cost, which is the hallmark of the specific phase.

The perception of quality is important for LED adoption. CFLs were not well liked during their early years in the market, and this dramatically slowed potential adoption. The Department of Energy is taking the right steps to counteract the introduction of low quality LED products, but more may need to be done.

LEDs have a bright future in lighting. The overall consensus is that LEDs are the future of lighting, but the race is still wide open to determine which company leads us to an energy efficient future lit primarily by Light Emitting Diodes.

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