SETTING PRIORITIES FOR IMPROVING BOSTON CITY STREET LIGHTS

Interactive Qualifying Project Report completed in partial fulfillment
of the Bachelor of Science degree at
Worcester Polytechnic Institute, Worcester, MA

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Submitted May 5, 2009

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Abstract

Boston spends 18 million dollars each year to operate and maintain 67,484 street lights. This project analyzed cost saving methods and technologies for the City of Boston to increase energy efficiency, decrease light pollution and maintenance cost. Researching lamp technology and a light level GIS map, created through fieldwork and surveying generated our findings. A rollout plan was created suggesting implementation of cut-offs on high wattage cobra head fixtures, saving a percentage of money to later purchase efficient green technologies.

Acknowledgments

Our team would first like to thank Laurie Pessah, Deputy Director of Capital Planning of the City of Boston, for her help in assessing the City's annual budget. We would also like to thank Joe Banks and Glenn Cooper of the City of Boston Street Lighting Division for their endless insight into the city's street lighting system. They were incredibly helpful in answering our questions and providing us with a profound understanding of Boston's lighting network. Our team would also like to thank Claire Lane, James Alberque, and the rest of the City of Boston MIS Department for their help and contributions in the GIS portion of our project. We would also like to extend a special thank you to our sponsor Bryan Glascock, Director of the Environment Department of the City of Boston, for giving us the opportunity to do this project and guiding us during our time in Boston. Last, but certainly not least, we would like to thank our advisors, Professor Robert Krueger and Professor Rick Brown, for their support, guidance, and motivation throughout all the stages of this project.

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Executive Summary

The City of Boston currently has 67,484 street lights, made up of 19 different fixture types and four different lamp types. The City spends 16 million dollars a year in energy cost and an additional 2 million dollars a year in maintenance. The current fixtures emit up to 70% of their light upwards, creating energy waste and resulting in the excess energy costs for the City. Additional costs are also accrued by the lamps used in these fixtures due to their requirement for frequent replacement, resulting in high maintenance costs. The goal of this project was to set priorities for the City of Boston for increasing energy efficiency and reducing maintenance costs for the current street lighting system. This goal was attained by making recommendations for replacement of the most inefficient street lights currently in place with newer, more energy efficient technologies. In working towards this goal, our primary objective was to analyze cost saving methods and technologies for the city of Boston with regards to increasing energy efficiency, decreasing light pollution, and reducing maintenance.

The primary methods we used to complete this objective were fieldwork and existing data research. We conducted fieldwork in order to assess the current levels of light pollution created by Boston city street lights. Our fieldwork focused on determining the various levels of light that are emitted from the different types of fixtures. We collected this data by using a light intensity meter. This allowed us to see where light can be eliminated to reduce costs and save energy. We also researched the implementation of light shields such as cut-offs as a means to reduce light pollution. As some of the current fixtures in the city emit up to 70% of their light upward, installing cut-offs would reduce upward lighting to as little as 3%. Because a cut-off focuses light downward, it allows for the lamp being used in the fixture to have a lower wattage while emitting the same amount of light, ultimately decreasing energy consumption and resulting in sizable energy savings.

In order to make recommendations for increasing energy efficiency and cutting energy costs for the city street lights, we researched energy efficient technologies such as solar lighting, induction lighting and light emitting diode (LED) lighting as options for replacement. We also conducted research regarding required maintenance of the current street lights as well as the potential replacement technologies. We researched the life spans of various lamp types as well as

the cost of replacement and repair. We used this data as a benchmark to research longer lasting, easily maintainable lamps and lighting technologies. We compared the life spans and required maintenance costs of each device to determine which would be most suitable to replace Boston's most labor intensive and costly lamps.

Our findings indicated that LED lights are over 75% more cost effective in terms of maintenance and replacement as compared to some of the current technology used in the city. Due to LED's substantially longer life span, some of the other lamps, such as mercury vapor (MV) lamps would have to be replaced at least four times during the lifespan of an LED.

In addition to their longevity, LEDs are also very efficient in energy consumption, resulting in substantial energy savings. By replacing some of the most commonly used lamps in the city, such as 175 watt and 250 watt MV lamps, with 90 watt and 120 watt LEDs respectively, the City could save millions of dollars on energy annually (see figures below).

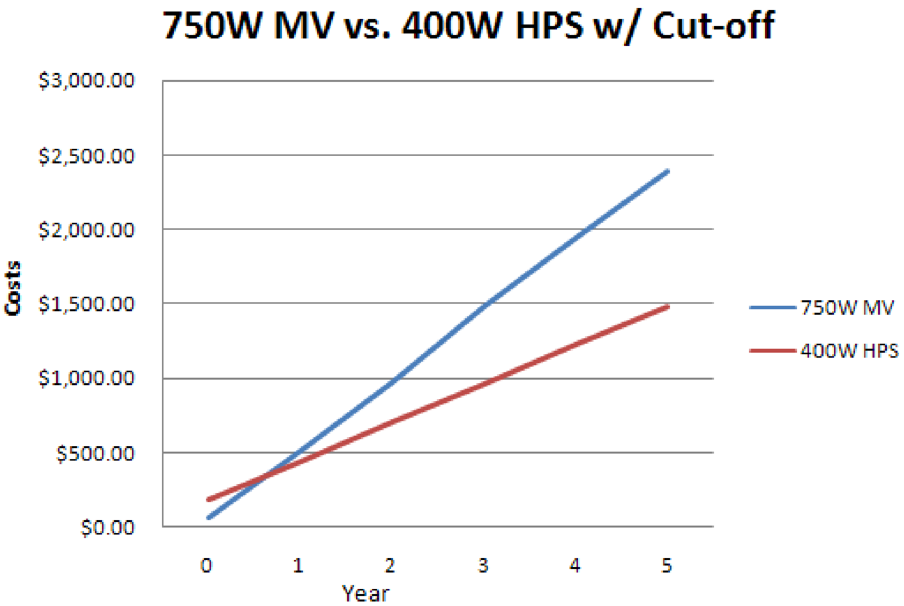
	250 W MV	**120 W LED**	Annual Savings
Annual kWh	1243	505	738
Number of lamps	11,832		
Annual Operation Cost per lamp	$163.29	$66.34	$96.95
Annual Operation Cost	$1,932,047.28	$784,934.88	$1,147,112.40

Annual Energy Savings of Replacing 250W MV with LED.

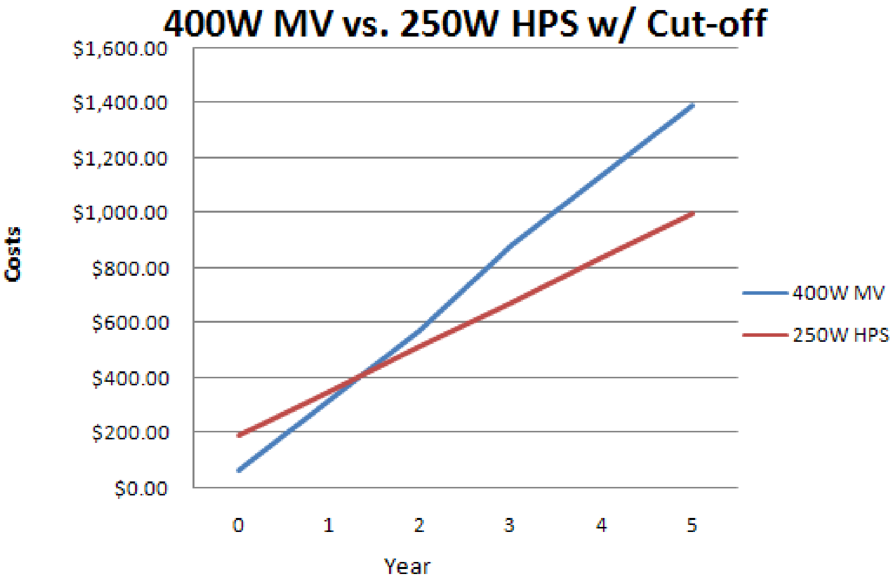
	175 W MV	**90 W LED**	Annual Savings
Annual kWh	895	442	453
Number of lamps	15,056		
Annual Operation Cost per lamp	$117.58	$58.07	59.51
Annual Operation Cost	$1,770,284.48	$874,301.92	$895,982.56

Annual Energy Savings of Replacing 175W MV with LED.

Our findings also indicated that there are significant savings in implementing cut-offs on all the cobra head fixtures in the city. By installing cut-offs on cobras with 750 watt MV lamps, the City would be able to replace this lamp with a 400 watt high pressure sodium (HPS) lamp, generating a savings of $193.12 per year per light. Similarly, installing cut-offs on cobra heads with 400 watt MV lamps would allow them to be replaced with 250 watt HPS lamps, resulting in an annual savings of $110.90 per lamp. Because the initial investment is only $120 per cut-off, the annual energy savings quickly add up to pay for this investment in less than 3 years (see figures below).



750W MV vs. 400W HPS with Cut-off



400W MV vs. 250W HPS with Cut-off

As a starting point for improving Boston city street lights, we are recommending a time phased plan. The first phase of the plan is to implement cut-offs in all the cobra head fixtures in the city and switch their lamps to lower wattage lamps. This will require an initial investment of

$120 per cut-off plus labor costs of approximately $58 per light. However, the payback period on this investment is less than three years. After year three Boston will save about $1 million on energy annually. This revenue can be saved up over the following 3-5 years as an investment in LED technology. At this point in time, LEDs are expected to drop up to 30% in purchase price, making them more affordable for the City. Also, at this time LEDs are expected be more thoroughly tested and developed, making them a far less risky investment for the City. Boston will then be able to use the savings generated from implementing cut-offs to invest in LED technology to replace all of the 175 watt and 250 watt MV lights in the city. These fixtures would be the best starting point for replacement as they are the most expensive for the city to maintain and operate.

1.0 Introduction

The City of Boston has 67,484 street lights, including 19 different types of lighting fixtures and four different lamp types (City of Boston Environment Department, 2009). Having this fixture variety makes it difficult and expensive for the city to maintain its street light network. The City spends about $2 million in maintenance costs on top of the $16 million spent annually to power the street lights (City of Boston Environment Department, 2009). These costs can be significantly reduced with the current advances in energy efficient lighting, and the savings can be distributed where they are more urgently needed. Aside from cost savings, energy efficient technologies can also improve the environmental quality in Boston. The City has begun working with the Boston Energy Alliance to implement long-term energy goals (City of Boston Environment Department, 2009). Through this alliance, Boston is developing a strategy to eventually install solar technology throughout the city streets to reduce the effects of environmental pollution and improve the quality of life for Boston residents. “In June 2007, the City of Boston became one of thirteen inaugural Solar American Cities under the Solar America Initiative of the U.S. Department of Energy (DOE) and launched Solar Boston, a half-million-dollar program to encourage widespread adoption of solar energy” (City of Boston Environment Department, 2009). This is one of many efforts the City is making to become more energy efficient.

The goal of this project was to set priorities for the City of Boston for increasing energy efficiency and reducing maintenance costs for the current street lighting system. Achieving this goal demonstrated several ways in which the city can reduce costs and make the street lighting system more environmentally friendly. Also, this project analyzed areas throughout the city that consume excess energy and are expensive to maintain. This was done by comparing the current lamps and fixtures to determine which are the most expensive to operate and maintain. Also, a GIS map was developed with gradients of light levels to determine over-lit areas based on the collected data.

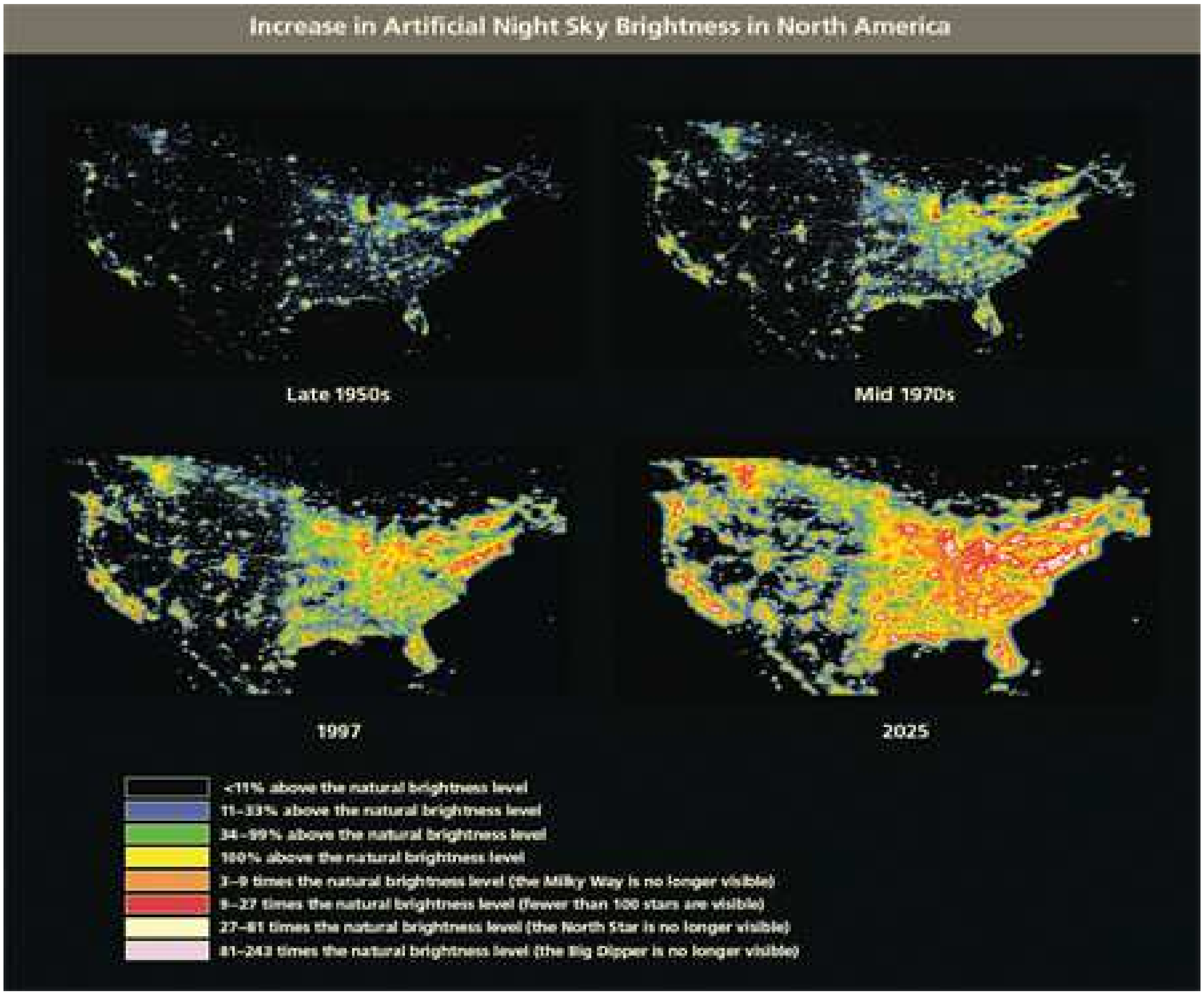
The remaining context will further discuss areas of the project. Background information regarding Boston street lights’ current energy efficiency, light pollution, light levels, and required maintenance will be discussed. Several newer technologies and how they improve the current street lighting system in Boston will be compared to examine various tradeoffs of each alternative. Also, data supporting the final recommendations will be presented, beginning with necessary background research acquired by the project team to determine the lighting system priorities.

2.0 Literature Review

Energy conservation is becoming a topic of great concern all over the world, especially in metropolitan areas. As cities continue to expand, people are searching for new ways to become more energy efficient and environmentally friendly (Ross, 2008). “Green” technology is rapidly growing in popularity and is being used more frequently in urban areas in order to benefit the environment by conserving energy. One way that some cities are trying to reduce energy consumption is by the renovating their street lights. Although street lights only contribute to about 8% of the world’s energy consumption, the current technology only allows for these lights to use 25% of the energy that is provided to them while the rest is converted to heat and ultimately wasted (Coltrin, 2003). In response to this growing problem, many cities worldwide have begun implementing energy efficient and environmentally friendly street lighting technology. One example is a town in northwest Germany that has implemented an energy savings plan developed by an engineer named Doerentup. He designed an energy plan that turns off the street lights in the town at 9p.m. to save electricity and associated costs. After a town resident registers on the town website, he or she can call a central number and enter a street code to illuminate the specific street for several minutes as needed. The reduction in energy consumption results in large saving on the town’s energy costs (Danigelis, 2008).

In addition to energy efficiency, several other concerns loom for street lights, such as evenness of light and proper visibility. Many people are under the impression that bright lighting will create a safer environment. Although being directly under the light may result in good visibility, bright lighting creates shadows that make certain areas very dark and in turn create a less than safe environment (IDA, 2008). Also, entering and leaving brightly lit areas takes time for one’s eyes to adjust, making it harder to see one’s surroundings (IDA, 2008). In order to address these problems, the City of Boston is looking to determine a standard level of light that will promote evenly lit streets as well as proper visibility.

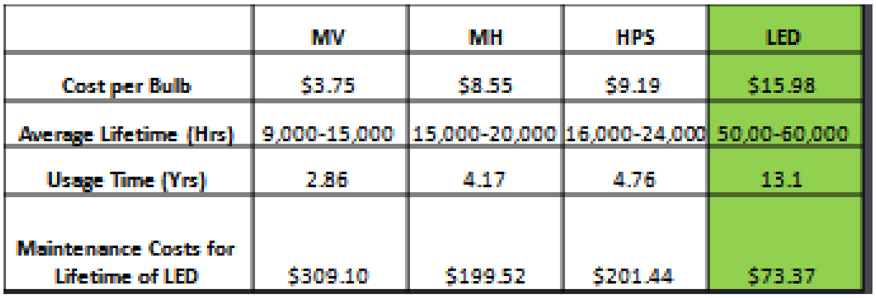
Another reason cities are implementing green technologies is to reduce energy waste such as light pollution. Many of the current fixtures are not directing light properly, creating over lit areas, and emitting light pollution into the atmosphere. Some of the problems associated with light pollution are the disruption of the ecosystem, adverse health effects created by carbondioxide emissions, the obstruction of the night sky for astronomical studies, and the disturbance of neighboring regions created by light trespass (Rogers, 2008). Due to light pollution, the night sky is not what it used to be several decades ago (see Figure 1). In 2001, *Monthly Notices of the Royal Astronomical Sky* published a report stating that two thirds of the U.S. has lost the ability to see the Milky Way (Earth's galaxy) with the naked eye (Chepesiuk, 2009). Many of the newer lighting technologies are aiming to address these issues and reduce the effects of light pollution on the atmosphere (Bazell, 2009).



http://www.ehponline.org/members/2009/117-1/map.jpg

Figure 1: Light Pollution

Boston is looking to incorporate newer technology into the current street lighting system that decrease the required maintenance costs (City of Boston Environment Department, 2009). By integrating greener technologies, Boston can reduce the amount of maintenance required by the street lights. One way of reducing maintenance is implementing lamps with longer lifespan. Figure 2 shows how greener technologies last longer and essentially reduce maintenance costs.



	MV	MH	HPS	LED
Cost per Bulb	$3.75	$8.55	$9.19	$15.98
Average Lifetime (Hrs)	9,000-15,000	15,000-20,000	16,000-24,000	50,00-60,000
Usage Time (Yrs)	2.86	4.17	4.76	13.1
Maintenance Costs for Lifetime of LED	$309.10	$199.52	$201.44	$73.37

Figure 2: LED vs. High Pressure Sodium vs. Mercury Vapor

The figure above shows that LED lights have a lifespan that is more than four times longer than mercury vapor lamps and almost three times longer than the high pressure sodium lamps, meaning they require replacement far less frequently. Also, in addition to lower maintenance, LED lighting is more contained, directing light downward, toward the areas where it is needed (Administration of LED Light Watching, 2008). Boston would gain environmental benefits as well as cost savings by implementing these, or similar technologies.

The goal of this project is to set priorities for the City of Boston for increasing energy efficiency and reducing maintenance costs for the current street lighting system. Setting priorities for increasing energy efficiency will simultaneously address the decreasing of light pollution and other energy waste. Implementing greener technologies will allow the city street lights to properly direct light and eliminate over-lit areas. The City of Boston must focus on these areas to improve the performance of the current street lights. Researching the current street lighting system, existing street lighting plans, energy efficient technologies and comparing various alternatives will allow for most suitable recommendations to be made for the City of Boston.

This chapter will discuss energy efficiency and the new technologies that have been developed to reduce energy consumption. The following chapter will discuss light pollution and the effects it has on Boston as well as other urban areas. This section will relate to energy efficiency, and how implementing newer, more efficient technology can reduce light pollution. The chapter will then discuss the maintenance currently required for Boston's street lights. It will examine the costs associated with the maintenance and focus on areas where they can be reduced. Along with maintenance, determining over-lit areas for the city streets will be discussed. Each section will present benefits and disadvantages associated with each potential alternative and how they relate to Boston's street lighting plan. Overall, the chapter will focus on the project objective:

- Analyze cost saving methods and technologies for the City of Boston pertaining to:
    a. Increasing energy efficiency
    b. Decreasing light pollution
    c. Reducing maintenance

2.1 Energy Efficiency

Energy consumption has become a growing problem throughout the world. As a result, several energy conservation and energy efficiency campaigns have been launched to reduce the levels of consumption and waste (Ross, 2008 and IDA, 2008). Even though the terms "energy conservation" and "energy efficiency" are used interchangeably at times, they hold significantly different meanings. Energy conservation refers to a reduced use of energy. Using light dimmers, turning down the heat, and lowering the consumption capacity standards on appliances are all examples of energy conservation. Conserving energy is simply a reduction in the normal use of energy. Energy efficiency, however, refers to getting the most use out of every unit of energy that is purchased. This is typically achieved by replacing old, outdated appliances and equipment with new, more efficient technologies (Herring, 2004).

The world has become increasingly dependent on electricity with countries using hundreds of terawatt hours (10^{12} watt hours) of electricity each year. A large percentage of that electricity is used for lighting (Geller and Leonelli, 1997). Improvements have been made and various plans have been implemented to replace the old electric devices with better, more efficient ones. However, even with the current advancements, energy consumption continues to grow, and creates a high demand for energy efficient street lighting.

Currently, Boston uses four different types of lamps: high pressure sodium, mercury vapor, metal halide, and incandescent (Street Lighting Division, 2009). Each lamp uses energy differently, creating various energy costs for the city. The current lamps in place are also relatively out of date and do not use energy in the most efficient manner (Environment Department, 2009).

2.1.1 High Pressure Sodium

The main type of light lamp in Boston is the high pressure sodium lamp (Street Light Division, 2009). There are approximately 33,000 lights, representing various wattages ranging from 70 watts to 1000 watts (Street Light Division, 2009). They are found in all nineteen types of fixtures, and are currently the most efficient lamps in place. High pressure sodium lamps output between 72 and 115 lumens per watt and provide between 5,000 and 30,000 lumens, depending on the wattage (Elert, 2004). The high lumen per watt ratio illustrates the higher energy efficiency amongst the current lamps in place. As well as having the highest efficiency, high pressure sodium lights are able to maintain the maximum lumen output for 70% of their usage time (Elert, 2004).

2.1.2 Mercury Vapor

The second most common type of lamp in Boston is mercury vapor, representing close to 30,000 lights throughout the city (Street Lighting Division, 2009). The mercury vapor lamps range in wattage from 175 watts to 1000 watts and are also found in all of the fixtures (Street Lighting Division, 2009). The lamps produce between 13 and 48 lumens per watt and last between 9,000 and 15,000 hours (Dark Sky, 2006). The mercury vapor lamps are the most expensive for the city to operate because of their low efficiency. Also, the light is produced by passing an electrical current through mercury at the proper voltage and current. The mercury content inside the lamp requires proper disposal, creating extra costs for Boston (Dark Sky, 2006).

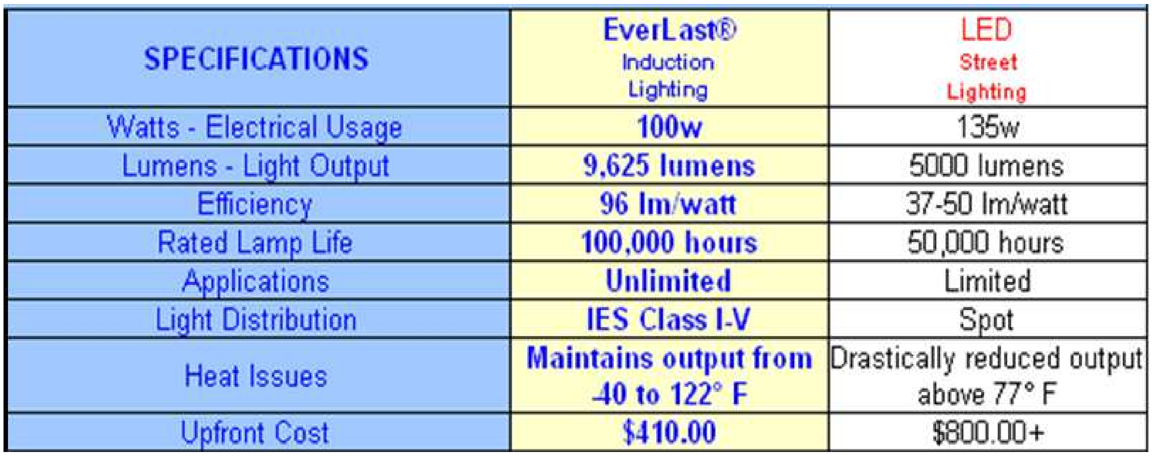
2.1.3 Metal Halide

Metal halide lamps are less common than the previous two lamps in Boston. There are approximately 500 lights scattered throughout the city (Street Lighting Division, 2009). The metal halide lamps are about twice as efficient as the mercury vapor lamps (Dark Sky, 2006). They range in wattage from 50 to 400 watts and produce between 2,000 and 19,000 lumens. Metal halide lamps are able to produce between 38 and 75 lumens per watt and maintain their maximum lumen output for 80% of their usage time (Elert, 2004). Metal halide lamps produce a white light that renders colors closely to what they would look like during the daytime. They are currently the most efficient form of white lighting used in Boston, and produce the quality of light new technologies are aiming for (Street Lighting Division, 2009, Dark Sky, 2006).

2.1.4 Incandescent

Incandescent lamps are the least common type of lamps found in Boston, representing close to 400 lights. The only two types of incandescent lamps used in Boston are 300 and 750 watt lamps and are found only in the flood and acorn fixtures (Street Lighting Division, 2009). The incandescent lamps are able to produce their maximum lumen levels, anywhere from 300 to 2,700 lumens, for 85% percent of their usage time (Elert, 2004). Although they are able to maintain their lumen levels for a high percentage of time, they have the shortest lifespan among the current lamps in place (Elert, 2004, Dark Sky, 2006). Also, incandescent lamps only use 10% of the energy supplied to them to produce light, the remaining electricity is converted to heat and ultimately wasted (Dark Sky, 2006).

Because the current lamps in place are highly inefficient, recent research has been directed towards developing energy efficient street lighting. A portion of the efforts has been dedicated to developing more efficient technologies in lighting. In recent years, newer technologies, such as LED and induction lights, have been developed to exceed the energy efficiency of the incandescent, metal halide, high pressure sodium, and mercury vapor light lamps (Haverhill, 2007). These new technologies are far more efficient in energy consumption than any of their predecessors and are beginning to be implemented into street lights of many urban areas. LED lights have been thoroughly marketed as environmentally friendly technologies and have been gaining popularity due to their increased efficiency of up to 55 lumens per watt (Roberts, 2009). Many cities have adopted LED lighting on their streets in an effort to conserve energy and save money. Induction lighting is a newer technology that has not yet gained as much popularity as LED lights, but still has impressive efficiency statistics. As you can see in Figure 3, induction lighting has an efficiency of up to 95 lumens per watt and is slowly being implemented in various outdoor fixtures (EverLast, 2009).



SPECIFICATIONS	EverLast® Induction Lighting	LED Street Lighting
Watts - Electrical Usage	100w	135w
Lumens - Light Output	9,625 lumens	5000 lumens
Efficiency	96 lm/watt	37-50 lm/watt
Rated Lamp Life	100,000 hours	50,000 hours
Applications	Unlimited	Limited
Light Distribution	IES Class I-V	Spot
Heat Issues	Maintains output from -40 to 122° F	Drastically reduced output above 77° F
Upfront Cost	$410.00	$800.00+

http://www.everlastlight.com/street_induction_light.html

Figure 3: LED Lights vs. Induction Lighting

2.1.5 LED

One way to improve the energy efficiency in Boston is to replace the current street lights with LED lights (Cheng, 2007). Cheng analyzes the benefits of implementing LED street lights and emphasizes on the energy conservation of these lamps. Cheng estimates that the United States alone could save up to 40 GW a year by replacing current lamps with LED lights. When comparing the LED lamps with current technology the benefits are clear (LED Lighting Watch, 2008).

Several benefits will result due to implementation of LED lamps in Boston. Power consumption can be reduced by 52% when replacing mercury vapor, and 26% when replacing high pressure sodium. Most importantly for this section is the increase in lifetime. The LED lamps can last for 60,000 hours, which is much longer than either of the previous two lamps (LED Lighting Watch, 2008). This reduces the amount of maintenance required because the lights do not have to be changed as often.

Remco (2008), an LED manufacturing company, has also designed a way to direct replace the LED lamps into current high and low pressure sodium fixtures. This is a major way to reduce implementation costs for Boston. Instead of having to replace the whole fixture, Boston will now be able to replace the lamp itself (Remco, 2008). The direct replacement includes installation of thermal management to ensure the long lifetime of LED lamps (Matthews, Business Wire, 2008).

One other benefit of LED light is the ruggedness of the lamps (Remco, Roberts 2009). This means that compared to other lamps they have more resistance to high vibration, such as areas with high transportation (Remco, Roberts 2009).

There are also several issues that arise with LED lights. To obtain a desired brightness the street lights must operate at a high temperature, but in order for an LED lamp to last a long time it must operate at a low temperature (Cheng, 2007). The contradicting requirements make it difficult for the LED street lights to improve light quality and decrease maintenance. Cheng conducts experiments using an 80W LED light in natural conditions to determine the heat distribution throughout the base of the light. From these experiments he was able to conclude that as the heat increases the light lamp becomes less reliable and lowers the lifetime of the lamp (Cheng, 2007). Also, LED lamps currently do not have the desired power available for street lights (Remco, Roberts 2009). This means that in order for the lamps to supply enough light there needs to be a bundle of smaller lamps encased in one larger lamp. This significantly increases the expense of the fixture (Remco, Roberts 2009). Not only do the more powerful LED lights cost more to power, but the fixtures will require some sort of resistor to deal solve thermal management issues. (Remco, Roberts 2009).

Cheng proposes a solution to this problem, which can be applied to the Boston project. A resistor that is placed between the LED lamp and substrate can substantially dissipate heat. LED lamp temperature can be highly reduced using these resistors, which would ensure longer life for the lamp and reduce maintenance for the street lights (Cheng, 2007, Owen 2007, Taub, 2008). Based on this information obtained from the article, it would be important to ensure that the LED lamps were operating at a temperature that allowed for a long life period and still maintained good light quality. If this temperature was too high for the lamps to be effective then resistors would have to be installed. (Remco, Roberts 2009). As mentioned early, Remco (2008) has also developed a form of thermal management that reduces the risk of the lamp overheating.

2.1.5.1 LED Case Studies

As LED technology grows in popularity due to its superior energy efficiency and long life span, many cities are beginning to implement this technology on their streets. In 2007, the City of Ann Arbor, Michigan launched a pilot project to switch some of their current street lights to LED technology in hopes of reducing energy consumption. The City hoped to cut its $1.39 million street lighting budget in half by switching to LED street lighting. This sum only accounts for the energy savings. The substantial maintenance savings will also allow the City to redirect work flow and allow crews to concentrate more on other projects within the city (Proefrock, 2007).

In August of 2008, New York City also launched a test project to replace some of the city's high pressure sodium lights with new LED technology. This included not only switching the lamp for the energy efficient LED, but also the implementation of a completely redesigned, LED compatible pole. The City expected that the payback period for these LED lights will be two to three years and the power usage will be reduced 25 to 30 percent. If this test project is successful, all 300,000 of New York City's street lights may eventually be replaced with LEDs (Taub, 2008).

Most recently, in April of 2009, the City of San Jose, California has also begun a test of the LED technology. The City will be implementing 125 LED street lights to test their performance in the next few years. San Jose expects to spend $150,000 to $200,000 on this pilot project. As a result, the city expects to save up to 60% on energy annually. These projected savings are also a result of the LEDs built in dimmer technology that will allow San Jose to dim the lights to lower wattage as needed (Smith, 2009).

Over the coming years, as LEDs grow in popularity and drop in price, more cities are projected to be implementing this technology in their street lighting system. As LEDs become more thoroughly tested, they will be a far less risky investment for cities worldwide.

2.1.6 Induction

Another type of lights that can be installed in Boston to reduce energy costs are induction lights. Induction lights offer several benefits that current lamps do not (Remco, Roberts 2009). They are able to produce high lumen levels using lower wattage lamp, as well as evenly distribute quality light. Induction lights are similar to fluorescent lights, but because the lamps do not have electrodes inside them induction lights are able to last much longer and maintain high levels of lights (Haverhill Energy Task Force, 2007). They have a longer life span that can last up to 100,000 hours, and are able to be installed in all of the fixtures (Everlast, Nu Vue, AMKO Solara, 2008). This would significantly reduce several costs pertaining to maintenance. Also, the lamps are protected by cast aluminum housing with a powder coat for corrosion-resistance (Everlast, 2008). The glass lens that protects the fixture design is "easy open" to make the maintenance easier for Boston (Everlast, 2008). The following chart illustrates that induction lamps produce high lumens after a much longer burning period.

Some of the negative effects of induction lights are they do not properly protect erosion all the time. (Remco, Roberts 2009). There are several climate changes throughout the year in the city of Boston, and the material to protect the lamps does not properly do so. (AMKO Solara, 2008). Also, induction lighting is susceptible to damage (Remco, Roberts 2008). The lamps are fragile and are difficult to protect from vibrations. Installing attachments to the fixtures to protect the lamps will create maintenance costs unnecessary for the city. Also it will increase the amount of maintenance required to properly uphold the lights. (Remco, Roberts 2009).

2.1.7 Solar Panels

Solar panels have recently been developed to be installed on street lights of various sizes and wattages. The panels convert the sun's energy in to electricity and supply the energy to the street lights (Solar Lights, 2008). Installing solar panels in certain areas of Boston would eliminate a large percentage of energy costs. The energy is stored in a battery that also has a backup charge to supply energy in case of bad weather or charger failure. The battery also requires very little maintenance (Solar Lights, 2008).

The solar panels are equipped with a controller that triggers operation of the lights at dusk and dawn, and has the ability to dim the lights at certain times. As well as reducing energy costs, solar panels are estimated for up to 20 years of usage and are reliable in climate changing conditions (Solar Lights, 2008). Boston can benefit greatly from implementing solar panels, especially since they are compatible with the types of lamps that Boston currently uses.

2.1.8 Electronic Dimmers

Another form of technology that is presented by Peter Van Tichelen (2000) is an electronic dimmer that is attached to the ballasts of high pressure sodium lamps. The remote powered ballasts allows for a dimmer to be controlled by a remote for automatic dimming to reduce the amount of energy supplied to street lamps when necessary (Van Tichelen, 2000). The dimming would allow for lower wattage to be supplied to the lamps which would increase their lifetime (Van Tichelen, 2000). As well as increasing lifetime, the city would reduce operational costs due to the reduction in energy supplied to the lights (Van Tichelen, 2000).

These new technologies use energy efficiently and significantly reduce the amount of energy that is wasted as it is converted to heat. Utilization of advanced technologies, such as LED and induction lights, for public street lighting would allow for energy savings of up to 40%. These devices would be 13 times more efficient than incandescent light lamps (NuVue, 2009).

All of the technological advancements in lighting have made significant contributions to the field of energy efficiency. Each newly developed device has displayed an improved performance over the previous technologies. However, as cities grow, the energy demand also grows. In order to meet these demands without completely draining the earth’s resources and causing more harm to the ecosystem, further technological advances in energy efficiency must be made and implemented throughout the world. These technologies must reduce energy consumption but, simultaneously they must maintain a proper level of light for public safety and visibility for drivers and pedestrians.

2.2 Light Pollution and Wasted Energy

One reason Boston's electricity bill for street lights was $16 million was because of the wasted energy caused by light pollution. Light pollution is defined as unwanted or harmful light, which is mainly from overly bright and poorly constructed street lights. Light pollution is broken down into two subcategories; ecological light pollution and astronomical light pollution. The three main problems that cause these two types of pollution are found in our streetlights and are defined as sky glow, light trespass, and glare (Connecticut Light and Power Company, 2003).

A main goal for the energy efficient street lighting system in Boston is to reduce pollution. In order to understand methods that actually reduce pollution it is important to understand fully light pollution itself. "Ecological Light Pollution," by Travis Longcore, describes the different forms of light pollution and the effects that they have on the environment. He thoroughly examines the effect of artificial night lighting and distinguishes astronomical light pollution from ecological light pollution. Astronomical light pollution is described as the pollution that obscures the night sky whereas ecological light pollution alters natural light in terrestrial and aquatic ecosystems (Longcore, 2004).

Longcore (2004) describes the astronomical light pollution as "stars and other celestial bodies washed out by light that is either directed or reflected upward." This as mentioned earlier is commonly known as "sky glow" and is major problem in Boston. Shielding or angling lights so the illumination goes directly down can reduce this form of pollution. The article further describes ecological light pollution having an effect on the behavior of living organisms in natural settings (Longcore, 2007). Longcore emphasizes that artificial light can expand outside of a city and have an effect on the habitats of animals and alter their living styles. One of the first principles you learn in astronomy is how to orient yourself to the night sky by looking for constellations. But in Boston it is said that, "astronomy students should find a new hobby" because the sky is so full of light pollution (Joe Roberts, 2001). Now, one can only see half of the constellations because they are partially, if not fully, washed out by light pollution.

2.2.1 Sky Glow

Sky glow is the illumination of the night sky caused by streetlights located mostly in urban areas (Kocian, 2009). This type of light pollution is mainly caused by unshielded lights that direct light in an upward direction. The main fixtures that cause this are cobra head fixtures (emits light 30% upwards), floodlights (emits light 50% upwards), and decorative lights (emits light 70% upwards) (Alin Tolea, 2000). For the full effect see Figure 4.

http://www.darkskies4ni.co.uk/images/moon_over_belfast_peter_paice.jpg

Figure 4: Sky Glow

Connecticut light and Power Company states that a main solution to the problem of sky glow is to use shielded lights. These shielded lights do not emit light above an imaginary horizontal line drawn from them, which gives the person putting up the shields the power to direct where the light from the fixtures will be directed. There are also different types of fixtures that can be used to eliminate sky glow. These fixtures are Box Design fixtures (emits light 0% upwards) and good decorative lights (emits light 5% upwards) (Alin Tolea, 2000).

2.2.2 Light Trespass

Light trespass is when illumination from a street light spills over into a neighbors' window or property in general (Starry Night Lights, 2009). Light trespass also occurs when the light is being emitted upwards or backwards due to bad fixtures. The main cause for this is that engineers did not have the improvements that they have today when they put together these streetlights and they did not know how important a perfect layout would be to lessen light pollution. Because of these bad layouts streetlights are being used where they are not needed, see Figure 5.

http://farm1.static.flickr.com/65/203272524_ab0d8d6814.jpg?v=0
http://www.darkskiesawareness.org/img/wash-dc.jpg

Figure 5: Light Trespass

A perfect solution to eliminating light trespass would be to redesign the current light system to separate the ballasts more efficiently, but this would come at a high cost and be very unlikely to happen (Connecticut Light and Power Company, 2003). A more probable solution to this problem is to look more closely at the pole height compared to the amount of wattage used on that pole. If it is a low pole then the engineers should implement a low wattage light lamp, but if the pole is high then the engineers should implement a high wattage light lamp, which will cover the area they specifically want that fixture to light (Connecticut Light and Power Company, 2003). The previously stated solution to using shielded fixtures would also help to eliminate light trespass because it would give the engineer the power to direct the light to only where it is needed. This gives the possibility of creating evenly lit streets for proper visibility.

2.2.3 Glare

Glare occurs when the street lights are too bright or when too much wattage is applied causing the light to reflect off of the ground, buildings, or vehicles (Bazell, 2009). The main cause for this is that the wattage used to illuminate the streetlights is too high. Engineers have to pay close attention to the amount of wattage used in the light compared to the height of the ballast. If the ballast is low and the wattage is high then glare will occur (Black, 2009). Adversely, if the ballast is high and the wattage is low then the streetlight is pointless, so it is very important to keep this in mind when putting up a streetlight. Another cause for this is that engineers poorly placed the streetlights, not giving them enough distance between each other, see Figure 6.

http://www.kwastronomy.com/images/Streetlight.jpg

Figure 6: Street Light Glare

A solution to the problem with glare would be to install LED light lamps into the fixtures. The type of light emitted from LED light lamps is a higher quality light that reduces the amount of glare from the light itself (Black, 2009). Another solution is the previously stated solution of making sure the wattage of the light used for the fixture corresponds well with the height of the ballast. It is also important to separate the poles appropriately to use less energy and not cause an overlap of light.

In attempting to implement these solutions to light pollution, one would have to consider maintenance costs as well as the technological devices that would be best suited for reducing the light pollution emitted from the current lighting system. In doing so, analysis and comparisons of modern light pollution reduction technologies will have to be done to determine which one will have the optimum performance.

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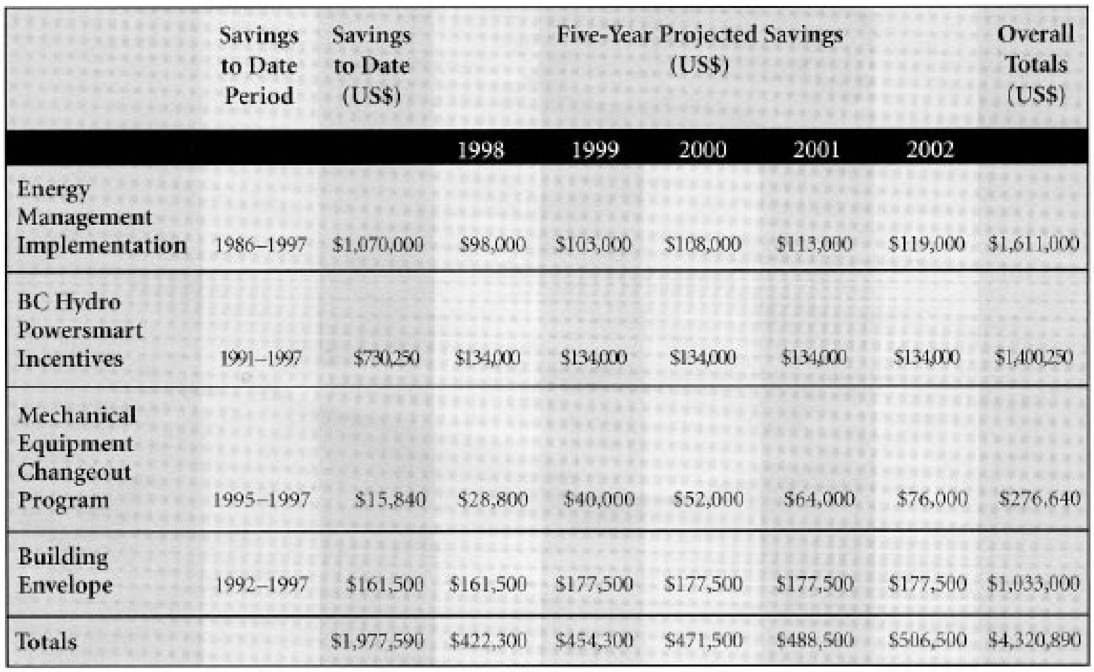
2.3 Maintenance

Reducing maintenance costs and improving technology will lead to the achievement of the project goal when working in Boston. This portion will discuss certain methods that can be taken to reduce maintenance and the overall costs associated with maintaining the streetlights. It will also examine several technologies that will help understand how to improve the overall situation in the city.

There are several different methods that will be discussed in this section that will improve the current process Boston uses to maintain street lights. Currently the lights are maintained by the street Lighting Division of Public Works, and lamps are changed or lights are repaired based a request from the residents of Boston. The maintenance section will also describe new ways to track and decrease energy usage and locate lights that need repair. In addition, this section discusses how the proper placement of street lights will help reduce costs for the city.

One new method for maintaining street lights is energy management systems. Maximizing energy savings with energy management systems (Van Gorp, 2009) describes the importance of energy management systems to various cities. A quality energy management system cuts costs by allowing the city maintain street lights in the most efficient manner. Incorporating an energy management system in Boston allows for the city to provide power for twenty-first century needs (US Department of Energy, 2008). Energy management can help save money and electricity at the same time by analyzing separate situations and determining the exact amount of energy that needs to be used (Van Gorp, 2005, World Port Development 2008).



	Savings to Date Period	Savings to Date (US$)	Five-Year Projected Savings (US$)					Overall Totals (US$)
			1998	1999	2000	2001	2002	
Energy Management Implementation	1986–1997	$1,070,000	$98,000	$103,000	$108,000	$113,000	$119,000	$1,611,000
BC Hydro Powersmart Incentives	1991–1997	$730,250	$134,000	$134,000	$134,000	$134,000	$134,000	$1,400,250
Mechanical Equipment Changeout Program	1995–1997	$15,840	$28,800	$40,000	$52,000	$64,000	$76,000	$276,640
Building Envelope	1992–1997	$161,500	$161,500	$177,500	$177,500	$177,500	$177,500	$1,033,000
Totals		$1,977,590	$422,300	$454,300	$471,500	$488,500	$506,500	$4,320,890

http://oee.rncan.gc.ca/publications/infosource/pub/ici/eii/m27-01-1310e.cfm?attr=16

Figure 7: Malaspina University Energy Management System

Figure 7 shows a chart with representations of the results due to the implementation of an energy management system at Malaspina University (MU, 2000). Although the system was applied to several buildings across campus, this same type of method can be used in Boston. Energy management systems, EEM, ensures that the energy is being used in the most efficient ways possible (Van Gorp, 2005). The table illustrates the benefits for the University, and Boston can maintain their street lights in a similar fashion. One major factor this chart represents is the importance of the equipment changeout program (MU, 2000). Boston will benefit more by replacing older technologies with newer forms instead of replacing lamps with technology currently in place.

Another way Boston is improving street light maintenance is mapping the exact placement of the lights. Using a geographical information system (GIS), Boston can correlate the lights on the map with a database (Environment Department, 2009). The database contains information regarding lamp type, fixture type, location of lamp, and anything else that is needed to describe the fixture. Boston currently has a program that maps close to 90% of the street lights (Environment Department, 2009). By mapping all of the street lights with the GIS program, Boston can develop efficient methods for replacing lamps that will reduce maintenance costs. For example, since lamps tend to burn out around the same time because they have similar lifespan, Boston can use the database information to see when the lamps were installed and replace whole streets instead of just one lamp at a time. Or, if the lifespan is known, Boston can be proactive and change a lamp before it hits a drop off point in efficiency. This will in turn reduce the costs of having to pay a maintenance team to travel out to a street several times.

This information can be directly related to the Boston project. In order to develop an energy efficient street lighting system we must analyze each aspect of the current systems. EEM systems will allow for an analysis of energy consumption and generate data to make appropriate changes. Being able to evaluate energy consumption can lead to valuable cost savings and ensure energy efficiency. GIS mapping will improve the way a city maintains their lights. Having information recorded in a database will illustrate streets or neighborhoods that commonly need repairs. The GIS system allows Boston to properly replace lights by sending teams out to replace whole streets instead of single lamps. GIS systems can also go a step further and help reduce the variety of fixtures. By having an understanding of the most commonly used fixtures and where they are located, Boston can replace out of date fixtures in an efficient manner. Most importantly, analyzing the current fixtures and required maintenance will allow for recommendations to reduce maintenance costs.

After analyzing several methods and technologies to reduce maintenance and associated costs it is clear that a plan including a combination of methods is needed. Reducing maintenance costs is one of four main goals, and using improved technology will help be more efficient. EEM systems are a good starting method to thoroughly analyze energy consumption in Boston. Boston currently records the amount of energy consumed and pays energy companies based on the estimates. Implementing EEM systems will allow the city to get an accurate reading of the energy consumed, and select areas that require the most improvement. LED light lamps are another means of reducing maintenance. With longer lifetimes, the city will not have to replace lamps as often. They will also improve the quality of light emitted and improve the overall street scene. Although the lamps will last longer, they are associated with high installation costs. The lamps are also more expensive but the lifetime and ruggedness will reduce maintenance costs in the long run (Remco, Roberts 2009). Controlling the intensity of light with remote dimmers is another technology that will help increase how long a lamp operates for. While dimming the lights will also help reduce pollution and energy consumption, installing the dimmers would require excessive funds. Also, maintaining the dimmers initially may be hard to integrate, as any new system is. Boston would need an experienced staff who could maintain the light intensity efficiently. In general, overall costs need to be reduced in the City of Boston. This section analyzed the benefits and disadvantages of several forms of technology. Continuing to research methods, and combining them with current techniques will lead to the successful development of a plan to improve the current maintenance of the city street lights.

2.4 Summary and Synthesis

After analyzing each individual goal and the solutions proposed to achieve them it is evident that in achieving some goals other goals will not be fully completed. Several technologies that have been developed can significantly increase energy efficiency in Boston (Geller and Leonelli, 1997). Although these technologies will allow the city to conserve energy usage and increase energy efficiency they do not meet requirements for satisfying other goals. For example in Ontario, Relume luminaires are used to save money on energy consumption, but are detrimental to maintenance cost (Owen, 2007). Implementing the Relume luminaires would reduce energy consumption, but would come at a high installation cost because of the city's size and Boston will not benefit from having to maintain this expensive equipment.

Previous research presents three solutions that would work best for decreasing the three problems of sky glow, light trespass, and glare. One of these solutions is utilizing the full cutoff or fully shielded, light fixtures because with these fixtures we have full control over where the light will shine (Bazell, 2009). The second approach we felt would work well with our project would be to change the light intensity of the lamps being used. In doing this we would have to pay close attention so the height of our poles corresponds with the light intensity. If the light is too intense and it is overlapping then we could lower the wattage or use a filter, which will cause the light to be dimmer. And our last solution is to change the lamp to LED lamps for a better quality of light (Black, 2009). Utilizing these three solutions is very realistic and will decrease sky glow, light trespass, and glare as a whole. When analyzing these three solutions it was evident that by decreasing light pollution, energy efficiency would be increased which are the objectives of the project in Boston. If light pollution is decreased and light is directed properly, the streets will be well lit for drivers and pedestrians, which will improve and uphold the standards of public safety. Also, if these new technologies are implemented the maintenance required for the street lights will be significantly reduced, along with the costs.

3.0 Methodology

Street lights are an essential part of daily life for drivers and pedestrians. However, their installation and maintenance has become very expensive for metropolitan areas. As the demand for energy grows, the cost of lighting the streets becomes more expensive for cities worldwide. In addition to that, as cities expand, their streets become illuminated, emitting pollution into the ecosystem. Light pollution has become a growing concern worldwide.

Boston is currently looking to address these looming problems. At this time, the City does not have an energy efficient street lighting system. The lamps and fixtures in place are inefficient in energy consumption and require frequent maintenance. This incurs immense costs for the City. In addition to this, the current street lights are emitting a great deal of pollution into the atmosphere. Our project assesses the current energy consumption of the street lights in the City of Boston and suggests alternative technologies for reducing the costs of powering and maintaining the street lights.

Our project goal was to set priorities for the City of Boston for increasing energy efficiency and reducing maintenance costs for the current street lighting system. From this we identified the following objectives:

- Assessing cost saving methods and technologies for the City of Boston pertaining to:
    a. Increase energy efficiency
    b. Decrease light pollution
    c. Decrease maintenance cost

To obtain the data necessary to reach our goal we used three research methods: fieldwork, public surveying and existing data research. Our team used fieldwork to obtain details about the structure, function and operations of the current city street lights. We surveyed the public to determine a level of light that is satisfactory to pedestrians without over-lighting the streets. We researched existing data in regards to street lighting to determine all the available alternatives for lighting city streets. This gave us a large scope of what methods and technologies have already been tested in this field and which were the most successful. The following chapter will discuss in detail how these methods were used to attain each of the project objectives.

3.1 Analyze Cost Saving Methods

Part of our objective was to determine cost saving methods and technologies for the City of Boston to implement into the current lighting system. We analyzed the current lighting system to find which street lights were the most inefficient in energy consumption. We then made recommendation for replacement of the most inefficient lights with newer, more energy efficient technologies. We focused our analysis on three categories; energy efficiency, light pollution and maintenance.

3.1.1 Increasing Energy Efficiency

One of the primary goals of this objective was to find ways in which the City of Boston could increase the energy efficiency of the street lights. In order to attain this goal, we first evaluated the current level of energy consumption by the city street lights. We did this by interviewing the head of the City Street Lighting Division, and gathering data such as the number of fixtures in place, the types of lamps used in each fixture, the number of watts (W) used by each lamp type, the number of annual operation hours per each fixture, the number of annual kilowatt hours (kWh) consumed by each lamp type and the cost per kWh. Obtaining this data allowed us to determine how much energy is consumed annually by the street lights and how much it costs the City. We used this data as a baseline to measure the increase in energy efficiency and the decrease in total energy cost when implementing energy efficient technologies as well as other cost saving methods.

After all the information regarding current energy consumption and cost had been collected, we researched alternative technologies as recommendations for replacement of the most inefficient and wasteful lights in the city. There was a great deal of existing data pertaining to various energy efficient technologies available to us. Numerous cities have implemented green technologies in an effort to reduce energy costs and made their reports available to the public. This data was easily accessible, previously tested and the best way in which we were able to explore alternative technologies for Boston's street lights.

To get more specific data regarding the new, energy efficient technologies we contacted several manufacturers. Through them we were able to obtain detailed reports that included specifications, measures and costs which allowed us to better evaluate these technologies.

Once all the data for alternative technologies was gathered, we were able to analyze the data and evaluate each device by its ability to use energy more efficiently, provide a sufficient amount of light and reduce the overall cost of operation. Each device was compared to one another (and to Boston's current street lights) to gauge their overall performance and cost savings. These comparisons were also validated by Return on Investment (ROI) calculations. Factoring in installation costs, energy costs and maintenance costs, we calculated how many years it would take to regain the initial investment in each of the new technologies and begin saving money. The technologies with the best overall performance and a ROI within 10 years were proposed to the City of Boston as alternatives to the most inefficient lights that are currently in place.

We also examined over-lighting. Over-lighting is usually caused by street lights that are too close together, causing over lapping light. The most effective way we were able to measure this was by conducting research through field work. Currently, there is a GIS map that shows the locations of all the street lights in the city. This map helped us to examine where street lights are too close together and where there are too many on a particular street. These are areas that are most likely to be over-lit. To be certain, we explored some of these streets and measured the light being emitted from the fixtures with a light intensity meter. This is discussed in more detail in section 4.1.2.3 Finding Over-Lit Areas.

Field work and existing data research are the most effective ways in which our group was able to make recommendations for increasing energy efficiency in Boston's street lights. These methods allowed us to evaluate the amount of energy currently being consumed by the city street lights, how much this is costing the City, and what energy efficient technologies have already been implemented in other parts of the world and how various alternatives compare to one another. As a result, we were able to determine the most suitable lighting alternatives for the City of Boston that will not only increase energy efficiency, but decrease energy waste, such as light pollution as well.

3.1.2 Decreasing Light Pollution

A third part of our objective was to methods and technologies that would decrease light pollution. Light pollution is an inefficient use of energy because it has no benefit to people, making it a wasted cost for energy. By decreasing light pollution we reduced energy costs. There are two different methods we used to complete this objective of decreasing light pollution. First we measured the current light pollution emitted from Boston city streetlights through fieldwork. Also, we researched existing data on decreasing light pollution.

3.1.2.1 Fieldwork

There were two main aspects of measuring the current light pollution in the City of Boston. One was what disturbances light pollution was causing and how we could fix it. Another is what shields we should put on the lights in order to prevent light pollution and wasted energy.

Some disturbances that were caused by the light pollution were sky glow and over lit areas. To classify these different situations we used fieldwork.

3.1.2.2 Sky Glow

We measured the problem of sky glow by figuring out what type of fixture is being used and how much light is emitted upwards from that type of fixture. Also, we figured out which fixtures in the City of Boston already have a plan for the implementation of cut-off fixtures and which fixtures do not. We found out through the street lights division of Boston that the cobra head street light fixture is the only fixture without a plan for a cut-off. We were given a datasheet with all the fixtures that shows us how many cobra head fixtures are in Boston; as well as the lamp type, wattage, and operation cost. We also found that 30% of the light emitted by a cobra head fixture is emitted upwards. Solutions to the problem of sky glow are to use cut-offs, or fully shielded lights, that allow us to direct the light downward or to where it is specifically needed. These cutoffs will also decrease wasted energy caused by street lights.

Figure 8: Unshielded and Shielded Cobra Head Fixture

Figure 8: Unshielded and Shielded Cobra Head Fixture

Figure 8 shows an unshielded cobra head fixture (on the left) and a fully cut-off cobra head fixture (on the right). The unshielded cobra head fixture emits 30% of its light upwards but with the cut-off it emits 0% upwards.

3.1.2.3 Finding Over-Lit Areas

We measured the problem of light trespass by using a Reliability Direct AR823 Light Meter (specifications can be seen in Appendix A) a GIS map and intercept surveys. To create the GIS map we used fieldwork to measure light levels. For residential and commercial streets we are measuring the light directly under the fixture, then five feet away, then ten feet away, and finally fifteen feet away, this can be seen in Figure 9Figure 9: Street Light lux Measuring Method

When we finished, we worked with the MIS department and implemented the data we collected into a GIS map and we were able to see where the light was overlapping and where it is under lit. A representation of the GIS map can be seen in Figure 10Figure 10: Representation of GIS Results

3.1.2.4 Intercept Surveys

To analyze the public's opinions on comfort in relation to the amount of light emitted by the street lights, we used intercept surveys. An intercept survey is where random people are approached and interviewed on the spot. During our stay in Boston we conducted the survey for 4 weeks in which we acquired 166 surveys. We went to Charlestown and interviewed individuals in groups of 2 at various times of nights to evaluate the pedestrian's perception of safety in an area lit only by artificial light. We set up interview points by streets we chose in Charlestown, mainly conducting the survey on these streets and on the streets traveled on to reach the next interviewing point. We interviewed pedestrians one at a time and asked them questions that are ranked on a scale from 1 to 5. The 5 question survey asked for the pedestrian's opinions on visibility on the street, if the light on the street is dispersed evenly, if the light emitted by the street light is too bright, how comfortable they feel walking in the current amount of light, and then how comfortable they feel walking down the same street in the opposite time of day. We made notes on the gender of the person, the street light fixture(s) that are near the point of interview and the street as well, just for comparative purposes. The survey can be found in Appendix A.

After an interview was conducted, we placed the light intensity meter on the ground and measured the illuminance. The reason we took light measurements is because we wanted to have the amount of light that was affecting the interviewee at the time of the survey. This was so we would be able to relate to the public's perceptions of comfort to illuminance.

3.1.2.5 Integrating the Data

At the end of our 4 week span of interviewing, we compiled our data into an excel spreadsheet. It had a column for the time at which the survey was taken, the illuminance during the survey, a column for each of the questions, the gender of the interviewee, the fixture type the interview was taken closest to, and the street that the interview was conducted on, refer to Intercept Survey Results in Appendix B. Once all the surveys were acquired and their information inputted into the spreadsheet, we made a scatter plot that compared the illuminance to the scale used for the survey. The plot was used to find what light level the public favors. The level found was used to create highlighted areas on the GIS map which determined which areas were over-lit.

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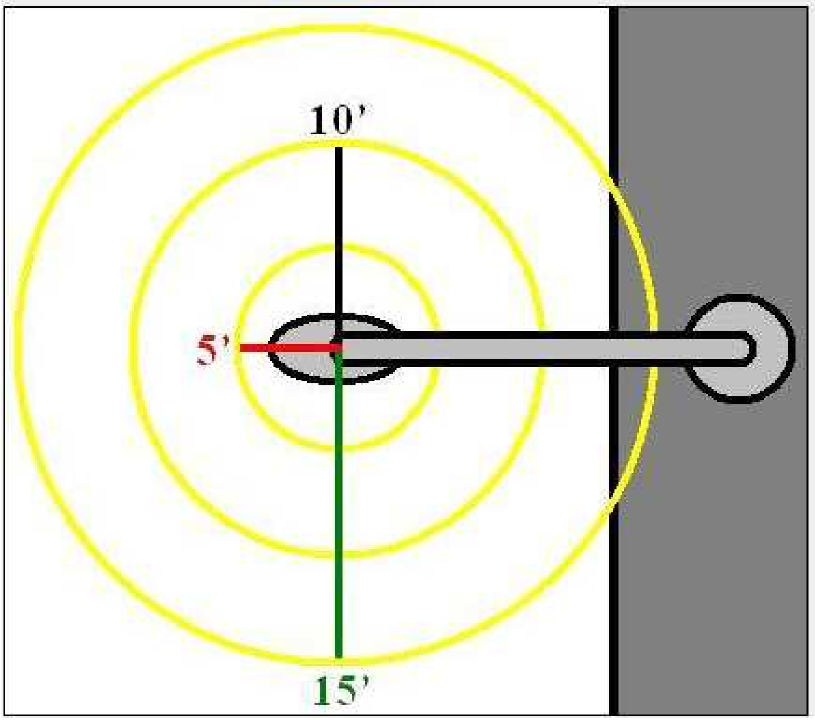
, and for highways and industrial streets we are measuring the light directly under the fixture, then ten feet away, then twenty feet away, then thirty feet away. All of these readings will be done in lux, and the light intensity meter will be placed on the ground at these different locations in order to keep the data consistent.



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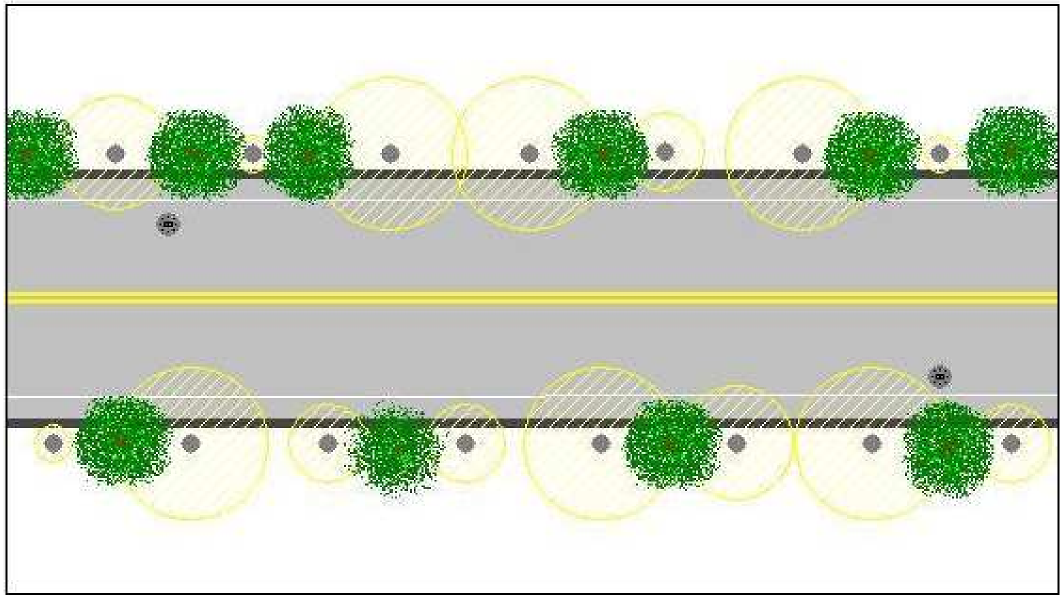

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3.1.2.6 Research Existing Data

For this approach we are researching existing cases that have dealt with examining different aspects of light pollution and how they dealt with the problem. We are also researching statistical data regarding cut-offs, or light shields, effectiveness in directing light. This approach is helping us come up with solutions to the problems we find through our fieldwork. Some cases that we are analyzing are a case on Salt Lake City, a case on New York, and a case on

> Ontario, Canada specifically on how they went about changing their street light systems. These cases are helping us because they are all different, but are all trying to accomplish the same goal of decreasing light pollution. This is keeping us creative and allowing us to come up with different ideas to achieve this objective.

Once again we used intercept surveys, and field work to determine the public's opinions on comfort and light levels in Charlestown, a district of the City of Boston. Once all our surveys were conducted, we analyzed scatter plots to find a correlation between light levels and comfort and to identify any outliers. This allowed us to find what types of fixtures produced too much light, thus finding which fixtures wasted light.

3.1.3 Decreasing Maintenance Costs

The next portion of our project was to suggest several methods and technologies that decrease the current maintenance costs for the City of Boston. To do this we compared existing maintenance costs to the savings created by implementing greener technology. By illustrating these benefits, Boston can select several technologies that require less maintenance and decrease costs for the city.

To recommend several methods and technologies to reduce maintenance and preservation costs the team analyzed the current costs of repairs, replacements, installations, and labor of the city street lights. We reviewed documents obtained from the Environment Department that showed the current maintenance funding. This data allowed our team to analyze specific areas of maintenance costs.

Our team also researched inventory of current fixtures and lamps through the Street Lighting Division of the City of Boston. The reason for this was to determine which technologies the maintenance budget is being invested in. Our team was able to find information regarding the current fixtures in place, the costs to replace each fixture, and the maintenance costs for each type of fixture. This information was used to determine which fixtures require less maintenance, creating evidence to support the recommendations made for reducing maintenance costs. By taking the number of each type of lamp replaced annually, and multiplying by the average costs of replacing each type we obtained the annual costs for replacement. We then took the average lifespan of each type of lamp and calculated how many lamps were needed to be replaced over a set amount of time. We then calculated this same information for newer technologies with longer lifetimes to illustrate the reduction in maintenance costs over several years.

Our team also followed the maintenance crew to get an understanding of how the repairs are done. This gave our team a sense of the general operations and an overall picture of the required methods for maintaining the street lights. Figure 11 shows the number and type of repairs made by the maintenance crew since October, 2008.

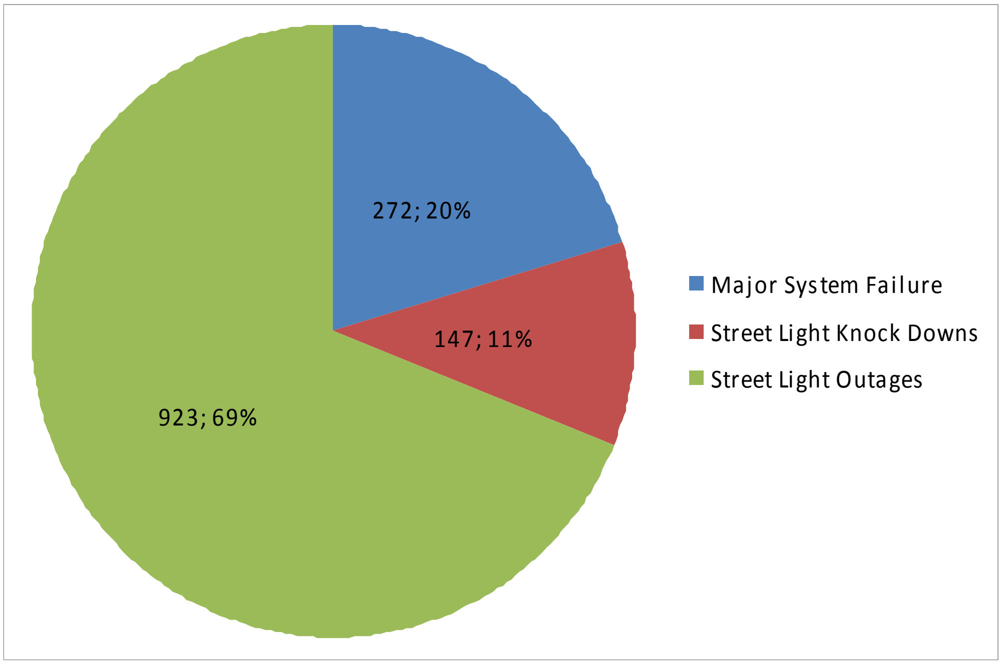


Figure 11: Percentages of Types of Street Light Repairs

Our team researched information regarding maintenance budgeting through the Office of Budget Management in the City of Boston. We examined the budget planning over the past several years. These reports allowed our team to construct a cost benefit analysis, along with a return on investment report that included the installation costs and maintenance fees. The analysis also showed the payback period for implementing easily maintainable technologies.

Our team also examined several specifications for current lamps and new technology. We examined the cost of each lamp, as well as the average lifespan. We were able to compare the lamps in place to the newer lamps, and determined the annual maintenance savings. In order to include all of the money being saved, our team also researched the cost of proper disposal for older lamps, such as mercury vapor. With newer technologies, there are no disposal costs so savings are evident. One important part of our analysis was examining the installation costs for the new technology. This was necessary to determine the exact amount of time Boston would have a return on the initial investment.

Research was the most suitable method for this objective because of the amount of available information. Data that has been developed by specialists was available to our team and was able to address several questions that arose during our project. Our research provided evidence to demonstrate which fixtures are easily maintainable. It also proposed several solutions to reduce maintenance costs. By examining previous data our team was able to see what areas Boston can reduce maintenance costs and effectively reduce the overall costs for city's street lighting system.

Overall, acquiring necessary evidence that helped our team reach this objective and our project goal required large amounts of research. As mentioned in the previous paragraph, there is an abundance of information relating to our topic. Applying energy plans utilized in other cities can produce the same positive results for Boston. Most importantly, the comparison of current street lights emphasized which current lamps and fixtures require the most annual maintenance. We were then able to see the annual savings generated by implementing newer, easily maintainable technologies. Completing this objective allowed our team to begin setting priorities for upgrading the current street lighting system in the City of Boston.

3.2 Methodology Synthesis

In conclusion, our project objective was completed by researching existing data. Fieldwork allowed our team to examine the current problems, but ultimately research directed us to solutions with the highest savings and fastest payback periods. Examining several tradeoffs of each alternative allowed us to see which technologies had the most to offer. Also, when considering maintenance for installation we examined which technologies provided the best return on investment. The main question we asked to provide reliable suggestions was; “will Boston benefit?” and the way we answered that question was looking at how other cities have dealt with similar problems in the past and what their solutions were. We were then able to analyze which solutions worked out and which solutions failed for each unique situation. Through this research we also determined why one solution failed and why another solution did work and recommended several technologies and methods for the city to decrease energy and maintenance costs.

4.0 Findings

This section will focus on the completion of our methodology. In information contained here will then be used to create our results section which will be a Return on Investment (ROI) focusing on Boston's top priority streets and efficient technologies.

4.1 Findings from Intercept Surveys

To obtain a level of light which we consider to be either under-lit or over-lit, we had to decide what level of light is suitable for pedestrian comfort. As we mentioned before, to accomplish this, we used intercept surveys, asking pedestrians how they felt in the measured level of illuminance. We compiled all our surveys into an excel spreadsheet and created a graph which can be seen in Figure 12Figure 12: Intercept Survey Graph

. The graph compares the illuminance on the x-axis to the comfort score, which is what the pedestrian gave us when using our survey's number scale of 1 to 5, 1 being lowest, and 5 being highest, on the y-axis.

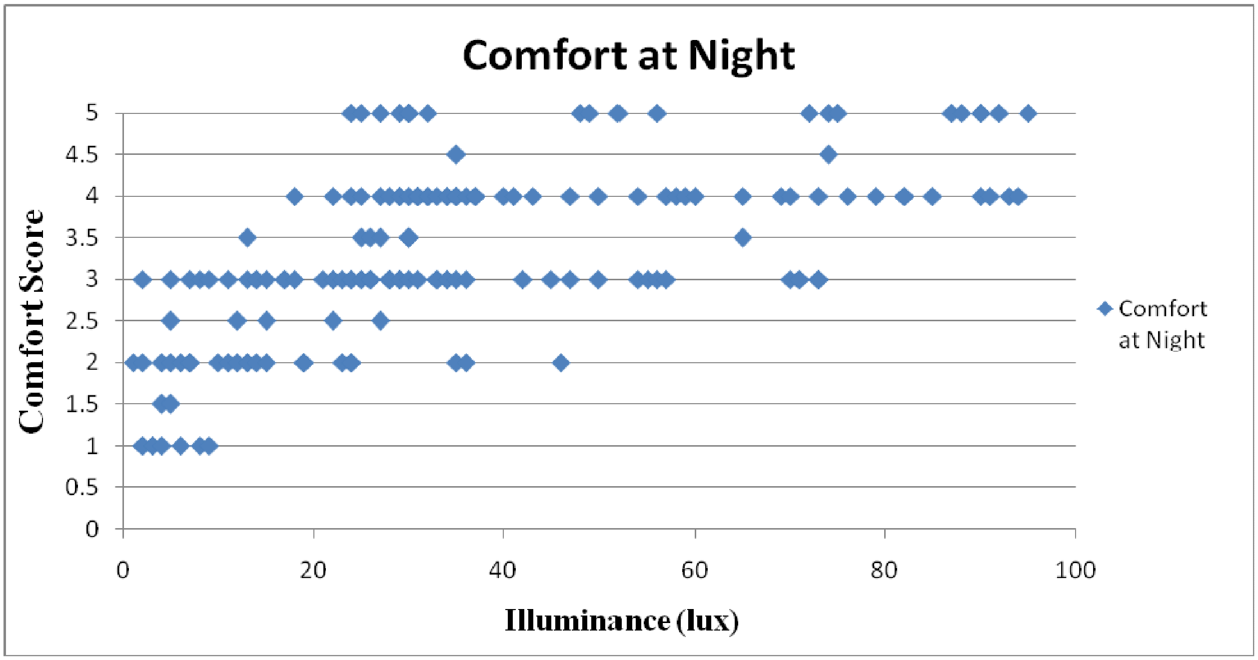


Figure 12: Intercept Survey Graph

Before viewing our graph for any type of correlation, we analyzed the mean, median and mode of all the data, the outcomes can be seen in Figure 13. Using these methods of analysis, we found that of all the 166 intercept surveys there was a mean comfort level at night of 3.3 which means that it is just over the medreately comfortable level from the survey. Also, for visibility, evenness and brightness, which are also important in street lighting, they averaged out at a little more that moderate as well. The mode and the median for all three catigories were 3s and one 4 for the mode of brightness. The average measured light value was 34.09 lux, but the median and mode was 29 lux. This means that at some point more light did not mean a higher comfort level.

	Mean	Mode	Median
Measured Light Value	35.77	24	30
Comfort Night	3.307228916	3	3
Visibility	3.548192771	3	3.5
Evenness	3.542168675	3	3
Brightness	3.289156627	4	4

Figure 13: Complete Survey Data Analysis

We then sectioned off a portion of the graph to see if we could find a where the illuminance and the scale fall closely to the mean, median and modes, thus finding the amount of light that will be a reasonable level of light. We used 30 lux as a center point because it was the median of the Measured Light Value and went out 10 lux in the positive and negative directions, thus our range was 20 lux to 40 lux; the area can be seen in Figure 14**Error! Reference source not found.**. As you can see there are many data points in this area, to be accutate, our of the 166 data entries, this 20 lux area accounted for 60 data entries, 36% of the total data collected. Also there is a decent range for the comfort score with a minimum of 2, and max of 5 with a good concentration of 3s and 4s. This means that in this block of data, many pedestrians felt more than moderately safe.

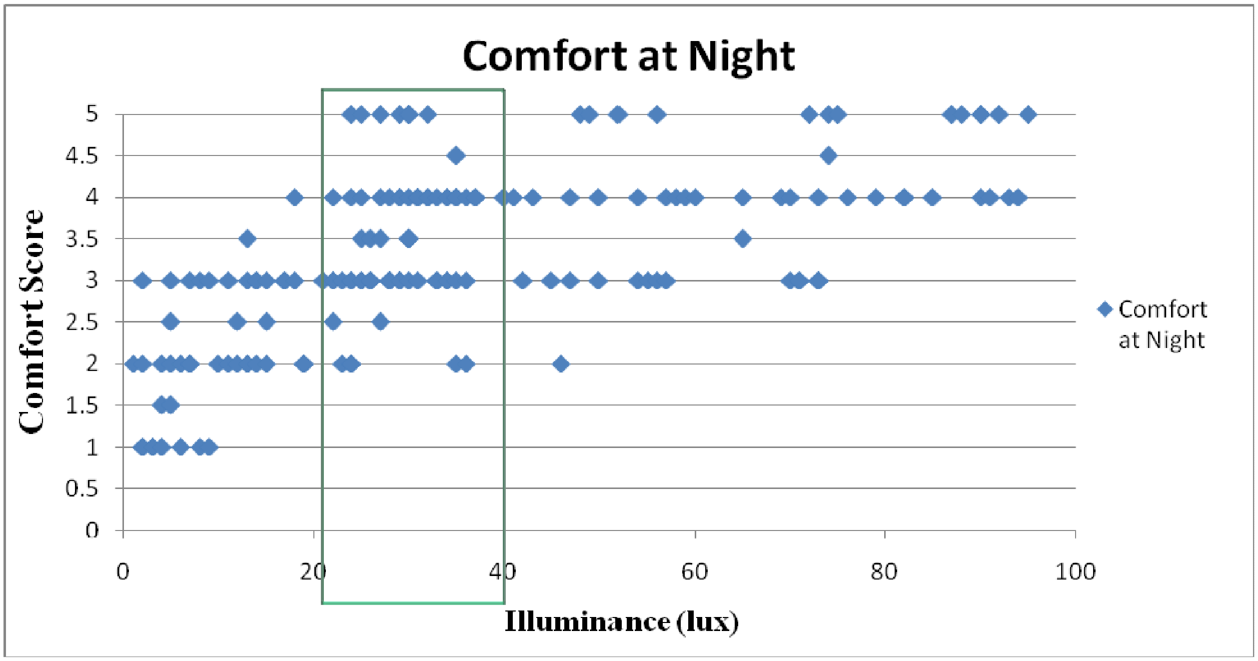


Figure 14: Intercept Survey Graph, Sectioned Area

To look at this section of data closer, once again we performed the standard mathamatical analysises of mean, median, and mode. As you can see in Figure 15, the mean numbers are now a lot closer to the median number.

	Mean	Mode	Median
Measured Light Value	29.38028169	24	29
Comfort Night	3.521126761	3	3.5
Visibility	3.61971831	3	4
Evenness	3.718309859	3	4
Brightness	3.450704225	4	4

Figure 15: Data Analysis Between 20 and 40 lux

This confirmed that an illuminance of 29 lux allows for a person to feel as comfortable at night as they would during the day. This number was then considered to be "good" lighting which was what we were trying to determine. We used this level to find what is considered to be an over-lit area.

4.2 Setting Priority Areas

4.2.1 Light Levels and GIS Map

As mentioned before, Boston is using an average maintain to properly light a street. Although they use this, there are still areas of the city that are under lit. The average maintain is 1.6 Foot Candles, which is 17.22 lux, and for certain streets it can go up to 2 Foot Candles, which is 21.53 lux (1 fc = 10.764 lux) and the Boston standard is that the level should never exceed a 4 to 1 ratio. To find the ratio used in Boston we used the equation:

$$\frac{x + 4x}{2} = Average\ lux$$

The Average lux is the 17.22 lux. The range for Boston is 6.89 lux to 27.56 lux. Using the GIS program, we used our minimum and maximum levels. These levels are what we decided to be where it is over-lit, and where it is under lit. For the minimum and maximum we used an illuminance of 4 lux and 31 lux, respectively. We chose these numbers because when researching how they measure an average maintain, we noticed that it did not match up with the method we used, they measured at 1 meter above ground level; we measured directly at ground level. Also, with our findings in the previous section, we want 29 lux to be considered proper lighting. Because of this we adjusted the minimum and maximum numbers so that they fall within the highest uniformity ratio used anywhere which is 8. Although the uniformity ratio is 7.75, it only applies for the minimum and maximum light levels we measured. The areas will not have the maximum and minimum, therefore they will fall in the uniformity ratio range. The GIS map of Charlestown with a minimum and maximum level can be seen in Figure 16. The lux levels higher and lower than 17.22 lux are shaded in red and blue color gradients, respectively.

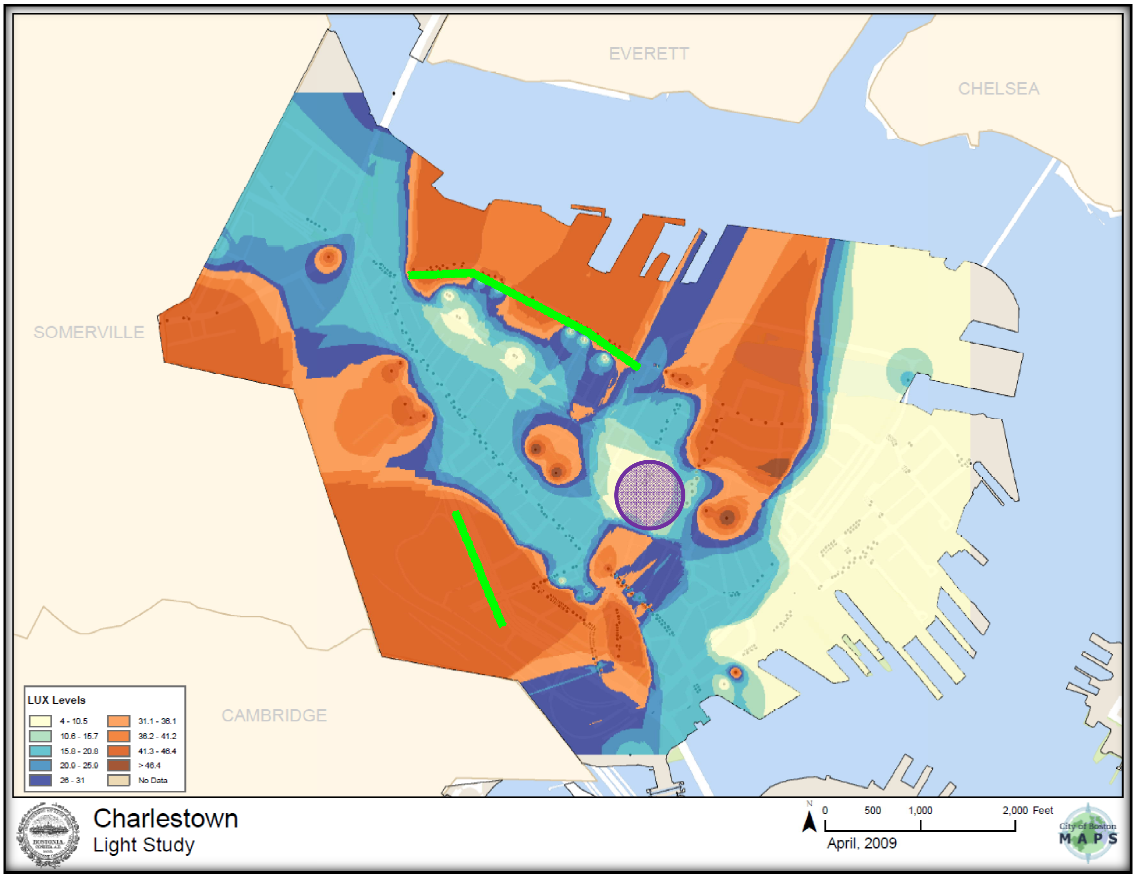


Figure 16: Charlestown GIS Street Light Gradient Map

We worked with the Management Information Systems Department in the City of Boston to develop this GIS map. The department used the data that we collected from the light survey and created the gradients using the equipment codes we provided. The whole process was recorded in detail by one of the GIS experts and can be seen along with the light survey results in Appendix A. Please notice that the light levels that were placed on the graph were also spread to areas without street lights, this is because we used raster data for the graph. The purpose of this map was to demonstrate that it is possible to locate over-lit and under-lit areas using light levels. The graph shows these areas and we used these areas to set as priorities for implementing our methods of cost savings.

4.2.1.1 Over-Lit Areas

From this map the following streets are over-lit: Medford Street and Rutherford Avenue which are marked with green lines.

Medford Street and Rutherford Avenue are both made up of mostly 250 Watt high pressure sodium lamps and 400 Watt high pressure sodium cobra head fixtures. There are also 400 Watt high pressure sodium box fixtures at one end of Rutherford Avenue mostly because it is becomes an urban road and is no longer a highway. The 400 Watt fixtures are the reason these streets are in red. They produce a high number of lumens and since the cobras are not full-cutoffs, the light gets spread outwards and the light overlaps.

4.2.1.2 Under-Lit Areas

From this map the following streets are under-lit: The Bartlett Street, Cross Street, Green Street and Trenton Street neighborhood marked with the shaded purple circle.

This neighborhood contains mostly 175 Watt mercury vapor box and lollipop fixtures, and 250 Watt mercury vapor box fixtures. There are also a few gas lamps that are scattered around. The lights on these streets are also spread relatively far apart. Although that means no light overlaps, it also means that there are not enough lights on the street to properly illuminate it. The light in this neighborhood is being directed completely downward with the box fixtures, or most of the light is being wasted due to lack of a cutoff as it is with the lollipop. This created unevenness on the street, thus it is poorly lit.

4.2.2 Priority Lamps through Maintenance

The project objectives were established to set priorities for increasing energy efficiency and reducing maintenance costs for the City of Boston's street lighting system. After completing our objectives, our team was able to collect data and compile it into our following findings. The team was able to prioritize the replacement of certain lamps and fixtures based on operational and maintenance costs. Also, our research allowed our team to construct a cost analysis for implementing several newer technologies in the City of Boston.

4.2.2.1 Priority Areas for Replacement

The main concern with the current lamps in place is the lifespan. By increasing the lifespan of lamps Boston can reduce the required number of lamp replacements. There are four types of lamps throughout the city: mercury vapor (MV), high pressure sodium (HPS), metal halide (MH), and incandescent (IN)

(Street Lighting Division, 2009). The lifespan for these lamps are 9,000-15,000 hours, 16,000-24,000 hours 15,000-20,000 hours, and 5,000-8,000 hours, respectively (U.S. Department of Energy, 2009). Boston considers annual operating time for street lights to be 4200 burning hours (Street Lighting Division, 2009). Our team took the average lifespan for each lamp and converted the hours into usage years to estimate the amount of time in between replacement of lamps. We found that MV last for 2.86 years, HPS for 4.76 years, MH for 4.17 years, and IN for 1.55 years.

Our team also wanted to consider the cost for the current lamps in place. Combining the costs for the lamps with the lifespan would determine which lamps create the highest replacement expenses for the city. We found that MV cost $3.75, HPS cost $9.19, MH cost $8.55, and IN cost $15.37 (Street Lighting Division, 2009).

Because incandescent lamps have the shortest lifespan and the highest lamp price our team determined that these lamps should be the first to be replaced with newer technology. However, incandescent lamps only make up 384 lights, less than one percent (Street Lighting Division, 2009). Only replacing incandescent lamps would not create significant savings for Boston. Although mercury vapor are the cheapest lamps, they have the second shortest lifespan and have a high disposal costs for the city. The city spends $.85 on proper disposal of each mercury vapor lamp (Boston about Results, 2009).

Our team has found that making the replacement of mercury vapor and incandescent lamps a priority for the City of Boston will create immediate savings for the city. As you can see from Figure 17 Boston's second most used lamp is the mercury vapor lamp but it has the second shortest lifetime out of all the lamps used. By switching them out, Boston will be able to eliminate the disposal costs for mercury vapor by implementing technology that can be used longer than 3 years.

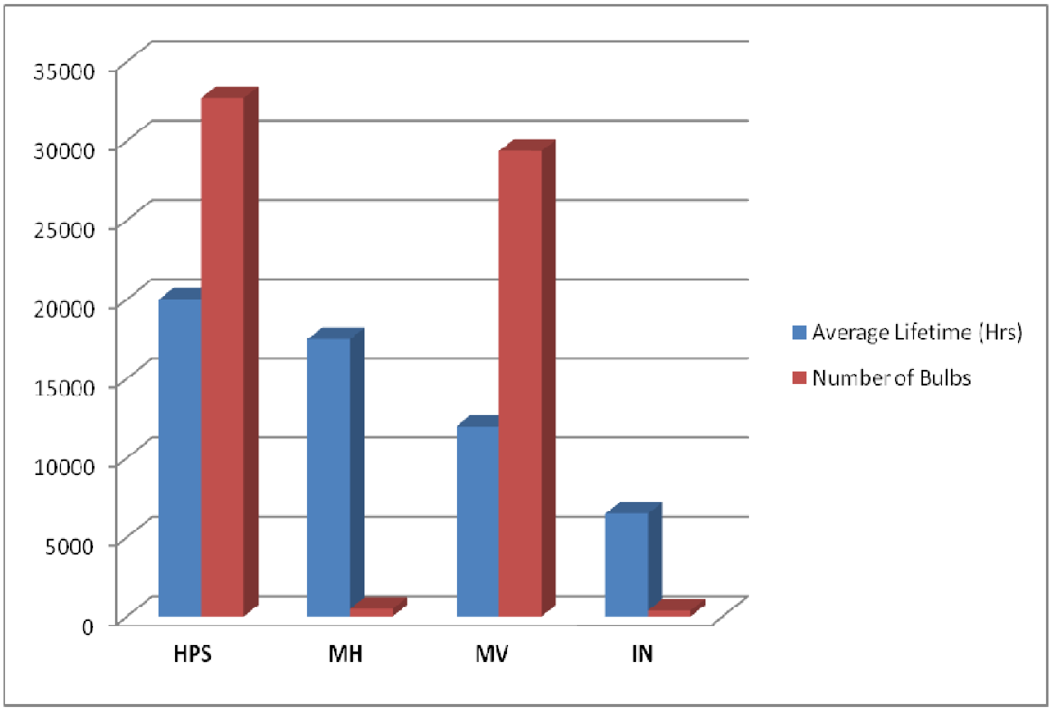


Figure 17: Lamp Comparison

The total number of mercury vapor lights in the City of Boston is 28,639 (Street Light Division, 2009). By removing the mercury vapor lights from Boston and installing LED lamps, we found that Boston can save up to $235.00 over the lifetime of one LED lamp. This is approximately $18.00 a year solely on maintenance costs. Applying this savings to all of the mercury vapor lamps can reduce Boston's maintenance costs by $500,000. Figure 18 illustrates the high replacement and maintenance costs for the current lamps in place compared to the newer LED lamps.

	MV	**MH**	**HPS**	**LED**
Cost per Bulb	$3.75	$8.55	$9.19	$15.98
Average Lifetime (Hrs)	9,000-15,000	15,000-20,000	16,000-24,000	50,00-60,000
Usage Time (Yrs)	2.86	4.17	4.76	13.1
Maintenance Costs for Lifetime of LED	$309.10	$199.52	$201.44	$73.37

Figure 18: Lamp Replacement Cost

It is clear that mercury vapor lamps and fixtures create the highest maintenance costs for the city of Boston. They make up approximately 50% of the street lights in place, and have the shortest lifespan, requiring frequent replacements. In addition to high maintenance, excessive disposal costs are created to properly dispose of the mercury vapor lamps. Our project team found that replacing the mercury vapor lamps will generate the highest savings and also have the quickest payback. Because mercury vapor lamps create high maintenance expenses, our team concluded that the replacement of these lamps with newer technology is a priority for the city of Boston pertaining to reducing maintenance costs.

4.3 Cost Savings Analysis

4.3.1 Every Other Light

One approach for cost savings is to just turn off the lights for a select amount of time. This idea seems extreme but it can be done with some restrictions. We can shut off every-other light on major thoroughfares, such as highways, after a certain amount of time, this idea was mentioned earlier in our background with the town in Germany.

The cost for a light is based on how many hours a year each lamp is on and on what type of lamp is used. Boston estimates that the street lights run for 4,200 hours a year which breaks down to 11.5 hours average per day. Our first assumption was that the lights would run from 7 PM to 6:30 AM every day. Our second assumption was that the lights would shut off at 3 AM, which would be an average of 8 running hours each day; this translates to 2,920 hours per year. We calculated the operational cost ($\mathrm{OC_X}$) per fixture per year with the following equation:

$$\mathrm{OC_X} = kW * h * C$$

$\mathrm{OC_X}$ is the operational cost. kW is the fixtures standard in kW hours. h is the amount of hours the fixture runs per year. C is the cost of kWh per year which is set by NSTAR and is \$0.13137/kWh.

We calculated the normal operational cost ($\mathrm{OC_N}$) by using 4,200 running hours per year. The operational cost for turning off the light after 3 AM ($\mathrm{OC_E}$) was calculated by using 2,920 hours a year. When we divided the every other light annual cost by the normal annual cost ($1 - \mathrm{OC_E}/\mathrm{OC_N}$), we found that this save 31% average per light per year, but this only the percentage of savings if all lights had the shortened running time.

We tested the method of turning every other light off on a street that was found to be over-lit through using the GIS map. We chose Rutherford Avenue which is a highway in Charlestown. Our third assumption to calculate savings is that only cobras and wall mount lights, of different lamp wattage, are located on the highways and would be affected by the every other light analysis. The analysis can be seen in Figure 19.

Fixture	**Watt**	**Number of Fixtures**	**Normal kWh**	**Every Other kWh**	**Normal Cost:**	**Every Other Light Cost:**	**Savings**
Double Cobra	250	18	2478	1723	$ 5,859.63	$ 2,058.44	$ 3,801.19
Cobra	250	97	1239	861	$ 15,788.44	$ 13,380.03	$ 2,408.41
Cobra	400	38	1953	1358	$ 9,749.49	$ 8,263.86	$ 1,485.64
Wall Mount	250	117	1239	861	$ 19,043.79	$ 16,138.80	$ 2,904.98
Total:					$ 50,441.35	$ 39,841.13	**$ 10,600.22**

Figure 19: Rutherford Avenue, Every Other Light Off After 3 AM

The normal cost was calculated by multiplying the normal operational cost (OC_N) by the number of fixtures (N). The every other light cost was calculated using the following equation:

$$\left(\frac{N}{2}\right) * OC_N + \left(\frac{N}{2}\right) * OC_E$$

This equation is derived from the assumption that exactly half of the lights would be turned off at 3 AM. When adding up the total savings for the four different types of fixtures used on Rutherford Avenue, there would be a savings of 10,600.22 per year. This translates to a 21% savings per year per street. Not only will it save money for the city, but it will solve the problem of the street being over-lit.

4.3.1.1 Tradeoffs for Every Other Light

The 21% energy savings would be almost automatic once implemented because there is no installation cost for lamp or cut-off, the lights just need to be programmed in the main control box on the street to be turned off. But, this cannot be used everywhere. If every other street light were to shut off everywhere it would decrease the visibility and evenness of the street for pedestrians, which is what we do not want. Residential areas have a higher chance of someone walking around a neighborhood at night, or having a car parked over night. Also, in the past, residents have complained about which lights on a street have been turned off. Thus it would be better to implement on highways since they are mainly car only roads. Also after 3 AM traffic flow is decreased and the vehicles headlights are sufficient for visibility. Also, it is difficult to determine how much money is actually saved with this method because it's hard to locate where and how many fixtures there are for the streets affected.

4.3.2 Use of a Cut-off

According to the street lights division of Boston the cobra head fixture does not have a plan for a cut-off and it emits 30% of its light upwards. For the acorn fixtures, when a lamp dies out they are they are not only putting in a new lamp but they are putting a cut-off on the fixture as well in order to save money on maintenance costs. Figure 20 below shows the total annual cost and how much money is wasted in energy each year.

	Lamp Type	Wattage	Number of Street lights	Total Annual Cost	Total Annual Wasted Energy
	Mercury	750	118	$53,387.72	$16,016.32
	Mercury	400	2,204	$559,390.28	$167,817.08
	Mercury	250	4,928	$804,830.94	$241,449.28
	Mercury	175	10,589	$1,244,927.52	$373,478.26
	HPS	400	1,425	$369,537.24	$110,861.17
	HPS	250	2,979	$484,891.83.17	$145,467.60
	HPS	150	1,712	$181,363.75	$54,409.13
Total			23,855	$3,698,321.62	$1,109,315.69

Figure 20: Wasted Energy Chart

Cut-offs allow the ability to lower the wattage but one must pay close attention to the lumen output because it shows how much light is being emitted. So it is essential to find a lamp that has a lower wattage than the lamp it is replacing and having either the same or a higher lumen output. Figure 21 below show how many lumens each of these wattages emit, compared to how many lumens are emitted downwards because 30% of the light in cobra head fixtures is emitted upwards without a cut-off, making them irrelevant.

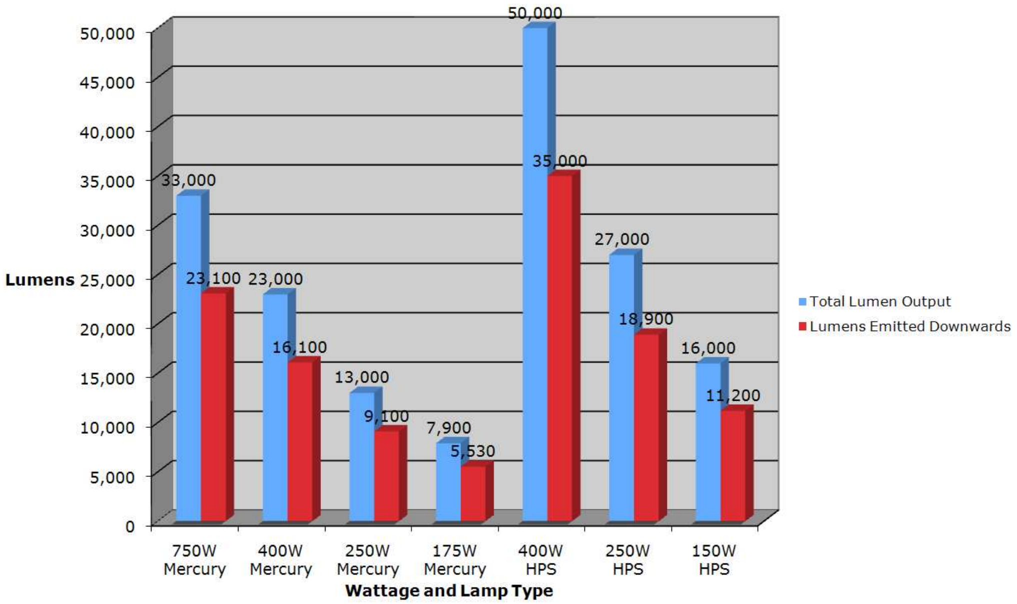


Figure 21: Total Lumens vs. Lumen Emitted Downwards

Figure 22 below shows lower wattage lamps with a cut-off that could replace higher wattage lamps with no cut-off because the downward lumen output is higher. The graph only shows downward lumens because the lumens emitted upwards are irrelevant, and it's just wasted energy. The high pressure sodium (HPS) lamps can fit into any mercury vapor fixture. The red bars show the downward lumens of the lamps already in place and the blue bars show the total lumens of a lower wattage lamp with a cut-off that could replace these lamps because of a more focused light.

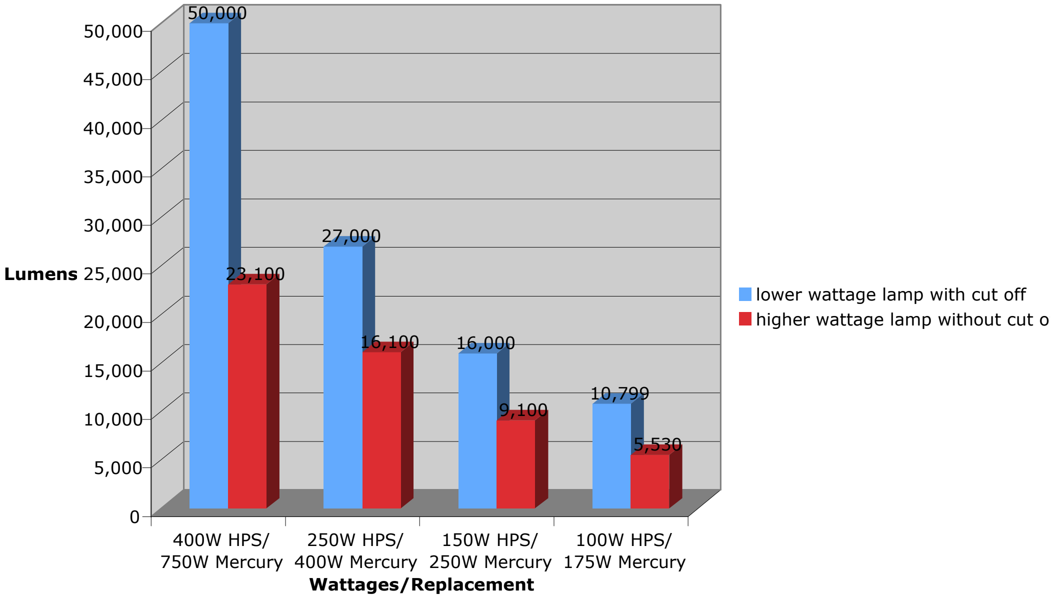


Figure 22: Lumen Output, with and Without Cut-offs

4.3.2.1 Cut-offs Payback Period

Figure 23 shows the costs associated with implementing cut-offs. The cut-off itself costs $120. The installation cost includes the price for labor, disposal cost for lamp, and the cost for the new lamp. Then it shows the annual cost of the lamp in place and the lamp it is being replaced by along with the energy savings per lamp.

	750W MV	**250W MV**	**175W MV**	**400W MV**
Cobra Cut-off Cost	$120.00	$120.00	$120.00	$120.00
New Lamp and Wattage	400W HPS	150W HPS	100W HPS	250W HPS
Installation Cost	$67.43	$67.43	$67.43	$67.43
Annual Energy Cost of Old Lamp	$452.44	$163.32	$117.52	$253.81
Annual Energy Cost of New Lamp	$259.32	$105.94	$73.94	$162.32
Energy Savings per Light	$193.12	$57.38	$43.58	$91.49

Figure 23: Energy Savings per Light with Cut-off

Below are a series of cost comparisons that compare the costs of the higher wattage lamps with no cut-offs to the lower wattage lamps with cut-offs. The bumps in the blue lines show where the lamps have burnt out and the maintenance crew had to go and put in a new lamp. There is no bump in the red lines because high pressure sodium lights have a longer lifespan. Where the lines intersect is where the city would start making money on this investment.

Figure 24 shows the return on investment for switching the 750W mercury vapor cobra head with no cut-off to a 400W high pressure sodium with a cut-off. Boston would start making money in about ¾ of a year with this investment.

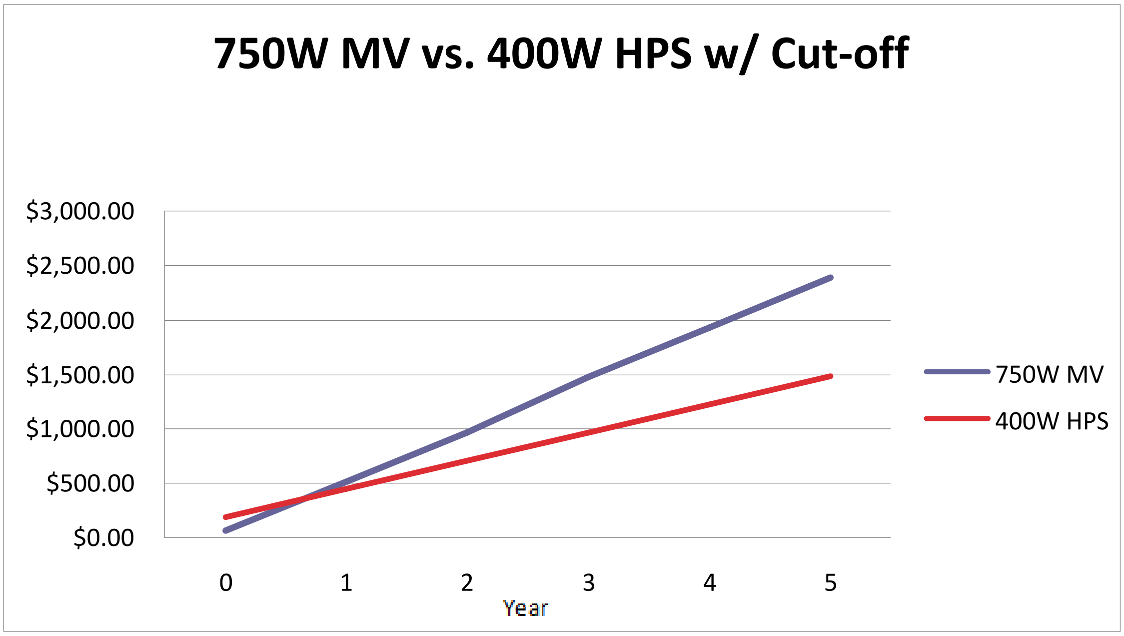


Figure 24: 750W MV vs. 400W HPS with Cut-off

Figure 25 shows the cost comparison of a 400W mercury vapor with no cut-off to a 250W high pressure sodium with a cut-off. Boston would start making money on this investment in about a year and a half.

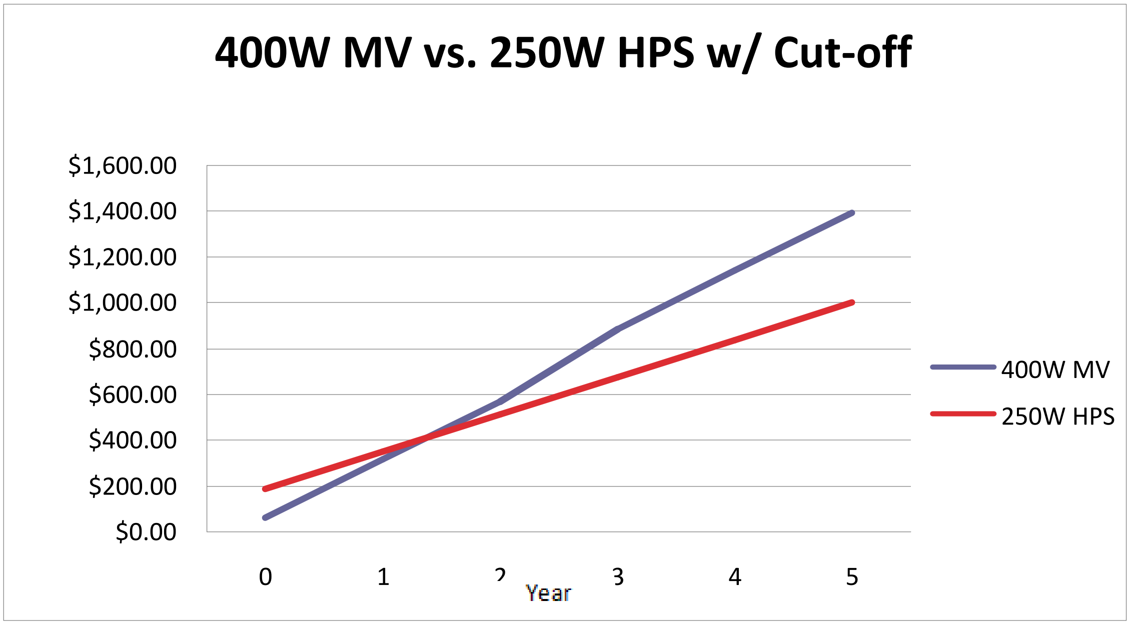


Figure 25: 400W MV vs. 250W HPS with Cut-off

Figure 26 shows a cost comparison of a 250W mercury vapor to a 150W high pressure sodium with a cut-off. This graph shows that Boston would start to make money on this investment in approximately two years.

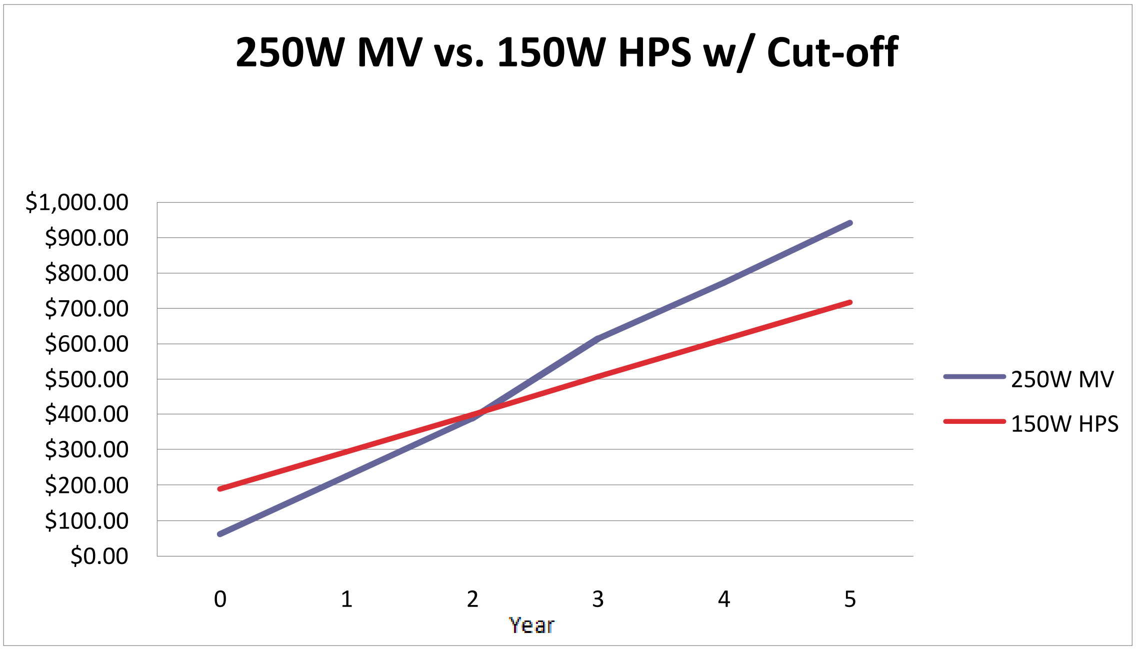


Figure 26: 250W MV vs. 150W HPS with Cut-off

Figure 27 shows a cost comparison of a 175W mercury vapor to a 100W high pressure sodium with a cut-off. This figure shows that Boston would start to make money on this investment in approximately 2 ¼ years.

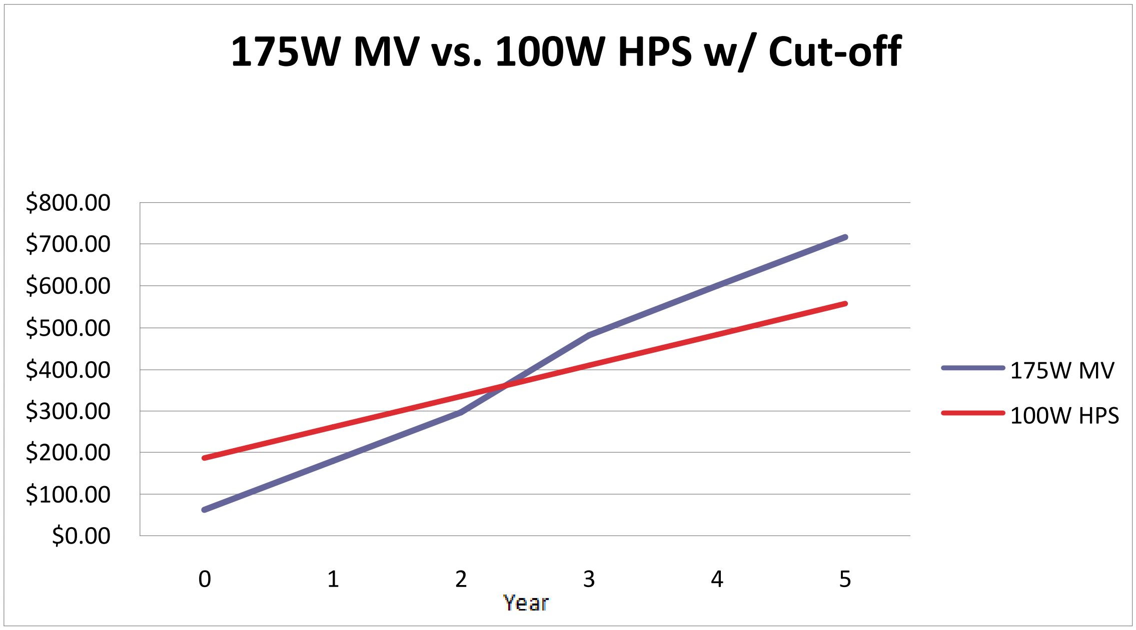


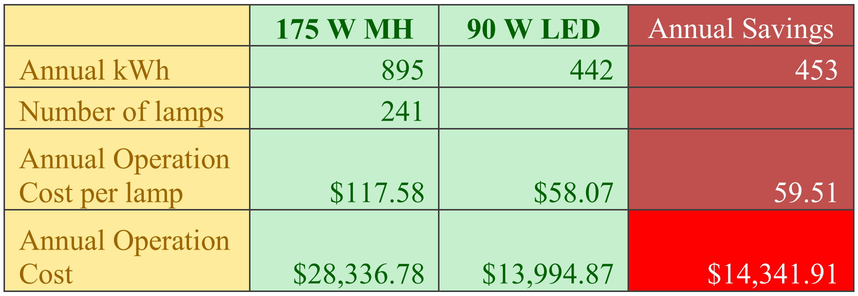
Figure 27: 175W MV vs. 100W HPS with Cut-off

4.3.2.2 Tradeoffs of Cut-off

Replacing higher wattage lamps with lower wattage lamps that have a cut-off saves more money on energy. The cut-offs also eliminate sky glow and reduce over-lighting. The cut-offs also meet the requirements for the dark sky association, which is trying to decrease light pollution. The only problem with this is that there is an initial investment, but there is a fast payback period.

4.3.3 Use of a LED

Boston city street lights use millions of kilowatts (kW) annually. At $0.13137 per kilowatt hour (kWh) this adds up to a substantial electric bill. An energy efficient technology that would be able to greatly reduce the City's energy costs is the light emitting diode (LED) lamp. There are 241 175 watt (W) metal halide (MH) lamps in the City of Boston. As each of these lights consumes 895 kWh per year, it costs $28,336.78 to power them annually. If all of the 175 W metal halide lamps were replaced with 90 watt LED lamps the energy consumption would be reduced by 49% to only 442 kWh per year per light. This would result in an annual savings of $14,341.91 for the City, refer to Figure 28.



	175 W MH	90 W LED	Annual Savings
Annual kWh	895	442	453
Number of lamps	241		
Annual Operation Cost per lamp	$117.58	$58.07	59.51
Annual Operation Cost	$28,336.78	$13,994.87	$14,341.91

Figure 28: Annual Energy Savings of Replacing a 175W MH with a 90W LED

Even more savings can be incurred if all 160 250 W metal halide lamps in the city were replaced with 120 W LED lamps. The 250 W metal halide lamps consume 1243 kWh per year, whereas the 90 W LED lamps consume 505 kWh, a 41% savings resulting in an annual savings of $15,512.00 (See Figure 29).

	250 W MH	**120 W LED**	Annual Savings
Annual kWh	1243	505	738
Number of lamps	160		
Annual Operation Cost per lamp	$163.29	$66.34	$96.95
Annual Operation Cost	$26,126.40	$10,614.40	$15,512.00

Figure 29: Annual Energy Savings of Replacing a 250W MH with a 120W LED

These savings can be nearly tripled by replacing 175 W high pressure sodium (HPS) lamps with 90 W LED lamps. Even though 175 W HPS lamps consume the same amount of energy (895 kWh) as the 175 W MV lamps, there are nearly 5 times more 175 W HPS lamps in the city. Therefore, replacing these with 90 W LED lamps would result in an annual energy savings of $44,692.01 (See Figure 30).

	175 W HPS	**90 W LED**	Annual Savings
Annual kWh	895	442	453
Number of lamps	751		
Annual Operation Cost per lamp	$117.58	$58.07	59.51
Annual Operation Cost	$88,302.58	$43,610.57	$44,692.01

Figure 30: Annual Energy Savings of Replacing a 175W HPS with a 90W LED

These savings are significant, however, they pale in comparison to the potential savings of replacing a 250 W HPS lamp with a 120 W LED lamp. There are 15,374 250W HPS lamps in the city. At 1239 kWh per year, these lights cost over $2 to operate annually. Replacing these lamps with 120 W LED lamps would result in savings of $1,482,514.82 (See Figure 31).

	250 W HPS	**120 W LED**	Annual Savings
Annual kWh	1239	505	734
Number of lamps	15,374		
Annual Operation Cost per lamp	$162.77	$66.34	$96.43
Annual Operation Cost	$2,502,425.98	$1,019,911.16	$1,482,514.82

Figure 31: Annual Energy Savings of Replacing a 250W HPS with a 120W LED

Similarly, replacing all the 175 W mercury vapor (MV) lamps in the city would result in significant energy savings. There are 15,056 175 W MV lamps in Boston and at

895 kWh they cost $1,770,284.48 to power annually. If all of the 175 W MV lamps were replaced with 90 W LED lamps, the City would save $895,982.56 per year, refer to Figure 32.

	175 W MV	90 W LED	Annual Savings
Annual kWh	895	442	453
Number of lamps	15,056		
Annual Operation Cost per lamp	$117.58	$58.07	59.51
Annual Operation Cost	$1,770,284.48	$874,301.92	$895,982.56

Figure 32: Annual Energy Savings of Replacing a 175W MV with a 90W LED

Replacing all 11,832 250 W MV lamps in the city with 120 W LED lamps would result in an annual kWh reduction of 738 kWh. This translates to a savings of $1,147,112.40 per year (See Figure 33).

	250 W MV	120 W LED	Annual Savings
Annual kWh	1243	505	738
Number of lamps	11,832		
Annual Operation Cost per lamp	$163.29	$66.34	$96.95
Annual Operation Cost	$1,932,047.28	$784,934.88	$1,147,112.40

Figure 33: Annual Energy Savings of Replacing a 250W MV with a 120W LED

If all of the previously mentioned lamps that are currently in place in Boston were switched to LEDs, the city would incur an annual savings of $3,600,155.70. This is a significant sum of money that can be invested in a variety of necessities for the City.

In addition to LED's superior energy efficiency, this technology is also proficient in properly directing light. LEDs are designed with built in cut-offs that prevent light from being emitted upward and ultimately wasting energy. The cut-offs are engineered to direct light downward, onto the street and sidewalk where it is needed.

4.3.3.1 LED Tradeoffs

Even though LEDs are evidently superior to the current technologies with regard to energy consumption and maintenance, there are several tradeoffs associated with implementing LEDs. LEDs do provide a high quality, clean light.

However, the initial investment in LEDs is much higher than that of any of the current technology. These costs are estimated to drop at least 20% within the next five years. LEDs are also highly energy efficient and will generate substantial energy savings each year. A common problem in LEDs is when one lamp burns out on a grid, the power is then distributed to the remaining lamps on the grid, making them brighter and ultimately reducing their lifespan. Taking this into consideration, the lifespan of LEDs is still much higher than that of the current lamps in place and therefore they require far less maintenance. However, LEDs are still a fairly new technology that is in the testing stages.

4.3.4 Solar Lighting

An alternative technology that is even more efficient in energy consumption than LEDs is solar lighting. If solar lighting was used to replace any of the current lighting technology in Boston the result would be 100% in energy savings. The reason for this is that solar lighting absorbs energy from the sun to "charge" during the day and uses that energy to illuminate the streets at night (Solar Street Lights USA, 2009). So if solar lights were used to replace all 15,056 175 W MV lamps in the city, the savings would add up to $1,770,284.48 per year (the total annual cost of powering those lights). Similarly, if all 11,832 of the city's 250 W MV lamps were to be replaced with solar lights, the annual energy savings would amount to $1,932,047.28 (refer to Figure 33).

4.3.4.1 Solar Lighting Tradeoffs

Solar street lights would be the ideal replacement for Boston's current street lights in terms of energy savings. As this technology does not rely on electrical power, solar lights are also unaffected by power outages. Therefore, the City would never have to be concerned with dark streets and unlit alleys. Solar lights' long lifespan and low maintenance would also generate great savings for the City (Sol, 2009). However, the initial investment in solar lighting is far more expensive than that of the alternatives, such as LEDs. The purchase price of a single solar light unit ranges from $3,800 to $6,100. Due to the high cost, the return on investment in solar lighting would be 14-16 years (Eco Solar Lighting, 2008).

4.4 Return on Investment

Our team was able to combine the maintenance findings and the energy consumption findings to construct a return on investment for the 90 watt and 120 watt LED street lights. Our team calculated the installation and annual energy costs for the two LED lamps over the usage time of an LED lamp. We then compared this data to the maintenance and energy costs for the correlating high pressure sodium, mercury vapor, and metal halide lamps over the same period of time.

4.4.1 90 Watt LED

In order to calculate the initial investment cost for the 90 watt LED the following components were needed: material costs, lamp cost, labor cost, and cost to operate the truck. After talking to several manufacturers and distributors we found an average price of materials for LED street lights to be $525.00 and the lamp to be an additional $15.98. To calculate labor, our team averaged out the maintenance crew salaries to find an average annual salary of $40,651.75. We then divided this out to calculate the cost to pay a crew member per hour and came up with $13.89. Our team then took into consideration that four people are present on a maintenance call and found a total cost per hour to be $55.56. To calculate the cost to operate the trucks we looked at the annual budget for fuel for one truck, which was $1333.33. We then divided this out to get an hourly cost of $1.83. After totaling each cost the final price for installation was $598.37.

Next our team calculated the cost for replacing 175 watt mercury vapor, metal halide, and high pressure sodium lamps. To do this the following costs were required: disposal of the old lamps, fuel for the trucks, labor cost, and price of the new lamps. The price for fuel and labor are the same as installing an LED light, because it requires generally the same amount of time (one hour). The price for the mercury vapor, high pressure sodium, and metal halide lamp was $3.75, $9.19, and $8.55, respectively. Also, the disposal cost for all of these lamps was found to be $.85 per lamp. The final replacement cost for the metal halide lamp was $66.79. The replacement cost for the high pressure sodium was $67.43 and the mercury vapor was $61.99.

After calculating all of the cost, our team calculated the energy and maintenance cost over the lifetime of one LED lamp, thirteen years. The costs were determined by multiplying the price per kilowatt hour, $.1317, by the annual kilowatt hours for each light. The 90 watt LED consumes an annual 442kwh and the 175 watt lamps consume 895kwh a year. The annual cost of energy for the 90 watt LED is $58.07 and $117.52 for the 175 watt lights. These energy costs were combined with the various maintenance costs. The maintenance costs for the 175 watt lamps were included every year a mercury vapor, high pressure sodium, and metal halide lamp burned out. The usage time for the mercury vapor was found to be 2.87 years, the high pressure sodium was 4.76 years, and the metal halide 4.17 years. The following graph shows the payback period for installing one LED light, as well as the savings over the lifetime of one LED lamp.

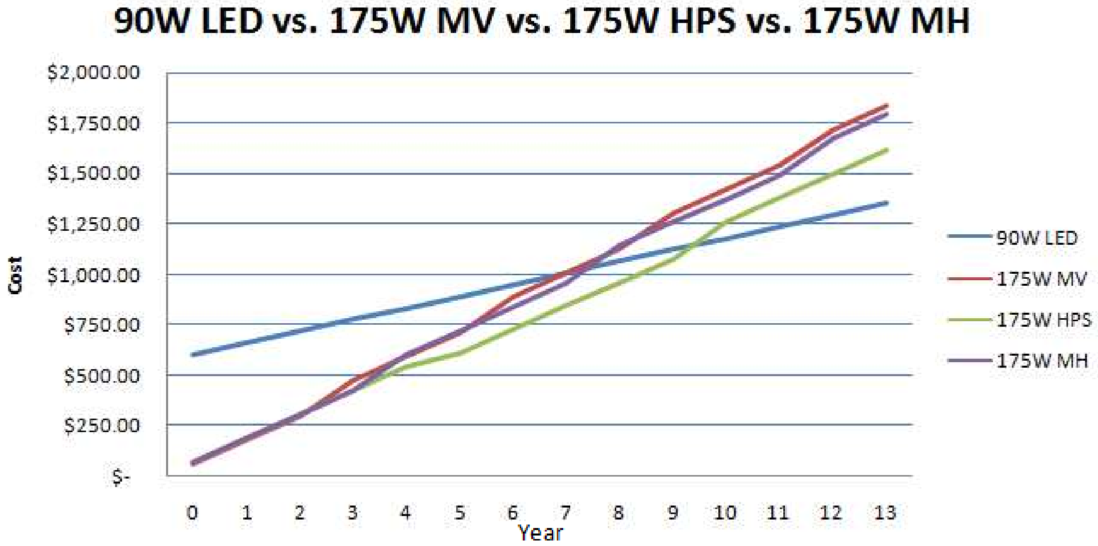


Figure 34: 90W LED vs. 175W MH vs. 175W HPS vs. 175W MH

From this graph we found separate payback periods and savings compared to the various 175 watt lamps. The mercury vapor had the fastest payback periods and the highest savings. This is because these lamps required the highest number of replacements over the lifespan of one LED. The replacement years can be seen by the increase in slope along the lines of the graph. The payback period for the mercury vapor was approximately 6.5 years with savings of approximately $500 per light after thirteen years. The metal halide had the second fastest payback in roughly 7 years with savings close to

$450 per light. Our team also found that replacing the high pressure sodium lamps had the slowest payback period of 9.5 years. Although the payback period takes longer, we found that replacing high pressure sodium lights still had significant savings, resulting at $400 per light after thirteen years.

4.4.2 120W LED

To calculate the initial investment of the 120 watt LED street lights for the 250 watt mercury vapor, high pressure sodium, and metal halide we needed the same costs as the 90 watt LED lights. The only cost that changed was the cost for materials. Because the 120 watt lights have more material the average price from various manufacturers was $700. After adding this up with the previous labor, fuel, and lamp cost the final installation price was $773.37. The price to install the 250 watt lamps stayed consistent with the 175 watt. The lamp, fuel, labor, and maintenance cost stay the same regardless of the wattage.

Next, our team needed to calculate the cost of annual operation. We used the same equation from the previous section. The 120 watt LED lights consume 505kwh a year. The 250 watt metal halide and mercury vapor consume 1243kwh a year, and the 250 watt high pressure sodium only consumes 12300kwh annually. The annual cost to power the 120 watt LED is $66.34 where as the metal halide and mercury vapor cost $163.29 and the high pressure sodium cost $162.77. After finding the annual energy costs we were able to combine the results with the maintenance cost to produce the following graph to illustrate the separate payback periods. We were also able to determine the different savings over the lifespan of one LED lamp.

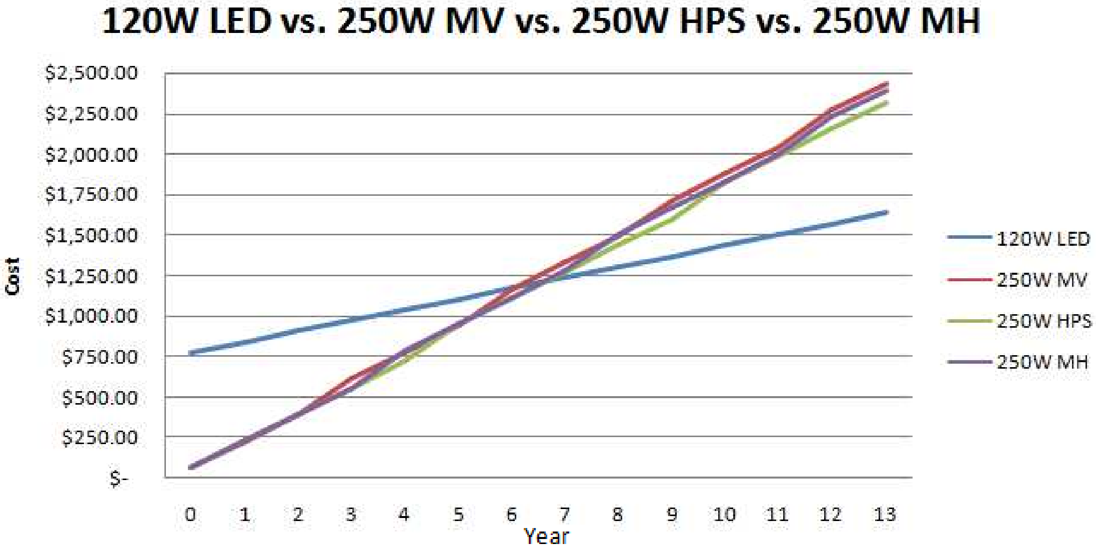


Figure 35: 120W LED vs. 250W MV vs. 250W HPS vs. 250W MH

We were able to find separate payback periods for replacing the 250 watt lamps as well. The payback period was also the fastest for replacing the 250 watt mercury vapor lamps with 120 watt LED lamps. This is because the lifetime of the lamps did not change and the same number of replacements was required. We found that the payback period for replacing 250 watt mercury vapor lights was just short of six years with a savings of roughly $800 per light after thirteen years. We also found that metal halide and high pressure sodium had approximately the same payback at six and a half years. Although the replacement of the two lamps had the same payback period, our team found they had different savings after thirteen years. Replacing the metal halide lamps saved $750 per lamp and replacing the high pressure sodium saved $700 per lamp.

5.0 Results

5.1 Recommendations

Our team was able to develop recommendations by determining priority fixtures and lamps that create high energy and maintenance costs for the City of Boston. After examining the operation and maintenance costs for the fixtures in place, we selected the following cobra head fixtures to be equipped with cut-offs: 750 watt mercury vapor, 400 watt mercury vapor, 250 watt mercury vapor, and 175 watt mercury vapor. Installing these cut-offs will allow for lower wattage lamps to be installed. The new lamps will be high pressure sodium lamps with the following wattages: 400, 250, 150, and 100, respectively. Installing these cut-offs will also allow for lower wattage lamps to be installed. The reasons for selecting these lamps and fixtures are because they generate the highest costs for the city, and are also high in numbers. The mercury vapors consume high energy for a lower lumen per watt ratio. The amount of light emitted can be increased with a more energy efficient high pressure sodium lamp. Also, the cobra head fixtures are the only type of lights in the city that do not have cut-offs to properly direct their light. Replacing these fixtures first will create savings that can be re-invested in future technologies.

The second part of our recommendations is to invest the money saved from installing cut-offs on the cobra head fixtures into LED lighting. The two types of LED lamps that we suggest for Boston are 90 watt and 120 watt lamps. The 90 watt LED will replace 175 watt mercury vapor, metal halide, and high pressure sodium lights, and the 120 watt LED will replace 250 watt mercury vapor, metal halide, and high pressure sodium lights. The LED lights require a full replacement of the fixture, so the initial investment is high. Creating a budget for the city from the savings generated from installing cut-offs will allow Boston to invest into green technology that will produce significant energy savings.

In order to properly understand the recommendations we developed three scenarios that will illustrate the savings for the City of Boston. The first scenario is examining Boston as it currently is. This will show the current maintenance costs and operation costs as time goes on. The following scenarios can then be compared to understand the benefits. . The second scenario is the installation of the cutoffs on the 750, 400, 250, and 175 watt mercury vapor cobra head fixtures and replacing the lamps with 400, 250, 150, and 100 watt high pressure sodium lamps, respectively. The third scenario is replacing the 175 watt mercury vapor, high pressure sodium, and metal halide lamps with 90 watt LED lights, and the 250 watt mercury vapor, high pressure sodium, and metal halide lamps with 120 watt LED lights. The savings that will be invested into LED lighting is made clear by separating the second and third scenario. It also allows for a further understanding of the potential savings from investing in LED lighting. The costs were collected from the street lighting division budget, as well as several manufacturers to determine costs of newer technologies.

5.1.1 Scenario 1: Current Situation

Boston currently spends $11,112,695.78 annually to operate the electric lights. In addition to the 11.1 million for electricity, the city spends $910,000 dollars to repair and service the electric lights (Street Lighting Division, 2009). If Boston were to continue to use the current lamps and fixtures, these prices would remain relatively consistent. Several variables would alter the costs, such as price per kilowatt hour, the number of street lights in the city, and the required number of maintenance visits, but the overall costs would stay relatively constant. Figure 36 is an estimate of the maintenance and operation costs over the next ten years.

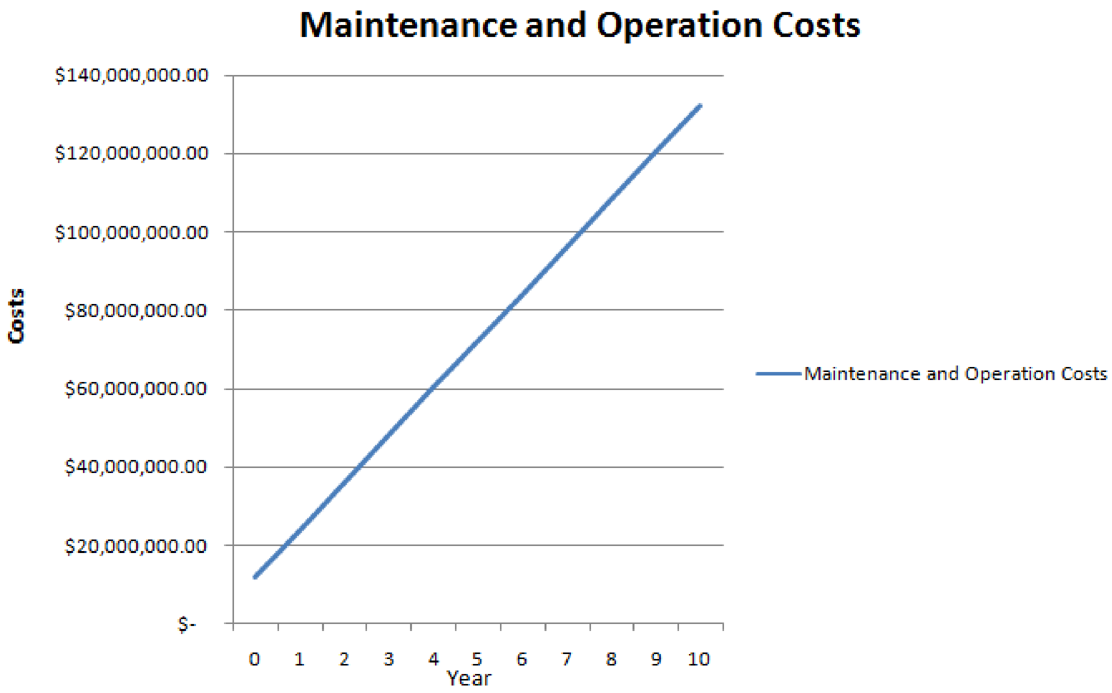


Figure 36: Maintenance and Operation Cost

5.1.2 Scenario 2: Installation of Cut-offs

The first lighting fixtures that we are recommending to install cut-offs on are the 750 watt mercury vapor cobra heads. Cobra head fixtures are currently the only fixtures in Boston that do not have their light completely directed downward. As well as installing the cut-offs, we recommend exchanging the 750 watt mercury vapor lamp with a 400 watt high pressure sodium lamp. The lamps produce the same amount of downward lumens. Also, the high pressure sodium lamp only costs $259.32 a year to operate, compared to the mercury vapor lamp that costs $452.44. Installing these cut-offs when the mercury vapor lamps burn out will eliminate doubling maintenance costs. The following graph illustrates the payback period and the savings created by installing these cutoffs. You can see that with this fixture the payback period is within the first year. The costs considered in the graph include the maintenance costs, replacing lamps when they burn out, and the annual energy costs (Street Lighting Division, 2009, Dark Sky, 2006).

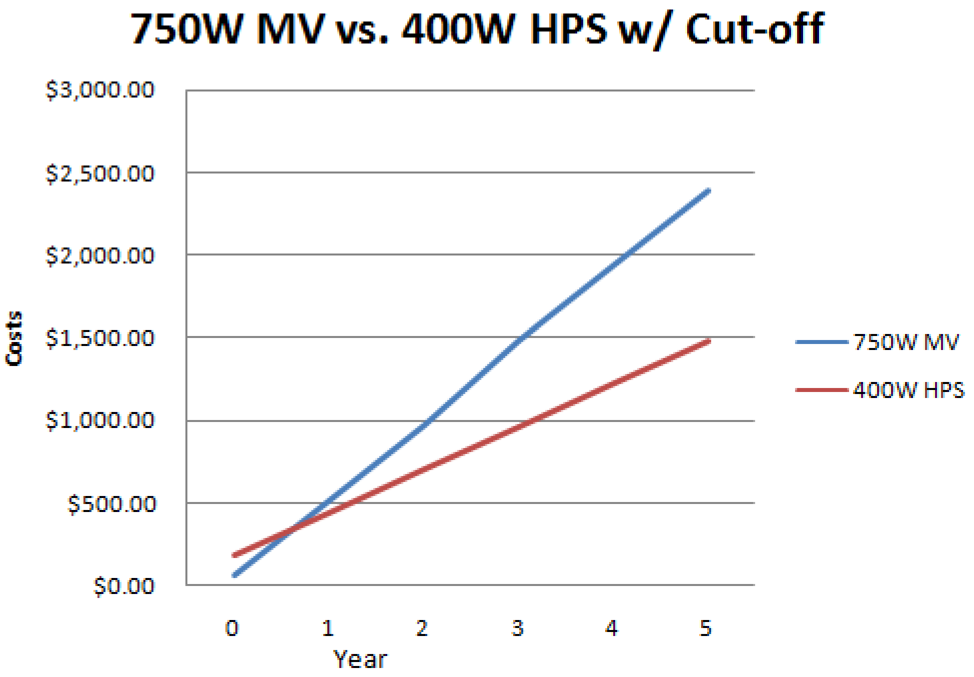


Figure 37: 750W MV vs. 400W HPS with Cut-off

The next recommendation for the installation of cut-offs is on the 400 watt mercury vapor. These lamps would also be replaced with a 250 watt high pressure sodium lamp. The high pressure sodium lamp has a lifespan of 4.76 years compared to the 2.86 year lifetime for the mercury vapor lamp. In addition to reducing maintenance the energy cost and consumption would be reduced. The 400 watt mercury vapor lamp costs $253.81 a year to operate and consume 2083kwh a year. The 250 watt high pressure sodium only costs $162.77 and consumes only 1230kwh a year (Dark Sky, 2006, Street Lighting Division, 2009). The following graph illustrates the savings and shows payback period being roughly two years.

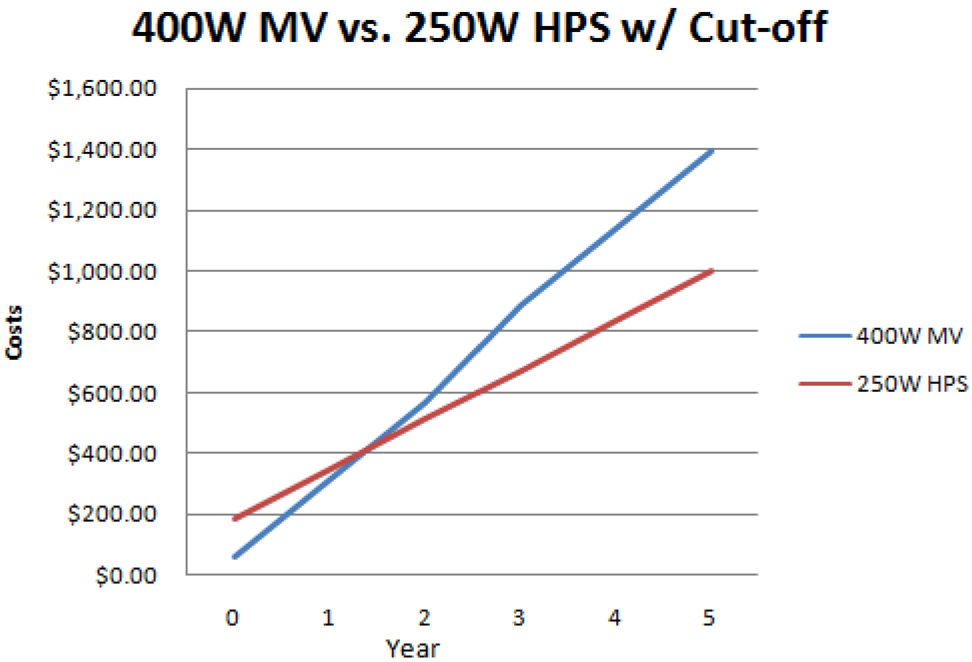


Figure 38: 400W MV vs. 250W HPS with Cut-off

The next recommendation for the installation of cut-offs is on the 175 watt mercury vapor cobra head. These lamps would be replaced with a 100 watt high pressure sodium lamp. The lifespan for these lamps is the same as the previous two, so replacement costs would be reduced. As well as reducing maintenance, the energy consumption and costs would be reduced. The 175 watt mercury vapor uses 895kwh a year and has an annual operation cost of $117.52 per unit, compared to the 100 watt high pressure sodium that only uses 563kwh and costs $73.94 (Street Lighting Division, 2009). The following figure shows the savings and a payback period of approximately two and a half years.

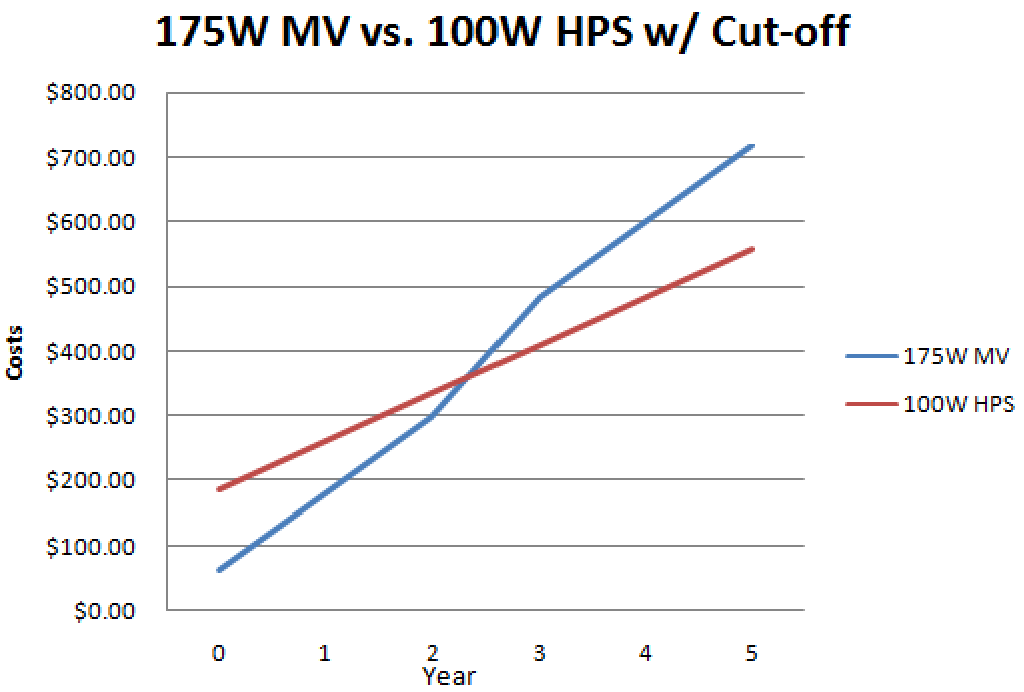


Figure 39: 175W MV vs. 100W HPS with Cut-off

The final recommendation for the installation of cut-offs is on the 250 watt mercury vapor cobra head. These lamps would be replaced with a 150 watt high pressure sodium lamp. Energy consumption and energy costs would be reduced with this switch as well. The 250 watt mercury vapor uses 1243kwh and costs $163.32 a year while the 150 watt high pressure only consumes 806kwh and costs $105.94 a year (Street Lighting Division). The figure below shows the payback period being close to two years.

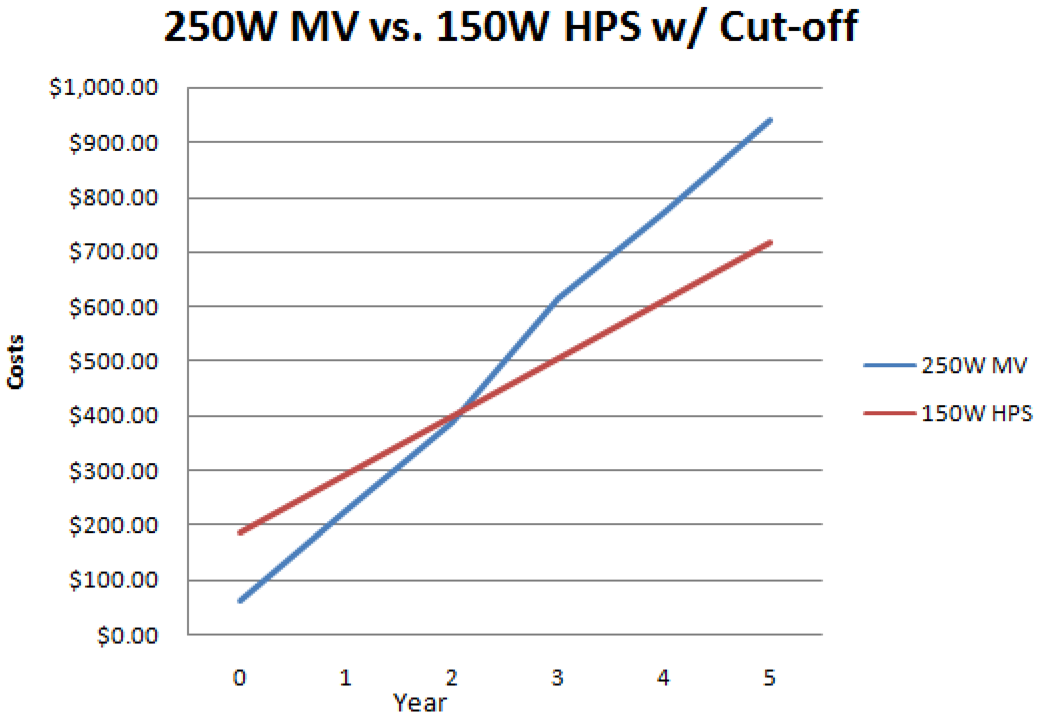


Figure 40: 250W MV vs. 150W HPS with Cut-off

In all situations, the money invested into installing the cut-off is quickly returned. The cut-offs only costing $120 per fixture allows for a fast payback period that supports our recommendation to install the cut--offs on these two fixtures. As well as saving money and reducing energy consumption, the high pressure sodium lights maintain the required lumen levels. The cut-offs also eliminate the sky pollution produced by the cobra head fixtures. The reason that we selected these four fixtures is because they produce the highest maintenance costs for the city, and waste the most energy supplied to them. By installing these cut-offs and replacing the lamps with a lower wattage and low maintenance lamp the city can see significant savings. These savings can then be reinvested into purchasing LED street lights for Boston.

5.1.3 Scenario 3: Installation of LED Lamps

With the savings from reduced wattage lamps and installation of cut-offs we recommend implementing two types of LED street lights. The first type of lamp that we recommend to be installed is the 90 watt LED for the 175 watt mercury vapor, mercury vapor, and metal halide lamps. The lights can replace all of the fixtures that house the 175 watt lights. The reason for this is because it requires full replacement. Retrofitting is a possibility, but creates several problems; the LED over heats, decreases the lifetime of the lamp, and over consumption of energy by the street lights (US Department of Energy, 2009). Currently, there are close to 20,000 fixtures in Boston. Replacing these fixtures for LED would generate significant savings for the city (Street Lighting Division, 2009).

The cost to install a 90 watt LED fixture is $525 dollars (Remco, 2009). This includes all the required materials to properly install the fixture. The 90W LED lights use 442 kilowatt hours (Remco, 2009). At $.13137 a kwh, the annual cost to operate a single light is $58.07. The 175 watt lights in place consume 895kwh a year and cost $117.52 a year to operate. As well as costing more to operate, the mercury vapor light last 2.86 years, the metal halide last 4.17 years, and the high pressure sodium last 4.76 years, compared to the LED that last 13.10 years. Replacing a mercury vapor lamp cost $61.99. This includes disposal of the old lamp, cost of the new lamp, labor of the maintenance crew, and cost to operate the maintenance trucks. The metal halide and high pressure sodium lamps include the same expenses and with replacement costs of $66.79 and $67.43, respectively. The replacement cost for LED lamps is $73.37, including the price for the lamp, labor of the maintenance crew, and cost to operate the maintenance trucks. LED lamps do not have to be properly disposed because they lack hazardous materials. In the lifetime of one LED a mercury vapor lamp would need to be replaced 4 times, a metal halide 3 times, and high pressure sodium two times. The highest replacement cost, being the mercury vapor, would cost $247.96. These energy and maintenance costs are included and displayed in the following graph to illustrate the savings generated from investing in one LED light (Remco, NuVue, Street Lighting Division, 2009). The graph is constructed for the lifetime of one LED lamp.

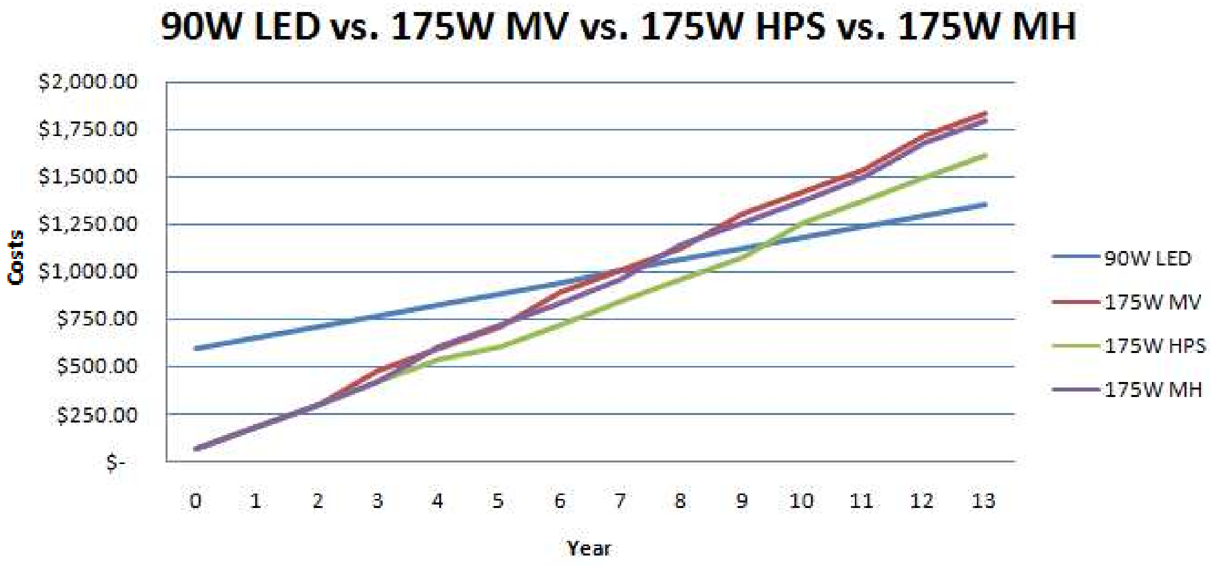


Figure 41: 90W LED vs. 175W MV vs. 175W HPS vs. 175W MH

It is clear from the graph that after a breaking even at 6.5 years significant savings are created for the city, except for the high pressure sodium that would take 9.5 years.

The next recommendation is the installation of a 120W LED light for the 250 watt mercury vapor, high pressure sodium, and metal halide lamps. The replacement requirements are the same as the 90 watt LED in order to work properly. Currently there are roughly 18,000 fixtures in Boston (Street Lighting Division, 2009).

The cost to install a 120 watt LED is $700.00. The 120 watt LED lights use 505kwh compared the 250 watt lights that use 1243kwh. Also, the 120 watt LED costs $66.34 and the 250 street lights costs $163.29 a year. The lifespan for these lamps are consistent for these wattages. The replacement costs are also the same for these wattages (NuVue, Remco, Street Lighting Division, 2009). The following graph illustrates the savings and payback period for implementing one 120 watt LED. It is clear in this graph that the payback is within seven years for all lights.

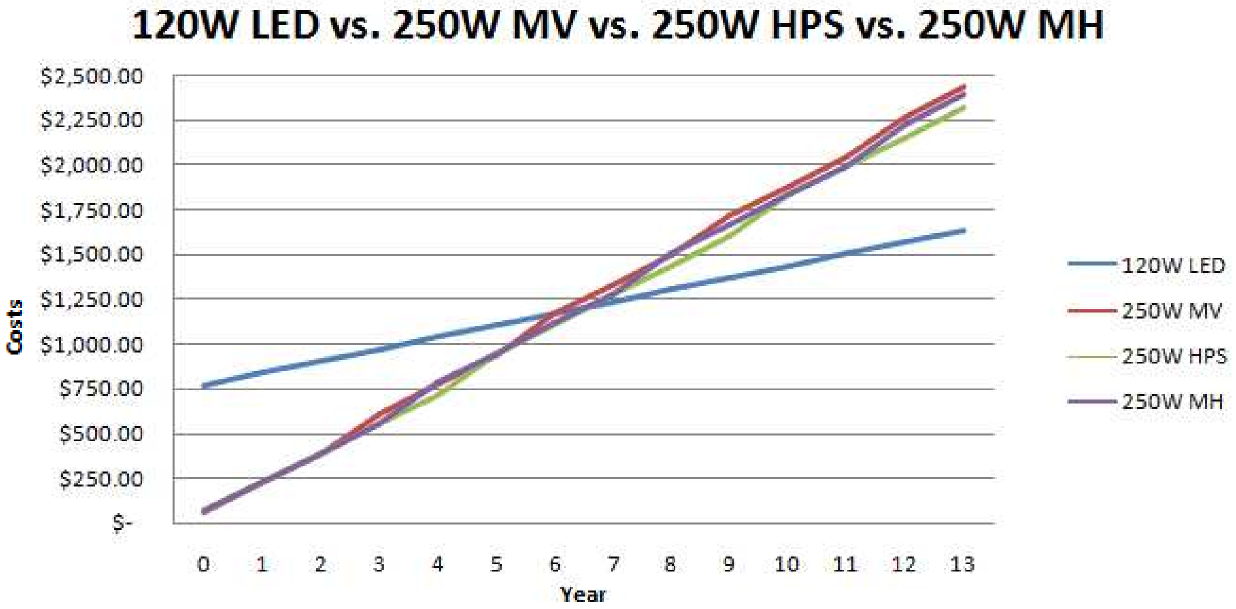


Figure 42: 120W LED vs. 250W MV vs. 250W HPS vs. 250W MH

Both graphs supply evidence to support our recommendation. The city would be able to save a significant amount of money, and the paybacks are in decent time. As well as saving money, the city would reduce the amount of maintenance required. The change in slope for the lamps in place represents a replacement year for the current street lights. The money saved could further be invested into other projects. Because the 250 and 175 watt lights represent a high percentage of the electric lights in Boston we felt that these fixtures would satisfy the city's need for energy efficient technology. The implementation could even be viewed as a pilot project to set an example for the rest of the city. The high concentration and low energy efficiency of these types of lamps are why our team suggested the replacement compared to the other types. As well as creating the highest savings, replacing these lamps have a fast payback period. The LED lamps also produce the same lumen levels as the previous mercury vapor lamps.

The reason for separate recommendations is because we felt that the city will benefit most by saving money for a budget to invest in LED. The city will receive the money back fastest in these two scenarios. Also, LED street lights are still being improved. Because the LED light has not been completely developed, installing them for the 750 watt and 400 watt mercury vapor would decrease the lumen output and create less visible streets. As the LED lights continue to improve, significant savings can be built up by Boston. The high quantity of fixtures requiring cut-offs will reduce energy costs and energy consumption for the city. Also, these savings can be put forward to future development. LED light lamps are estimated to drop 20% in price over the next five years, which is roughly the lifespan of the high pressure sodium lamps replacing the mercury vapor. The technology will advance to produce required lumen levels. Installing LED lights in the future with the savings created from the cut-offs will further reduce energy consumption and costs for Boston. Also, maintenance costs will stay minimal if the LED lamps are installed as the high pressure sodium lights burn out because a replacement visit will already be necessary.

6.0 Conclusion

Based on our research we found that the rollout plan is the most suitable recommendation for the city of Boston's current situation. The fixtures in place create high energy and maintenance costs, as well as produce high amounts of light pollution. As well as having inefficient fixtures, Boston lacks a plan to incorporate greener technology. By introducing a rollout plan, Boston will have an understanding of how to immediately reduce energy and maintenance costs, and reasons why the city should invest in newer technologies.

By installing cut-offs, the city will be able to reduce light pollution as well as increase energy efficiency by replacing mercury vapor lamps with high pressure sodium. The replacement of lamps will also reduce maintenance costs because the high pressure sodium lamps have a longer lifespan. Most importantly, Boston will be able to generate savings to invest in technology to reach the goal of becoming a greener city. Without the installation of cut-offs, Boston does not have a sufficient budget to become the desired green city. By reviewing the recommendations, the city can gain an understanding of the priority fixtures that require cut-offs, and generate considerable savings.

Boston's goal to become a greener city can be initiated by the installation of LED street lights. By using the money saved over several years from installing cut-offs, the city will have a reasonable budget that can be invested in the green technology. By waiting to implement LED street lights in Boston, the city will not spend a large amount of money on a technology that is still in development. Giving several years for this technology to develop will not only allow time for Boston to create funds for this project, it will ensure that the desired result from implementing this technology is reached. Boston will be able to review several manufacturers and select the street lights that will produce the highest energy and maintenance savings in the future. The savings from the LED street lights can be put forward to other new technologies that allow Boston to accomplish becoming a green city.

Boston can gain an understanding of how to become a greener city by reviewing our recommendations that suggest investing in cut-offs to reduce energy costs that essentially create a budget for LED lighting. The explanation of the tradeoffs of each alternative allows Boston to select the most appropriate energy efficient technology. The findings allow Boston to examine priority fixtures and lamps where high costs for the city are created. Reviewing the recommendations illustrates a proficient way to eliminate the priority fixtures and immediately save money for the city of Boston.

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8.0 Appendices

8.1 Appendix A: Surveying Tools

Measuring Light

Light can be measured using a variety of ways; luminous flux, luminous intensity illuminance (also known as illumination) and luminance (Salameh, 2006). Luminous flux has the unit of the lumen (lm), but it not necessarily the amount of light; it is "the quantity of the energy of the light emitted per second in all directions" (Salameh, 2006). Luminous intensity measured in candelas (cd), and is basically the luminous flux that is emitted by a light source in one direction (Salameh, 2006). Luminance is just the luminous intensity that is emitted upon 1cm2 and is measured in cd/cm2 (Salameh, 2006). Illuminance is the measurement this project will use. Illuminance is the measure of the amount of light that covers a surface and can be measured by $E = \theta/S$ where θ is the amount of lumens, and S is the surface area, the abbreviation for illuminance is lx or lux depending on the value (Salameh, 2006).

When measuring the light emitted by a street light, the light is normally measured in illuminance, which will be the unit of measurement used throughout the project. A simple way to measure the illuminance would be to use a light intensity meter. This device can measure the lux of any type of light, and display the measurements in a digital readout. Since we were interested in the emitted light, the light hitting the street surface is what was measured.

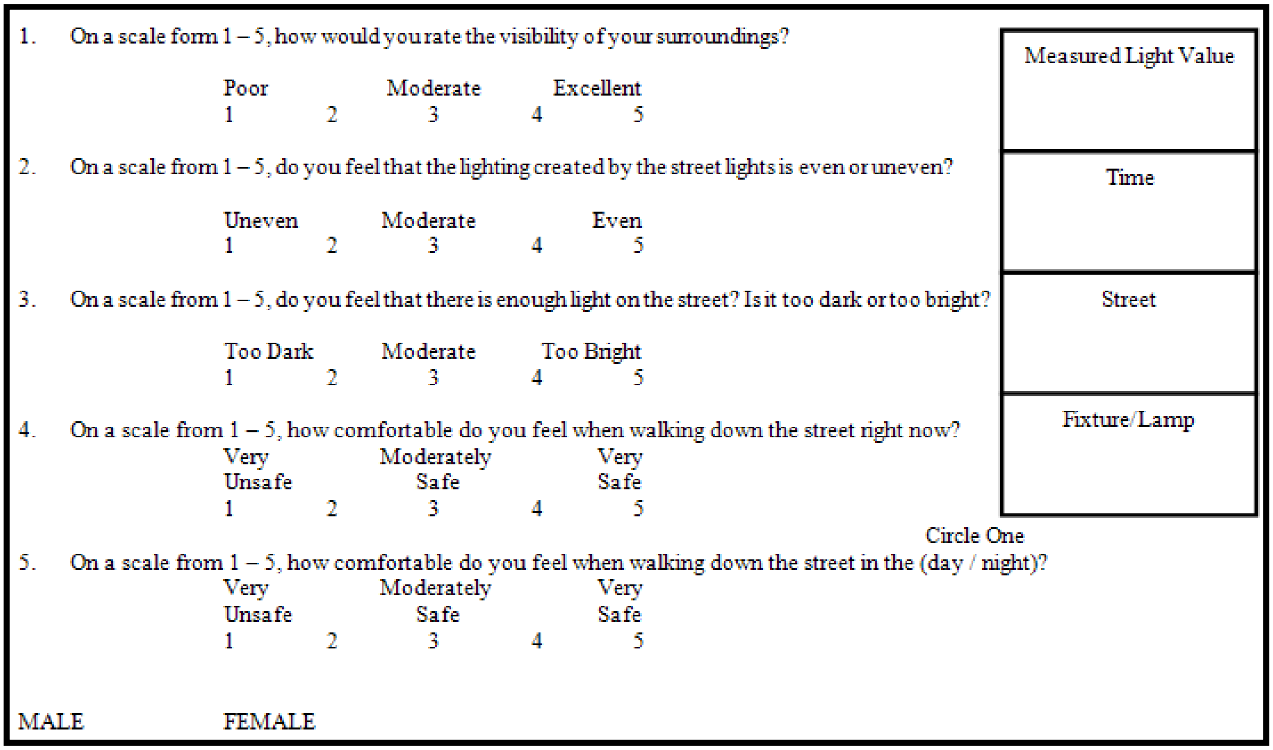
Light Intensity Meter

Reliability Direct AR823 Light Meter

Wide Range FC/Lux Light Meter

Display Counts:	4000 count LCD
Fc or Lux Range:	1-2,000, 2,000-10,000, 10,000-50,000, 50,000-100,000
Max. Resolution:	1 Fc/Lux
Sampling Frequency	1.5/sec
Response Time	1 Sec
Basic Accuracy:	±3%rdg + 0.5FC
Cosine & Color Corrected:	Yes
Dimensions:	5.9 x 3.25 x1.06" (151× 83 × 27mm)
Power	1 x 9V (66F22)
Weight:	7.4 oz (210g)

Comfort Survey:



1. On a scale form 1 – 5, how would you rate the visibility of your surroundings?

Poor Moderate Excellent
1 2 3 4 5

2. On a scale from 1 – 5, do you feel that the lighting created by the street lights is even or uneven?

Uneven Moderate Even
1 2 3 4 5

3. On a scale from 1 – 5, do you feel that there is enough light on the street? Is it too dark or too bright?

Too Dark Moderate Too Bright
1 2 3 4 5

4. On a scale from 1 – 5, how comfortable do you feel when walking down the street right now?
Very Unsafe Moderately Safe Very Safe
1 2 3 4 5

Circle One
5. On a scale from 1 – 5, how comfortable do you feel when walking down the street in the (day / night)?
Very Unsafe Moderately Safe Very Safe
1 2 3 4 5

MALE FEMALE

Measured Light Value
Time
Street
Fixture/Lamp

Light Survey Data Processing For GIS:

1. Initially, we were able to identify an exact location for several street lights with a particular light fixture:

- 5 Monument Street
- 12 Monument Street
- 53 Monument Street
- Monument & Walford
- High Street & Pearl Street
- High Street & Green Street
- High Street & Cedar Street

2. As specified in the original raw data these addresses have the following light fixtures:

Street	Fixture	Lamp	Approximate Height
53 Monument	Cobra	HPS	20 ft
Monument & Walford	Cobra	HPS	20 ft
High St. & Pearl	Box	HPS	20 ft
High St. & Green	Box	MV	20 ft
High St & Cedar St	Box	MV	20 ft
5 Monument St.	Box	HPS	15 ft
12 Monument St.	Box	HPS	15 ft

3. The corresponding Equipment Codes were identified for each available light fixture type, on the basis of the field EQUIPCODE in the attributes table of the "streetlights_new" dataset. In this way, we found that:

- Cobra HPS 20ft Equipment Code is 91 (referring to 53 Monument)
- Box HPS 15ft Equipment Code is 81 (referring to 5 Monument St and 12 Monument St)
- Box HPS 20ft Equipment Code is 85

Also, we found that 5th Street has street lights, identified by Equipment Code 131. Hence, all street lights identified with 131 Equipment Code in the streetlights_new dataset are assumed to be Pendent MV fixture type, because all street lights at 5th Street are specified as Pendent MV.

Rutherford Avenue was located and the corresponding Equipment Codes were checked. It appeared that Cobra HPS with 35ft approximate height has an Equipment Code 40.

At this stage, we were not able to find a corresponding code for:

- Double Box HPS 20ft
- Lollipop MV 10ft
- Double Cobra HPS 30ft
- Box MV 20ft

4. All lights on the same street usually have the same equipment code. This is how we identified an average LUX_0ft, LUX_5ft, LUX_10ft, LUX_15ft, LUX_20ft, LUX_30ft for all lights which had the same codes city-wide.

Until here the main assumptions we made are that if one street light corresponds to a specific Equipment Code, all lights are the same type if:

- they have the same equipment code
- they are located on the same street

These criteria were met, unless an equipment code is missing in the streetlights_new dataset. Street lights with missing equipment code are not included in the light pollution mapping.

5. The equipment codes are a subject to corrections before we proceed with the analysis, because it was discovered by the Street Lights Group that there is a difference in the corresponding Equipment Codes. The following would be used:

Fixture	Lamp	Approx. Height	Equipment Code
Cobra	HPS	20 ft	90, 91
Cobra	HPS	35 ft	40
Double Cobra	HPS	30 ft	173 and 174
Box	HPS	20 ft	13 and 65
Box	HPS	15 ft	21
Box	MV	20ft	77
Double Box	HPS	20 ft	67
Lollipop	MV	10ft	81
Pendent	MV	20 ft	131

6. In the attributes table of the streetlights dataset were added several fields to include average LUX values. The new fields are called avLUX_0ft, avLUX_5ft, avLUX_10ft, avLUX_15ft, avLUX_20ft, and avLUX_30ft. These all include average values of LUX per light fixture. The values were taken from the provided spreadsheet:

Fixture Types:		**Cobras**	**Cobras**	**Double Cobras**	**Box**	**Box**	**Box**	**Double Box**	**Lollipop**	**Pendent**
Lamp Types:		HPS	HPS	HPS	MV	HPS	HPS	HPS	MV	MV
Height:		20 ft	35 ft	30 ft	20 ft	15 ft	20ft	20ft	10ft	20ft
	Length	**Lux**	**Lux**	**Lux**	**Lux**	**Lux**	**Lux**	**Lux**	**Lux**	**Lux**
Averages:	**0 ft**	46.25	36.6	41	51.5	13.5	17.5	57.5	7.4	5.5
	5 ft					9	11.75		5	5
	10 ft	42.5	31.6	21	28.5	2.5	8.75	24.5	2.2	4.5
	15 ft					0.5	2.25		0.6	2.25
	20 ft	15.5	16.6	8	6.8			8.5		
	30 ft	9.75	8.8	3	2.25			4		

The above Equipment Codes are used.

7. After all average values are assigned to the appropriate locations and equipment codes we used Interpolation to create a continuous surface of the light distribution throughout Charlestown and Boston.

8. The final dataset allows mapping and analysis of all types of lengths, so that several outputs can be produced: by 0ft, 5ft, 10ft, 20ft, and 30ft.

8.2 Appendix B: Raw Data

Intercept Survey Data

Measured Light Value	Comfort Day	Comfort at Night	Visibility	Evenness	Brightness	Gender	Type	Street	Time
1	5	2	5	2	2	Male	Box/Gas	High	19:37
2	4	2	5	5	4	Female	Box	Adams	18:24
2	5	1	3	4	4	Male	Box	Adams	18:26
2	5	3	5	5	4	Female	Box	Adams	18:29
2	4	1	3	2	3	Female	Box	Essex	19:34
3	4	1	2	2	3	Female	Acorn	Bunker Hill	18:42
3	5	1	3	2	3	Female	Box	Essex	19:35
4	5	2	5	5	4	Female	Box	Adams	18:25
4	4.5	1.5	2	2	1	Male	Acorn	Bunker Hill	18:43
4	5	1	3	3	3	Female	Acorn	Bunker Hill	18:46
5	4	3	2	4	2	Female	Box	Essex	19:37
5	5	2.5	2	4	2	Female	Acorn	Bunker Hill	18:49
5	5	1.5	1	2	1	Male	Acorn	Bunker Hill	18:49
5	5	2	2	3	2	Male	Box	Essex	19:37
6	5	1	3	2	2	Female	Acorn	Bunker Hill	18:53
6	4.5	2	3	2	4	Female	Box	Essex	19:38
7	5	3	4	3	2	Female	Box	Essex	19:40
7	5	2	2	4	2	Female	Acorn	Bunker Hill	18:59
7	4	2	2	3	2	Male	Box	Essex	19:47
8	4	3	3	4	4	Female	Acorn	Bunker Hill	18:58
8	5	1	3	2	2	Male	Box	Essex	19:49
9	4	3	2	3	3	Female	Box	Adams	18:32
9	4	1	4	3	2	Female	Acorn	Bunker Hill	18:59
10	5	2	3	2	3	Female	Acorn	Bunker Hill	18:57
11	5	2	3	3	3	Female	Box	Main	21:54
11	5	3	4	3	4	Female	Acorn	Bunker Hill	18:58
12	5	2.5	2	2	4	Male	Box	Main	21:42
12	4.5	2	4	5	3	Female	Box	Main	21:45
13	4	2	3	3	3	Male	Box	Essex	22:36
13	4	3	3	4	4	Male	Box	Adams	18:30
13	5	2	2	2	2	Female	Acorn	Bunker Hill	19:02
13	4	3.5	2	4	2	Male	Box	Essex	22:29
14	4.5	3	5	5	3	Male	Acorn	Bunker Hill	21:58

14	5	2	5	5	4	Male	Box	Adams	18:27
14	5	3	4	3	4	Male	Box	Essex	22:34
15	4	2	3	3	3	Male	Box	Adams	18:28
15	5	3	3	4	4	Female	Box	Essex	22:27
15	5	2.5	3	3	3	Female	Box	Essex	22:27
17	4	3	5	5	4	Male	Acorn	Bunker Hill	19:08
17	5	3	3	3	3	Female	Acorn	Bunker Hill	19:10
18	4	3	4	4	3	Male	Cobra	Monument	22:01
18	5	4	4	3	4	Male	Cobra	Monument	22:02
19	5	2	3	4	4	Male	Acorn	Bunker Hill	19:13
19	5	2	4	3	4	Female	Acorn	Bunker Hill	19:14
21	4.5	3	5	4	4	Female	Cobra	Monument	23:23
22	4	3	5	5	2	Male	Acorn	5th St.	23:25
22	5	4	4	3	4	Female	Cobra	Monument	21:58
22	5	3	2	4	2	Male	Box	Adams	18:20
22	5	2.5	3	4	4	Male	Box	High	23:14
23	5	2	2	3	2	Female	Cobra	Monument	22:04
23	4	3	3	4	2	Female	Boulevard	Main	22:53
24	5	3	3	3	2	Male	Pendent	5th St.	23:32
24	4	2	2	4	2	Female	Cobra	Monument	22:05
24	4	2	3	4	4	Male	Box	High	23:15
24	4.5	4	3	4	4	Female	Boulevard	Main	22:46
24	5	3	5	5	4	Male	Boulevard	Main	22:49
24	5	5	4	3	4	Female	Bishop	Monument Sq.	23:45
25	4.5	3.5	2	2	4	Male	Box	High	22:13
25	4.5	4	5	5	4	Female	Lollipop	Constitution	23:30
25	4	5	4	3	4	Male	Box	High	20:54
25	5	3	2	3	3	Female	Box	High	20:54
25	4	3	4	4	3	Male	Box	High	20:55
26	4	3.5	2	4	2	Female	Box	Main	22:04
26	4	3	3	3	3	Female	Cobra	Monument	22:07
26	4.5	3	5	5	4	Female	Boulevard	Main	22:40
26	4	3	4	3	4	Male	Boulevard	Main	22:52
27	5	3.5	4	3	3	Female	Box	High	20:59
27	5	4	3	4	4	Female	Box	High	20:59
27	4.5	2.5	5	5	4	Female	Boulevard	Main	22:47
27	4	5	3	3	3	Male	Bishop	Monument Sq.	23:44
28	5	3	4	4	3	Male	Pendent	5th St.	22:29
28	4	3	4	3	4	Male	Boulevard	Main	22:52
28	5	3	3	4	4	Male	Boulevard	Main	22:57

28	5	4	4	3	2	Male	Bishop	Monument Sq.	23:44
29	5	4	4	5	4	Male	Lollipop	Constitution	22:19
29	5	3	3	4	4	Male	Cobra	Main	22:11
29	4.5	3	3	4	4	Female	Cobra	Main	22:13
29	4	4	5	5	4	Female	Box	High	23:17
29	5	5	4	3	3	Female	Bishop	Monument Sq.	23:47
29	5	3	5	5	4	Male	Bishop	Monument Sq.	23:48
30	5	3.5	3	2	3	Female	Box	Main	22:42
30	4.5	4	4	3	3	Male	Box	Main	22:26
30	5	5	3	4	3	Female	Box	High	21:32
30	5	3.5	3	3	3	Female	Acorn	Bunker Hill	22:36
30	5	3	3	2	4	Male	Bishop	Monument Sq.	23:50
30	4	5	4	3	4	Female	Bishop	Monument Sq.	23:51
31	4	4	4	3	3	Female	Box	Main	22:19
31	5	4	4	3	2	Male	Box	High	23:24
31	5	4	3	2	4	Female	Bishop	Monument Sq.	23:55
31	5	3	3	4	4	Female	Bishop	Monument Sq.	23:53
32	5	4	3	4	3	Male	Box	Main	22:22
32	5	5	5	5	4	Male	Box	Main	22:24
32	5	4	4	3	4	Male	Flood	Park	21:27
32	5	4	5	5	4	Male	Bishop	Monument Sq.	23:57
32	5	4	4	3	4	Female	Bishop	Monument Sq.	23:56
33	4	4	3	4	2	Female	Acorn	Bunker Hill	22:45
33	4	3	3	3	2	Male	Box	Main	22:16
33	5	3	3	3	3	Female	Bishop	Monument Sq.	23:46
33	5	3	4	3	4	Male	Bishop	Monument Sq.	23:46
34	5	4	5	4	5	Male	Lollipop	Constitution	23:08
34	5	3	4	3	4	Male	Box	High	23:18
34	4	4	5	5	4	Female	Bishop	Monument Sq.	23:28
34	4	3	3	4	4	Female	Bishop	Monument Sq.	23:27
35	5	4	4	5	4	Female	Box	Constitution	20:56
35	5	4	3	4	5	Male	Cobra	Monument	23:11
35	5	4.5	3	5	3	Male	Box	Constitution	20:54
35	4	2	3	3	3	Female	Box	Main	22:45
35	5	3	3	4	4	Male	Flood	Park	21:30
35	5	4	3	3	3	Female	Bishop	Monument Sq.	23:30
36	5	3	3	3	4	Female	Box	Main	23:02
36	5	2	4	3	4	Male	Box	Main	22:50
36	4	4	5	5	4	Female	Bishop	Monument Sq.	23:32
37	5	4	5	5	4	Male	Flood	Park	21:32

37	4	4	3	4	3	Male	Bishop	Monument Sq.	23:31
40	5	4	4	5	3	Female	Box	Main	20:57
41	5	4	5	5	4	Male	Box	Main	22:19
42	5	3	3	3	3	Male	Box	Main	22:22
43	4	4	3	4	4	Female	Box	Main	22:11
45	5	3	3	4	2	Female	Acorn	Bunker Hill	22:54
46	5	2	4	3	4	Female	Box	Main	22:30
47	4.5	4	4	3	5	Male	Box	Main	22:59
47	5	3	4	3	2	Female	Box	Main	22:40
48	5	5	3	3	3	Male	Flood	Park	21:34
49	4	5	4	3	4	Male	Flood	Park	21:35
50	4	4	4	3	3	Male	Box	Main	22:48
50	5	3	5	5	4	Female	Box	Main	22:43
52	5	5	4	3	2	Female	Flood	Park	21:39
54	5	3	3	3	3	Female	Box	Main	22:45
54	4	4	5	5	4	Male	Box	High	23:19
55	5	3	5	5	4	Male	Flood	Park	21:38
56	5	5	4	3	2	Male	Box	Main	22:39
56	5	3	4	3	2	Female	Flood	Park	21:33
57	5	3	4	3	4	Male	Box	Main	22:56
57	4.5	4	4	3	2	Female	Flood	Park	21:38
58	5	4	4	3	4	Female	Flood	Park	21:41
59	4	4	3	4	4	Male	Flood	Park	21:43
60	5	4	5	4	4	Male	Box	Main	21:02
65	4	3.5	4	3	4	Female	Box	Main	21:00
65	5	4	4	3	4	Female	Box	Main	23:15
69	5	4	3	4	4	Female	Cobra	Monument	22:19
70	5	3	4	3	2	Female	Pendent	5th St.	22:53
70	5	4	3	4	4	Male	Pendent	5th St.	22:53
71	5	3	4	3	2	Female	Cobra	Monument	22:21
71	5	3	5	5	4	Female	Pendent	5th St.	22:55
72	4	5	3	3	3	Female	Cobra	Monument	22:24
73	4	3	3	4	4	Male	Cobra	Monument	22:25
73	5	4	4	3	3	Female	Cobra	Monument	22:25
73	5	3	2	3	2	Female	Pendent	5th St.	22:58
74	5	4.5	4	5	3	Male	Cobra	Monument	20:16
74	5	5	2	4	2	Female	Cobra	Monument	22:26
75	5	5	3	5	3	Female	Cobra	Monument	20:19
76	5	4	5	5	4	Male	Cobra	Monument	22:30
79	5	4	3	4	4	Male	Cobra	Monument	22:33

82	5	4	4	3	4	Male	Cobra	Monument	22:37
82	4.5	4	4	3	4	Female	Box	Main	23:16
85	5	4	4	3	2	Male	Box	Main	23:19
87	4	5	3	4	4	Male	Box	Main	23:17
88	5	5	3	3	3	Male	Box	Main	23:22
90	5	4	4	1	3	Male	Box	Main	21:20
90	5	5	3	3	3	Male	Box	Main	23:26
90	5	5	4	3	2	Male	Box	Main	23:24
91	5	4	4	3	4	Female	Box	Main	23:29
92	4.5	5	4	3	4	Female	Box	Main	23:28
93	5	4	3	4	4	Female	Box	Main	23:30
94	5	4	5	5	4	Male	Box	Main	23:32
95	4	5	3	3	3	Male	Box	Main	23:31

Street Light Equipment Codes Provided by Boston Street Lighting Division

Code #	Number Hds/Lamp	Type	Lamp Watts	Unit KW	Annual KWH	Lamp HPS	Lamp MV	Lamp MH	Lamp Inc.	Number of Units	Number of Street Lights	Operational Cost per Year	Operational Cost per Unit
2	2	Rectilinear	175	0.426	1789		X			5	10	$ 1,175.24	$ 235.05
5	1	Rectilinear	100	0.117	491	X				2	2	$ 129.11	$ 64.56
9	1	Rectilinear	250	0.296	1243		X			29	29	$ 4,736.26	$ 163.32
13	1	Rectilinear	250	0.295	1239	X				1082	1082	$ 176,114.36	$ 162.77
21	1	Rectilinear	400	0.47	1974	X				1198	1198	$ 310,670.61	$ 259.32
27	1	Ball	100	0.117	491	X				13	13	$ 839.22	$ 64.56
31	1	Rectilinear	150	0.192	806	X				34	34	$ 3,601.85	$ 105.94
32	2	Rectilinear	250	0.59	2478	X				206	412	$ 67,060.18	$ 325.53
33	2	Rectilinear	150	0.384	1613	X				11	22	$ 2,330.61	$ 211.87
35	1	Chn. Rect.	250	0.295	1239	X				23	23	$ 3,743.65	$ 162.77
39	1	Wall Mount	150	0.192	806	X				20	20	$ 2,118.74	$ 105.94
40	1	Wall Mount	250	0.295	1239	X				156	156	$ 25,391.72	$ 162.77
41	1	Bishop	150	0.192	806	X				74	74	$ 7,839.32	$ 105.94
42	1	Bishop	100	0.117	491	X				80	80	$ 5,164.42	$ 64.56
49	1	Rectilinear	150	0.192	806	X				4899	4899	$ 518,984.23	$ 105.94
55	1	Flood	250	0.295	1239	X				22	22	$ 3,580.88	$ 162.77
59	1	Flood	400	0.47	1974	X				36	36	$ 9,335.68	$ 259.32
60	1	Flood	400	0.496	2083		X			35	35	$ 9,578.45	$ 273.67
61	1	Flood	1000	1.095	4599		X			2	2	$ 1,208.34	$ 604.17
62	2	Rect.&Flood	400/400	0.92	3864	X				3	6	$ 1,522.84	$ 507.61
64	1	Ball	150	0.192	806	X				1	1	$ 105.94	$ 105.94
65	1	Rectilinear	250	0.295	1239	X				6029	6029	$ 981,324.84	$ 162.77
66	1	Rectilinear	400	0.47	1974	X				1	1	$ 259.32	$ 259.32

67	2	Rectilinear	250	0.59	2478	X				86	172	$ 27,996.00	$ 325.53
69	2	Rectilinear	250	0.592	2486		X			4	4	$ 1,306.55	$ 326.64
74	1	Cube	175	0.213	895		X			26	26	$ 3,055.61	$ 117.52
75	1	Wall	400	0.46	1932		X			10	10	$ 2,538.07	$ 253.81
77	1	Cobra	400	0.46	1932		X			2204	2204	$ 559,390.28	$ 253.81
79	1	Cobra	250	0.296	1243		X			4928	4928	$ 804,836.94	$ 163.32
81	1	Ball	175	0.213	895		X			940	940	$ 110,472.19	$ 117.52
82	1	Cobra	750	0.82	3444		X			118	118	$ 53,387.72	$ 452.44
83	1	Cobra	175	0.213	895		X			10593	10589	$ 1,244,927.52	$ 117.52
84	1	Rectilinear	175	0.213	895		X			210	210	$ 24,679.96	$ 117.52
85	1	Rectilinear	250	0.296	1243		X			5538	5538	$ 904,461.64	$ 163.32
86	1	Rectilinear	400	0.47	1974		X			334	334	$ 86,614.34	$ 259.32
87	1	PMC	175	0.213	895		X			8	8	$ 940.19	$ 117.52
90	1	Cobra	400	0.47	1974	X				1425	1425	$ 369,537.24	$ 259.32
91	1	Cobra	250	0.295	1239	X				2979	2979	$ 484,884.17	$ 162.77
93	1	Cobra	150	0.192	806	X				1712	1712	$ 181,363.75	$ 105.94
94	1	Colonial	175	0.213	895	X				751	751	$ 88,260.23	$ 117.52
95	1	Victorian	70	0.088	370	X				224	224	$ 10,876.17	$ 48.55
98	1	Nautical	175	0.213	895	X				84	84	$ 9,871.98	$ 117.52
99	2	Rectilinear	250	0.592	2486		X			20	40	$ 6,532.77	$ 326.64
105	1	Acorn	750	0.75	3150				X	364	364	$ 150,628.84	$ 413.82
106	2	Ball	175	0.426	1789		X			230	460	$ 54,060.86	$ 235.05
107	2	Ball	175	0.426	1789		X			21	42	$ 4,935.99	$ 235.05
116	2	Ball	175	0.426	1789		X			33	66	$ 7,756.56	$ 235.05
125	1	Acorn	175	0.213	895		X			226	226	$ 26,560.33	$ 117.52
127	2	Acorn	175	0.426	1789		X			1	2	$ 235.05	$ 235.05
130	1	Acorn	150	0.192	806	X				284	284	$ 30,086.04	$ 105.94
131	1	Acorn	175	0.213	895		X			306	306	$ 35,962.22	$ 117.52
133	2	Acorn	150	0.384	1613	X				184	368	$ 38,984.73	$ 211.87
134	2	Acorn	175	0.426	1789		X			3	6	$ 705.14	$ 235.05
136	1	Acorn	150	0.192	806	X				318	318	$ 33,687.89	$ 105.94
137	1	Acorn	175	0.213	895		X			276	276	$ 32,436.51	$ 117.52
139	2	Acorn	150	0.384	1613	X				41	82	$ 8,686.81	$ 211.87
149	1	Wall	150	0.192	806	X				50	50	$ 5,296.84	$ 105.94
152	2	Flood	400	0.92	3864	X				3	6	$ 1,522.84	$ 507.61
153	3	Flood	400	1.38	5796	X				1	3	$ 761.42	$ 761.42
154	2	Flood	250	0.59	2478	X				25	50	$ 8,138.37	$ 325.53
156	2	Flood	1000	2.1	8820		X			7	14	$ 8,110.78	$ 1,158.68
158	2	Flood	400	0.92	3864		X			22	44	$ 11,167.50	$ 507.61
159	3	Flood	400	1.38	5796		X			38	114	$ 28,933.98	$ 761.42
164	1	Flood	300	0.3	1260				Quartz	4	4	$ 662.10	$ 165.53
165	1	Acorn	150	0.188	790	X				6	6	$ 622.38	$ 103.73
166	1	Acorn	100	0.134	563	X				3	3	$ 221.81	$ 73.94
168	2	Cobra	1000	2.2	9240	X				2	4	$ 2,427.72	$ 1,213.86
170	2	Cobra	400	0.92	3864	X				179	358	$ 90,862.85	$ 507.61
171	2	Cobra	400	0.92	3864	X				434	868	$ 220,304.34	$ 507.61

172	3	Cobra	400	1.38	5796	X				31	93	$ 23,604.04	$ 761.42
173	2	Cobra	250	0.59	2478	X				303	606	$ 98,637.06	$ 325.53
174	2	Cobra	250	0.59	2478	X				199	398	$ 64,781.44	$ 325.53
175	3	Cobra	250	0.885	3717	X				75	225	$ 36,622.67	$ 488.30
179	2	Cobra	750	1.56	6552		X			9	18	$ 7,746.63	$ 860.74
182	2	Cobra	400	0.92	3864		X			95	190	$ 48,223.30	$ 507.61
183	2	Cobra	400	0.92	3864		X			19	38	$ 9,644.66	$ 507.61
186	2	Cobra	250	0.592	2486		X			2	4	$ 653.28	$ 326.64
191	1	Bishop	150	0.192	806	X				18	18	$ 1,906.86	$ 105.94
194	1	Bishop	175	0.213	895		X			38	38	$ 4,465.90	$ 117.52
198	1	Acorn	175	0.213	895			X		19	19	$ 2,232.95	$ 117.52
199	1	Acorn	250	0.295	1239	X				70	70	$ 11,393.72	$ 162.77
200	2	Acorn	250	0.59	2478	X				96	192	$ 31,251.35	$ 325.53
201	1	Acorn	175	0.213	895			X		152	152	$ 17,863.59	$ 117.52
202	2	Acorn	175	0.213	895			X		29	58	$ 3,408.18	$ 117.52
203	1	Acorn	250	0.296	1243			X		70	70	$ 11,432.34	$ 163.32
205	1	Acorn	250	0.296	1243		X			202	202	$ 32,990.48	$ 163.32
207	4	Acorn	250	1.18	4956	X				2	8	$ 1,302.14	$ 651.07
208	1	Rectilinear	250	0.296	1243			X		67	67	$ 10,942.39	$ 163.32
210	1	Rectilinear	175	0.213	895			X		9	9	$ 1,057.71	$ 117.52
212	2	Rectilinear	175	0.426	1789			X		1	2	$ 235.05	$ 235.05
213	1	Acorn	175	0.213	895		X			998	998	$ 117,288.55	$ 117.52
214	1	Bishop	175	0.213	895			X		1	1	$ 117.52	$ 117.52
215	1	Bishop	250	0.296	1243		X			18	18	$ 2,939.75	$ 163.32
216	1	Acorn	70	0.088	370	X				16	16	$ 776.87	$ 48.55
217	2	Acorn	70	0.176	739	X				8	16	$ 776.87	$ 97.11
218	4	Acorn	150	0.768	3226	X				15	60	$ 6,356.21	$ 423.75
220	1	Ball	300	0.3	1260				X	20	20	$ 3,310.52	$ 165.53
225	1	Ball	175	0.213	895		X			2	2	$ 235.05	$ 117.52
227	1	Acorn	150	0.192	806	X				1390	1390	$ 147,252.11	$ 105.94
228	2	Acorn	150	0.384	1613	X				1245	2490	$ 263,782.55	$ 211.87
229	1	Flood	250	0.295	1239	X				1	1	$ 162.77	$ 162.77
230	1	Flood	400	0.458	1924			X		16	16	$ 4,043.25	$ 252.70
231	1	Flood	1000	1.1	4620			X		6	6	$ 3,641.58	$ 606.93
233	2	Flood	400	0.916	3847			X		7	14	$ 3,537.85	$ 505.41
235	1	Acorn	250	0.295	1239	X				481	481	$ 78,291.13	$ 162.77
236	2	Acorn	250	0.59	2478	X				126	252	$ 41,017.39	$ 325.53
237	1	Acorn	250	0.296	1243		X			808	808	$ 131,961.90	$ 163.32
238	2	Acorn	250	0.592	2486		X			80	160	$ 26,131.07	$ 326.64
241	1	Fort Point	150	0.192	806	X				57	57	$ 6,038.40	$ 105.94
242	2	Fort Point	150	0.192	806	X				6	12	$ 635.62	$ 105.94
243	1	Fort Point	150	0.192	806	X				133	133	$ 14,089.59	$ 105.94
244	2	Fort Point	150	0.192	806	X				17	34	$ 1,800.93	$ 105.94
245	1	Cannister	150	0.192	806	X				8	8	$ 847.49	$ 105.94
246	2	Flood	250	0.295	1239	X				1	2	$ 162.77	$ 162.77
247	3	Flood	250	0.295	1239	X				1	3	$ 162.77	$ 162.77

249	1	Frank Sq.	150	0.192	806	X				12	12	$ 1,271.24	$ 105.94
250	1	Frank Sq.	175	0.213	895		X			67	67	$ 7,874.08	$ 117.52
251	1	Frank Sq.	250	0.296	1243		X			31	31	$ 5,062.89	$ 163.32
252	4	Acorn	175	0.852	3578		X			4	16	$ 1,880.38	$ 470.09
253	1	Boulevard	250	0.295	1239	X				1981	1981	$ 322,442.28	$ 162.77
254	2	Boulevard	250	0.59	2478	X				115	230	$ 37,436.51	$ 325.53
255	1	Boulevard	150	0.192	806	X				57	57	$ 6,038.40	$ 105.94
256	2	Boulevard	150	0.384	1613	X				1	2	$ 211.87	$ 211.87
257	1	Boulevard	250	0.295	1239		X			85	85	$ 13,835.23	$ 162.77
259	4	Flood	400	1.84	7728	X				1	4	$ 1,015.23	$ 1,015.23
260	1	Rectilinear	100	0.134	563			X		12	12	$ 887.22	$ 73.94
261	1	Flood	100	0.134	563			X		4	4	$ 295.74	$ 73.94
262	2	Flood	100	0.268	1126			X		18	36	$ 2,661.66	$ 147.87
263	1	Flood	100	0.134	563			X		5	5	$ 369.68	$ 73.94
266	1	Architect	250	0.296	1243			X		21	21	$ 3,429.70	$ 163.32
269	1	Fort Point	250	0.296	1243		X			14	14	$ 2,286.47	$ 163.32
270	1	Flood	250	0.296	1243			X		2	2	$ 326.64	$ 163.32
271	2	Flood	250	0.296	1243			X		2	4	$ 326.64	$ 163.32
		Fire Alarms	60	0.06	252				X	1197	1197	$ 39,626.97	$ 33.11

Diesel	1.83	1.83	1.83	1.83
Labor	55.56	55.56	55.56	55.56
Disposal		0.85	0.85	0.85
Lamp	15.98	3.75	9.19	8.55
Materials	700.00			
Kwh	505.00	1243.00	1230.00	1243.00
Energy Costs	66.34	163.29	162.77	163.29
Lifespan	13.10	2.86	4.76	4.17
Initial Cost	773.37	61.99	67.43	66.79
Total Costs (TC)	839.71	225.28	230.20	230.08
TC Year 2	906.05	388.57	392.97	393.37
TC Year 3	972.39	613.85	555.74	556.66
TC Year 4	1038.73	777.14	718.51	786.74
TC Year 5	1105.07	940.43	948.71	950.03
TC Year 6	1171.41	1165.71	1111.48	1113.32
TC Year 7	1237.75	1329.00	1274.25	1276.61
TC Year 8	1304.09	1492.29	1437.02	1506.69
TC Year 9	1370.43	1717.57	1599.79	1669.98
TC Year 10	1436.77	1880.86	1829.99	1833.27
TC Year 11	1503.11	2044.15	1992.76	1996.56
TC Year 12	1569.45	2269.43	2155.53	2226.64
TC Year 13	1635.79	2432.72	2318.30	2389.93

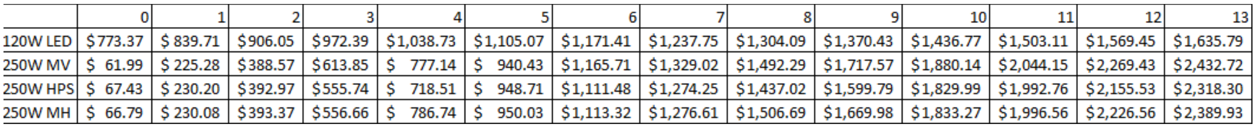
	90W LED	175W MV	175W HPS	175W MH
Diesel	1.83	1.83	1.83	1.83
Labor	55.56	55.56	55.56	55.56
Disposal		0.85	0.85	0.85
Lamp	15.98	3.75	9.19	8.55
Materials	525.00			
Kwh	442.00	895.00	895.00	895.00
Energy Costs	58.07	117.52	117.52	117.52
Lifespan	13.10	2.86	4.76	4.17
Initial Cost	598.37	61.99	67.43	66.79
Total Costs (TC)	656.44	179.51	184.95	184.31
TC Year 2	714.50	297.03	302.47	301.83
TC Year 3	772.57	476.54	419.99	419.35
TC Year 4	830.63	594.06	537.51	603.66
TC Year 5	888.70	711.58	604.94	721.18
TC Year 6	946.76	891.09	722.46	838.70
TC Year 7	1004.83	1008.61	839.98	956.22
TC Year 8	1062.89	1126.13	957.50	1140.53
TC Year 9	1120.96	1305.64	1075.02	1258.05
TC Year 10	1179.03	1423.16	1259.97	1375.57
TC Year 11	1237.09	1540.68	1377.49	1493.09
TC Year 12	1295.16	1720.19	1495.01	1677.40
TC Year 13	1353.22	1837.71	1612.53	1794.92

Maintenance/Laborer	Annual Salary	Daily	Hourly
1.00	36127.15		
2.00	31095.39		
3.00	19194.40		
4.00	38474.39		
5.00	34869.61		
6.00	33696.37		
7.00	55267.51		
8.00	28919.72		
9.00	45390.65		
10.00	37678.45		
11.00	47729.99		
12.00	54022.92		
13.00	33312.76		
14.00	40415.68		
15.00	47585.16		
16.00	47170.01		
17.00	39228.34		
18.00	47170.66		
19.00	49703.00		
20.00	39492.81		
21.00	40344.90		
22.00	36745.21		
23.00	49285.25		
Average	40561.75	111.13	13.89

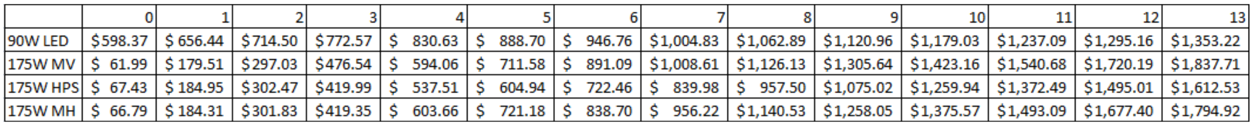
Lamp	Average Lifetime (Hrs)	Number of Lamps
HPS	20000	32705
MH	17500	498
MV	12000	29369
IN	6500	384

	Annual Costs	Daily Costs	Hourly Costs	Total Cost
Truck	1333.33	3.65	0.46	1.83
Labor	40561.75	111.13	13.89	55.56
Disposal				0.85

4 TRUCKS NECESSARY, AS WELL AS 4 PEOPLE. MAINTENANCE TAKES AN HOUR ON AVERAGE.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13
120W LED	$773.37	$ 839.71	$906.05	$972.39	$1,038.73	$1,105.07	$1,171.41	$1,237.75	$1,304.09	$1,370.43	$1,436.77	$1,503.11	$1,569.45	$1,635.79
250W MV	$ 61.99	$ 225.28	$388.57	$613.85	$ 777.14	$ 940.43	$1,165.71	$1,329.02	$1,492.29	$1,717.57	$1,880.14	$2,044.15	$2,269.43	$2,432.72
250W HPS	$ 67.43	$ 230.20	$392.97	$555.74	$ 718.51	$ 948.71	$1,111.48	$1,274.25	$1,437.02	$1,599.79	$1,829.99	$1,992.76	$2,155.53	$2,318.30
250W MH	$ 66.79	$ 230.08	$393.37	$556.66	$ 786.74	$ 950.03	$1,113.32	$1,276.61	$1,506.69	$1,669.98	$1,833.27	$1,996.56	$2,226.56	$2,389.93



	0	1	2	3	4	5	6	7	8	9	10	11	12	13
90W LED	$598.37	$ 656.44	$714.50	$772.57	$ 830.63	$ 888.70	$ 946.76	$1,004.83	$1,062.89	$1,120.96	$1,179.03	$1,237.09	$1,295.16	$1,353.22
175W MV	$ 61.99	$ 179.51	$297.03	$476.54	$ 594.06	$ 711.58	$ 891.09	$1,008.61	$1,126.13	$1,305.64	$1,423.16	$1,540.68	$1,720.19	$1,837.71
175W HPS	$ 67.43	$ 184.95	$302.47	$419.99	$ 537.51	$ 604.94	$ 722.46	$ 839.98	$ 957.50	$1,075.02	$1,259.94	$1,372.49	$1,495.01	$1,612.53
175W MH	$ 66.79	$ 184.31	$301.83	$419.35	$ 603.66	$ 721.18	$ 838.70	$ 956.22	$1,140.53	$1,258.05	$1,375.57	$1,493.09	$1,677.40	$1,794.92

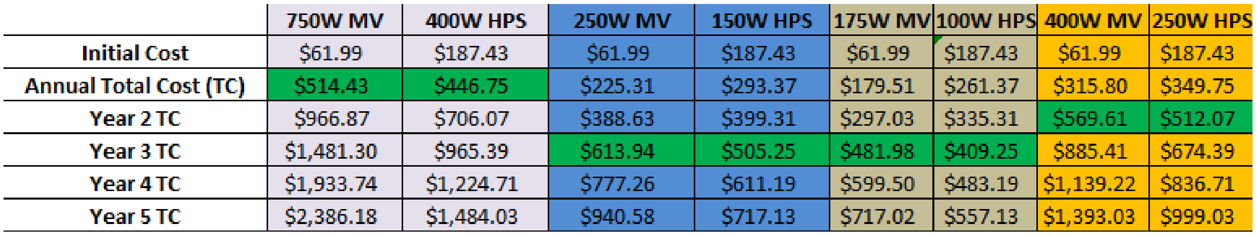
	0	1	2	3	4	5
750W MV	$61.99	$ 514.43	$ 966.87	$ 1,481.30	$ 1,933.74	$ 2,386.18
400W HPS	$187.43	$ 446.75	$ 706.07	$ 965.39	$ 1,224.71	$ 1,484.03

	0	1	2	3	4	5
400W MV	$61.99	$ 315.80	$ 569.61	$ 885.41	$ 1,139.22	$ 1,393.03
250W HPS	$187.43	$ 349.75	$ 512.07	$ 674.39	$ 836.71	$ 999.03

	0	1	2	3	4	5
175W MV	$61.99	$ 179.51	$ 297.03	$ 481.98	$ 599.50	$ 717.02
100W HPS	$187.43	$ 261.37	$ 335.31	$ 409.25	$ 483.19	$ 557.13

	0	1	2	3	4	5
250W MV	$61.99	$ 225.31	$ 388.63	$ 613.94	$ 772.26	$ 940.58
150W HPS	$187.43	$ 293.37	$ 399.31	$ 505.25	$ 611.19	$ 717.13

	750W MV	**250W MV**	**175W MV**	**400W MV**
Cobra Cut-off Cost	$120.00	$120.00	$120.00	$120.00
New Lamp and Wattage	400W HPS	150W HPS	100W HPS	250W HPS
Installation Cost	$67.43	$67.43	$67.43	$67.43
Annual Energy Cost of Old Lamp	$452.44	$163.32	$117.52	$253.81
Annual Energy Cost of New Lamp	$259.32	$105.94	$73.94	$162.32
Energy Savings per Light	$193.12	$57.38	$43.58	$91.49



	750W MV	400W HPS	250W MV	150W HPS	175W MV	100W HPS	400W MV	250W HPS
Initial Cost	$61.99	$187.43	$61.99	$187.43	$61.99	$187.43	$61.99	$187.43
Annual Total Cost (TC)	$514.43	$446.75	$225.31	$293.37	$179.51	$261.37	$315.80	$349.75
Year 2 TC	$966.87	$706.07	$388.63	$399.31	$297.03	$335.31	$569.61	$512.07
Year 3 TC	$1,481.30	$965.39	$613.94	$505.25	$481.98	$409.25	$885.41	$674.39
Year 4 TC	$1,933.74	$1,224.71	$777.26	$611.19	$599.50	$483.19	$1,139.22	$836.71
Year 5 TC	$2,386.18	$1,484.03	$940.58	$717.13	$717.02	$557.13	$1,393.03	$999.03