Energy Economics and Policy - ETH Zurich

The Effects of Efficient Lighting in the USA

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Introduction

With a fast growing population, humans are in great need of scare resources and energy. Due to the increasing use of these resources, the ecosystem has been drastically affected, and its sustainability is compromised. The United Nation reported that as of 2004 our "global carbon footprints would require more than two planets Earth to be under the annual carbon celling" (UNDP). With an increasing awareness of the problem, world organizations and governments try to promote ways to make us live more sustainably. Energy saving has been receiving enormous attention in the past few decades. Electricity saving is also part of it and many technologies have been developed to help consumers reduce their consumption. Lighting is one the main sectors that has received great attention. Companies have invested considerable amount of money in research and development to design products that are energy efficient. Governments also try promoting efficient lighting by giving incentives to encourage people to consider energy efficient technologies.

This study aims to evaluate various ways of saving electricity in the United States of America (USA or US) by improving lighting consumption. First, the situation of electricity consumption in the world will give the reader the motivation being this study. Secondly, there will be a focus on the US electricity market and its lighting sector by analyzing different users and technologies that are involved.

Two models will then be proposed on a time horizon of 2012-2030: (1) instant change to light-emitting diode (LED) lighting and (2) progressive change to LED lighting depending on the life span of other technologies to be replaced. Energy savings, investments, return on investments and greenhouse gazes will be evaluated.

Electricity in the World

The increasing energy demand in the world, combined with the necessity of reducing greenhouse gases; represent one of the biggest challenges for humankind. With an increasing population and industrialization in most countries of the world, demand for energy has tremendously augmented. As it is also the case for electricity, demand has increased in the last years and will keep on doing so for the next many years. As figure 1 shows, the electricity demand has grown significantly in the last decade. From 1990 to 2008, the production of electricity changed from 11,865 TWh to 20,201 TWh (International Energy Agengy, 2009).

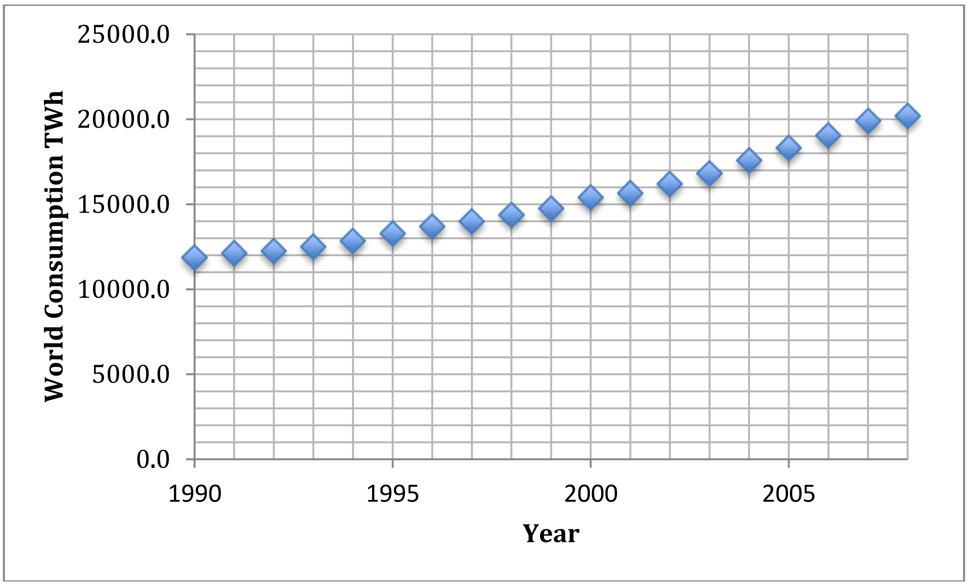

Figure 1 - World Electricity Production from 1990 to 2008 (TWh)

Utilization of renewable energies that produce less CO_2 is one way of reducing consumption, e.g.: Wind and solar energy. Another approach is to reduce consumption at the source by improving energy efficiency and having sustainable energy policies. For example, Australia banned in 2007 the sales of incandescent light bulbs because they were not energy efficient compared to other lighting technologies (BBC, 2007).

The global electricity consumption in 2009 did not follow a normal pattern compared to previous years. It was cut down by 1.5% in 2009 (Enerdata, 2010) due to the global financial distress. It was the first time since WWII. This reduction is also reflected in the US annual consumption. Asia and Middle East were the only exception with a rising consumption due their booming economies.

As for the largest electricity consumers, figure 2 shows that the US is ranked first followed closely by China with respectively 3'747 TWh and 3'149 TWh in 2009 (Enerdata, 2010).

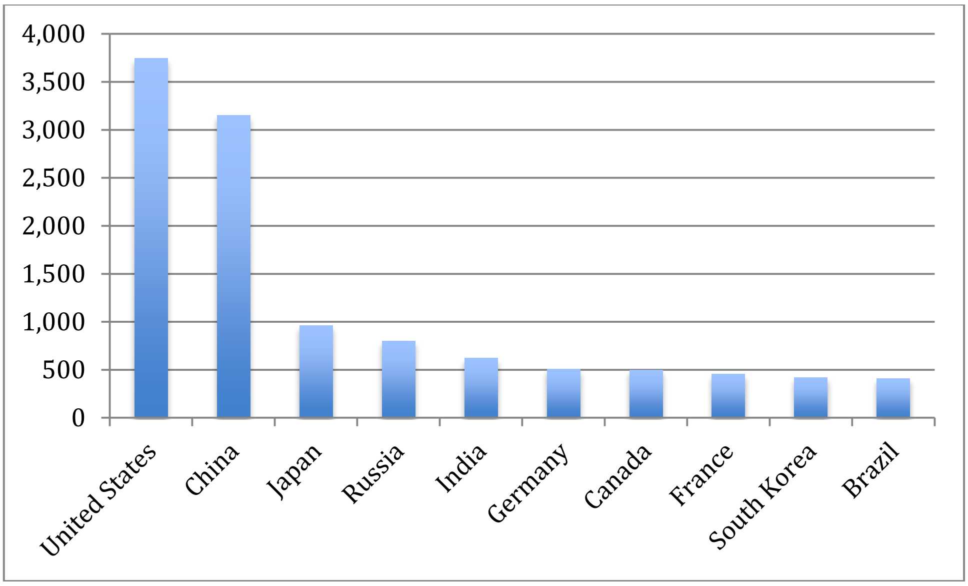

Figure 2 - Total Domestic Electricity Consumption in 2009 (TWh)

Electricity in the USA

Being one of the world's highest developed countries with more than 307'006'550 inhabitant as of July 2009 (U.S. Census Bureau, 2009), the U.S. has always been in great need of electricity. Figure 3 shows real US consumption data from 1960 to 2009 (EIA, 2009) and US forecasted data from 2010 to 2030 (EIA, 2009).

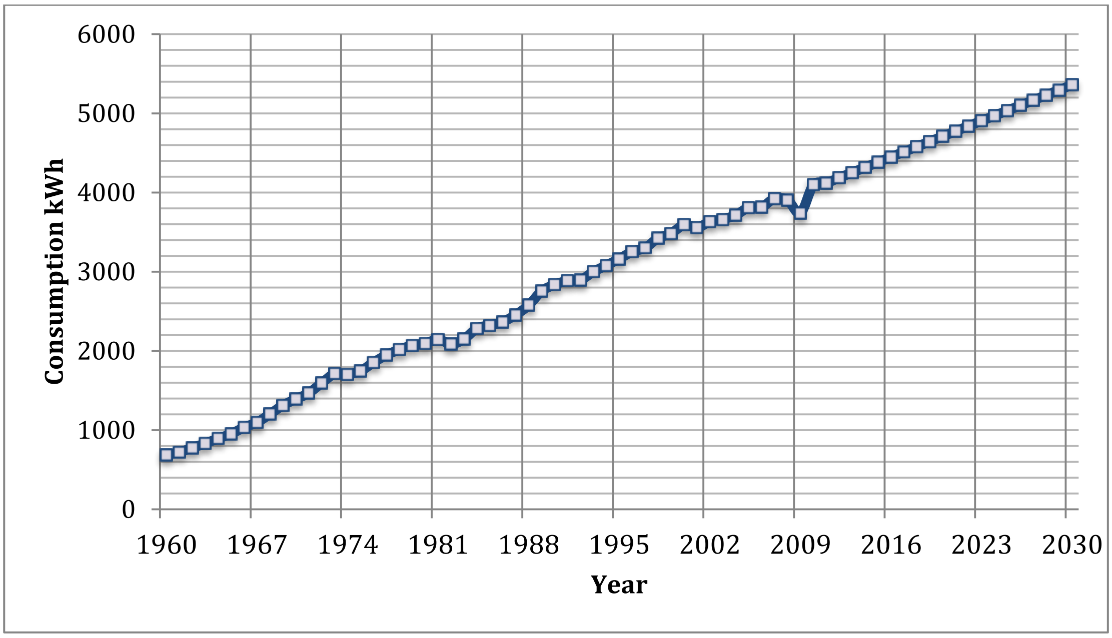

Figure 3 - US Total Electricity Consumption in TWh from 1960 to 2030

Figure 4 shows real average US electricity cost in ¢/kWh from 1960 to 2009 (EIA, 2009) and forecasted from 2010 to 2030 (EIA, 2009).

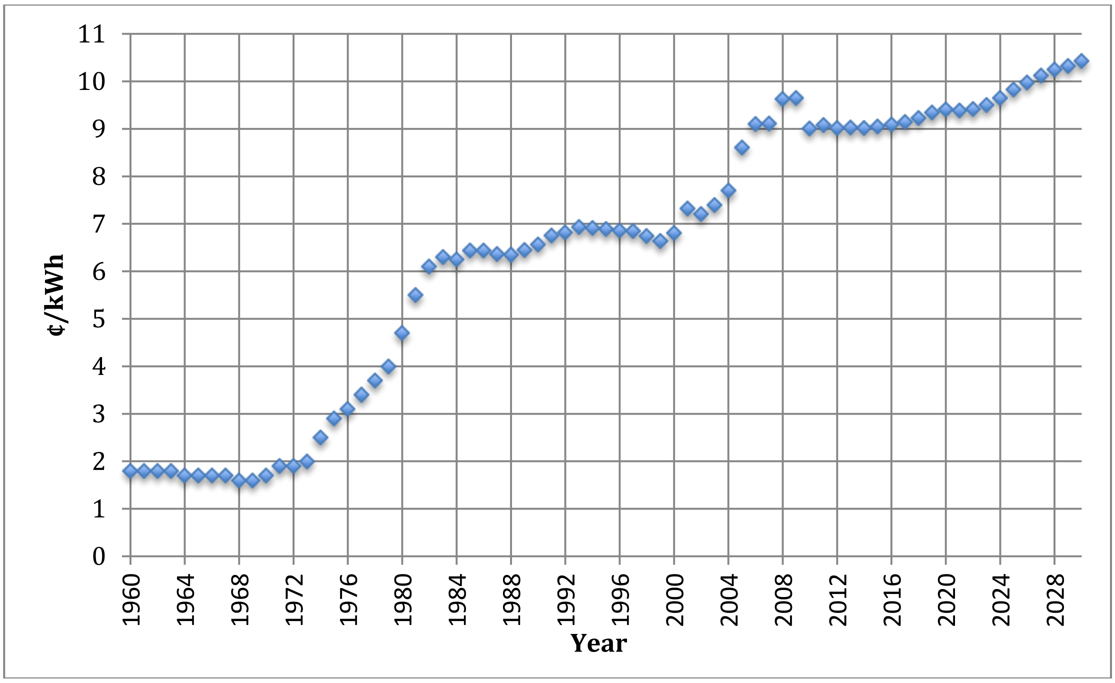

Figure 4 – US Average Electricity Cost per kWh from 1960 - 2030

Figure 5 shows the US electricity generation by source as of 2009. We can see that coal, natural gas and nuclear are the biggest producers with respectively 44.9%, 23.4% and 20.3%. Renewables including hydroelectricity only count for 10.5% of the total production.

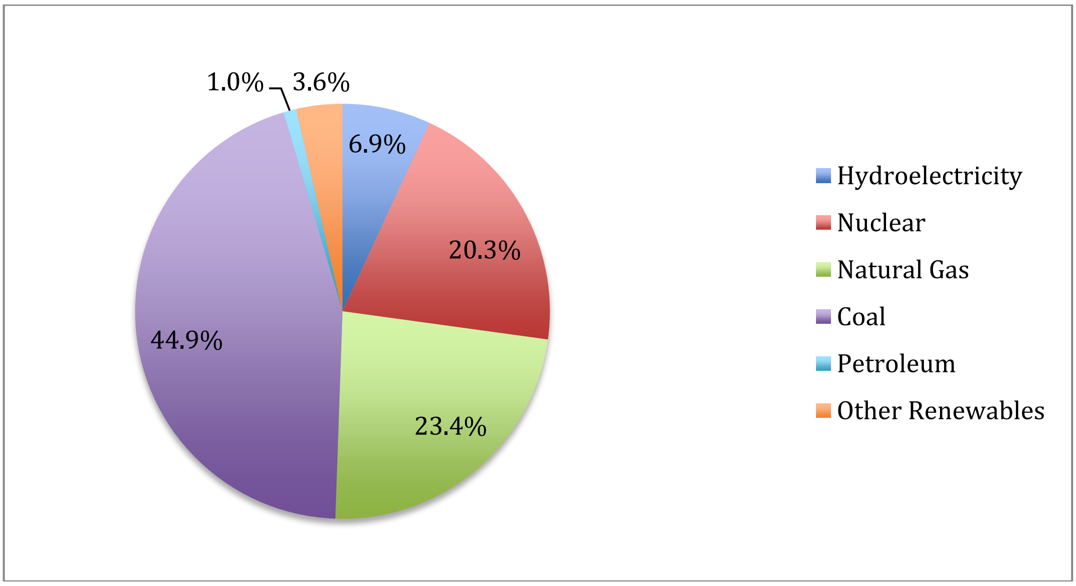

Figure 5 - 2009 US Electricity Generation by Source

Greenhouse Gas Equivalencies are nowadays used to quantify the sustainability of projects. In this paper, the emission calculator of the US Environmental Protection Agency is used as a reference. Data used to calculate the reference comes from the "Emissions & Generation Resource Integrated Database (eGRID)". The emission factor is the following:

6.91×10^{-4} metric tons CO_2 / kWh

Notes:

- Line losses are not included in the calculation.
- Only CO_2 is included in the calculation. No other greenhouses gases are included.
- See Appendix B for more details on the calculation.

Lighting in the USA

Table 1 and figure 6 (Navigant Consulting, 2002) show the estimation of the total US electrical lighting consumption by sector in 2001. The total consumption is 765 TWh in 2001. If we compare this number with the total electricity consumption in the US in 2001 (3,631.65 TWh), lighting is roughly 21% of the US total consumption.

If we look at different sectors, we see that commercial buildings account for the largest lighting consumption with 51%, followed by residential with 27%, industrial with 14% and outdoor stationary with 8%. Thus, residential and commercial consumers account for more than 78% of the total lighting consumption.

Table 1 - US Lighting Consumption by Sector in 2001

Sector	Electricity Use per Building	Number of Buildings	Site Energy (TWh/yr)	Percent of Total
Residential	1,946	106989000	208	27%
Commercial	83933	4657000	391	51%
Industrial	475063	227000	108	14%
Outdoor Stationary	n/a	n/a	58	8%
Total			765	100%

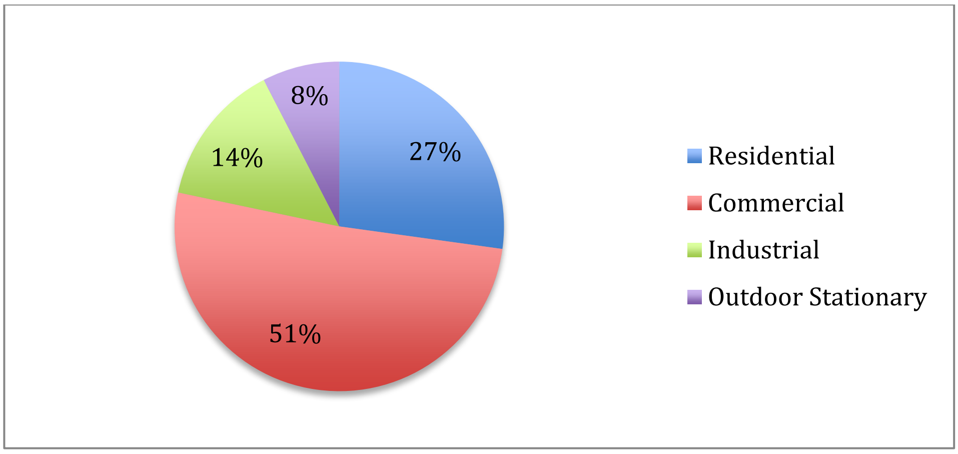

Figure 6 - US Lighting Consumption by Sector in 2001

Table 2 and figure 7 (Navigant Consulting, 2002) provide further breakdowns by showing lighting usage by different light source technologies. As we can see, high intensity discharge lights (HID) are the primary source of outdoor stationary lighting with 87%. The industrial sector mostly uses fluorescent and HID with respectively 67% and 31%. The commercial sector mostly uses fluorescent and incandescent with respectively 56% and 32%. HID usage is also not negligible in this sector. As for residential lighting, it is mainly driven by incandescent technologies with more than 90%. Existing LED technology does not appear here since the usage is less than 1% for each sector.

Table 2 - US Lighting Consumption by Technology and Sector in 2001

Sector	**Incandescent**	**Fluorescent**	**HID**
Residential	90%	10%	0%
Commercial	32%	56%	12%
Industrial	2%	67%	31%
Outdoor Stationary	11%	2%	87%

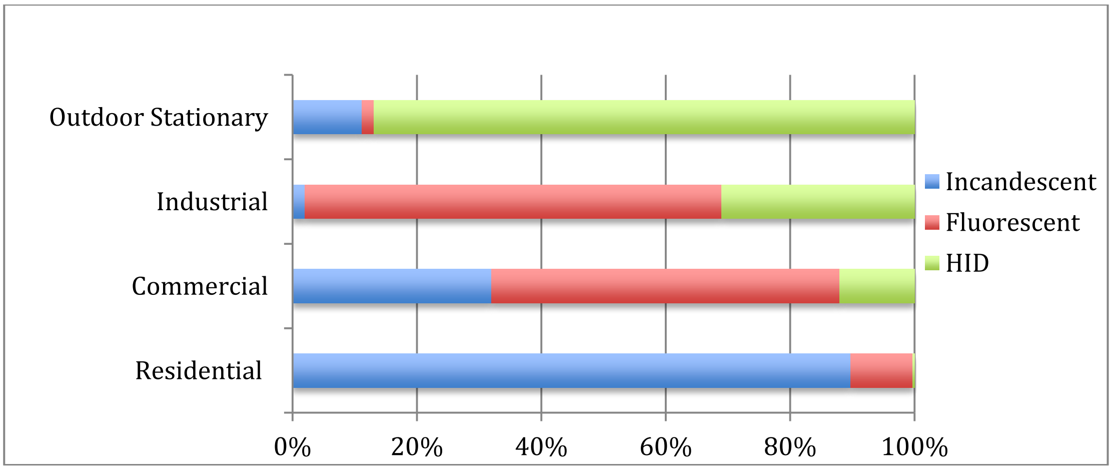

Figure 7 - US Lighting Consumption by Type of Fixture

Table 3 (Navigant Consulting, 2002) shows the estimated average number of lamps installed for a standard building. Since the sector of outdoor stationary cannot be represented in a "per building" column, only the total number of lamps is included.

Table 3 – Average Number of Lamps per Building and Total Consumption per Sector in 2001

Technologies	Residential	Commercial	Industrial	% of lamps	Consumption (TWh)
Incandescent	37	91	33	63%	321.2
Fluorescent	6	324	1340	35%	313.4
HID	0.04	7	67	2%	130
LED	0	0.4	0.3	0%	0.1
Total	43.04	422.4	1440.3	100%	764.7
Number of buildings	106989000	4657000	227000	n/a	n/a

Table 4 (Navigant Consulting, 2002) gives an estimate of the average daily operating hours by light source. It shows that incandescent lighting has a longer usage in the commercial, industrial and outdoor stationary sector, but still, the national average is still low (2.8 h/day) due to the large number of residential lights that are turned on only 1.9 h/day on average.

Table 4 – Average Number of Lighting Usage per Day per Sector and Technology

Lamp Type	Residential (hour/day)	Commercial (hours/day)	Industrial (hours/day)	Outdoor stationary (hours/day)	National Avg. (hours/day)
Incandescent	1.9	10.2	16.7	7.9	2.8
Fluorescent	2.2	9.7	13.4	10.8	8.2
HID	2.8	10.1	13.9	11.3	11
LED	-	23	23.4	7	22.2
Total	2	9	13.5	10.5	4.8

Lighting Technology Comparison

This section presents a comparison of four well-known lighting technologies available on the U.S. market: incandescent, fluorescent, HID and LED.

Thomas Edison invented the first electric light in December 1879 (Energy Star, 2011). It is known today as the first incandescent lamp. The technology is very simple and inexpensive to produce. However, it has a major disadvantage. It has the lowest lighting efficiency compared to newer lighting technologies developed. Incandescent lamps come in two common types: standard incandescent lamps and halogen lamps (see figure 8)

Figure 8 - Incandescent Lamps
(source: geconsumerproducts.com)

Figure 9 - CFL Lamp
(source: seco.cpa.state.tx.us)

Fluorescents are more energy efficient than incandescent lamps (Energy Star, 2011). For example, Energy star compact fluorescent lamps (CFL) are known to consume 75% less electricity than an incandescent bulb and can last up to 10 times longer. The CFL's technology is the same than a fluorescent lamps but it has been made in a compact way to replace incandescent in a retrofit way. Older fluorescent lighting technologies often result in poor light quality and flickering. (see figure 9)

High intensity discharge (HID) lighting systems are widespread in the industry because they are advantageous for lighting large areas where high ceilings are present. They normally range from 50 to 15'000 watts each (Wikipedia, 2011). The oldest HID lamps are using of mercury vapor and are not lighting efficient. Newer technologies use Metal halide (MH) or ceramic MH lamps. One of HID major disadvantage is that it takes some time for the lamp to warm-up and emit light. (see figure 10)

Figure 10 - HID Lamp
(Source: Wikipedia)

In the last two decades, light-emitting diode (LED) has reached consumers market precipitously. This technology is becoming more and more versatile and an efficient lighting source. Many retrofit models have been introduced into the market in the last few years, making LED attractive to both residential but also industrial consumers. LED has the potential to provide high efficiency and durability. It is also design to have an extremely long life compare to other technology. However, it presently has some disadvantages: it has a high initial price and it is highly sensitive to temperature and voltage change.

Figure 11 shows a retrofit model for stationary outdoors lamps. GE estimates that it can reduce energy consumption by 15 to 30 percent compared to already existing models. It also has an estimated life span of more 50,000 hours resulting in less maintenance. (GE Appliances & Lighting, 2010).

Figure 11 - GE Outdoors LED Lighting
(Source: GE Industrial Products)

Figure 12 shows a Philips LED 12.5 Watts A19 bulb that can replace a 60-Watts A19 incandescent model. Its efficiency of 65 lumens per watt uses only about 20% of the energy of a 60-watt bulb. Philips rates it at 25,000 hours of operation.

**Figure 12 - 12.5W A19 Philips Bulb
(Source: Philips)**

Table 5 (Lighting Research Center, 1999-2004) shows the different averaged performance metrics of the different technologies. Appendix A shows the different products that were evaluated for each technology. An important remark is that not all models available to the market were included in those averaged results. This table only gives a general idea of the different parameters that will be required to model energy savings in further sections.

Table 5 shows that LED is the most efficient technology with 140 lm/W as compared with the most energy intensive one, incandescent with 18 lm/W. LED has also the longest life span with an average 60,000 hours compared to 1,500 hours for incandescent.

A comparable 60W incandescent bulb with LED only requires 7.7 W. Fluorescent and HID are also efficient technologies with respectively 10.8W and 12.0 W as compared to 60W for incandescent. However, when it comes to initial price, LED has the highest initial cost with $7.12 per Watt as compared to $0.02 per Watt for incandescent and $0.28 per Watt for fluorescent. HID is also expensive because it requires many parts (ballast & lamp) with $2.76 per Watt.

Table 5 - Average Performance of Different Lighting Technologies

	Incandescent	Fluorescent	HID	LED
Efficacy (lm/W)	18	100	90	140
Life Span (in hours)	1500	10000	20000	60000
60 Watts incandescent example (W)	60.0	10.8	12.0	7.7
Cost ($)	1.345	2.98	33.12	54.95
Lamp Cost per Watt ($)	0.02	0.28	2.76	7.12

It is also important to consider the amount of embodied carbon of each lighting product. Embodied carbon can be defined as the energy used to make a product, bring it to the market and dispose of it. It has a life cycle perspective of the product. The embodied CO_2 of incandescent, CFL and LED per single lamp are presented in table 6 (PhotonStar). It shows that LED is the one with the largest embodied CO_2 (4.760 kg CO_2/luminaire). This can be explained by the fact that the manufacturing process of LED is significantly more complex and energy consuming than incandescent and CFL.

Table 6 - Embodied $C0_2$ per Single Lamp

Type of Lamp	Average Embodied CO_2 per single lamp (kg CO_2/luminaire)
Conventional LED Luminaire[1][2]	4.760
Incandescent Lamp[1][2]	0.355
Compact Fluorescent lamp[1][2]	0.194

[1] Excluding transport and operation

[2] Excluding ballast or driver

The models

Summary

The modeling part compares two different approaches for improving lighting consumption in the US. The first model will be called "*Instant Change to LED*". All incandescent, fluorescent and HID lights will instantly be replaced by LED. The model will only include the initial investments costs of the lights but will not include any installation costs.

The second model will be called "*Only LED Replacement Policy*". This will imply that only LED will be allowed, as replacement once incandescent, fluorescent or HID needs to be replaced. The replacement will be done by using the previously estimated life spans. Consequently, we will estimate the required time to replace all incandescent, fluorescent and HID lights.

Energy savings, investments, return on investments and greenhouse gases will be evaluated in each model.

Assumptions

- All modeling is performed from 2001 to 2030.
- Years 2001 to 2009 are based on real data. Years 2010 to 2030 are based on forecasted data and on available information that was found.
  (see sources in the introduction part)
- The last US census for lighting was performed in 2001; all calculations for usage habits will be based on 2001. We will therefore estimate that the lighting habits of 2001 are the same one as today. For example, we will assume that the average number of light in one building has not change from 2001 to 2030. However, lighting consumption will be adjusted with the ratio of increased or decreased electricity consumption for every year. For example, if the US total electricity consumption increases of 1 TWh between 2012 and 2013 and that lighting consumption is 30% of the total consumption, then lighting consumption increases of 0.3 TWh.
- The investments calculated in each model will only include the acquisition of the lights but will not include any installation costs.
- Savings from having less maintenance due to the better life span of LED will not be considered in the calculations.
- Light consumption, cost and life span are averaged with all available information that was found (see appendix A)
- All lights that have to be replaced have a retrofit LED model. Therefore no other parts than the light is included in the cost.
- We suppose that LED cost remain constant over time. This is a conservative assumption because it is likely that the technology will become more affordable in the near future.
- Since it is impossible to tell how old the existing lights are, we will pretend that at t = 0, they are brand new.

Instant Change

In this model, the simulation of a complete change of incandescent, fluorescent and HID to LED is performed on year 2012. From 2001 to 2011, electricity consumption remained the same as measured or predicted with data. In 2012, we see a decrease of electricity consumption due to the instant switch to LED. From 2012 to 2030 we see an increase of electricity consumption due to the overall increasing US electricity demand.

For 2012, the estimation of the consumption of LED lighting is the following (including all replacements).

$$C_{LED\ in\ 2012\ with\ instant\ conversion} = C_{LED\ in\ 2012\ without\ conversion} + C_{Inc\ \ without\ conversion} * ratio\ power_{\frac{incadescent}{LED}} + C_{fluo\ without\ conversion} * ratio\ power_{\frac{fluorescent}{LED}} + C_{HID\ without\ conversion} * ratio\ power_{\frac{HID}{LED}}$$

$$C_{LED\ in\ 2012} = 0.12 + 403.51/\frac{1}{0.12833} + 393.71/\frac{0.18}{0{,}12833} + 163.31/\frac{0.2}{0.12833}$$

$$C_{LED\ in\ 2012} = 437.39\ TWH$$

Let's now calculate the power required to convert in 2012:

$$P_{LED\ in\ 2012} = \frac{C_{LED\ in\ 2012} * 10^{12}}{3600\ seconds}$$

$$P_{LED\ in\ 2012} = \frac{437.39\ \ * 10^{12}}{3600\ seconds}$$

$$P_{LED\ in\ 2012} = 1.2149 * 10^{11}\ \text{Watts}$$

Let's now calculate the investment required in 2012:

$$Investment_{2012} = P_{LED\ in\ 2012}(Watts) * Cost\ of\ LED\ tech.per\ Watt$$

$$Investment_{2012} = 1.2149 * 10^{11} * 7.12$$

$$Investment_{2012} = 8.6482 * 10^{11}\$$$

Therefore, more than $1.2149 * 10^{11}$ Watts need to be converted for a total cost of $8.6482 * 10^{11}\$$

Finally, the savings of switching to LED are calculated:

$$Consumption\ Cost\ Savings\ with\ LED\ switching = Consumption\ Cost\ without\ switching\ to\ LED - Consumption\ Cost\ with\ LED\ switching$$

Appendix D shows all calculations in details.

Figures 13 and 14 show the effect on electrical consumption and cost by instantly switching to LED lighting in 2012. From 2012 to 2030, it would represent savings of more than $1'156'659'300'716 or 12'060 TWh

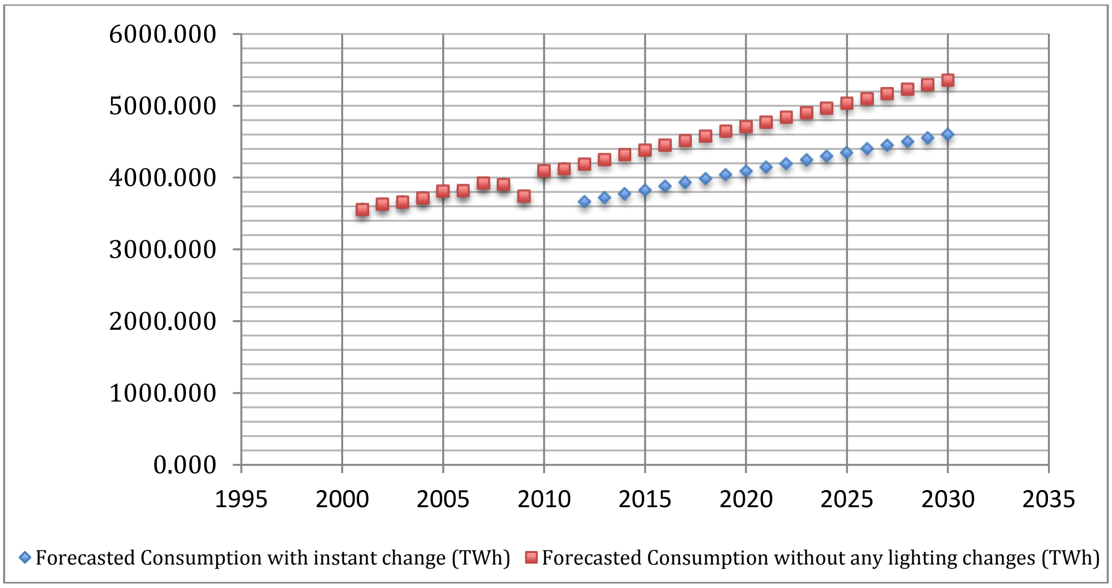

Figure 13 – Comparison between the Forecasted Electrical Consumption with Instant Change to LED and without any Change

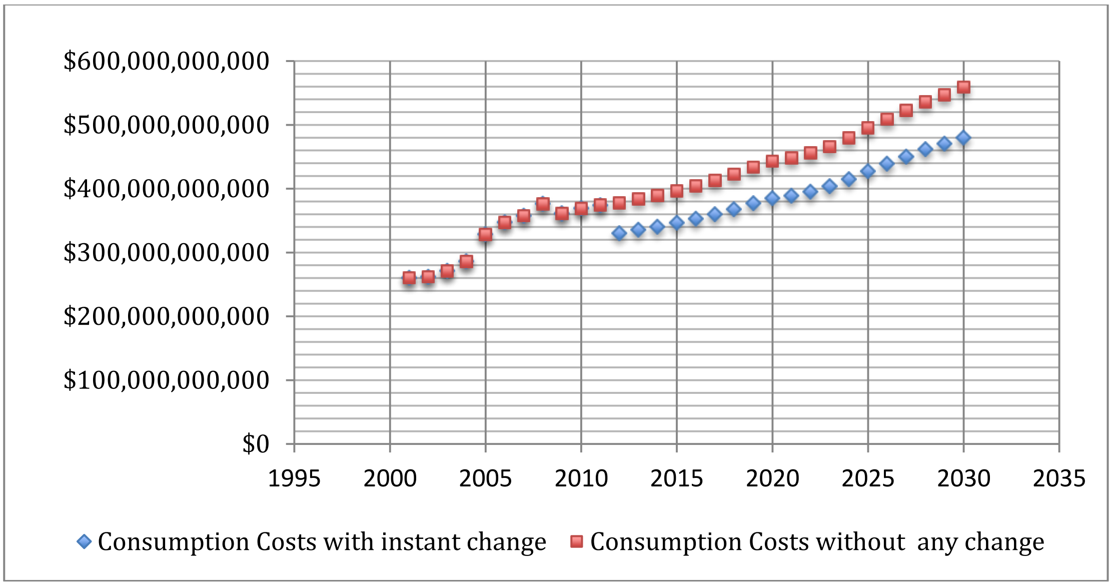

Figure 14 - Comparison between the Forecasted Electrical Consumption Cost with Instant Change to LED and without any Change

Figure 15 shows the return on investment of instantly switching to LED in 2012. It would take until 2027 to payback all the investment that was made in 2012 not including any interest rate. Note that only electrical consumption is calculated as savings. The fact that LED has a very long life span has not been taken into account in this study and would improve the payback of this study. The reduce maintenance on LED leading to less working hours would also improve the payback.

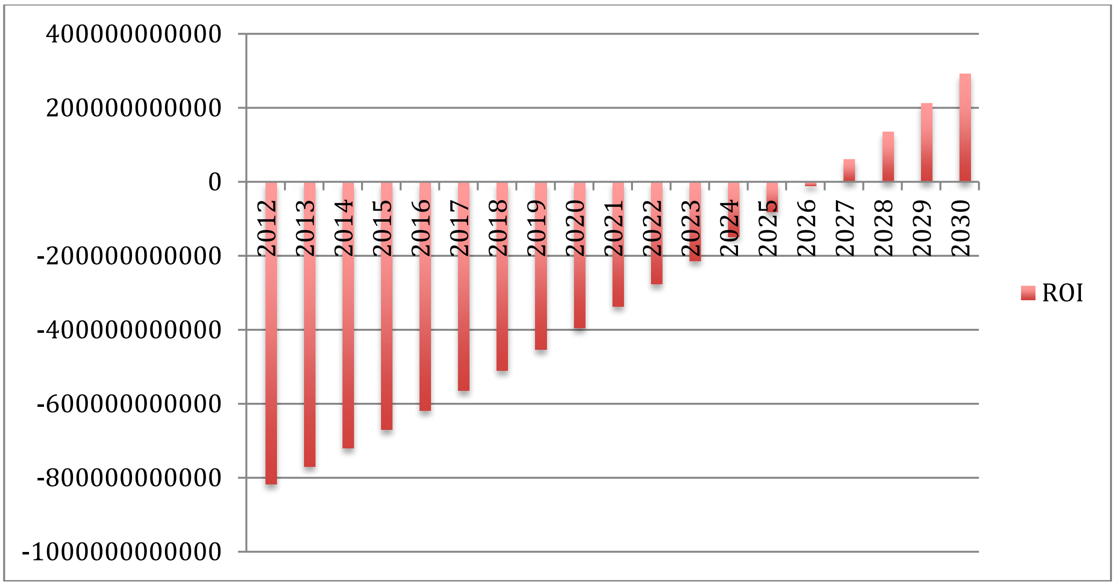

Figure 15 - Return on Investment of Instant Switching to LED

Figure 16 shows the decrease of emissions expressed as metric tons of CO_2 equivalent. The y-axis is positive and represents the amount of saved metric tons of CO_2 equivalent. From 2012 to 2030 it is 8'333'669'796 metric tons of CO_2 equivalent that could be saved with an instant switch to LED. A comparison with the amount of embodied CO_2 in LED is presented in the conclusion of this study.

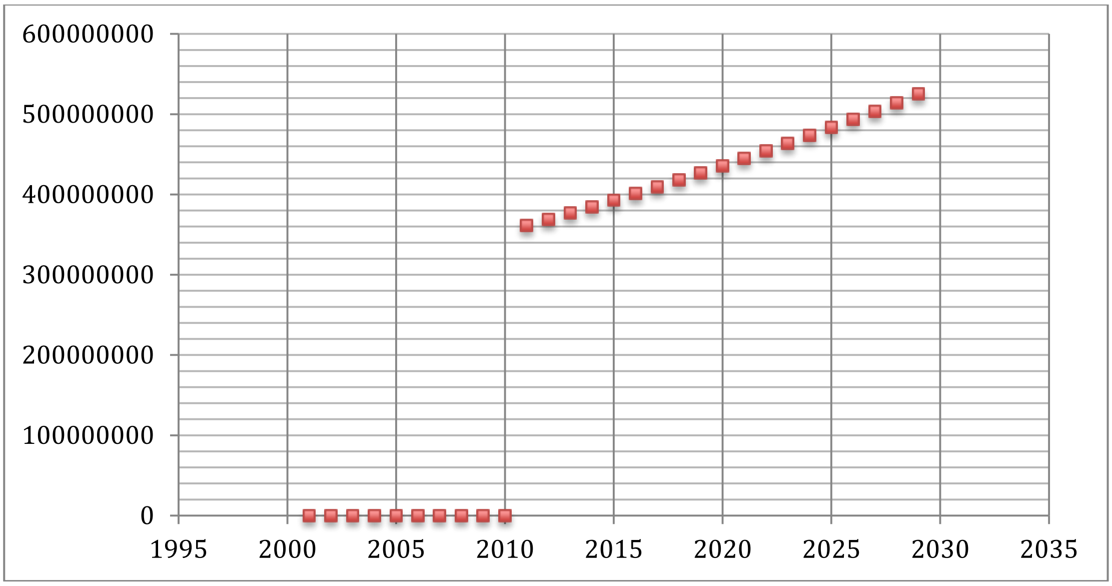

Figure 16 - Decrease of Tons of CO_2 Equivalent due to LED Switching first model

Only LED Replacement Policy

In this model, we simulate a progressive change of incandescent, fluorescent and HID to LED technology depending on the life span of the three first technologies. As written in the introduction part, incandescent lights have an average life span of 1'500 hours, fluorescent lights have 10'000 hours and HID lights have 20'000 hours. Only LED will be allowed as replacement once the life span for each technology is over.

To calculate the number of days that each technology will be functioning before being change to LED, we have to use the average national usage in hours per days of each technology. Those numbers are presented in Table 4. The average use of incandescent, fluorescent and HID (in hours per days) is respectively 2.8, 8.2, and11 hours/day.

Here are the equations to find out how long each technology will last before being changed to LED. As said in the assumptions, we assume that all lights are brand new on the first day of 2012.

$$t_{inc} = \frac{t_{national\ avg\ inc} * n_{inc}}{t_{inc\ life\ span}} = 1$$
$$t_{inc} = \frac{2.8 * n_{days}}{1500} = 1$$
$$n_{\ inc} \ = 535.71\ days\ or\ 1.47\ years$$

$$t_{fluo} = \frac{t_{national\ avg\ fluo} * n_{fluo}}{t_{fluo\ life\ span}} = 1$$
$$t_{inc} = \frac{8.2 * n_{days}}{10000} = 1$$
$$n_{\ inc} \ = 1219.51\ days\ or\ 3.34\ years$$

$$t_{HID} = \frac{t_{national\ avg\ HID} * n_{HID}}{t_{HID\ span}} = 1$$
$$t_{HID} = \frac{8.2 * n_{days}}{20000} = 1$$
$$n_{\ inc} \ = 1818.15\ days\ or\ 4.98\ years$$

Incandescent lights will all be replaced after 1.47 years, fluorescent lights after 3.34 years and HID lights after 4.98 years. Table 7 shows the different percentages of each technology usage depending of the year. After 4.98 years, all lights will be LED.

Table 7 - Percentage of each Technology on the US Market depending of the Year

Year	Incandescent	Fluorescent	HID	LED
2012	63.02%	35.44%	1.51%	0.03%
2013	29.47%	35.44%	1.51%	33.57%
2014	0.00%	35.44%	1.51%	63.05%
2015	0.00%	12.09%	1.51%	86.40%
2016	0.00%	0.00%	1.48%	98.52%
2017	0.00%	0.00%	0.00%	100.00%

Since this model only takes in account the initial number of incandescent, fluorescent and HID lights as of 2012, calculations must only take in account energy savings and investments costs that are made with the initial number of watts in the first day of 2012. In other words, calculations exclude the additional lights from 2012-2017 that are due to an increased electricity demand in the US. Table 8 shows the different powers in watts for each category only including only the lights of 2012.

Table 8 - Power in Watts for each Lighting Technology

Year	Incandescent	Fluorescent	HID	LED
2012	112086020424	109364130762	45364827693	34179742
2013	52422631752	109364130762	45364827693	10773589703
2014	0	37304105003	45364827693	71585659451
2015	0	0	45364827693	98182035603
2016	0	0	44457531140	98764216046
2017	0	0	0	127291057765

Table 9 shows the investment depending on the year. As we can see, there are not any investments in 2012 since all lights are still functional. In 2016, only a small number of HIDs has to be replaced. By 2017, all lights used are LEDs.

Table 9 - LED Investments ($) depending on the Year

Year	Incandescent	Fluorescent	HID	LED
2012	0	0	0	0
2013	0	0	0	$ 76464598922
2014	0	0	0	$ 432981936603
2015	0	0	0	$ 189366198202
2016	0	0	0	$ 4145124756
2017	0	0	0	$ 203111113037

Appendix E shows all calculations in details.

Figures 17 and 18 show the effect on electrical consumption and cost of progressively switching to LED lights. From 2012 to 2030, it would represent savings of more than $1,049,648,869,667 or 10,875 TWh.

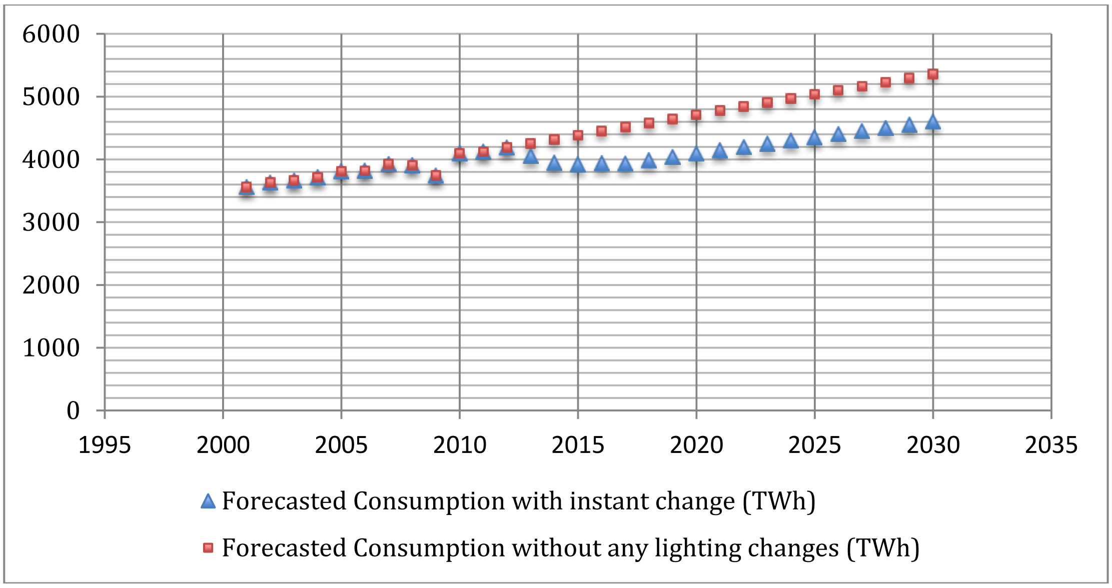

Figure 17 - Comparison between Forecasted Consumption with Progressive Change to LED and without any Change

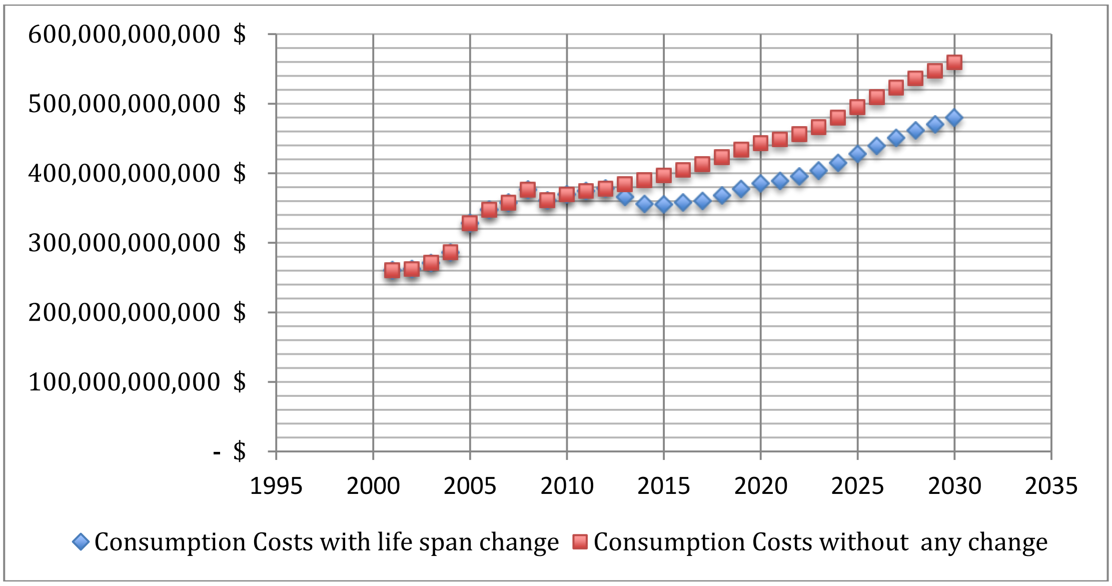

Figure 18 - Comparison between Forecasted Consumption Cost with Progressive Change to LED and without any Change

Figure 19 shows the return on investment of progressively switching to LED depending on the life span of the other technologies. It would take up to 2029 to payback all the investments that were made from 2012 to 2017 not including any interest rate. Same than the previous model, only electrical consumption is calculated as savings. The fact that LED has a very long life span has not been part of this study and would for sure improve the payback of this study. The reduced maintenance on LED leading to less working hours would also improve the payback.

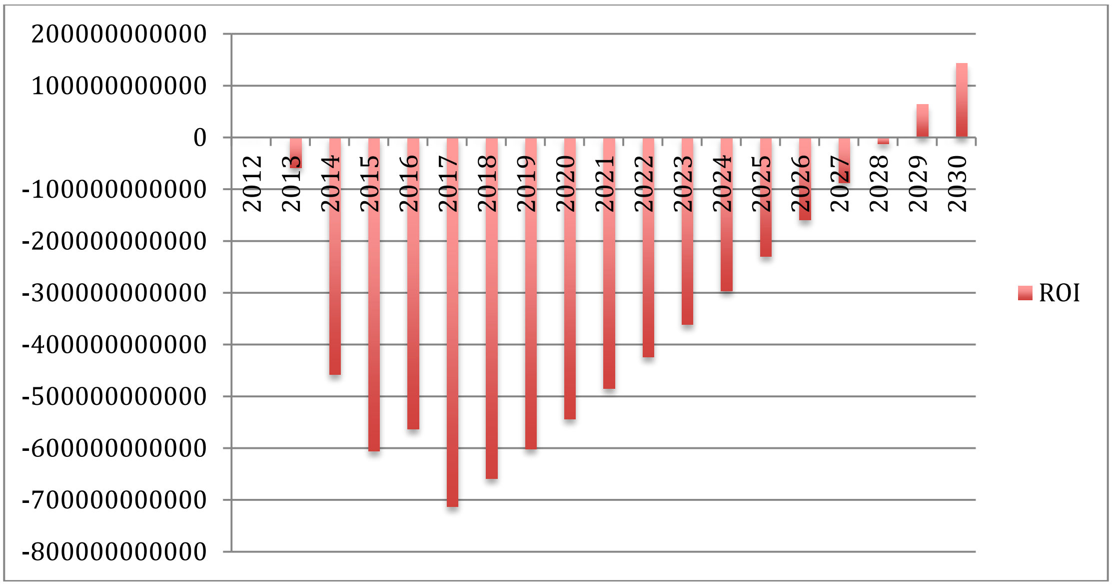

Figure 19 - Return on Investment of Progressive Switching to LED depending of the Life Span of other Technology

Figure 20 shows the decrease of emissions expressed as metric tons of CO_2 equivalent. The y-axis is positive and represents the amount of saved metric tons of CO_2 equivalent. From 2012 to 2030 it is 7,514,675,353 metric tons of CO_2 equivalent due to the progressive switch to LED. A comparison with the amount of embodied CO_2 in LED is presented in the conclusion of this study.

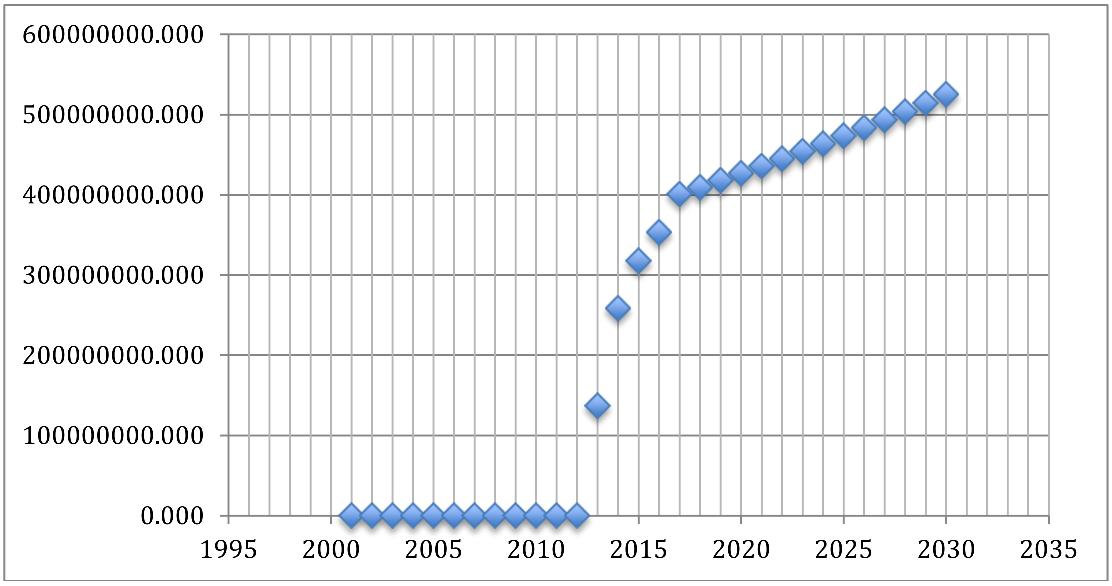

Figure 20 – Decrease of Tons of CO_2 Equivalent due to LED Switching First Model

Conclusion

Table 10 sums up the results from the two different models used in this paper. Those numbers are the sums from year 2012 to 2030. We can see that the instant change proposition is the cheapest one ($864,815,777,791) with the highest savings ($1,156,659,300,715 or 12,060 TWh). These savings represent 12.5 times the electricity consumption of Japan in 2009.

As for the second model, the savings are not as big as the first model ($1,049,648,869,667 or 10,875 TWh) but the investments are divided over many years ($906,068,971,519 over five years).

Table 10 - Summary of the two Models with Horizon 2012-2030

Model	Consumption Savings in TWh	Consumption Cost Savings	Metric tons of CO2 Equivalent Savings	Investment required
Instant Change to LED	12,060	$1,156,659,300,715	8,333,669,797	$864,815,777,791
Only LED Replacement Policy	10,875	$1,049,648,869,667	7,514,675,353	$906,068,971,519

This paper showed the amount of energy and greenhouse gases that can be reduced with the help of LED. It is more that 8,333,669,797 metric tons of CO_2 equivalent saved in the first model and 7,514,675,353 metric tons in the second model. The high amount of embodied CO_2 in LED was discussed in the introduction of this study. With the total number of lights in the US presented in table 3, the total amount of embodied CO_2 that would result in a complete switch to LED is 1,014,441,989 metric tons of CO_2. This would reduce roughly a little less than 15% of the GHG savings estimated in the two models.

Additionally, the high initial costs of LED as it is in 2011, require huge investments from the ones who want to convert to LED. The long payback of switching to LED in the two models presented is mostly justified by these high initial costs. Conversions policies & programs that would oblige customers to entirely change to LED lights would require significant investments. From an economical point of view, it is very unlikely that a government would opt from such a program.

One approach that could be feasible is an incentive that would encourage customers to buy LED when they have to replace their lights. For example, Energy Trust of Oregon has an incentive program called "Change a LIGHT Change the WORLD" (Energy Trust) that encourages their customers to buy energy efficient lights. Customers receive an order form with preapproved efficient LED or CFL lights. The offered products are highly subsidized by Energy Trust. Customers have the incentive to buy such products because they have lower acquisition costs but also lower consumption costs. This type of incentive offered by Energy Trust is particularity good when a technology is still expensive. The acquisition cost is shared between two parties and it encourages both sides to save money. One of the disadvantages of such a program is that only few customers (early movers) will consider the incentive. It is likely that a majority of consumers will still consider buying incandescent bulbs that are significantly cheaper than any of the products on the order form.

But as it is with any new technology, time will help to get lower prices and the models presented in this paper will become more feasible. LED still has major issues that need to be fixed. The uncertainty in predicting long term performance, the color stability, the lack of application levels (retrofit) and the high sensibility to temperature and voltage change will have to be improved to make the technology more attractive to consumers.

The global lighting industry is and will still be in an incandescent lock-in as long as a suitable replacement will not be found. CFL has become a standard in industrialized countries but it is still too expensive for the global market. Recently, LED has also become a standard for individuals and companies that want to set a new trend in the lighting sector. The technology is still too often used to impress rather than for its energy efficiency property. Besides, other technologies such as Electron Stimulated Luminescence (ESL) lights are presently being developed with the potential of reaching the global market faster than LED. With such a fast development, it is not an easy task to tell what technology will win. This study mainly focused on the period between 2011 and 2030. What if a better technology than LED becomes available during that period? A study similar to this one comparing LED and the new better technology would be appropriate to evaluate its potential.

But the future looks great for LED technology. As written in "Global and China LED Industry Report 2009–2010", the LED market made a great leap in second-half of 2009, expanding dramatically from US$7bn in 2009 to US$10.7bn in 2010 (a growth rate unattainable by any other electronic product) (Semiconductor Today, 2010). Big companies such as GE, Philips, Cree, Toshiba and Osram are spending enormous amount of money in research and development to create products that end consumers will want in their houses and firms. Nowadays, streets are often lighted by LEDs. The transition from older technologies to LED will be faster than one might think!

It is important for the reader of this paper to understand that there are great uncertainties with the numbers that were calculated in this study. The assumptions presented in the two models would not hold in the real world. The goal of this paper was to give the potential of LED lighting in replacement of older lighting technologies.

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Appendix A

Lighting properties

Table A-1. Approximate Properties of Lighting Technologies Considered

Lamp Type	Available Wattage	Efficacy (lm/W)	CRI	CCT (K)	Life (1000 hrs)
Incandescent					
Standard - General Service	15-250	10-19	97	2,500-3,000	0.75 - 2.5
Standard - Reflector	30-120	8-12	97	2,500-3,000	2
Halogen - General Service	42-150	14-20	99	3,000	2 - 3.5
Quartz Halogen	35-150	11-17	99	2,800-3,000	2 - 5
Halogen - refl. - low volt	15-73	7-10	99		4
Low wattage (less than 25W)	3-25	3-17	99		0.2 - 9
Misc incandescent	0.5 - 37.5		99		0 - 3
Fluorescent					
T5	4-13	25-55	52-75	3,000-6,500	6 - 7.5
T8 □less than 4□	17-30	35-82	60-90	3,000-6,500	15 - 20
T8 □4□	32	78-87	70-90	3,000-5,000	15 - 20
T8 □More than 4□	35-86	78-87	52-84	3,000-4,100	7.5 - 20
T8 □U-bent	32	80-82	75-84	3,000-4,100	20
T12 □less than 4□	14-55	35-75	52-90	3,000-6,500	7.5 - 18
T12 □4□	32, 34, 40	60-75	50-90	3,000-7,500	20
T12 □More than 4□	50-220	45-92	60-92	3,000-6,500	9 - 20
T12 □U-bent	34-40	48-74	52-82	3,000-6,500	10 - 20
Compact □Pin-base	5-50	42-77	82	2,700-6,500	10 - 20
Compact □Screw-in	5-55	40-70	82	2,700-5,000	10
Compact □Pin-base □reflector					
Compact □Screw-in □reflector					
Circline	20-40	29-50	60-85	3,000-6,500	10 - 12
Induction discharge	55-85	50-56	80+	3,000-4,000	100
Miscellaneous fluorescent					
HID					
Mercury vapor	40-1000	25-50	15-50	4,000-7,000	29
Metal halide	36-1650	50-115	65-70	3,000-4,400	3 - 20
High pressure sodium	35-1000	50-124	22	1,900-2,200	29
Low pressure sodium	18-180	75-150	0	1,700-1,800	18
Xenon					
Electrodeless (e.g. mercury)					
Solid State					
LED	2-25	3-30	0		
Electroluminescent					
Total					

Table A-2. Ballast Prevalence in Fluorescent Lamps in XenCAP□

	Magnetic			Hybrid	Electronic		
	Standard	High Eff.	T8		Standard	T8 Full Output	T8 Reduced Output
T8	8%	1%	29%	0%	0%	62%	1%
T12	91%	7%	0%	0%	1%	0%	0%
Both	89%	7%	1%	0%	1%	2%	0%

Table A-3. Efficacy Assumptions Used to Calculate National Lumen Production

	Residential		Commercial		Industrial	
Lighting Technology	Wattage	efficacy	Wattage	efficacy	Wattage	efficacy
Standard - General Service	63	15	83	16	126	17
Standard - Reflector	102	9	104	9	102	9
Halogen - General Service	200	18	64	15	-	15
Halogen □Double Ended	205	19	226	20	452	20
Halogen - refl. - low volt	-	-	48	11	58	11
Low wattage (<25W)	-	-	15	9	19	9
Misc incandescent	-	-	-	13	-	13
T5	-	-	8	50	10	50
T8 □less than 4□	-	-	23	82	23	82
T8 □4□	-	-	33	85	31	85
T8 □More than 4□	-	-	50	88	53	88
T8 □U-bent	-	-	34	74	32	74
T12 □less than 4□	-	-	29	63	32	63
T12 □4□	-	-	45	74	44	74
T12 □More than 4□	-	-	93	79	95	79
T12 □U-bent	-	-	46	69	46	69
Compact Plug-in	-	60	17	60	31	60
Compact Screw base	18	55	16	55	14	55
Compact Plug-in □reflector	-	55	16	55	-	55
Compact Screw base □reflector	11	55	16	55	14	55
Circline	-	58	30	58	35	58
Induction discharge	-	53	-	53	-	53
Miscellaneous fluorescent	41	60	18	60	34	60
Mercury vapor	179	40	331	40	409	46
Metal halide	-	65	472	65	438	65
High pressure sodium	79	80	260	104	394	112
Low pressure sodium	-	-	104	140	90	140
Xenon	-	-	-	40	-	40
Electrodeless (e.g. mercury)	-	-	-	150	-	150
LED	-	-	6	20	6	20
Electroluminescent	-	-	2	10	2	10

Table D-7. Average Wattage and Efficacy for the Residential Sector

	Average Wattage	Estimated Efficacy
Standard - General Service	63	15
Standard - Reflector	102	9
Halogen - General Service	200	18
Halogen □Quartz	205	19
Halogen - refl. - low volt	-	-
Low wattage (less than 25W)	-	-
Misc incandescent	-	-
T5	-	-
T8 □less than 4□	-	-
T8 □4□	-	-
T8 □More than 4□	-	-
T8 □U-bent	-	-
T12 □less than 4□	-	-
T12 □4□	-	-
T12 □More than 4□	-	-
T12 □U-bent	-	-
Compact □Plug-in	-	60
Compact □Screw base	18	55
Compact □Plug-in □reflector	-	55
Compact □Screw base □reflector	11	55
Circline	-	58
Induction discharge	-	53
Miscellaneous fluorescent	41	60
Mercury vapor	179	40
Metal halide	-	65
High pressure sodium	79	80
Low pressure sodium	-	-
Xenon	-	-
Electrodeless (e.g. mercury)	-	-
LED	-	-
Electroluminescent	-	-

Table 5.1.7. Lamp Life Data (175W MV Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MV	175	16,000	24,000	24,000
Substitute 1	PMH	150	2,800	12,000	20,000
Substitute 2	HPS	100	9,000	24,000	40,000

Table 5.1.8. Lamp Life Data (250W MV Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MV	250	12,000	24,000	24,000
Design Option 1	PMH	150	2,800	12,000	20,000
Design Option 2	HPS	150	9,000	24,000	40,000

Table 5.1.9. Lamp Life Data (400W MV Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MV	400	12,000	24,000	24,000
Design Option 1	PMH	250	10,000	15,000	20,000
Design Option 2	HPS	150	9,000	24,000	40,000

Table 5.1.10. Lamp Life Data (175W Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MH	175	10,000	10,000	10,000
Design Option 1	PMH	150	2,800	12,000	20,000
Design Option 2	HPS	100	10,000	24,000	40,000

Table 5.1.11. Lamp Life Data (250W MH Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MH	250	10,000	10,000	15,000
Design Option 1	PMH	175	10,000	15,000	15,000
Design Option 2	HPS	150	9,000	24,000	40,000

Table 5.1.12. Lamp Life Data (360W Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MH	360	20,000	20,000	30,000
Design Option 1	PMH	320	10,000	20,000	20,000
Design Option 2	HPS	250	9,000	24,000	40,000

Table 5.1.13 Lamp Life Data (400W Baseline)

	Lamp Type	Lamp Power W	Minimum Rated Life Hours	Median Rated Life Hours	Maximum Rated Life Hours
Baseline	MH	400	8,000	20,000	20,000
Design Option 1	PMH	320	10,000	20,000	20,000
Design Option 2	HPS	250	9,000	24,000	40,000

Table 5.2.1. LCC-PBP Analysis for 175W MV Baseline

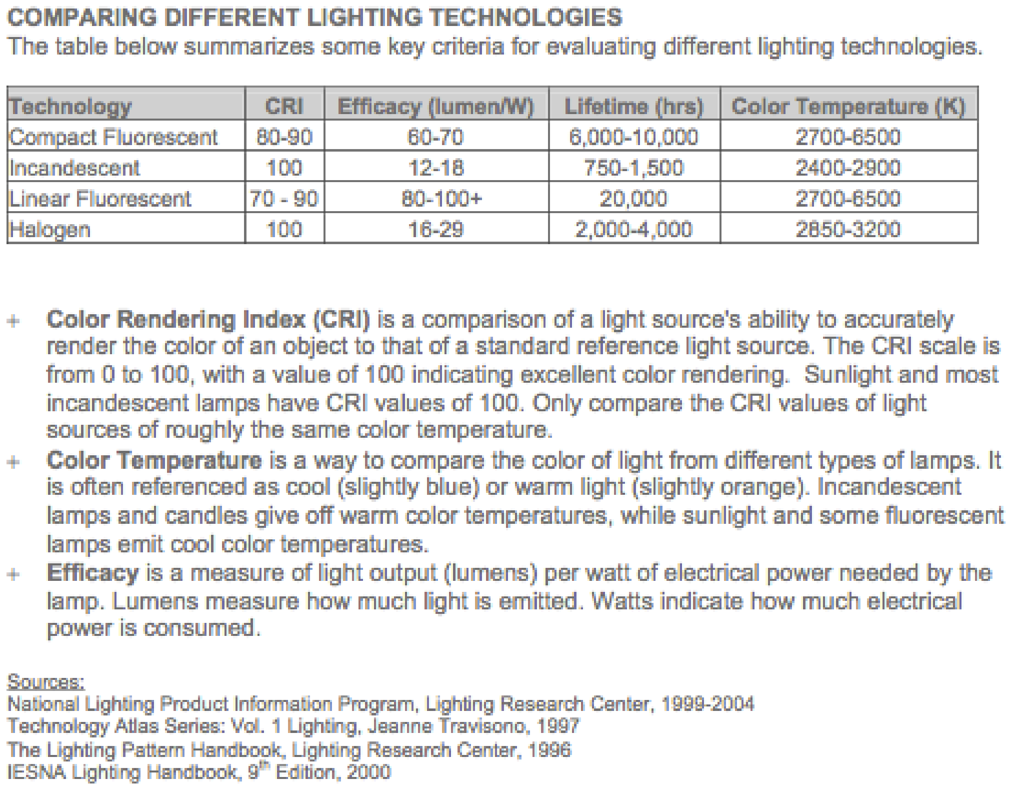
	Commercial/Exterior		
	Baseline 175 W MV $	Substitute 1 150 W PMH $	Substitute 2 100 W HPS $
Ballast Price	--	190.22	234.10
Lamp Price	45.17	64.09	49.23
Total First Cost	45.17	254.31	283.33
Incremental First Cost	--	209.14	238.16
Annual Operating Cost	294.90	288.18	263.26
Annual Operating Cost Differential	--	6.72	31.64
Life-Cycle Cost (7% Discount Rate)	1,837.32	2,191.63	2,059.27
LCC Savings	--	-354.31	-221.95
Payback Period (years)	--	31.12	7.53

Table 5.2.2. LCC-PBP Analysis for 250W MV Baseline

	Commercial/Exterior		
	Baseline 250 W MV $	Substitute 1 150 W PMH $	Substitute 2 150 W HPS $
Ballast Price	--	190.22	260.18
Lamp Price	52.60	64.09	60.91
Total First Cost	52.60	254.31	321.09
Incremental First Cost	--	201.71	268.49
Annual Operating Cost	326.94	288.18	288.18
Annual Operating Cost Differential	--	38.76	38.76
Life-Cycle Cost (7% Discount Rate)	1,874.13	2,193.63	2,126.51
LCC Savings	--	-319.50	-252.38
Payback Period (years)	--	5.20	6.93

Table 5.2.3. LCC-PBP Analysis for 400W MV Baseline

	Commercial/Exterior		
	Baseline 400 W MV $	Substitute 1 250 W PMH $	Substitute 2 150 W HPS $
Ballast Price	--	312.34	260.18
Lamp Price	64.29	80.90	60.91
Total First Cost	64.29	393.24	321.09
Incremental First Cost	--	328.95	256.80
Annual Operating Cost	394.58	327.73	288.18
Annual Operating Cost Differential	--	66.85	106.40
Life-Cycle Cost (7% Discount Rate)	1,943.34	2,255.98	2,126.51
LCC Savings	--	-312.64	-183.17
Payback Period (years)	--	4.92	2.41



COMPARING DIFFERENT LIGHTING TECHNOLOGIES

The table below summarizes some key criteria for evaluating different lighting technologies.

Technology	CRI	Efficacy (lumen/W)	Lifetime (hrs)	Color Temperature (K)
Compact Fluorescent	80-90	60-70	6,000-10,000	2700-6500
Incandescent	100	12-18	750-1,500	2400-2900
Linear Fluorescent	70 - 90	80-100+	20,000	2700-6500
Halogen	100	16-29	2,000-4,000	2850-3200

- **Color Rendering Index (CRI)** is a comparison of a light source's ability to accurately render the color of an object to that of a standard reference light source. The CRI scale is from 0 to 100, with a value of 100 indicating excellent color rendering. Sunlight and most incandescent lamps have CRI values of 100. Only compare the CRI values of light sources of roughly the same color temperature.
- **Color Temperature** is a way to compare the color of light from different types of lamps. It is often referenced as cool (slightly blue) or warm light (slightly orange). Incandescent lamps and candles give off warm color temperatures, while sunlight and some fluorescent lamps emit cool color temperatures.
- **Efficacy** is a measure of light output (lumens) per watt of electrical power needed by the lamp. Lumens measure how much light is emitted. Watts indicate how much electrical power is consumed.

Sources:
National Lighting Product Information Program, Lighting Research Center, 1999-2004
Technology Atlas Series: Vol. 1 Lighting, Jeanne Travisono, 1997
The Lighting Pattern Handbook, Lighting Research Center, 1996
IESNA Lighting Handbook, 9th Edition, 2000

Source:
http://www.energystar.gov/ia/partners/promotions/change_light/downloads/Fact%20Sheet_Lighting%20Technologies.pdf

Appendix B

Greenhouse Gas Equivalencies

Electricity use (kilowatt-hours)

The Greenhouse Gas Equivalencies Calculator uses the Emissions & Generation Resource Integrated Database (eGRID) U.S. annual non-baseload CO_2 output emission rate to convert reductions of kilowatt-hours into avoided units of carbon dioxide emissions. Most users of the Equivalencies Calculator who seek equivalencies for electricity-related emissions want to know equivalencies for emissions **reductions** from energy efficiency or renewable energy programs. These programs are not generally assumed to affect baseload emissions (the emissions from power plants that run all the time), but rather non-baseload generation (power plants that are brought online as necessary to meet demand).

Emission Factor

6.91×10^{-4} metric tons CO_2 / kWh (eGRID2010 Version 1.0, U.S. annual non-baseload CO_2 output emission rate, year 2007 data)

Notes:

- This calculation does not include any greenhouse gases other than CO_2.
- This calculation does not include line losses.

Individual subregion non-baseload emissions rates are also available on the eGRID Web site.
To estimate indirect greenhouse gas emissions from electricity use, please use Power Profiler or use eGRID subregion annual output emission rates as a default emission factor (see eGRID2010 Version 1.0 Year 2007 GHG Annual Output Emission Rates (PDF) (1 p, 278K, About PDF).

Sources:
(EPA 2011) eGRID2010 Version 1.0, U.S. annual non-baseload CO_2 output emission rate, year 2005 data U.S. Environmental Protection Agency, Washington, DC.

Appendix C

Calculations with no light changes

Year	Average Nominal Price ($/kWh)	% Incandescent	% Fluorescent	% HID	% LED	Incandescent Consummation (TWh)	Fluorescent Consummation (TWh)	HID Consummation (TWh)	LED Consummation (TWh)	Forecasted Consumption without any lighting changes (TWh)	Consumption Costs
2001	0.073	63.020%	35.444%	1.510%	0.026%	321.200	313.400	130.000	0.100	3557.107	260,380,211,831 $
2002	0.072	63.020%	35.444%	1.510%	0.026%	327.931	319.968	132.724	0.102	3631.650	261,841,987,135 $
2003	0.074	63.020%	35.444%	1.510%	0.026%	334.803	326.673	135.506	0.104	3662.029	270,990,146,888 $
2004	0.077	63.020%	35.444%	1.510%	0.026%	341.820	333.519	138.345	0.106	3715.949	286,128,110,345 $
2005	0.086	63.020%	35.444%	1.510%	0.026%	348.983	340.508	141.245	0.109	3810.984	328,125,726,188 $
2006	0.091	63.020%	35.444%	1.510%	0.026%	356.296	347.644	144.205	0.111	3816.845	347,332,936,132 $
2007	0.091	63.020%	35.444%	1.510%	0.026%	363.763	354.929	147.227	0.113	3923.814	357,459,476,717 $
2008	0.096	63.020%	35.444%	1.510%	0.026%	371.386	362.367	150.312	0.116	3906.443	376,190,500,190 $
2009	0.097	63.020%	35.444%	1.510%	0.026%	379.169	369.961	153.462	0.118	3741.484	361,053,240,547 $
2010	0.090	63.020%	35.444%	1.510%	0.026%	387.115	377.714	156.678	0.121	4097.000	369,139,700,000 $
2011	0.091	63.020%	35.444%	1.510%	0.026%	395.227	385.630	159.961	0.123	4121.539	374,235,705,111 $
2012	0.090	63.020%	35.444%	1.510%	0.026%	403.510	393.711	163.313	0.126	4187.037	377,670,736,334 $
2013	0.090	63.020%	35.444%	1.510%	0.026%	411.966	401.962	166.736	0.128	4252.503	384,001,005,372 $
2014	0.090	63.020%	35.444%	1.510%	0.026%	420.599	410.385	170.230	0.131	4317.936	389,477,841,131 $
2015	0.091	63.020%	35.444%	1.510%	0.026%	429.413	418.985	173.797	0.134	4383.337	396,691,998,470 $
2016	0.091	63.020%	35.444%	1.510%	0.026%	438.412	427.766	177.439	0.136	4448.705	404,387,320,492 $
2017	0.092	63.020%	35.444%	1.510%	0.026%	447.600	436.730	181.158	0.139	4514.041	413,034,785,855 $
2018	0.092	63.020%	35.444%	1.510%	0.026%	456.980	445.882	184.954	0.142	4579.345	422,673,540,764 $
2019	0.093	63.020%	35.444%	1.510%	0.026%	466.556	455.226	188.830	0.145	4644.616	433,807,154,268 $
2020	0.094	63.020%	35.444%	1.510%	0.026%	476.333	464.766	192.787	0.148	4709.855	443,197,368,163 $
2021	0.094	63.020%	35.444%	1.510%	0.026%	486.315	474.506	196.828	0.151	4775.062	448,378,300,008 $
2022	0.094	63.020%	35.444%	1.510%	0.026%	496.507	484.450	200.952	0.155	4840.236	455,950,244,833 $
2023	0.095	63.020%	35.444%	1.510%	0.026%	506.912	494.602	205.164	0.158	4905.378	466,010,938,201 $
2024	0.097	63.020%	35.444%	1.510%	0.026%	517.535	504.967	209.463	0.161	4970.488	479,652,116,720 $
2025	0.098	63.020%	35.444%	1.510%	0.026%	528.380	515.549	213.853	0.165	5035.566	494,996,143,155 $
2026	0.100	63.020%	35.444%	1.510%	0.026%	539.453	526.353	218.334	0.168	5100.612	509,041,050,009 $
2027	0.101	63.020%	35.444%	1.510%	0.026%	550.758	537.384	222.910	0.171	5165.625	522,761,279,859 $
2028	0.103	63.020%	35.444%	1.510%	0.026%	562.300	548.645	227.581	0.175	5230.607	536,137,197,070 $
2029	0.103	63.020%	35.444%	1.510%	0.026%	574.084	560.143	232.350	0.179	5295.556	547,030,962,903 $
2030	0.104	63.020%	35.444%	1.510%	0.026%	586.114	571.881	237.219	0.182	5360.474	559,097,411,157 $

Appendix D

Calculations for the first model

Year	Average Nominal Price ($/kWh)	% Incandescent	% Fluorescent	% HID	% LED	Incandescent Consummation (TWh)	Fluorescent Consummation (TWh)	HID Consummation (TWh)	LED Consummation (TWh)	Forecasted Consumption with instant change (TWh)	Consumption Costs with instant change	Forecasted Consumption without any lighting changes (TWh)	Consumption Costs without any change	Delta Consumption (TWh)	CO2 EQUI. Saved	Delta Consumption Costs	Investment	ROI
2001	0.073	63.020%	35.444%	1.510%	0.026%	321.200	313.400	130.000	0.100	3557.107	$260,380,211,831	3557.107	$260,380,211,831	0.000	0.000	$0	0	0
2002	0.072	63.020%	35.444%	1.510%	0.026%	327.931	319.968	132.724	0.102	3631.650	$261,841,987,135	3631.650	$261,841,987,135	0.000	0.000	$0	0	0
2003	0.074	63.020%	35.444%	1.510%	0.026%	334.803	326.673	135.506	0.104	3662.029	$270,990,146,888	3662.029	$270,990,146,888	0.000	0.000	$0	0	0
2004	0.077	63.020%	35.444%	1.510%	0.026%	341.820	333.519	138.345	0.106	3715.949	$286,128,110,345	3715.949	$286,128,110,345	0.000	0.000	$0	0	0
2005	0.086	63.020%	35.444%	1.510%	0.026%	348.983	340.508	141.245	0.109	3810.984	$328,125,726,188	3810.984	$328,125,726,188	0.000	0.000	$0	0	0
2006	0.091	63.020%	35.444%	1.510%	0.026%	356.296	347.644	144.205	0.111	3816.845	$347,332,936,132	3816.845	$347,332,936,132	0.000	0.000	$0	0	0
2007	0.091	63.020%	35.444%	1.510%	0.026%	363.763	354.929	147.227	0.113	3923.814	$357,459,476,717	3923.814	$357,459,476,717	0.000	0.000	$0	0	0
2008	0.096	63.020%	35.444%	1.510%	0.026%	371.386	362.367	150.312	0.116	3906.443	$376,190,500,190	3906.443	$376,190,500,190	0.000	0.000	$0	0	0
2009	0.097	63.020%	35.444%	1.510%	0.026%	379.169	369.961	153.462	0.118	3741.484	$361,053,240,547	3741.484	$361,053,240,547	0.000	0.000	$0	0	0
2010	0.090	63.020%	35.444%	1.510%	0.026%	387.115	377.714	156.678	0.121	4097.000	$369,139,700,000	4097.000	$369,139,700,000	0.000	0.000	$0	0	0
2011	0.091	63.020%	35.444%	1.510%	0.026%	395.227	385.630	159.961	0.123	4121.539	$374,235,705,111	4121.539	$374,235,705,111	0.000	0.000	$0	0	0
2012	0.090	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	437.392	3663.769	$330,472,006,078	4187.037	$377,670,736,334	-523.268	361577864.115	($47,198,730,256)	864815777791	$(817,617,047,535)
2013	0.090	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	446.555	3718.267	$335,759,506,068	4252.503	$384,001,005,372	-534.236	369157106.857	($48,241,499,304)	0	$(769,375,548,231)
2014	0.090	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	455.911	3772.502	$340,279,686,989	4317.936	$389,477,841,131	-545.434	376894843.520	($49,198,154,142)	0	$(720,177,394,089)
2015	0.091	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	465.463	3826.470	$346,295,538,368	4383.337	$396,691,998,470	-556.867	384795071.281	($50,396,460,102)	0	$(669,780,933,988)
2016	0.091	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	475.214	3880.166	$352,707,085,966	4448.705	$404,387,320,492	-568.539	392860475.104	($51,680,234,526)	0	$(618,100,699,462)
2017	0.092	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	485.170	3933.585	$359,923,014,629	4514.041	$413,034,785,855	-580.456	401095193.200	($53,111,771,226)	0	$(564,988,928,236)
2018	0.092	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	495.335	3986.722	$367,974,406,870	4579.345	$422,673,540,764	-592.623	409502745.517	($54,699,133,894)	0	$(510,289,794,342)
2019	0.093	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	505.713	4039.571	$377,295,939,474	4644.616	$433,807,154,268	-605.045	418086035.269	($56,511,214,794)	0	$(453,778,579,547)
2020	0.094	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	516.308	4092.128	$385,069,235,745	4709.855	$443,197,368,163	-617.727	426849423.490	($58,128,132,418)	0	$(395,650,447,130)
2021	0.094	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	527.125	4144.387	$389,157,907,690	4775.062	$448,378,300,008	-630.675	435796657.617	($59,220,392,318)	0	$(336,430,054,812)
2022	0.094	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	538.169	4196.342	$395,295,400,161	4840.236	$455,950,244,833	-643.894	444930873.118	($60,654,844,672)	0	$(275,775,210,140)
2023	0.095	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	549.445	4247.988	$403,558,835,508	4905.378	$466,010,938,201	-657.390	454256668.144	($62,452,102,693)	0	$(213,323,107,447)
2024	0.097	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	560.956	4299.319	$414,884,248,137	4970.488	$479,652,116,720	-671.169	463778032.221	($64,767,868,583)	0	$(148,555,238,864)
2025	0.098	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	572.709	4350.329	$427,637,302,010	5035.566	$494,996,143,155	-685.237	473499038.972	($67,358,841,145)	0	$(81,196,397,719)
2026	0.100	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	584.708	4401.012	$439,220,961,799	5100.612	$509,041,050,009	-699.600	483423847.882	($69,820,088,210)	0	$(11,376,309,509)
2027	0.101	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	596.959	4451.362	$450,477,793,086	5165.625	$522,761,279,859	-714.263	493556015.097	($72,283,486,773)	0	$60,907,177,264
2028	0.103	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	609.466	4501.372	$461,390,648,652	5230.607	$536,137,197,070	-729.235	503901259.256	($74,746,548,418)	0	$135,653,725,682
2029	0.103	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	622.236	4551.037	$470,122,122,493	5295.556	$547,030,962,903	-744.519	514462626.370	($76,908,840,410)	0	$212,562,566,092
2030	0.104	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	635.273	4600.350	$479,816,454,324	5360.474	$559,097,411,157	-760.124	525246019.736	($79,280,956,833)	0	$291,843,522,925

Appendix E

Calculation for the second model

Year	Average Nominal Price ($/kWh)	% Incandescent	% Fluorescent	% HID	% LED	Incandescent Consummation (TWh)	Fluorescent Consummation (TWh)	HID Consummation (TWh)	LED Consummation (TWh)	Forecasted Consumption with instant change (TWh)	Consumption Costs with life span change	Forecasted Consumption without any lighting changes (TWh)	Consumption Costs without any change	Delta Consumption (TWh)	CO2 EQUI. Saved	Delta Consumption Costs	Investment	ROI
2001	0.073	63.020%	35.444%	1.510%	0.026%	321.200	313.400	130.000	0.100	3557.107	260,380,211,831 $	3557.107	$260,380,211,831	0.000	0.000	$0	0	0
2002	0.072	63.020%	35.444%	1.510%	0.026%	327.931	319.968	132.724	0.102	3631.650	261,841,987,135 $	3631.650	$261,841,987,135	0.000	0.000	$0	0	0
2003	0.074	63.020%	35.444%	1.510%	0.026%	334.803	326.673	135.506	0.104	3662.029	270,990,146,888 $	3662.029	$270,990,146,888	0.000	0.000	$0	0	0
2004	0.077	63.020%	35.444%	1.510%	0.026%	341.820	333.519	138.345	0.106	3715.949	286,128,110,345 $	3715.949	$286,128,110,345	0.000	0.000	$0	0	0
2005	0.086	63.020%	35.444%	1.510%	0.026%	348.983	340.508	141.245	0.109	3810.984	328,125,726,188 $	3810.984	$328,125,726,188	0.000	0.000	$0	0	0
2006	0.091	63.020%	35.444%	1.510%	0.026%	356.296	347.644	144.205	0.111	3816.845	347,332,936,132 $	3816.845	$347,332,936,132	0.000	0.000	$0	0	0
2007	0.091	63.020%	35.444%	1.510%	0.026%	363.763	354.929	147.227	0.113	3923.814	357,459,476,717 $	3923.814	$357,459,476,717	0.000	0.000	$0	0	0
2008	0.096	63.020%	35.444%	1.510%	0.026%	371.386	362.367	150.312	0.116	3906.443	376,190,500,190 $	3906.443	$376,190,500,190	0.000	0.000	$0	0	0
2009	0.097	63.020%	35.444%	1.510%	0.026%	379.169	369.961	153.462	0.118	3741.484	361,053,240,547 $	3741.484	$361,053,240,547	0.000	0.000	$0	0	0
2010	0.090	63.020%	35.444%	1.510%	0.026%	387.115	377.714	156.678	0.121	4097.000	369,139,700,000 $	4097.000	$369,139,700,000	0.000	0.000	$0	0	0
2011	0.091	63.020%	35.444%	1.510%	0.026%	395.227	385.630	159.961	0.123	4121.539	374,235,705,111 $	4121.539	$374,235,705,111	0.000	0.000	$0	0	0
2012	0.090	63.020%	35.444%	1.510%	0.026%	403.510	393.711	163.313	0.123	4187.037	$377,670,736,334	4187.037	$377,670,736,334	0.000	0.000	$0	0	$-
2013	0.090	29.474%	35.444%	1.510%	33.572%	188.721	393.711	163.313	36.850	4054.307	366,103,964,234 $	4252.503	$384,001,005,372	-198.196	136953113.583	($17,897,041,138)	$76,464,598,922	$(58,567,557,783)
2014	0.090	0.000%	35.444%	1.510%	63.046%	0.000	393.711	163.313	70.424	3944.040	355,752,384,259 $	4317.936	$389,477,841,131	-373.896	258362317.876	($33,725,456,872)	$432,981,936,603	$(457,824,037,514)
2015	0.091	0.000%	12.090%	1.510%	86.400%	0.000	134.295	163.313	264.925	3923.541	355,080,448,766 $	4383.337	$396,691,998,470	-459.796	317719125.595	($41,611,549,704)	$189,366,198,202	$(605,578,686,012)
2016	0.091	0.000%	0.000%	1.480%	98.520%	0.000	0.000	160.047	372.517	3937.516	357,920,228,601 $	4448.705	$404,387,320,492	-511.189	353231415.028	($46,467,091,891)	$4,145,124,756	$(563,256,718,877)
2017	0.092	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	485.168	3933.582	359,922,778,687 $	4514.041	$413,034,785,855	-580.459	401096975.015	($53,112,007,168)	$203,111,113,037	$(713,255,824,745)
2018	0.092	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	495.332	3986.719	367,974,168,865 $	4579.345	$422,673,540,764	-592.626	409504527.332	($54,699,371,899)	$-	$(658,556,452,846)
2019	0.093	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	505.710	4039.569	377,295,698,632 $	4644.616	$433,807,154,268	-605.047	418087817.085	($56,511,455,636)	$-	$(602,044,997,210)
2020	0.094	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	516.305	4092.125	385,068,993,099 $	4709.855	$443,197,368,163	-617.730	426851205.305	($58,128,375,064)	$-	$(543,916,622,146)
2021	0.094	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	527.123	4144.384	389,157,665,559 $	4775.062	$448,378,300,008	-630.678	435798439.432	($59,220,634,449)	$-	$(484,695,987,697)
2022	0.094	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	538.167	4196.339	395,295,157,257 $	4840.236	$455,950,244,833	-643.897	444932654.933	($60,655,087,576)	$-	$(424,040,900,121)
2023	0.095	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	549.442	4247.985	403,558,590,541 $	4905.378	$466,010,938,201	-657.393	454258449.960	($62,452,347,660)	$-	$(361,588,552,461)
2024	0.097	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	560.954	4299.316	414,883,999,302 $	4970.488	$479,652,116,720	-671.172	463779814.036	($64,768,117,418)	$-	$(296,820,435,043)
2025	0.098	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	572.706	4350.326	427,637,048,533 $	5035.566	$494,996,143,155	-685.240	473500820.787	($67,359,094,622)	$-	$(229,461,340,421)
2026	0.100	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	584.706	4401.009	439,220,704,454 $	5100.612	$509,041,050,009	-699.603	483425629.698	($69,820,345,555)	$-	$(159,640,994,866)
2027	0.101	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	596.956	4451.359	450,477,532,131 $	5165.625	$522,761,279,859	-714.266	493557796.912	($72,283,747,728)	$-	$(87,357,247,138)
2028	0.103	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	609.464	4501.370	461,390,384,345 $	5230.607	$536,137,197,070	-729.237	503903041.071	($74,746,812,725)	$-	$(12,610,434,413)
2029	0.103	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	622.233	4551.034	470,121,856,123 $	5295.556	$547,030,962,903	-744.522	514464408.186	($76,909,106,780)	$-	$64,298,672,367
2030	0.104	0.000%	0.000%	0.000%	100.000%	0.000	0.000	0.000	635.270	4600.347	479,816,185,375 $	5360.474	$559,097,411,157	-760.127	525247801.551	($79,281,225,782)	$-	$143,579,898,148