Life Cycle Assessment of Streetlight Technologies

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Executive Summary

The city council of Pittsburgh, PA will begin replacing 40,000 streetlights in 2010. Our team assessed four major streetlight technologies to aid the task force in their choice of light technology. Pittsburgh also began a pilot program in which approximately 150 new streetlights were installed in the Southside neighborhood.

Several other cities are considering a streetlight retrofit based on economics, light quality, and greenhouse gas emissions. These cities include Los Angeles, CA, Ann Arbor, MI, and Raleigh, NC. Los Angeles is working with the Clinton Climate initiative on the largest streetlight replacement to date of 140,000 streetlights. Currently, less than 1% of the streetlights in the U.S. have been replaced with newer technology. Pittsburgh has the chance to be an early adopter and is the first to complete a total life cycle assessment. The retrofit projects of other cities and the Department of Energy programs that assist them are described in Appendix A.

The impact assessment was a comparative life cycle assessment (LCA). Our LCA was performed on high-pressure sodium (HPS), metal halide (MH), induction, and light-emitting diode (LED) streetlight technologies and focused on the categories of global warming, ecotoxicity, and respiratory effects. These categories were selected for their relevance to climate change and to the historic concerns of air quality and industrial pollution in Pittsburgh.

Models were based on materials and prices found in data collected from sales companies, manufacturers, government documents, lighting professionals, and industry reports. We found the manufacture of induction and LED could have environmental impacts three times higher than HPS and MH. However, because induction and LED lights use half the electrical power of HPS and MH, they have a lower overall impact. Induction and LED also have lower maintenance costs because their lifespan is up to five times that of HPS and MH. We also found that adding wind-generated electricity can significantly lower the impacts of any streetlight technology. Induction lights last up to twice as long as LED and use slightly less electricity. However, the efficiency of induction lighting appears to have been maximized, while LED lighting efficiency is increasing rapidly.

Our recommendation is that the city of Pittsburgh use LED lighting. This will allow the city to realize immediate electricity savings and compete its retrofit with a single technology. We also recommend that the city require sufficient data from its vendors to continue the impact assessment and require the vendors to recycle the older lights and bulbs.

Abstract

A comparative life cycle assessment (LCA) of four major streetlight technologies (high-pressure sodium (HPS), metal halide (MH), induction, and light-emitting diode (LED) streetlights) was developed. The City Council of Pittsburgh may use the LCA in their decision to retrofit 40,000 HPS streetlights in an effort to save money and reduce greenhouse gas emissions [1]. Data was collected from manufacturers participating in a streetlight retrofit pilot program, government sponsored studies, industry sources, and lighting professionals. The hybrid analysis modeled products in SimaPro and used the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) life cycle impact assessment method. The analysis concluded that LED and induction technologies offer the lowest environmental impacts. These technologies are currently similar in their impacts, but LED technology is improving more rapidly [2]. It was found that the use phase impacts of the life cycle are at least ten times more significant than the manufacturing phase However, data collection difficulties restricted the amount of modeling that could be done. It is recommended that companies involved in a pilot program also provide useful LCA data with their lights.

Introduction

Recently, several cities have sought to reduce energy use and emissions by replacing their aging streetlights with newer technology. Cities such as Los Angeles, CA, Anchorage, AK, and Ann Arbor, MI have chosen LED technology. These cities and programs by the Department of Energy have taken on the responsibility of testing new lighting technology and replacing an unprecedented number of streetlights. These projects and studies, described in Appendix A, evaluate streetlight technology based on light quality, greenhouse gas emissions, and economic performance. As yet, no comprehensive life cycle analysis has been performed on streetlight technology to account for manufacturing, disposal and energy use impacts. Pittsburgh is contributing to the effort with the first life cycle assessment of major streetlight technologies.

The City Council of Pittsburgh is considering retrofitting 40,000 older streetlights in an effort to save money and reduce greenhouse gas emissions [1]. When the project began, it was thought that LED lighting would be the best choice of technology. However, as noted, before the Pittsburgh study, the analysis of streetlight replacement was limited. To determine the best lighting technology choice from an environmental perspective, our team at the Mascaro Center conducted a comparative life cycle assessment (LCA) of four major lighting technologies: high-pressure sodium (HPS), metal halide (MH), induction, and light-emitting diode (LED). These technologies were modeled and analyzed in terms of nine impact categories and focused on global warming, ecotoxicity, and respiratory impacts. These categories were selected for their relevance to the issue of climate change and to the historic concerns of air quality and industrial pollution in Pittsburgh.

The U.S. national average emissions per kWh were 0.718 kg CO_2 equivalent in 2005 [3]. It is estimated that there are 131 million street and area lights in the U.S. and 34.7 million of these are streetlights. The street and area lights are commonly run at full power for an average of 12 hours per night and consume 178.3 TWh of electricity per year. Thus, the approximate kg CO_2 equivalent output of the nation's street and area lights is over 128 million metric tons CO_2. It has been estimated "seven 1,000 MW coal plants and 44.7 TWh/yr could be avoided by completely switching to LED street and area lights. This is 5.8 % of all annual lighting electrical consumption" [4]. Streetlights are generally a municipal concern, while area lighting may be on private property. Multiplying this number by the ratio of streetlights to total lights, as shown in the equations below, gives 33 million metric tons of CO_2 and 11.84 TWh/yr for streetlights alone

[4]. This data is displayed in Table 1 below.

$$178.3\ TWh * 0.61\ kg\frac{CO_2}{kWh} = \ 128{,}376{,}000{,}000\text{ kg } CO_2$$

$$128{,}376{,}000{,}000\text{ kg}\frac{CO_2}{\{1000\text{ kg}\}} = 128{,}376{,}000\text{ metric tons } CO_2$$

$$128{,}376{,}000\text{ metric tons } CO_2\ * \frac{34.7}{131} = \ 34{,}004{,}940\ \text{ metric tons } CO_2$$

Table 1. Carbon Dioxide Emissions of Streetlights [4]

Number of street and area lights in U.S.	131 M
Number of streetlights in U.S.	34.7 M
Metric tons CO_2 per kWh	0.00718
Wh/ yr street and area lights	178.3 TWh
Metric tons CO_2 street and area lights	128,019,400
Metric tons CO_2 streetlights	33,910,482

The task force estimated a reduction in CO_2 emissions of 6,818 metric tons per year from streetlight replacement in Pittsburgh [1]. In addition to emissions, the task force estimated a savings of $1 million in energy costs and $700,000 in maintenance costs per year. It is noted that the Pittsburgh estimation of CO_2 emissions savings on a per streetlight basis is more conservative than DOE estimates [1].

Currently fewer than one percent of streetlights in the U.S have been replaced with LED technology [4]. Traffic lights and exit signs do use LED, but traffic lights and exit signs do not provide area illumination and require lower light intensity. Streetlights are more difficult to replace because they need to create more light than traffic and exit signs and allow visibility over a wide area.

Life Cycle Assessment

The life cycle assessment is based on the ISO 14040 standard, and includes a goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [5]. LCA has been used in many industries since the early 1990's to gage the environmental impact of the entire life cycle of a product including manufacture, use, and disposal. LCA is based on an inventory of the inputs of the raw materials, capital goods, factories, transportation, and energy and fuels needed to create a product. Figure 1 shows the life cycle stages. The input, modification, and emissions of energy and materials are known as process flows.

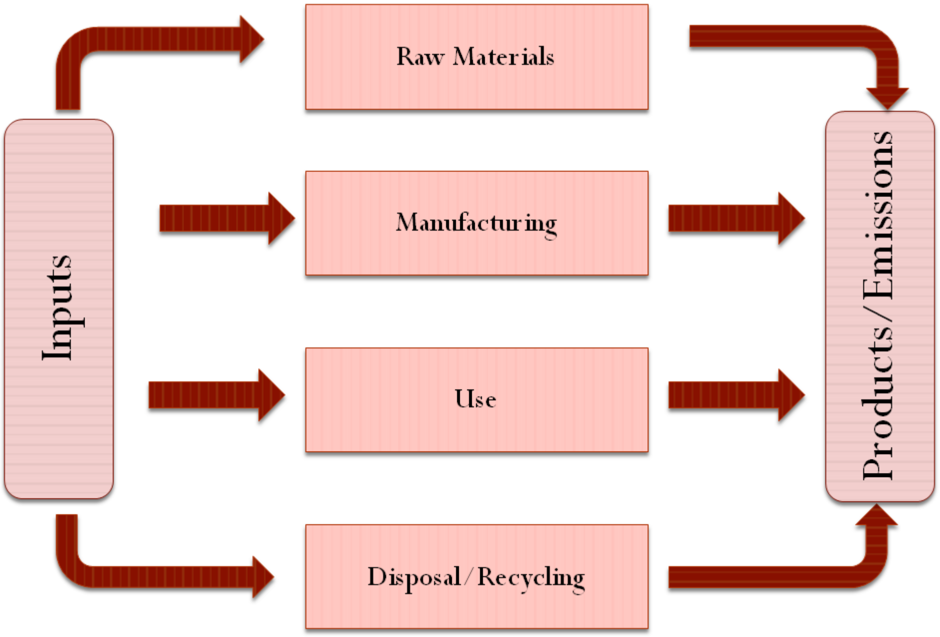


Figure 1. Life Cycle Stages

Inputs can be materials or energy and the infrastructure required to create them. Products and emissions are finished goods and material or energy. For example, plastic requires petroleum feedstock, which requires oil or natural gas wells, pipelines, and refineries before the plastic can be manufactured. Disposal of the plastic at the end of its useful life can create emissions from burning or ultraviolet degradation. The outputs of each process are assessed for impacts in specific categories. The sum of emissions in each category is used to judge the overall impact of the product. Several products can be judged against one another in a comparative LCA.

A product or life cycle phase may be modeled using the process or input-output (I/O) method. These methods are approximations of the use of a material or energy source based on large amounts of data collected by a third party from many sources. Models made from process methods are based on the amount of a specific material by weight. I/O methods are based on economic data and require the producer price of a product.

Streetlights are expected to create the most emissions of their life cycle during their use phase because they use a large amount of electricity, produced by burning coal, relative to the energy and materials used in production. In contrast, a personal computer requires more energy during the manufacturing phase than is expected to be used during the use phase. [6]

The collected data and results are presented in five sections: a streetlight primer, comparative LCA model, life cycle inventory, results, and discussion.

The streetlight primer explains current street lighting technology and operation. The work and results of several other cities is discussed as well as research efforts from the Department of Energy. A description of the Pittsburgh pilot program is given.

The comparative LCA section describes the goal and scope and the databases, modeling, and assessment methods used to evaluate the technologies. The lifecycle inventory section describes the data collected and the models built from the data using the chosen methods.

The impacts of the technologies in three impact categories are given in the results section. The technologies are compared on a one-to-one replacement with HPS lights, since they are the most common currently installed technology.

In the discussion section, important “hotspots” particular to specific technologies, such as toxic metals, are identified and their importance is discussed. We also discuss non-LCA issues such as color temperature and light quality, the difficulty of ensuring quality and reputation of vendors, glare, and dark-skies approval.

In Appendix M we provide a questionnaire to assist future assessments of lighting technology. Future assessments may be made to account for technology improvements and phased purchasing.

Street Light Primer

Streets were first illuminated with gas or oil lamps. In 1875, Pavel Yablochkov invented the carbon arc lamp and Thomas Edison improved on the lifespan and light quality of the carbon arc lamp with the incandescent lamp in 1879. Shortly before the turn of the century, there were more than 130,000 streetlights installed in the United States. These lamps operate by heating electrodes or a filament with an electric current, causing it to glow. Improvements in light output occurred through the twentieth century with the introduction of high-intensity-discharge (HID) lamps including the mercury vapor lamp in 1938 and the high-pressure sodium lamps, shown in Figure 2, in the 1970's. HID lamps create light by exciting a gas with an electric current passed between metal electrodes. Light is emitted when electrons move from high to low energy states, emitting a specific frequency, or color, of light. This wavelength produces the familiar orange glow of HPS lamps [4]. In spite of this unsatisfactory light color, HID remains the most common type of street light in use today; 90% of roadway lights are HPS or some other form of HID [7]. Incandescent and LED lighting are the only technologies that contain no mercury [8].

In areas of social or architectural significance where light color is important, HPS lamps are often replaced with metal halide (MH), shown in Figure 3, a similar HID technology that produces a wider range of wavelengths of light because there is more than one type of gas in the lamp. Induction lamps also produce a high quality of light and use an electric current to excite a gas, as in HID lamps. Induction lamps, shown in Figure 4, differ from fluorescent lamps in that the electric current is passed through the glass tube by inductance, rather than metal electrodes. The light from this gas then excites a phosphorous coating on the inside of the tube, and the light emitted from the phosphorus coating is used for illumination [4].

LED lamps, shown in Figure 5, are solid state electronics made of materials such as gallium arsenide, which emits light when charged with an electric current. The material of the LED varies among manufacturers and is undergoing technological improvements. The light emitted by the solid state electronic material strikes a phosphorous coating, which then emits the usable light. LED and induction lights both use the phosphorous coating to convert ultraviolet light into white light [4].

Figure 2. HPS Bulb

Figure 3. Metal Halide Bulb [9]

Figure 4. Induction Fixture [10]

Figure 5. LED Bulb [11]

Table 2 displays the percentage of installed street lights by technology. The largest group of lights is HPS, with MH not far behind. Note that of the four technologies considered in this study, LED street lighting had not, as of 2007, reached even 1% installation in the U.S. Incandescent, mercury halide, and halogen quartz (a high brightness incandescent) were not considered for this study [4].

Table 2. Installation of Streetlight Technology [4]

Technology	Percentage (%)	Number Installed
Incandescent	2	3,159,000
Halogen Quartz	8	9,917,000
Fluorescent	6	7,530,000
Mercury Vapor	13	17,675,000
Metal Halide	27	38,330,000
High Pressure Sodium	39	54,745,000
Total	100	131,356,000

Streetlight Operation

The majority of streetlights in the U.S., including those in Pittsburgh, are individually controlled by photocell. The photocell is mounted on the top of the light facing north and turns on the light at a preset level of darkness. Some municipalities have installed or are upgrading to systems that allow light levels to be controlled in specific areas or for certain time periods. For example, cities with a lighting "curfew" will set their lights to emit low light at dusk, dawn, and the middle of the night to save electricity when less light is needed because the sky is not fully dark or there are few people outside.

Maintenance of streetlights consists almost entirely of replacing spent bulbs. Lights controlled by photocell are not monitored remotely in Pittsburgh and are replaced when reported by citizens or noticed during regular inspections. Bulb replacement is performed by one or two workers in trucks**.** Two workers are shown installing a streetlight in Figure 6.

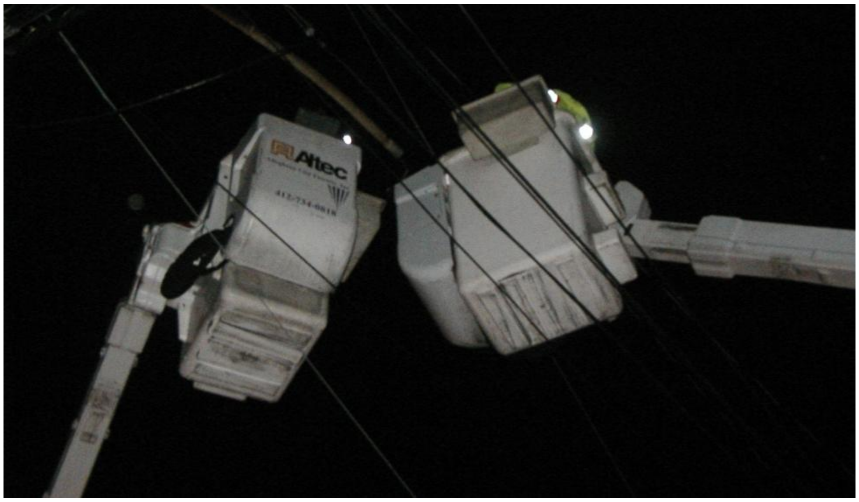


Figure 6. Trucks Used to Replace Streetlights [12]

Streetlights are designed to spread light in a pattern to cover the greatest amount of useful area with a constant amount of light. Designers focus light on the street instead of buildings or the sky with devices such as reflectors, shaped bulbs, and prismatic lenses, among others. Because the pattern is designed into the light fixture, there is limited opportunity for post-manufacture adjustment or focusing; therefore, streetlights work optimally when installed at the height and angle anticipated by the designer.

In Pittsburgh, existing streetlights generally share poles with electrical and telephone utilities. High voltage cables are strung at the top of the poles and telephone and lower voltage cables are hung below them at a distance calculated to minimize electromagnetic interference. The streetlight fixtures are mounted on a horizontal arm as low as possible below the high voltage cables, but still above the telephone cables. The sharing of poles reduces the cost of installation, but often results in less than optimal height and angle. A typical HPS streetlight installation from Pittsburgh's Southside neighborhood is shown in Figure 7**.**

Figure 7. Typical HPS Streetlight Placement [12]

Many cities, including Pittsburgh, have no lighting code to require minimum or maximum light levels. In Pittsburgh, a draft lighting code is under development.

As shown in Figure 8, streetlight fixtures consist of three components: housing, power supply, and bulb. The horizontal arm to which they attach to the pole is not considered a part of the streetlight. The housing contains the power supply and bulb, protecting them from the weather with a solid top and clear lens. The housing also contains mounting hardware that attaches the streetlight to the horizontal arm. Electrical power to the bulb is controlled by the power supply. The power supply is specific to the lamp technology, modifying the voltage and current from the utility line level to that required by the bulb. Gas lamps such as HPS, MH, and induction create less resistance as they warm with use and the power supply prevents the current from increasing and burning out the bulb. LED bulbs require a steady DC current. An LED streetlight contains approximately 100 small LED bulbs. HPS and MH contain one bulb and induction can have one to four bulbs [12] [13] [14].

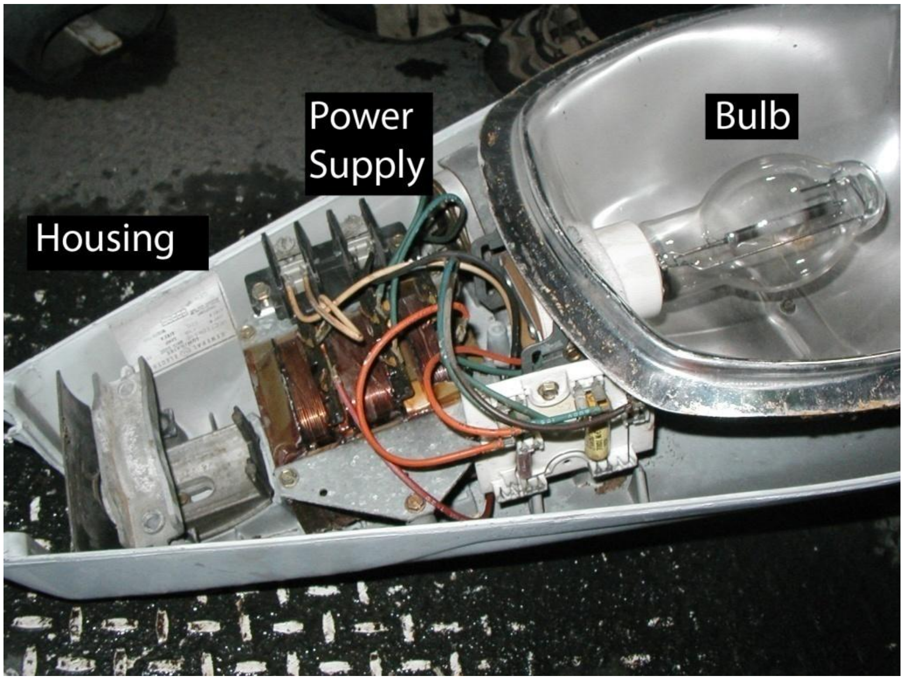


Figure 8. Typical HPS Housing [12]

The Pittsburgh Retrofit

The first step in Pittsburgh's retrofit is a nine-month pilot program. The streetlight initiative is a joint project between Councilman Peduto and the Mayor's Office. A task force has been assembled to provide guidance. The City issued a request for information in February 2009 for LED, induction, and metal halide manufacturers to submit three streetlights matching the following RFI specifications:

> Lighting fixtures must meet the following illumination specification: an average footcandle of 1 at grade in middle of roadway with a 4:1 ratio minimum [to be mounted on] Poles with a mounting height of approximately 25’ spaced approximately 150’ apart on a right of way of approximately 40’ to 50’ wide, with fixture arms for lamp head mounting [15].

In May 2009, installation of the submitted lights began in the Southside neighborhood in a one-to-one replacement with HPS. The Southside was chosen for its regularly spaced street grid and light poles. The streets between cross streets are each lit with three streetlights. One block was assigned to each submitting company and that company’s set of lights were installed on consecutive poles in that block. Of the 126 replaced HPS streetlights, 96 were 150 watts, 24 were 200 watts, and 6 were 100 watts. Therefore, this report assumes that each light submitted to the pilot program is approximately equivalent to a 150 watt HPS in terms of general area lighting ability. During installation, the crew recorded existing foot-candles directly under the light, existing wattage, replacement foot-candles, and replacement wattage. Due to the existence of extraneous light sources such as buildings and other streetlights, no attempt was made by our team to create or validate laboratory photometrics. Photometric verification is being handled by Mike Cherock, a task force member and lighting professional.

As noted in the introduction, the Pittsburgh project includes a full life cycle analysis of the environmental impacts of streetlight technology. Assisting greatly in this effort are the results of other cities and utilities pioneering the testing of advanced streetlight technology. These projects are summarized in Appendix A.

LCA Method

We conducted a comparative LCA of four major streetlight technologies: high-pressure sodium (HPS), metal halide (MH), induction, and light-emitting diode (LED) streetlights. The comparative LCA examined the potential environmental and health impacts of the process flows used to create several products. The life cycle consisted of four main parts: raw materials acquisition, manufacturing, use, and disposal, as detailed in the flow chart shown below.

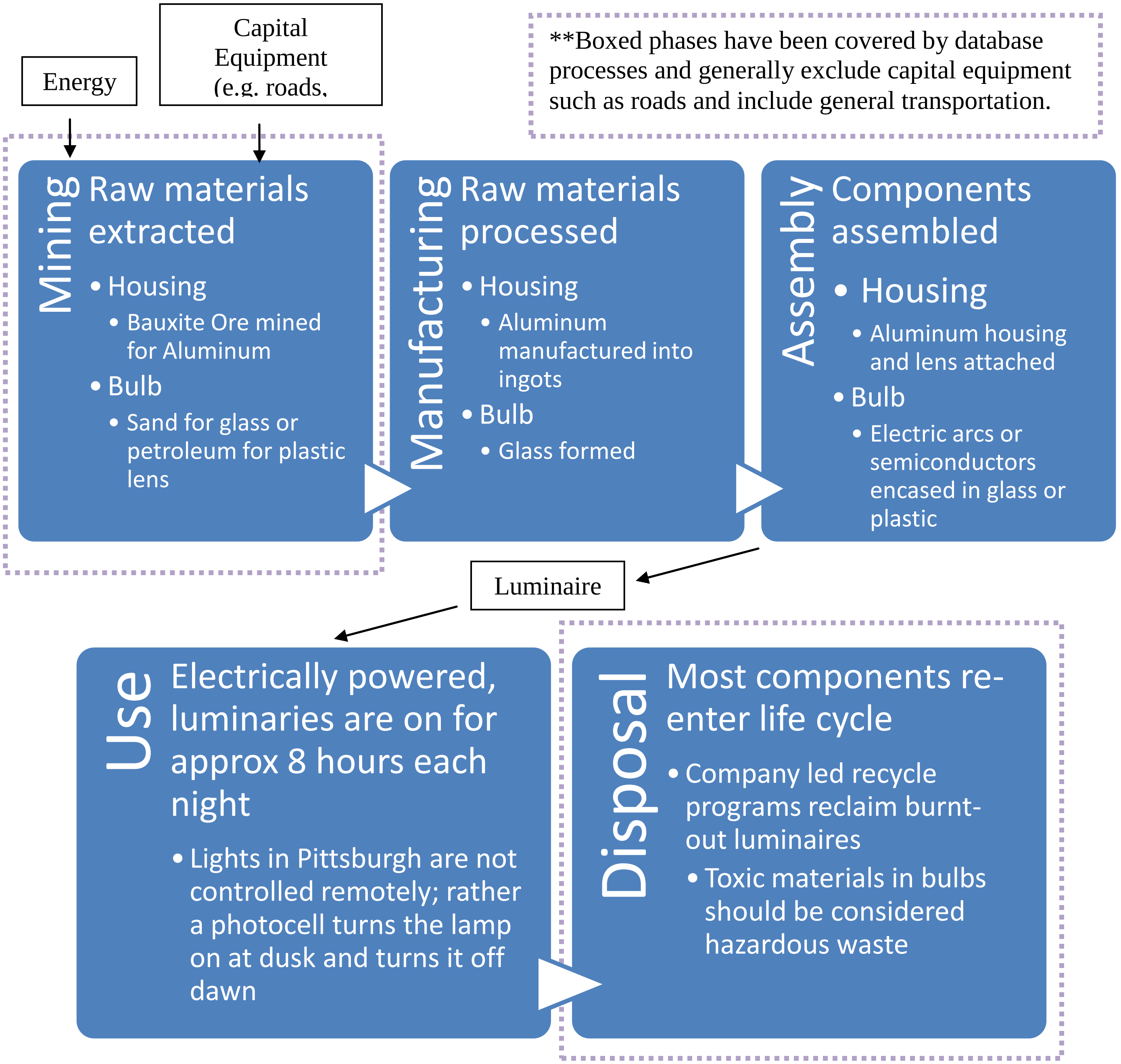


Figure 9. LCA Flow Chart

Methods are process-based, created with the input of materials, as shown above, Figure 1or input/output, created with the input of producer prices. For example, the production of aluminum is modeled as a process. Bauxite Ore is mined processed, and rolled into sheets. Those sheets are cast into shape as housings, used for a number of years as a streetlight, then, after disassembly, the aluminum may enter a second life cycle as part of another product. Processes, such as general metal manufacturing, were included in the assemblies. With the aid of databases, the impact of each material and process was evaluated in the categories global warming potential, ecotoxicity, and respiratory effects. These LCA results aid in making a more informed decision among differing technologies.

Methods

Goal and Scope

Our goal was to create a comparative life cycle assessment of street lighting technologies to inform the City in their decision-making process as well as cities involved in future lighting retrofits. An inclusive analysis is useful for comparing options that will be implemented on a large scale and over a long term. The scope of the assessment included raw materials acquisition, manufacturing, use, and disposal of housings, bulbs, and power. Figure 10 shows the life cycle phases and the LCA methods used to model them as well as the method sources.

Street lighting phase	Methodology & Tool	Sources	Database/Sector
Housing Manufacturing			
150W HPS GE Cobrahead Housing	Process LCA with SimaPro	Our weights and measurements	Databases: Franklin USA 98, ETH ESU 96, Zurich, Ecoinvent, Industry Data 2.0, IDEMAT 2001, USLCI
Generic Housing	Input-Output LCA with SimaPro	Company data	Sector: "Lighting fixture manufacturing" sector
LED Housing	Process LCA with SimaPro	Company data	Databases: Franklin USA 98, ETH ESU 96, Zurich, Ecoinvent, Industry Data 2.0, IDEMAT 2001, USLCI
Bulb and Ballast Manufacturing			
HPS Bulb	Input/Output LCA with SimaPro	Company prices	Sector: "Electric lamp bulb and part manufacturing" sector
MH Bulb	Input/Output LCA with SimaPro	Company prices	Sector: "Electric lamp bulb and part manufacturing" sector
Induction Bulb	Input/Output LCA with SimaPro	Company prices	Sector: "Electric lamp bulb and part manufacturing" sector
LED Bulb	Input/Output LCA with SimaPro	Company prices	Sector: "Electric lamp bulb and part manufacturing" sector
Electricity Use			
Wind	Process LCA with SimaPro	Allegheny City Electric test pilot data, company data	Databases: Ecoinvent
Coal	Process LCA with SimaPro	Allegheny City Electric test pilot data, company data; Database: Franklin USA 98	Databases: Ecoinvent
U.S. Average Mix	Process LCA with SimaPro	Allegheny City Electric test pilot data, company data; Database: Franklin USA 98	Databases: Franklin USA 98

Figure 10. Methodology of Modeling Phases

Our data came mostly from companies involved in the City's pilot test, as well as established companies in the lighting industry not participating in the pilot. The wattage of the lights being replaced for the pilot varied from 70 to 200W, and the wattage of the test lights being installed varied over a larger range. An example of these discrepancies is that a 100W HPS light may be replaced with a 60W LED light from one company or a 65W induction light from another. For this assessment, we chose the equivalent of the most common city light, a 150W HPS streetlight, as our functional unit. The longest lifespan of any technology was the lifespan of induction bulbs which was 100,000 hours and this lifespan was chosen as a second functional unit. All models were scaled to match the citywide use of 40,000 streetlights over a 100,000 hour lifespan.

Since the lights varied greatly in their components, weights, and materials, each cross section of street lighting technology provided trends that made the creation of ranges possible. The life cycle assessment software, SimaPro, was used as the modeling tool. As shown in Figure 10, materials were selected from Franklin USA 98, ETH ESU 96, Zurich, Ecoinvent, Industry Data 2.0, IDEMAT 2001, USLCI, and USA I/O database. Most of these databases include mining, around half include capital equipment, and all include transportation to some degree.

The U.S. I/O database needs special attention as it is developed from a matrix of cross-sector purchases, making it more applicable while at the same time more difficult to extract specific data from. I/O is generally found to over-estimate impacts while process databases underestimate [16]. This is because I/O calculates impacts based on monetary input across all economic sectors utilized the production of the product. This includes advertising, real estate, and finance; sectors not generally included in process databases. Since the I/O model is based on the 1997 United States economy, we adjusted current prices quoted by manufacturers to 1997 by upward by 26% to account for inflation [17]. The wholesale markup was calculated as 162% in the “other manufacturing” sector from a study reported in an Organisation for Economic Co-operation and Development (OECD) report [18].

The use phase is expected to contribute most to the environmental impact because of the long-term use of streetlights. To communicate the influence of electricity choice, we propose three scenarios of energy generation: 1) pure renewable energy (wind), 2) pure coal, and 3) U.S. average. The U.S. average was calculated from the fuel mix used in U.S.A. utilities and includes coal, natural gas, petroleum, hydropower, nuclear, wood, and other renewable sources. Electricity data was from the Franklin database [19].

Disposal is often addressed by recycling a percentage of the light fixture, and this will apply to streetlights as well. Housings, made of metals, and parts of the bulbs are all recyclable, so it was assumed that equal amounts of materials between technologies would be recycled. We suggest that companies submitting proposals to the City be required to offer a return program. Since the materials themselves vary, as does the manner in which different databases address waste treatment, disposal was not included in our assessments.

The impact assessment was performed with TRACI through SimaPro. TRACI, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, focuses on the U.S. through nine inclusive categories. Our analysis focuses on greenhouse gas contributions and also on impacts that were of importance to the City, including respiratory effects and ecotoxicity.

Life Cycle Inventory

Regardless of technology, each streetlight is composed of many parts. As seen previously in Figure 8, the main components of a light include a housing, bulb, and power supply. The production of the three main components specific to HPS, MH, Induction, and LED technologies was modeled in SimaPro. Electricity consumption was also modeled using SimaPro to compare the use phase of the four technologies. The modeling of each of these components and the use phase are discusses in detail in the sections below.

Bulbs

Each lighting technology uses a different bulb and each of these bulbs contains different chemicals and materials that are potentially harmful to the environment. For example, HPS bulbs contain mercury and lead [20]**.** Although the amount of mercury contained in one bulb is not considered dangerous, the amount contained in the 40,000 lights the City of Pittsburgh will replace is a hazardous waste issue. MH and induction bulbs also contain mercury, and MH bulbs contain iodine and other toxic chemicals [21]. LED bulbs do not contain as many of these harmful materials but the manufacturing process is energy intensive [6].

We were unable to obtain data on the production of the HPS, MH, induction, and LED bulbs such as the weights of specific materials used to make the bulbs or information concerning the manufacturing processes. The input-output database in SimaPro aided us in modeling bulbs as it requires only prices. We selected the 'Electric lamp bulb and part manufacturing' sector (sector number 335110) for the HPS, MH, and induction bulbs. This sector contains information pertaining to the production of light bulbs, including incandescent filament lamps, vapor lamps, and fluorescent lamps in addition to other electric bulbs. The LED bulb was modeled using the "Semiconductors and related device manufacturing" sector (sector number 334413). LED prices are highly uncertain. The average price was $0.10 per LED [22]. It was felt that this price was a low estimate since it implied that each fixture only contained $9.20 worth of LEDs, assuming the average of 92 LEDs per fixture described above. Two more LED models were created using a total LED price of $250.00 and $322.00 based on our estimates from fixture prices. These three models were used to create a bounding range to cover the uncertainty. The dollar amount entered for each of the models was the price, in 1997 dollars, of all of the bulbs needed to last the same lifetime multiplied by 40,000 to represent all of the fixtures in Pittsburgh. Table 3 below displays the prices used in the models.

Table 3. I/O Bulb Modeling [23]

Technology	**Cost per bulb ($)**	**Bulbs per 100,000 hours**	**Scaled to city**	**Total Price (million $)**	**1997 Total Price (million $)**
HPS	12.39	4.17	40,000	2.07	1.53
MH	27.29	8.28	40,000	9.04	6.69
Induction	280.00	1.0	40,000	11.2	8.29
LED	9.20	1.7	40,000	0.626	0.463
LED	250.00	1.7	40,000	17.0	12.6
LED	322.00	1.7	40,000	21.9	16.2

As shown in column three of Table 3, the four bulb technologies have different lifetimes. To make a one-to-one comparison of the bulbs, we scaled each to the lifespan of the longest-lasting bulb, an induction bulb. For example, one HPS bulb will need to be replaced numerous times in only one lifespan of an induction bulb. Figure 11 below compares the average lifespan of a bulb for each of the four technologies.

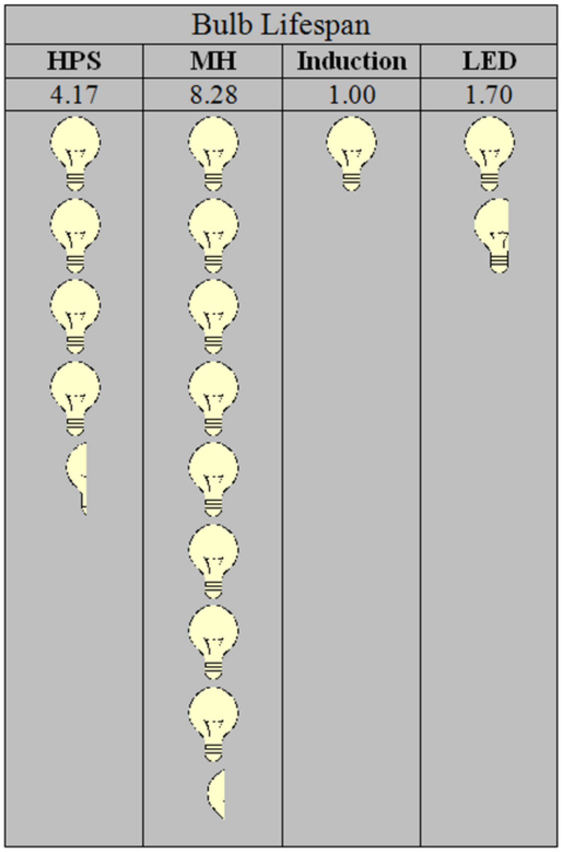


Figure 11. Bulb Chart [21]

As shown in Figure 11, induction bulbs last the longest, followed closely by LEDs. The lifespan of HPS and MH are the shortest, with MH bulbs burning out the quickest at 8.28 times the rate of our base, the induction bulb.

We built one process-based bulb model. This was an LED bulb model based on the Ecoinvent System Process “Light emitting diode, LED, at plant/GLO S” based on the weight of an average LED bulb, and the Ecoinvent “Production efforts, diode.” The weight was scaled to match bulbs per fixture, citywide usage, and a 100,000 hour lifespan. The weight data can be seen in Table 4.

Table 4. Process Model for LED [23]

Weight per LED (g)	**LEDs per fixture**	**Bulbs per 100,000 hours**	**Scaled to city**	**Total Weight (kg)**
0.24	92	1.7	40,000	1,501.44

Ballasts

The ballast of the streetlight is the power supply. Initially, the ballasts were made of large amounts of copper and other metals, such as the one found in our weighed GE Cobrahead. These are called magnetic ballasts and are being removed from production by most manufacturers. Current ballasts are electrical ballasts, and they are quite different from magnetic ballasts [21]. Information on the manufacturing of electrical ballasts is scarce. Further, the input-output method did not contain a sector applicable to electrical ballasts. Since all four lighting technologies require electronic ballasts, we assumed the ballasts were constant and did not include them in the LCA model.

Housings

The housing of a streetlight is the casing that protects the bulb and power supply; it is built to last for many years and in all weather. A typical housing includes an outer covering, lens, and bracket that attaches to the pole arm. There were many options in the way the housing could be represented due to the differences between process-based modeling and input-output modeling.

The housing of the most common technology, high-pressure sodium, was modeled first. Allegheny City Electric provided an HPS GE 150W Cobrahead streetlight after a demonstration of one Southside street light test pilot installation. The model for this housing is based on data collected by inspection of the streetlight. This is in contrast to later models built on data sent by manufacturers.

The Cobrahead was disassembled; each component was weighed and its material type was determined. The results can be found in columns 1, 2, and 3 in Appendix B. It was possible then to model the housing using the process-based method. In SimaPro, we created a new assembly by selecting the different materials from the Cobrahead and entering their weights. The processes we selected and the databases used can be seen respectively in columns 4 and 5 of the table in Appendix B. Due to our uncertainty of the manufacturing process and its proprietary nature, we entered a general metal working process to account for the manufacture of all the metals in the fixture. This process, from the Ecoinvent System Process database, is called “Metal product manufacturing, average metal working/RER S.” We added the weights for all of the metals in the fixture and used this sum (4,495.66 grams) as the weight needed for the manufacturing process.

Unlike the HPS fixture, we lacked a physical LED fixture. The materials used in the model were from lists sent by various manufacturers. Unfortunately, the level of detail in each list fluctuated; some were nearly complete while others were minimal. Additionally, the housing of LED fixtures, like any new product, varies greatly. Therefore, we did not have a standard to model as in the case of the HPS GE Cobrahead housing. Instead, we developed four different LED housing models. We created two process-based models from the most complete company material lists we received, which were from XUS and Appalachian Lighting Systems, Inc. (ALSI). The two models were made in a very similar fashion to the HPS housing by selecting materials from existing databases in SimaPro. Like the HPS fixture, we also included some general manufacturing processes such as metal forming and wire drawing. The materials lists from XUS and ALSI, along with the SimaPro models, can be seen in Appendices C and D, respectively.

The other two models were created using the less detailed LED housing material lists. All of the lists sent by companies were compiled into one spreadsheet. Next, the list was sorted by component name and material. Each sorting produced a range, the highest of which we assigned to the “high” category and likewise for the “low” category. For example, there were five material sheets with ‘heat sink’ listed as a component. The heat sink with the highest weight was assigned to the “high” category and the heat sink with the lowest weight was assigned to the “low” category. These two LED housings were also represented using process-based models in SimaPro, and many of the same materials and SimaPro processes were selected for both the high and low model, with only the weights differing between the two. The LED High and Low models can be seen in Appendices E and F, respectively. By creating four LED fixture models and applying a TRACI impact assessment to each, we were able to create an impact range and specify an average, as well as a high and low bound.

With the housing models for HPS and LED complete, metal halide and induction housings posed a challenge. We were unable to obtain detailed data for these housings and therefore could not create a process-based model for them. The best alternative was to use the lighting fixture sector in the economic input-output database. I/O requires only the price of the housing. In the Industry Group List "Lighting, Elec. Components, Batteries, and Other", there is a "Lighting Fixture Manufacturing" sector (sector number 335120) that includes street lighting fixtures. Since most housings of lighting fixtures are very similar and the use phase is expected to dominate the other phases, we assumed that one of the housing models made (either HPS, LED, or the generic housing made in I/O) would closely describe the MH and induction housings. For the generic I/O model, we entered the average price for one unit in 1997 dollars which was $226.47 [21]. This price was found using the adjustment rate of 26% mentioned earlier.

The five process-based models are each representations of one streetlight. These results were multiplied by 40,000 afterwards to get the values reported in this paper. For the input-output generic housing model, the results were also scaled by 40,000 to get the values for emissions for the entire City.

Electricity

We developed three electricity models, found in Table 5. The first scenario assumes 100% of the electricity was generated by wind power. The specific process that was selected is similar to a plant using wind turbines such as those found in Somerset, near Pittsburgh. The second scenario is a worst case scenario of electricity being produced 100 percent by coal. Finally, a model between these two extremes was selected, that is, the U.S. average electricity mix. We ran each of these three scenarios for each of the four technologies.

Table 5. Electricity Scenario Description

Electricity Source	**SimaPro Process**	**Database**	**Description**
Wind Power	Electricity, at wind power plant 2MW, offshore/OCE S	Ecoinvent System Process	Includes the operation of a wind power plant with the necessary change of gear oil
Coal	Electricity, hard coal, at power plant/US S	Ecoinvent System Process	Information pertaining to the 2004 electricity production at hard coal power plant of the 8 modeled U.S. regions
Average Mix	Electricity avg. kWh USA	Franklin USA 98	Fuel consumption pertaining to the generation & delivery of an average kWh in the USA

In addition to the electricity source, the kilowatt hours used by the technology must be estimated. The kilowatt hours that a lighting technology would use over 100,000 hours are calculated in Table 6. Wattages were estimated from company data and from data collected during the pilot study.

Table 6. kWh of Electricity for 40,000 Lights [23, 24]

	Wattage	**Lifespan (hours)**	**Wh (billions)**	**kWh**	**KWh*40000 (billions)**
HPS	150	100,000	15.00	15,000	600.0
MH	162.9	100,000	16.29	16,290	651.6
Induction	109	100,000	10.90	10,900	436.0
LED	105	100,000	10.50	10,500	420.0

Each model began with the bare minimum value of 1 kWh. After running the model through SimaPro, the results were multiplied by the number found in the last column of Table 6. This represents the number of bulbs needed for 100,000 hours of life then scaled to the 40,000 streetlights in Pittsburgh.

Results

We quantitatively modeled the housings and electricity use. Since data availability for the bulbs was limited, we qualitatively discuss reported environmental impacts. The environmental impacts in terms of global warming, ecotoxicity, and respiratory effects are discussed below. For other environmental impacts, see Appendices G-L.

Global Warming

The manufacturing processes of materials produce different gases which have global warming potential. All emissions are expressed in the kilograms of CO_2 that would produce the same global warming effect.

Bulbs

LED bulbs have similarities with the semiconductors used in computer manufacturing. Reports on the production of computer chips stress that more energy is used in the manufacturing phase than in the use phase [25]. It was found that due to the range of LED prices, the global warming impacts of LEDs varied widely. It was noted that induction and the LED average bulb had similar estimated impacts and that the older technologies, HPS and MH, had lower impacts. This data is shown in Figure 12. It is noted that the range of LED impacts encompasses the range of all other bulbs. This is due to the use of estimated prices. The width of the range should suggest caution when using the results.

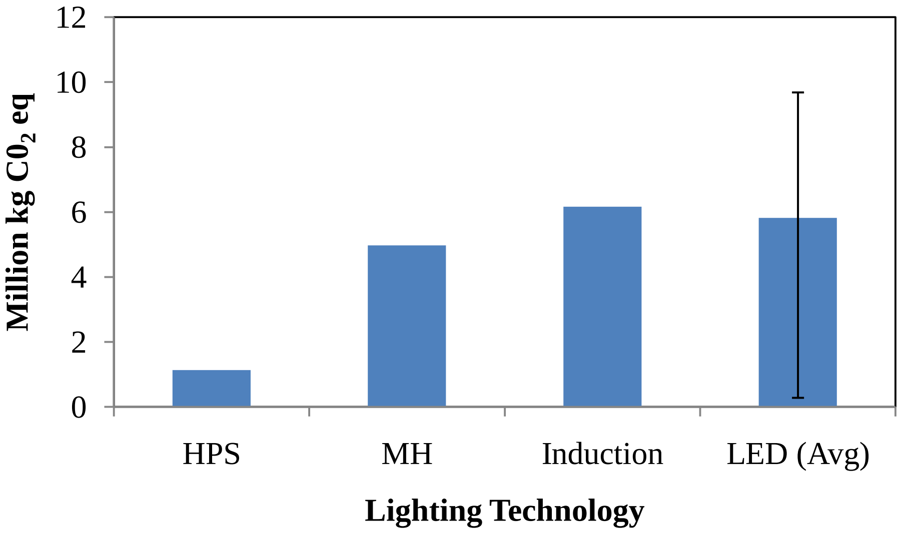


Figure 12. Global Warming Impacts of Bulb Manufacturing

Housings

The results of the modeling on global warming are shown in Figure 13. As mentioned earlier, the environmental impact of the LED housing was averaged from four housings. The average LED housing is presented here.

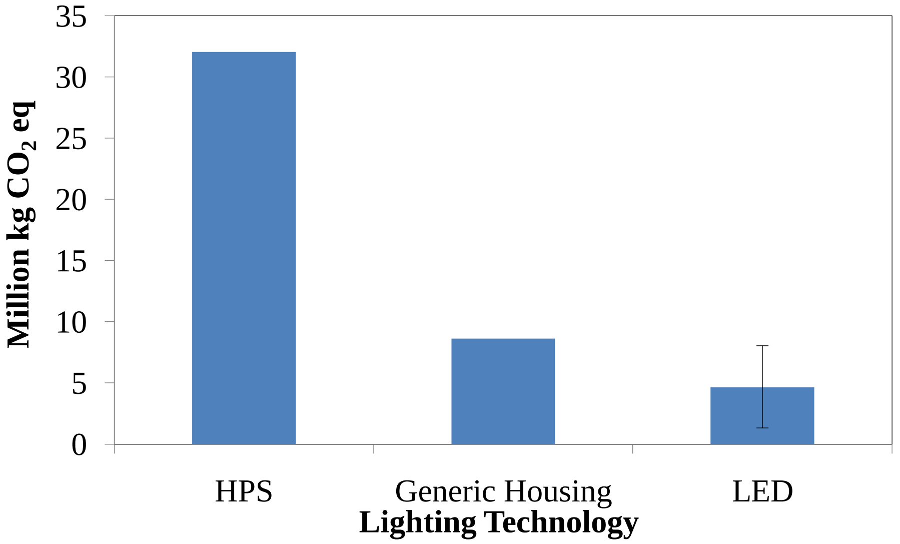


Figure 13. Global Warming Potential of Housings

The total weights of the modeled housings are given in Table 7. It is noted that though the global warming high and low effects vary by a factor of eight, the weights are quite similar. It was shown that the production of aluminum and electronics in general were major contributors to CO_2. The HPS housing had a total of 801 kg CO_2 equivalent emissions. It is also noted that of these emissions, the 110.1 g assigned to the process "Aluminum, cast, semi-permanent mold (SPM), at plant/kg/US" alone produced 762.95 kg CO_2 equivalent, which is more than the I/O model total of 215.60 kg CO_2 equivalent. This process is from the USLCI database. The next highest was 22.21 kg CO_2 equivalent from "Aluminium alloy, AlMg3, at plant/RER S" of the Ecoinvent System Process database which was assigned 3,811 grams. The housing models with processes and assigned weights can be found in Appendices B-F.

Table 7. Total Weights of Housing Models

Technology	Weight (kg)
HPS	7.27
LED High	15.04
LED Low	6.88
ALSI	8.17
XUS	4.93
Avg LED	8.75

Other cast aluminum processes from the Ecoinvent System Process database were tried in the same HPS model and TRACI calculated a much lower CO_2 equivalent emission, on the order of 0.046 kg CO_2 equivalent, a difference of four orders of magnitude. Of the three cast aluminum processes in the USLCI database, two gave similarly high readings, and one, the lost foam process, gave 0.369 kg CO_2 equivalent. It was found that the processes resulting in low CO_2 equivalent readings also gave lower readings in all other TRACI categories, although this is not always the case in general.

The USLCI database also noted that it was still subject to review. However, since it was the only U.S. specific database, and because the housing was expected to contribute minimally to the overall environmental impact, the high USLCI process was used for the final model. It is noted that this produces as high an impact as is likely and represents a worst-case scenario.

The LED housings that made up the average produced much less kg CO_2 equivalent, with a total of 116 kg CO_2 equivalent. Major contributors are: “Printed wiring board, surface mounted, unspec., solder mix, at plant/GLO S up to 48 kg/light”, “Aluminum alloy, AlMg3, at plant/RER S up to 36 kg/light”, “Integrated circuit, IC, logic type, at plant/GLO S up to 22 kg/light”. The average total weight of these housings is 8.75 kg, which is more than the HPS housing which has far higher CO_2 equivalent emissions.

Components that produced the least CO_2 were wire, polyurethane, and rubber. Note that this is due to the process chosen and also the amount of the material assigned to each process. Table 8 gives an overview of materials and their relative contribution to kg CO_2 equivalent.

Table 8. Global Warming Impacts of Housings

HIGH	aluminum, printed circuit boards,
MEDIUM	glass, steel, galvanized steel, ceramics,
LOW	plastics and wire

Electricity

The electricity use of each lighting technology was found to create the most significant environmental impact over the lifetime of the fixture. As described in the modeling section above, we created three electricity use models: 100% wind power and 100% coal power from the Ecoinvent System Process database as well as the U.S. average electricity mix from the Franklin USA 98 database.

Figure 14 below shows the results from running the four competing technologies through TRACI with three different electricity generation models. Results are the effects on global warming.

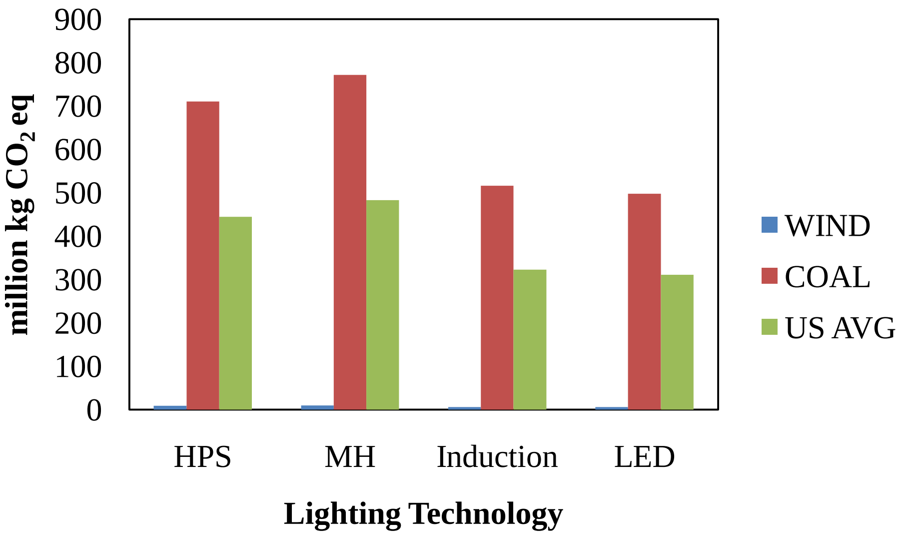


Figure 14. Global Warming Emissions Graph – Use Phase

As shown in Figure 14, generating electricity by coal has the most adverse effect in terms of global warming, despite which technology is chosen. Generating electricity solely from wind power is the least harmful in terms of CO_2 emissions, with the U.S. average coming in between the other two options. From these results, it seems that generating electricity from wind power will release the smallest amount of CO_2 equivalent to the environment despite which technology is chosen. Therefore, a municipality could reduce emissions to the environment by using wind power instead of coal. This generation method would reduce global warming impacts independent of the selection of lighting technology.

However, we are most interested in seeing which lighting technology is best for the environment from a global warming perspective. To look at these results, we decided to look solely at emissions from each technology by producing electricity from the U.S. Average mix. Figure 15 below shows the same results as Figure 14 above, but removes the wind and coal generation bars to show a better, more simplified view of the emissions from competing technologies in terms of the U.S. Average mix.

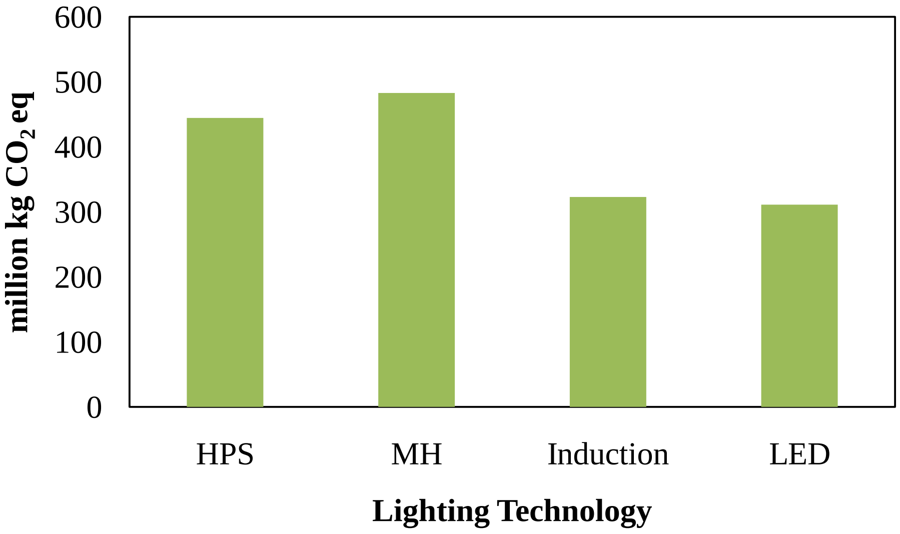


Figure 15. CO_2 Emissions via U.S. Average Electricity Mix – Use Phase

Figure 15 indicates that MH technology releases the most kilograms of CO_2 equivalent to the environment. This technology is followed by HPS, induction, and finally LED technology. While LED appears to be the most environmentally friendly option of the competing technologies, induction is a close second and is only slightly higher than LED. Both of these newer technologies have lower emissions than the older technologies, high-pressure sodium and metal halide, in terms of global warming potential from electricity use.

Ecotoxicity

The measure of ecotoxicity is based on equivalence to 2,4-D in kg. This chemical is a very commonly used herbicide [26].

Bulbs

High intensity discharge lamps, which include high-pressure sodium and metal halide lamps, contain a vapor of chemicals: xenon or argon and mercury. Average mercury content is 15mg per HPS and MH bulb, and 6 mg per induction bulb [27]. Though generally considered non-hazardous in such small amounts, lamps containing mercury should be regarded as hazardous in a city-wide, 40,000 light retrofit. While such hazards are not present in LEDs, numerous chemicals in the manufacturing process of semiconductors are known carcinogens or pose other health risks, though occurring in "clean rooms" said to be cleaner than hospital operating rooms [28]. However, the health impacts of these plants have been under scrutiny due to worker safety cases, so the improvement of worker safety at these plants needs to occur on multiple levels as LED use increases. This data is shown in Figure 16. The range of LED impacts encompasses the range of all other bulbs. This is due to the use of estimated prices. The width of the range should suggest caution when using the results.

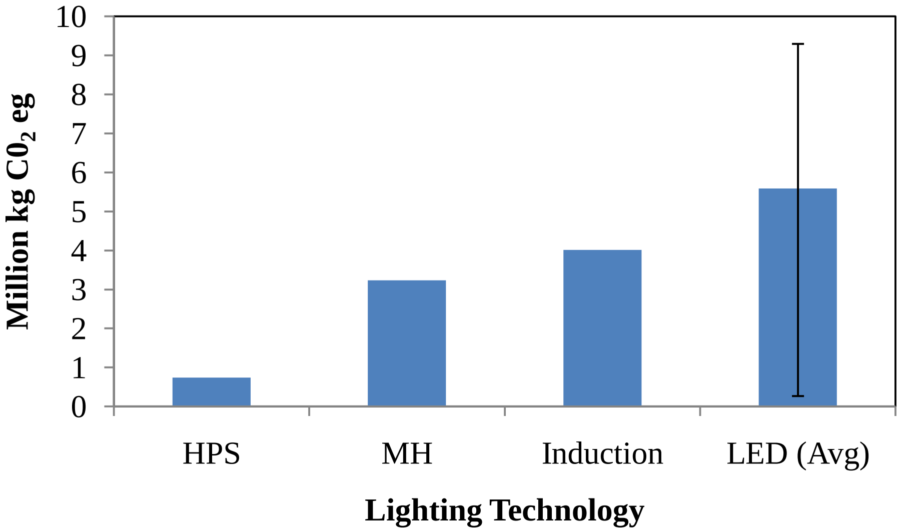


Figure 16. Ecotoxicity of Bulb Manufacture

Housings

As in global warming impact, the ecotoxicity impact of the housings modeled from LED data ranked higher than the other housings. However, it is noted that the greater ecotoxicity of LED housings was due to the inclusion of printed circuit boards. As mentioned, the models used to create an average LED model were based on data sheets sent by the manufacturers and it was not always clear if the manufacturer included components such as power supplies and other circuitry in with the housing materials. Therefore, a maximum of materials from the data was included in the LED High model, and a minimum in the LED Low model. The lower end of the LED error bar is lower that the HPS model and not much higher than the I/O model. Both the HPS and I/O model specifically exclude power supplies. For comparison, the total ecotoxicity results are shown in Figure 17.

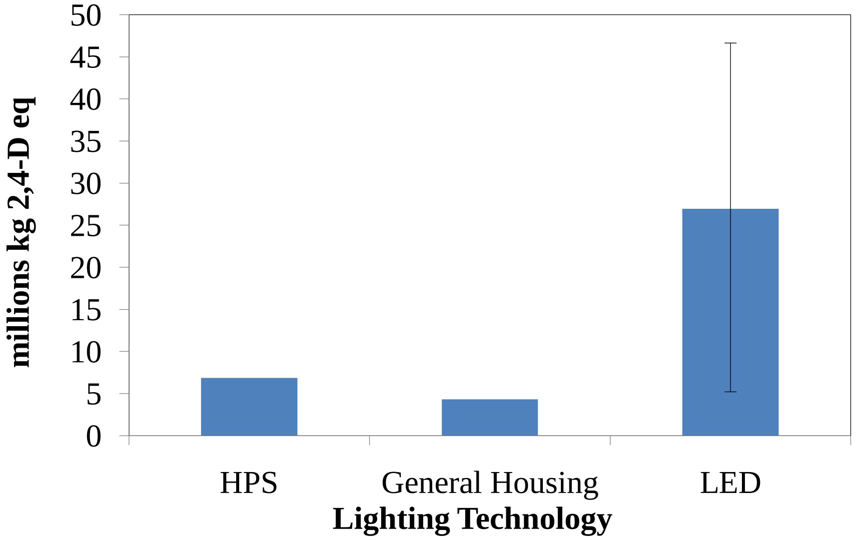


Figure 17. Ecotoxicity of Housings

Inspection of several streetlights showed that housings are much the same in material types and amounts regardless of the lighting technology inside. The low ecotoxicity scores of housing models built specifically to exclude any type of technology-specific power supply materials, and the high ecotoxicity of housings suspected to contain at least some power supply materials, further validates that assumption.

Inspection of the ecotoxicity scores of individual processes within each housing model also confirms this theory. The largest contributor was printed circuit boards and integrated circuits. It is noted that these were included in some models simply to follow the manufacturer’s materials list. Table 9 below displays the processes for each housing model producing the most ecotoxicity. Note that the ecotoxicity of a single process of three LED housings is larger than that of the entire I/O housing because these processes are printed circuit boards or integrated circuits. Note also that aluminum in the HPS housing, which weighs seven times the heaviest printed circuit board, produces 18% of the board's ecotoxicity.

Table 9. Housing Components with High Ecotoxicity

Technology	**Process**	**Weight (kg)**	**kg 2,4-D eq**
HPS	Aluminium alloy, AlMg3, at plant/RER S	3.8113	75.08
LED High	Printed wiring board, surface mounted, unspec., solder mix, at plant/GLO S	0.194	401.44
LED Low	Printed wiring board, surface mounted, unspec., solder mix, at plant/GLO S	0.194	401.44
ALSI	Integrated circuit, IC, logic type, at plant/GLO S	0.0215	219.48
XUS	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S	0.263	84.92

Electricity

Figure 18 below shows the results from the four competing technologies with three different electricity generation models. Results are the environmental effects in terms of ecotoxicity.

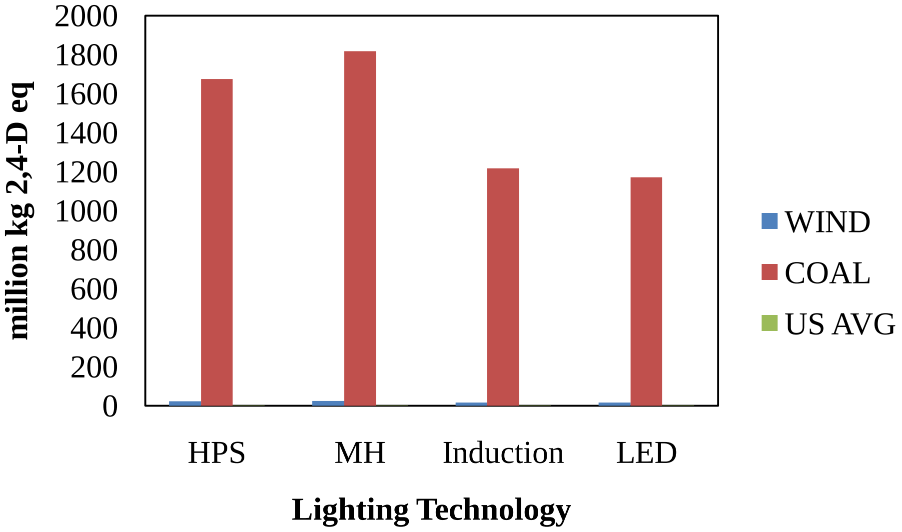


Figure 18. Ecotoxicity Emissions

Figure 18 shows that the effects in terms of ecotoxicity are significantly higher for each technology when the electricity is generated from coal. In fact, coal generation dominates the chart and the other generation methods, wind power and the U.S. average mix, are barely visible. It appears that just as in the global warming category, it is best to generate electricity from methods other than coal power. In terms of ecotoxicity, the U.S. average mix emits fewer toxins than wind or coal power because it includes natural gas, nuclear, and hydroelectric power. The construction of the wind turbines blades, made from carbon fiber, may be the cause of the ecotoxicity impacts of wind power.

To compare the actual technologies in terms of electricity use and ecotoxicity, we used the U.S. average mix results which are shown in Figure 19.

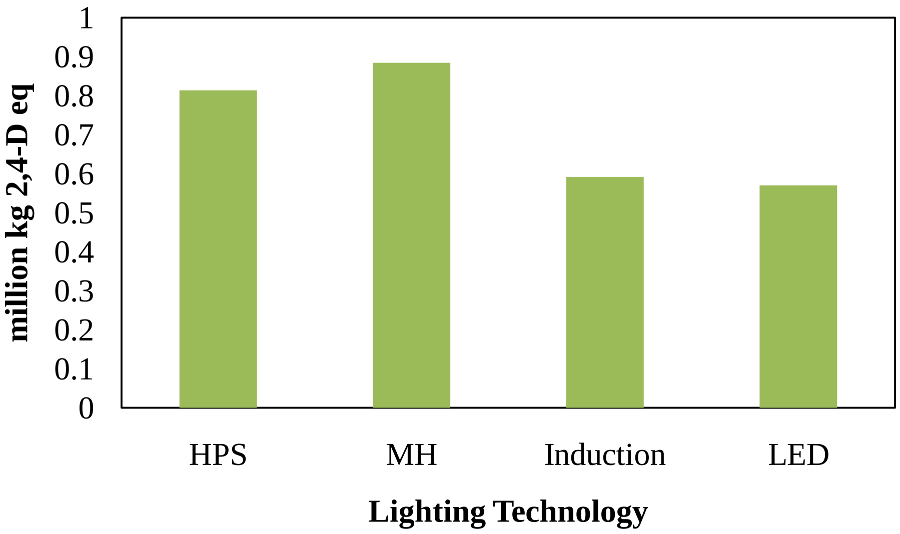


Figure 19. 2,4-D Emissions via U.S. Average Electricity Mix

Metal halide technology releases the most ecotoxicity emissions to the environment, followed closely by high-pressure sodium. The next worse is induction technology, and then LED. The newer technologies once again show that they use less electricity than the older technologies, and therefore produce fewer emissions in terms of ecotoxicity.

Respiratory Impacts

The measure of an emission's respiratory impact is based on the equivalence of particles in that emission to particles designated as "fine". These are particles of less than 2.5 microns in diameter [29].

Bulbs

It is thought that the higher energy required for the manufacture of LEDs accounts for the fact that their respiratory impacts are higher than older technologies. However the lower wattages of LED and induction will require less energy generation during their lifetimes. The respiratory impact of bulb manufacture is shown in Figure 20. The range of LED impacts encompasses the range of all other bulbs. This is due to the use of estimated prices. The width of the range should suggest caution when using the results.

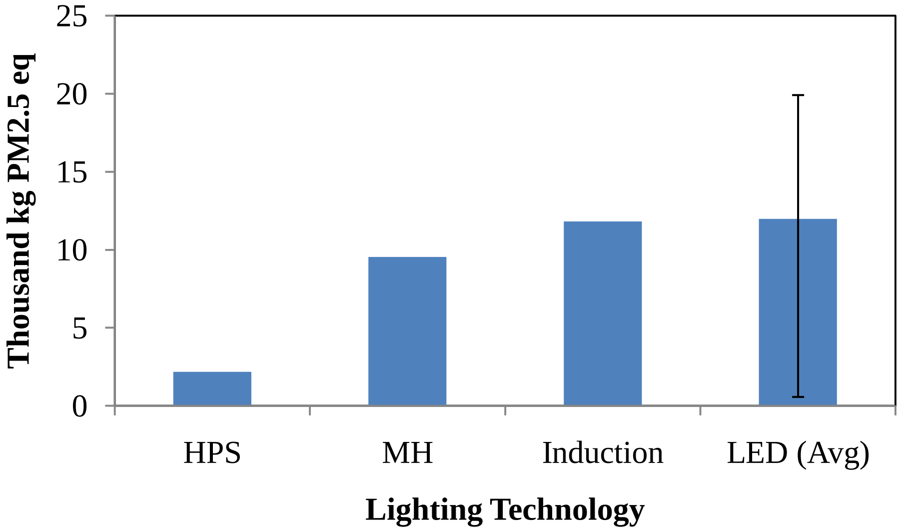


Figure 20. Respiratory Impacts of Bulb Manufacture

Housings

Aluminum and electronic processes were leading causes of respiratory shown in Figure 21. Unlike ecotoxicity, printed circuit boards and integrated circuits do not, as single processes, contribute more to respiratory effects than another complete housing model. The respiratory impact of any single process in the LED housings was below the total effects of the I/O housing. The greater impacts in this category from the HPS housing help to confirm its choice as a representative worst-case housing.

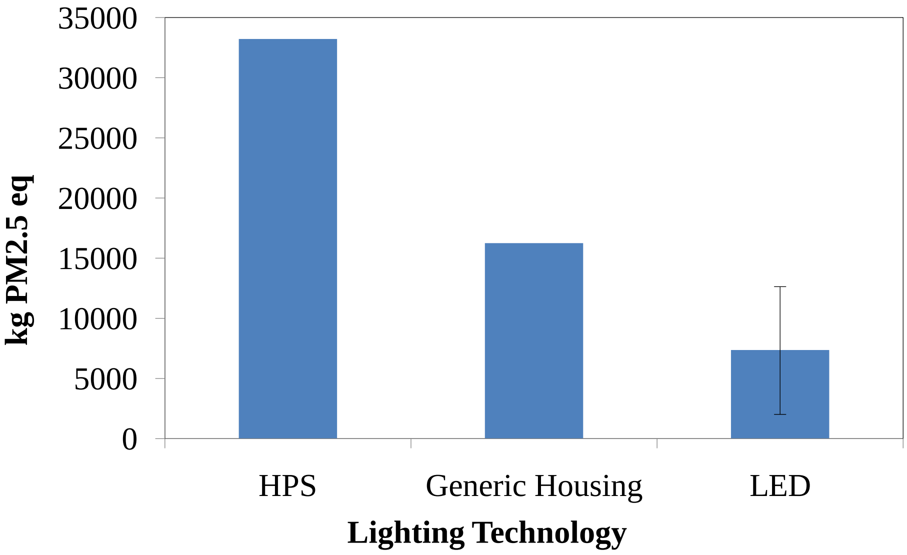


Figure 21. Respiratory Impacts of Housings

Electricity

Figure 22 below shows the results from running the four competing technologies with three different electricity generation models.

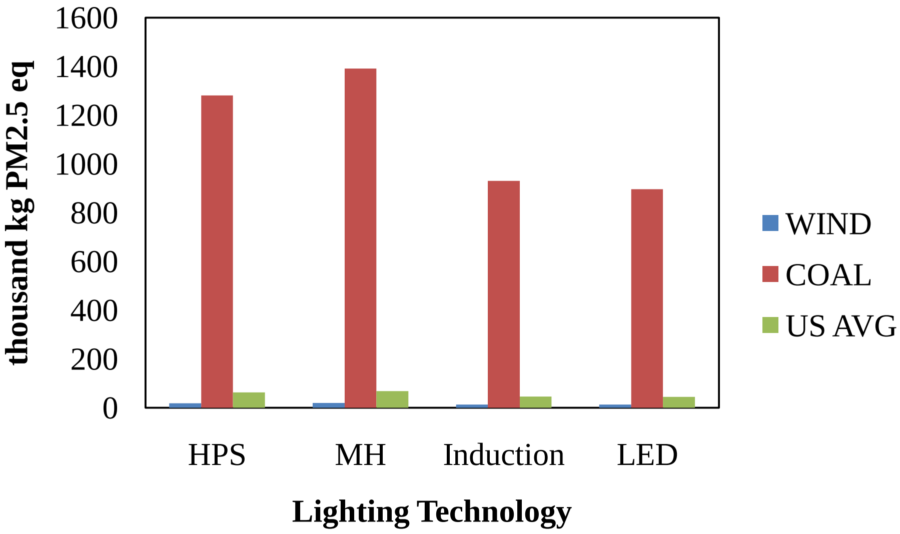


Figure 22. Respiratory Effects Emissions

Figure 22 indicates that respiratory effects are at a maximum when coal is used to generate electricity, no matter which lighting technology is selected. Once again, coal should not be used if respiratory effects are trying to be minimized. Wind-generated electricity has the least respiratory effects, and the U.S. average mix is in between the other two technologies, but much closer to wind than coal.

In order to compare the actual lighting technologies, however, we used the U.S. average electricity mix shown in Figure 23 below.

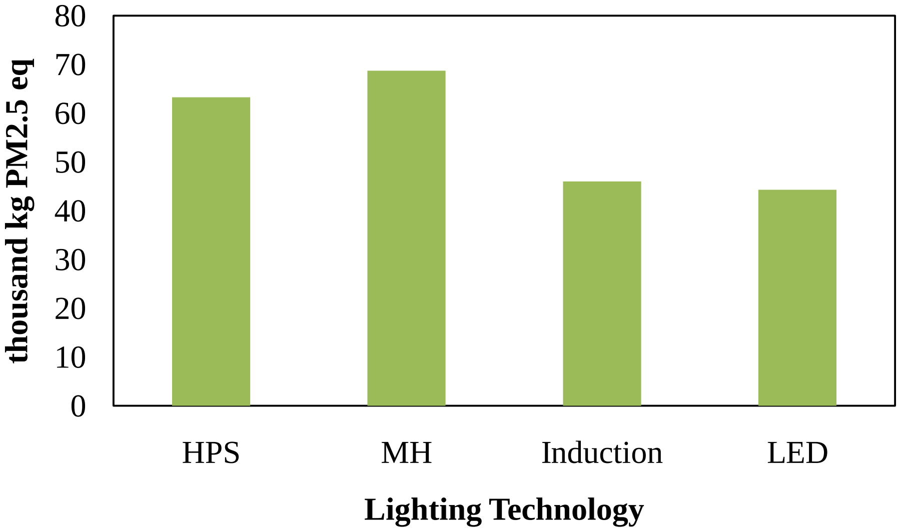


Figure 23. PM2.5 Emissions via U.S. Average Electricity Mix

Once again, metal halide is the worst technology in terms of respiratory effects followed closely by the other old technology, high-pressure sodium. LED is the best technology, but only slightly better than induction. LED and induction technology produce the least amount of respiratory effects when looked at from the electricity use perspective.

Discussion

Life cycle assessments often do not offer simple solutions. To keep HPS lights and switch to wind power would obviously benefit the environment; to switch to LED lights powered by wind is even better. However, when considered over an entire life cycle, any combination of lighting technology and electricity source will have advantages and disadvantages. Balancing these tradeoffs depends on priorities.

We identified several areas of focus for the City of Pittsburgh in their selection of new lighting technology. These are discussed below after the discussion of the LCIA results.

Discussion of LCIA Results

As expected, the impact of housing and bulb manufacturing of any of the potential lighting technologies was dominated by its use phase. Figure 24 and Figure 25 show that electricity use creates 10 to 100 times more effects in the global warming and ecotoxicity categories.

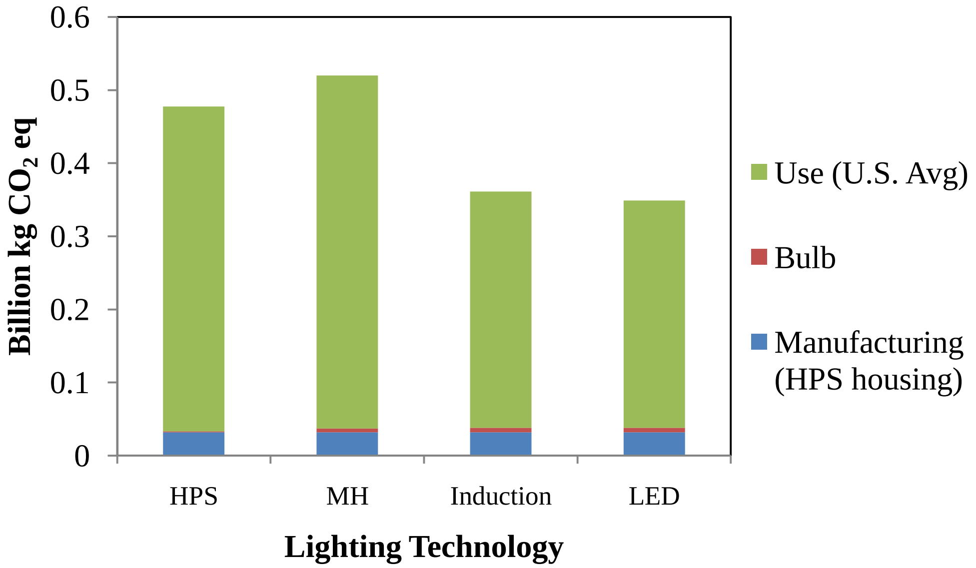


Figure 24. Global Warming Emissions

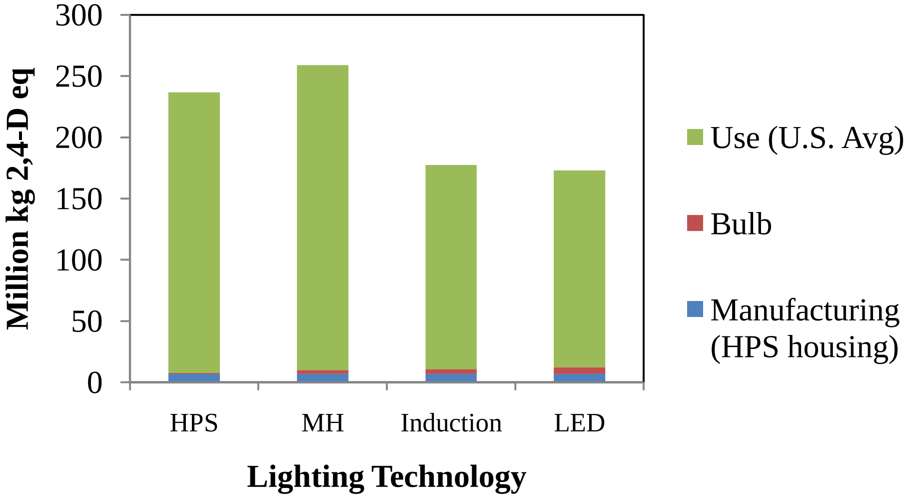


Figure 25 Ecotoxicity Emissions

There was not as great a difference between manufacturing and electricity use in the respiratory impact category. These results are shown in Figure 26. The low respiratory impacts of the U.S. electricity average mix are thought to show that the amount of coal used in the U.S. average mix is significantly lower than 100%. It was shown in Figure 22 that the respiratory impacts of the U.S. average were about 5% of the impacts from electricity generation from 100% coal.

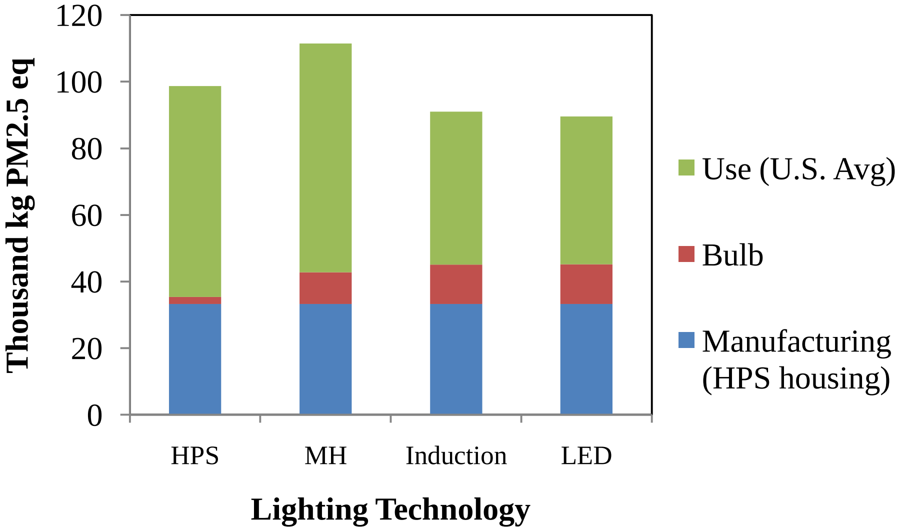


Figure 26: Respiratory Effects Emissions

Due to the dominance of the use phase, changing the source of electricity can have the most significant effects on environmental impacts. However, considering the manufacturing phase is still important because there is a lack of manufacturing data and electricity generation is expected to become cleaner. Acquiring manufacturing data could reveal unknown materials and energy use and have a strong influence on relative impacts between the phases. As electricity generation becomes cleaner, the manufacturing impacts become more significant. When 100% wind energy is used, the impact of the manufacture of the bulb and housing is expected to be higher than the lifetime electricity use.

Potential Vendors and Information Requests

It was noted by a local lighting expert Mr. Mike Cherock that many lighting companies participating in the pilot program are new to the field, while other companies who are not in the pilot program have a long history with a proven track record of quality. We have some recommendations that will make dealing with the companies easier and some recommendations related to getting information that will help deciding which companies are the most reputable.

Many times in citywide retrofits, such as Pittsburgh's, the contract often goes to the low-bidder. However, the low-bidder may not necessarily be the best choice. We therefore recommend restricting consideration to suppliers that meet a few criteria. One obvious criteria choice is company history, which will let the City know how long the company has been around, how much experience it has, and the outcomes of other projects it has done. We have also discovered that the best companies have had their photometrics tested from an independent laboratory and these results should be trusted much more than numbers simply given by the company without any other testing. Additionally, larger companies may be doing internal research to attempt to upgrade the existing technology. Pittsburgh will reap the benefits of any discoveries if such a company is chosen to retrofit the cities streetlights.

Disposal

As described, this comparative LCA addressed disposal by including outputs to the environment after use. For process data, the scope of inclusion varied by database. In reality, disposal needs to be carefully considered. A retrofit implies an initial creation of thousands of discarded bulbs. In Pittsburgh's case, some 40,000 mercury containing bulbs will need to be properly discarded. Many companies offer recycling programs for their own lights. Companies bidding on retrofit programs should be required to be responsible for recycling old fixtures, bulbs, and power supplies.

Non-LCA issues

While life cycle assessments are helpful for comparing environmental and health impacts of processes and for identifying hotspots, there are certain applications in which they are limited. Within the bounds of an environmental impact comparison, a few non-LCA issues need to be addressed. These include: color-rendering index, color temperature, and light pollution.

Color-Rendering Index

Color rendering index (CRI) is a way of measuring how well a light source will make colors appear. A higher CRI rating means a better color rendering ability. The color rendering index of incandescent bulbs is defined as 100 and other technologies are measured in comparison. HPS and MH lights have much lower CRIs; HPS can be as low as 20 and MH is in the 60s and 70s. LED and induction usually rate in the high 70s and mid 80s [21]. Municipalities have often employed bulbs for specific uses due to varying CRIs. Lights with a high CRI are preferred in business districts and historical areas while lower rated lights may be installed over less-used roadways.

Color Temperature and Circadian Rhythm

The color temperature of a visible light is determined by matching the color of the light source to the color of a theoretical black-body heated to a temperature measured in Kelvins. It should not be confused with CRI. CRI describes how well the light source makes other objects appear while color temperature describes the appearance of the light source itself. Data on color temperature was collected from companies and market studies. The yellow-orange nighttime glow of many cities can be attributed to the 2,000 K high pressured sodium bulbs. Some cities also use the slightly more yellow 3,000-4,000 K metal halide bulbs. LED and induction lighting, both around 5,000 K, have been advertised as producing a whiter light [21]. However, some lighting professionals believe higher color temperatures can upset the circadian rhythm of plants, animals, and people. The city of San Diego, CA for example, has decided to set a maximum color temperature of 3,500 K [8]. While the actual effects are unknown at this time, it is felt that the subject needs to be studied further.

Light Pollution

In addition to color temperature, too much excess light spilling from fixtures is considered a problem. Excess light can affect the appearance of the night sky, astronomy, and animal behavior, such as migration. Some manufacturers of newer technologies, most notably

LED, are seeking the Dark Skies Friendly rating from the International Dark-Sky Association [30]. Light pollution from HPS is attributed to bulbs that sit in lenses that drop down and distribute light out into a circular light distribution. It is felt that LED lights are able to focus light more accurately.

Data Collection Difficulties

As mentioned in the section on modeling, life cycle assessments are limited by the accuracy of data obtained. This report is based on data collected mostly from the companies participating in the pilot program and from lighting companies recommended to us. Government sources, industry groups, and on-site field measurements were also utilized. Every effort was made to collect sufficient data. However, companies were reluctant to release materials lists at the level of detail desired. Many companies requested non-disclosure agreements, which the team was not able to sign. Data collection was also difficult because fixtures, fixture components, and bulbs are manufactured, assembled, and sold through different companies. Sales and assembly companies had to forward materials requests to their many suppliers creating an increase in response time as well as additional concerns regarding confidentiality.

This report seeks to remedy this issue by collecting enough data to create ranges and allow a meaningful comparison of current technology. It is also hoped that this report will enable more accurate research in the near future.

Future Technology

There are many considerations that go into selecting a lighting technology for Pittsburgh’s streetlight retrofit including cost, environmental impacts, light quality, and maintenance. Any analysis of streetlights must be based not only on currently available technology, but also on likely improvements, and each technology has a unique history, rate of change and future prospects.

Street lighting technology can be divided into two basic categories: solid-state and gas. Gas technology includes HPS, MH, and induction because each produces light through the electrical excitation of gas molecules. Solid state includes LED [3].

LED lighting has been under development for about 40 years. In that time it has grown from a laboratory curiosity to a widely dispersed technology. LED is currently used mainly in indicator lights for electronic equipment such as control panels and for exit signs and traffic lights. Few of the common uses for LED have, until recently, required the illumination of areas. LEDs have been used as indicators, not to illuminate. This is due to the fact that only recently has LED been available in white light, and also due to the limited output of light from LED. Other lighting generally began as bright sources and developed over years.

Because of their long history, HPS, MH, and induction are well tested in large installations over many years, rapid changes in the future are not expected, and lifespan and energy use forecasts are highly reliable. LED lighting is in a much more dynamic state and has very little installed base for use in area lighting.

As noted, LED technology has grown rapidly. This growth has been fast enough to compare it to the development of computer chips. Both are also semiconductors. A scientist, Roland Haitz, noticed this growth and estimated that LED increases in light output by a factor of 20 while costs fall by a factor of ten, both over ten years [22]. Figure 27 below shows the efficiencies changes of major lighting technologies. The current efficiency of LED varies among manufacturers but is about 60-90 lm/W [22]. Induction lighting has an efficiency of about 85 lm/W [27]. However, Induction currently has a lifespan of 100,000 hours compared to LED lifespan of 55,000 hours, according to company data collected by the team. Since the lifespan of LED is a factor of the amount of electricity used per bulb, as their efficiency improves, their lifespan is expected to increase.

The relative changes in lumens per watt of LED (here labeled SSL for solid-state-lighting), fluorescent/HID, and incandescent lighting are shown in Figure 27. It is not known how long the rapid increase in lumens per watt from LED will continue, but it can be seen that assuming it continues, it will overtake fluorescent/HID soon.

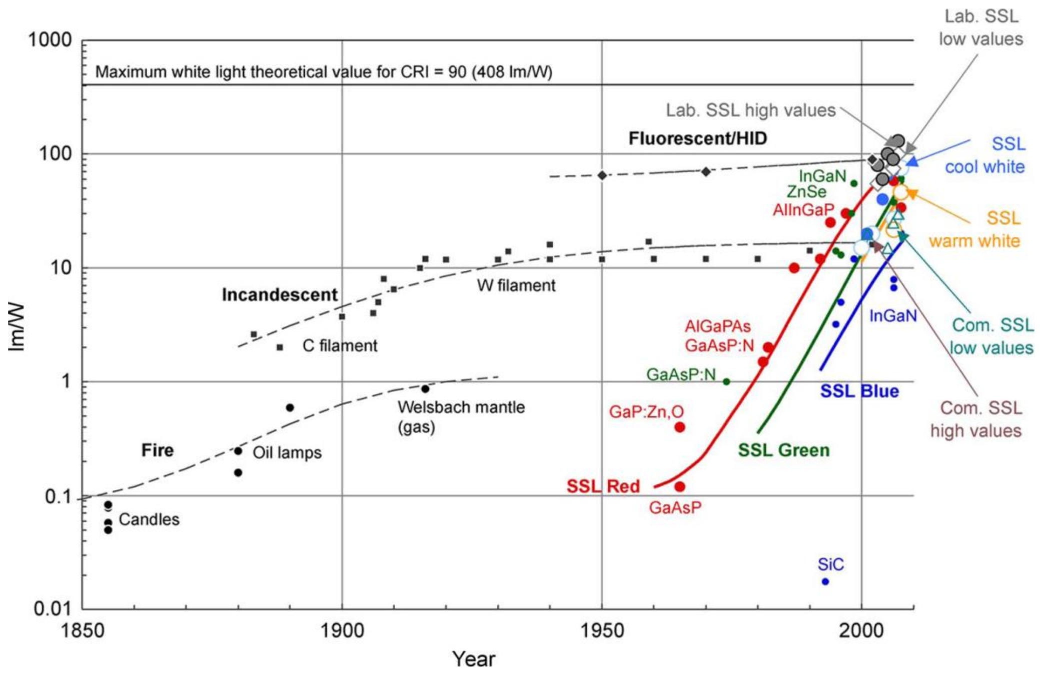


Figure 27. Changes in Lighting Efficiency [2]

Most municipalities and companies retrofitting or installing new lights are looking for a long-term, phased purchasing solution, in which many lights will not be purchased for several years. Pittsburgh and Los Angeles, CA plan to purchase several thousand lights per year over the next five or more years**.** LED lighting will be more efficient in lumens per watt within that time period and will also improve in lifespan. The lighting industry in general is quickly adopting LED and that it will become a dominant lighting technology. The two Department of Energy lighting studies programs, Caliper and Gateway, both focus exclusively on LED [31] [32]. Any city considering new or retrofit lighting must balance for the reliability and proven record of gas lighting, particularly induction, against the likely gains expected from LED.

The effects of single- or mixed-technology installations across the City must be weighted as well. Some issues that have been considered in discussions are stocking multiple technologies for repair and replacement, multiple technology vendors, worker training, and the visible/driving safety effect of a street with mixed lighting.

Finally, comparisons among different neighborhoods due to socio-economic factors such as which neighborhood gets which technology are a reason we recommend continuing with one technology. If the areas that get new lights first realize later that other areas have gotten a different type of light, then some people may become angry. By sticking with one technology, everyone gets the same light and this fairness will keep people from getting upset.

Recommendations for Future Retrofitters

Given the rapid changes, how is a city to assess their options? We recommend three concentrations: lighting needs, available technology, and future technology expected within the timeframe of the project.

Lighting needs must be addressed in detail greater than square footage required to light. As noted in the sections above, the color temperature, CRI, glare, light-leakage (dark skies), and photometrics all affect how the lighting is perceived by the user. Many cities have replaced HPS lights in high-profile areas of shopping and attractions with MH. Despite the shorter lifespan of MH, the lights have a much better CRI. Cities such as San Diego, CA have specifically investigated lights based on their impact on the nearby Mt. Palomar observatory [33]. Each of these qualities must be judged in relation to the area where the lights will be installed. This report seeks only to make cities aware of the issues.

Assessing the available technology will require the gathering of a great amount of data. As noted, this data is often difficult to acquire due both to proprietary concerns and to lack of understanding of the life cycle analysis process. A questionnaire for companies wishing to participate in pilot studies or bids is included in Appendix M**.** Every effort should be made to require this questionnaire for each light. If necessary, proprietary concerns may be met by using a third party to collect and average the data by technology for the City. It is also recommended that each company prepare a take-back plan for recycling the bulbs and housings at the end of their useful life. It was estimated that 99.9% of the components are recyclable and many of the companies we spoke to either had or were willing to provide this service.

The future potential of each technology can only be assessed at a particular time. We recommend that cities follow the DOE programs and speak with suppliers of other technologies. It is felt, however, that within a few years, the choice of LED over other current technologies will be clear.

A final note for other projects is to work with quality vendors. The rapid improvement of LED technology and the apparent ease of entry into the market have had the benefit of stimulating innovation at companies not traditionally involved in area lighting, but also may result in less than optimum designs offered for sale. In discussions with industry experts, they emphasized the need to establish overall product quality and the long-term prospects of the vendor. It was recommended that each vendor be required to supply complete photometric analysis for each specific product and that these be conducted by a reputable third-party lab. It was also recommended that each light supplied to a pilot program be inspected for workmanship and overall quality.

We also recommend a public survey period as was done on the retrofit project in Anchorage, AK. LCA and other methods cannot substitute for a qualitative assessment of light quality, especially in residential areas [34].

Conclusion

The comparative life cycle assessment (LCA) performed on high-pressure sodium (HPS), metal halide (MH), induction, and light emitting diode (LED) streetlights focused on environmental impacts from life cycles of streetlights in the categories of global warming, ecotoxicity, and respiratory effects. Several important conclusions were reached. The use phase of any streetlight technology was found to have at least ten times more environmental impact than manufacturing. Due to the high percentage of fossil fuels used in electricity generation. The manufacturing phase of the streetlight housings is believed to be approximately equivalent for each bulb technology. The manufacturing of the bulbs differs between technologies. Induction and LED were found to create greater impacts than HPS or MH. However, the lower electricity use of these technologies resulted in lower overall life cycle impacts. The higher impact of LED manufacturing is due to their high chemical and energy inputs.

These results were found using database models analyzed in SimaPro using the TRACI life cycle impact assessment method. The models were created from data collected from sales companies, manufacturers, government documents, lighting professionals, and industry reports. Data was modeled using the process and input-output (I/O) methods. Process methods assigned the weights of material of the fixtures and bulbs to appropriate manufacturing processes. I/O methods assigned the producer price of products to their economic sectors. Electricity consumed in the use phase was modeled on an average mix of fuels used in electricity generation in the U.S. An alternative modeling of electricity showed that the manufacturing of the bulbs became significant if 100% wind generated electricity were used by the streetlights. While every effort was made to collect thorough and accurate data, the manufacturing supply chain, proprietary manufacturing technologies, and time constraints resulted in data collection difficulties.

Analyses of these models indicated that induction and LED lighting currently have similar impacts. However, it is felt that the rapid increase in LED lighting efficiency will soon surpass that of induction. Therefore, we recommend that the city choose LED technology in a multi-year phased purchase of new streetlights. The use of a single technology will benefit the city with reduced maintenance costs and uniform lighting.

Pittsburgh has the opportunity to join other cities leading the replacement of streetlights with more efficient technology. Pittsburgh can also make a significant contribution by continuing their unique analysis of the total environmental impact of streetlights.

Acknowledgements

We would like to thank our advisors Dr. Melissa Bilec and Dr. Joe Marriott from the University of Pittsburgh's Mascaro Center for Sustainable Innovation for giving us the opportunity to conduct this research project and for guiding through the research and LCA process. We appreciate their continuous support and feedback. We would also like to thank Maria Fernanda Padilla for proofreading our drafts and helping us with any modeling issues that arose. We would like to acknowledge Mr. Rick Frontera and his crew from Allegheny City Electric for allowing us to watch a streetlight replacement in the Southside and for providing us with a HPS 150W GE Cobrahead. His help was invaluable to our work. Additionally, we would like to thank Lindsay Baxter, Ben Carlise, and Dan Gilman from the city of Pittsburgh for answering any questions we had regarding the City's retrofit. We want to thank all of the companies we spoke to for data they sent us and for giving us great insight into this project. We would like to thank Mike Cherock, Nancy Clanton, Robert Koenig, Orlando Nova, and the Clinton Climate Initiative for giving up their time to speak with us and give us more information regarding the lighting field. We are grateful to the National Science Foundation for making our research possible.

Appendices

Appendix A: Other Projects

Several other cities and utilities are pursuing streetlight retrofit programs. Several partner with the Department of Energy Gateway program which tests LED products as replacements for older technologies and focuses on lighting and economic performance. The Gateway program has partnered with San Francisco, CA and Oakland, CA as well as Raley's supermarket in Sacramento, CA and other companies and agencies.

The LED test project in San Francisco replaced about 25 HPS streetlights with four types of LED streetlights on four residential blocks in the Sunset District. The new lights were evaluated on lighting and economic performance. The lighting performance results showed that both HPS and LED performance is based strongly on light design and appropriate use. Some LED lights worked better than HPS, some did not. Similarly, the economic performance was strongly based on design. The LED lights were not found to necessarily perform better than HPS, but only when use properly. The report estimates that 8.1 TWh and 5.7 M metric tons of CO_2 could be saved if all HPS in nation replaced with LED [7].

Residential streets and a parking lot in Oakland were used as a test bed for comparison in a similar project. Here, fifteen HPS lights were replaced with LED. A residential street was lit on one end with new HPS lights and with LEDs on the other end to allow visual comparison. The LED lights were found to draw 35% less power (77.7W) than the HPS. Based on an operating time of 4100 hr/yr, the report concluded that 178 kWh could be saved per light per year. The problem of comparison between HPS and LED noted by the report is caused by the tendency of HPS lights to create a "hotspot" of excess light directly underneath. This extra light is wasted to ensure that areas farther from the center received the minimum required amount of light. LED lights are noted as tending to create a more even distribution of light [35].

In Sacramento, Pacific Electric and Gas replaced 16 MH with bi-level LED in a supermarket parking lot. Some LED lights were entirely new and some were retrofit in the old HPS housing. The lights were equipped with motion sensors to use high power when motion was detected and low power otherwise. The report estimated an annual savings of $277 per light. New and retrofit payback periods were 3.3 and 4.7 years, respectively [36].

To save money, Ann Arbor, MI imposed a moratorium on the installation of new streetlights. This led to a search for more efficient lighting. The report noted that Honolulu, HI and San Diego, CA had concluded that LED was not an acceptable replacement in earlier tests. However, in 2006, they ran a new test pilot with the latest LED technology in downtown Ann Arbor. With the newer technology, the city concluded that LED was a viable option and has committed to replace 1000 lights with LED. They estimate a savings of over $100,000 and 267 tonnes [sic] CO_2 equivalent per year. We note this experience to highlight the rapidly changing efficiency of LED lights [33].

In February 2009, the city of Los Angeles, CA and the Clinton Climate Initiative announced the largest LED retrofit to date. The project will replace 140,000 HPS lights over a five year period. The project is expected to save over $10 million and 40,500 tons of CO_2 equivalents per year. The project is expected to pay for itself in seven years. The project considered both LED and Induction lighting and their motives were economic savings, light quality, and greenhouse gas emissions. It was noted in the report that LED is the only technology that does not contain mercury. The city chose to go with LED based mainly on the rapid increase in LED efficiency and its future promise [37].

Appendix B: HPS Housing List and Model

Materials Model

Component	Material	Weight (g)	SimaPro Process	SimaPro Database
Bottom Housing	Aluminum	957	Aluminum Alloy, AlMg3, at plant/RER S	Ecoinvent System Process
Metal Separator	Aluminum	15.3		
Reflector	Aluminum	422		
Top Housing	Aluminum	2417		
Screws (brass)	Brass	39.2	Brass, at plant/CH S	Ecoinvent System Process
Bracket Rocker	Cast Aluminum	110.1	Aluminum, cast, lost foam, at plant/kg/US	USLCI
Ceramic bulb holder	Ceramic	176.9	Sanitary ceramics, at regional storage/CH S	Ecoinvent System Process
Photocell circuitboard	Circuit Board	40.8	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S	Ecoinvent System Process
Copper from circuitboard	Copper	5.0936	Copper, secondary, from electronic and electric scrap recycling, at refinery/SE S	Ecoinvent System Process
Felt Heat Shield	Felt	2.867	Textile, jute, at plant/IN S	Ecoinvent System Process
Attachment	Galvanized steel	147.3	Galvanized steel sheet, at plant/RNA	USLCI
Bolt	Galvanized steel	44		
Bracket Pieces	Galvanized steel	295.2		
Photocell Holder cover	Galvanized steel	5.3622		
Screws (steel)	Galvanized steel	17.8		
Small Screws (steel)	Galvanized steel	1.8052		
Lens	Glass	2359	Glass bottles FAL	Franklin USA 98
Paper Insulator	Paperboard	1.2603	Paperboard Unbl. Semichem. FAL	Franklin USA 98
Black Plastic Insulator (3 caves)	Plastic	73.9	PS (GPPS) FAL	Franklin USA 98
Photocell cap	Plastic	24.4		
Photocell plastic	Plastic	11.3		
Photocell plugin	Plastic	54.3		
Plastic circuitboard	Plastic	22.7554		
weather guard	Plastic	10.175		
Metal bulb holder (screws into)	Stainless Steel	18.5	X5CrNiMo18 (316) I	IDEMAT 2001
Big Capacitor	Capacitor	220.9	*Component not contained in housing model*	
Capacitor from circuitboard	Capacitor	7.1458		
Ballast		4800		
Brown circuit component		1.7982		

Component	Material	Weight (g)	SimaPro Process	SimaPro Database
Diode (black w/ green band)		0.4275		
Green circuit component		3.9695		
Lightbulb		114.4		
Screws		54.2		
Wires		60		

Manufacturing Model

Manufacturing Process	Weight (g)	SimaPro Process	SimaPro Database
General metal manufacturing	4,495.66	Metal product manufacturing, average metal working/RER S	Ecoinvent System Process

Appendix C: XUS LED Housing List and Model

Materials Model

Component	Material/Brand	Weight (g)	SimaPro Process	SimaPro Database
Driver Board Bracket	30% glass filled, UV stabilized polypropylene	13.61	PET 30% glass fibre I	IDEMAT 2001
Air Inlet Duct	30% glass filled, UV stabilized polypropylene	22.68		
Cover	30% glass filled, UV stabilized polypropylene	263.08		
Upper Housing	30% glass filled, UV stabilized polypropylene	1124.91		
Lower Housing with Screens	30% glass filled, UV stabilized polypropylene, epoxy coated aluminum screens	430.91		
Terminal Block Screws	300 Series stainless steel	9.07	X12Cr13 (416) I	IDEMAT 2001
LED Board Screws	300 Series stainless steel	18.14		
Lens Screws	300 Series stainless steel	18.14		
Lens nut	300 Series stainless steel	4.54		
Ground Screws	300 Series stainless steel	4.54		
Power Supply/Bracket Screws	300 Series stainless steel	9.07		
Tri-lobal Screws for Plastics 1,2,3,4	301 Series stainless steel	83.91		
die cast bracket	380 Alloy aluminum with e-coating	576.06	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent System Process
Heat Sink	6063 T5 Aluminum; clear chromate coating	1138.52		
Lens	Acrylic	353.80	Acrylic filler, at plant/RER S	Ecoinvent System Process
LED Board	Aluminum Substrate	263.08	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S	Ecoinvent System Process
AC Wire Harness	Copper wire, nylon 6 connectors,	13.61	G-CuZn40 I	IDEMAT 2001
Driver Board Wire Harness	Copper wire, nylon 6 connectors,	4.54		
LED wire harness	Copper wire, nylon 6 connectors,	27.22		
Driver Board	Glass filled epoxy	104.33	Glass fibre reinforced	Ecoinvent System

	resin, conformal coating		plastic, polyester resin, hand lay-up, at plant/RER S	Process
Heat Sink Fans	Polybutylene Terephthalate - fan blade and housing	376.48	PS (GPPS) FAL	Franklin USA 98
Power Supply Fan	Polybutylene Terephthalate - fan blade and housing	72.57		
Terminal Block	Phenolic, zinc plated steel connectors	58.97	*Component not contained in housing model*	
Power Supply		653.17		
Thermal Grease	Aluminum Oxide, boron nitride, polyol ester, polyether glycol	1.81		
Screens	epoxy coated aluminum	2.27		

Manufacturing Model

Manufacturing Process	**Weight (g)**	**SimaPro Process**	**SimaPro Database**
General metal manufacturing	986.56	Metal product manufacturing, average metal working/RER S	Ecoinvent System Process
Wire-making	45.36	Wire drawing, copper/RER S	Ecoinvent System Process

Appendix D: ALSI LED Housing List and Model

Materials Model

Component	**Material**	**Weight (kg)**	**SimaPro Process**	**SimaPro Database**
LED Square board Assembly (12 LEDs ea.)	Silican-based LED's and PF4 Fiberglass boards	0.343	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S	Ecoinvent System Process
Computer Board	PF4 Fiberglass			
Driver Board	PF4 Fiberglass			
Decorative Cover	Aluminum	6.180	Aluminium alloy, AlMg3, at plant RER S	Ecoinvent System Process
Luminaire Shell	Aluminum			
Mounting Plate	Aluminum			
Aluminum U-bolt mounting bracket	Aluminum			
Reflector rivets	Aluminum			
Ground Screw Ring Terminal	Aluminum			
Reflector	Reflective aluminum			
Power Supply Cover	plastic-wrapped copper w/paper insulation	0.190	G-CuZn40 I	IDEMAT 2001
Power Cord	plastic-wrapped copper w/paper insulation			
Lens	Poly carbonate	0.615	Polycarbonate E	Industry Data 2.0
Lens Gasket	poly foam	0.0425	Polyurethane, flexible foam, at plant/RER S	Ecoinvent System Process
Dusk to Dawn Control	PVC with misc resistors and capacitors	0.215	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S (0.194 kg)	Ecoinvent System Process
Dusk to Dawn Control	PVC with copper components		Integrated circuit, IC, logic type, at plant/GLO S (0.0215 kg)	Ecoinvent System Process
Gore Plugs	PVC	0.159	Polystyrene, high impact, HIPS, at plant/RER S	Ecoinvent System Process
Water tight connector	PVC			
Water tight connector - nut	PVC			
Head boalts for Mounting Bracket	Zinc Plated steel	0.113	Steel, low-alloyed, at plant/RER S	Ecoinvent System Process
U-Bolts, and misc fasteners	Zinc Plated steel	0.0794		
Various fastners	Stainless steel	0.232	X12Cr13 (416) I	IDEMAT 2001
Power Supply	Various electronic components	0.794	*Component not contained in housing model*	

Manufacturing Model

Manufacturing Process	**Weight (kg)**	**SimaPro Process**	**SimaPro Database**
Wire-making	0.19	Wire drawing, copper/RER S	Ecoinvent System Process
General steel manufacturing	0.425	Steel product manufacturing, average metal working/RER S	Ecoinvent System Process

Appendix E: LED “High” Housing List and Model

Materials Model

Component	Material	Weight (kg)	SimaPro Process	SimaPro Database
Heat Sink	Aluminum alloy 6063	3.63	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent System Process
Housing	Aluminum alloy 6063	6.8		
Bracket	Aluminum-guess	1.26		
Frame for lens	Aluminum-guess	0.26		
Sealant	EPDM	0.02 (guess)	EPDM rubber ETH S	Ecoinvent System Process
Lens	Glass (low lead)	1.36	Glass tube, borosilicate, at plant/DE S	Ecoinvent System Process
Plugs	n/a	0.159	PVC FAL	Franklin USA 98
Finish	Paint - polyester powder	0.002 (guess)	Polyester resin, unsaturated, at plant/RER U	Ecoinvent Unit Process
LED Board	PC Board-FR4 w/582 LEDs	0.5	Printed wiring board, hole-through mounted, unspec., solder mix, at plant/GLO S	Ecoinvent System Process
Terminal block (AC&DC)	Plastic	0.07	General purpose polystyrene, at plant/RNA	USLCI
Cap	Plastic - Polycarbonate	0.004	Polycarbonate E	Industry Data 2.0
Photocell	PVC	0.215	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S (0.194 kg)	Ecoinvent System Process
			Integrated circuit, IC, logic type, at plant/GLO S (0.0215 kg)	Ecoinvent System Process
Gasket	Silicone	0.07	Polyurethane, flexible foam, at plant/RER S	Ecoinvent System Process
Screws	Stainless steel	0.49	X12Cr13 (416) I	IDEMAT 2001
Bolts	Steel zinc plated	0.14		
Wires	Wires	0.06	G-CuZn40 I	IDEMAT 2001
LEDs	Leds - 84 -Nichia 084B	0.05	*Component not contained in housing model*	
Power Supply	Driver	0.91		

Manufacturing Model

Manufacturing Process	Weight (kg)	SimaPro Process	SimaPro Database
General metal manufacturing	13.08	Metal product manufacturing, average metal working/RER S	Ecoinvent System Process
Wire-making	0.06	Wire drawing, copper/RER S	Ecoinvent System Process

Appendix F: LED “Low” Housing List and Model

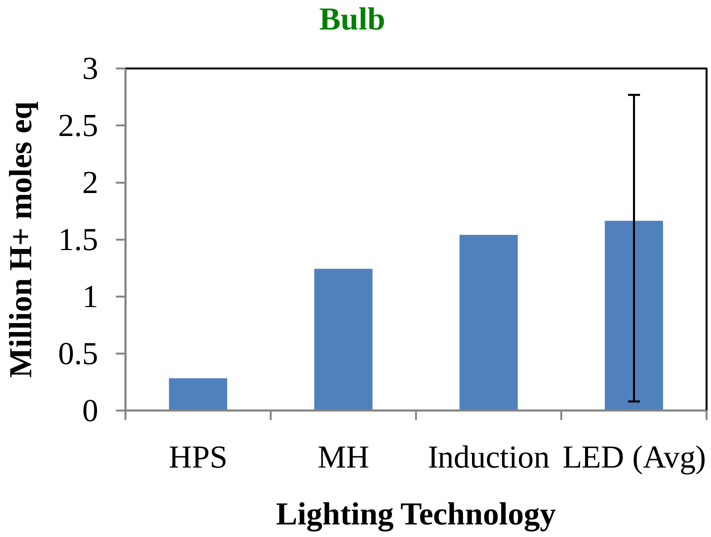
Materials Model

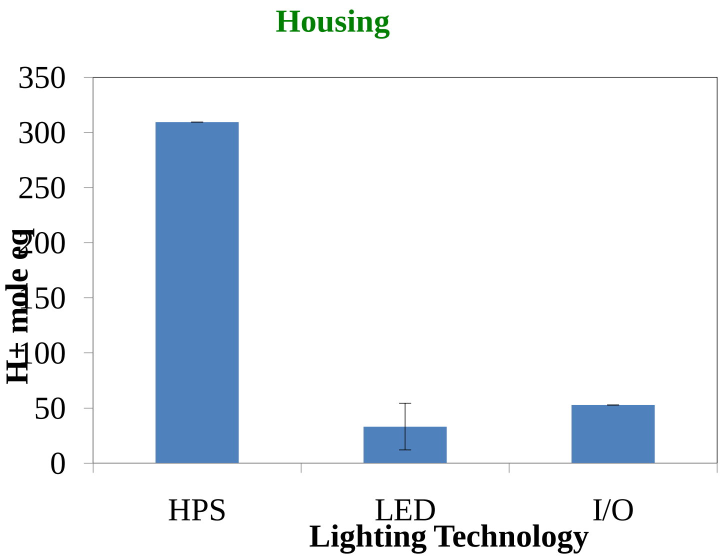
Component	Material	Weight (kg)	SimaPro Process	SimaPro Database
Heat Sink	Aluminum alloy	1.27	Aluminium alloy, AlMg3, at plant/RER S	Ecoinvent System Process
Brackets	Aluminum alloy w/powder coating	0.64		
Housing	Aluminum HE24	3.58		
Frame	Aluminum-guess	0.16		
LED Board (includes weight of thermal grease)	Circuit board	0.23	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S	Ecoinvent System Process
Sealant	EPDM	0.02 (guess)	EPDM rubber ETH S	Ecoinvent System Process
Plugs	N/A	0.159	PVC FAL	Franklin USA 98
Finish	Paint - polyester powder	.002-guess	Polyester resin, unsaturated, at plant/RER U	Ecoinvent Unit Process
Terminal block (AC&DC)	Plastic	0.07	General purpose polystyrene, at plant/RNA	USLCI
Cap	Plastic - polycarbonate	0.004	Polycarbonate E	Industry Data 2.0
Lens	Plastic - polycarbonate	0.07		
Photocell	PVC	0.215	Printed wiring board, through-hole mounted, unspec., solder mix, at plant/GLO S (0.194 kg)	Ecoinvent System Process
			Integrated circuit, IC, logic type, at plant/GLO S (0.0215 kg)	Ecoinvent System Process
Gasket	Silicon Rubber	0.05	Polyurethane, flexible foam, at plant/RER S	Ecoinvent System Process
Screws	Steel - stainless	0.25	X12Cr13 (416) I	IDEMAT 2001
Bolts	Steel - zinc plated	0.14		
Wires	Wires	0.06	G-CuZn40 I	IDEMAT 2001
LEDs	Leds - 84 -Nichia 084B	0.05	*Component not contained in housing model*	
Power Supply	Aluminum alloy and ac/dc	0.54		

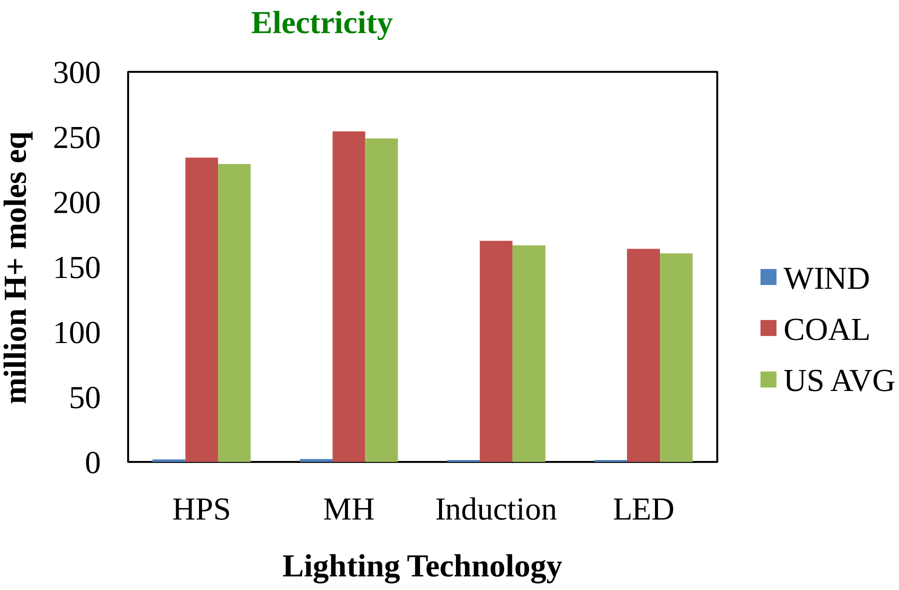
Manufacturing Model

Manufacturing Process	Weight (kg)	SimaPro Process	SimaPro Database
General metal manufacturing	6.27	Metal product manufacturing, average metal working/RER S	Ecoinvent System Process
Wire-making	0.06	Wire drawing, copper/RER S	Ecoinvent System Process

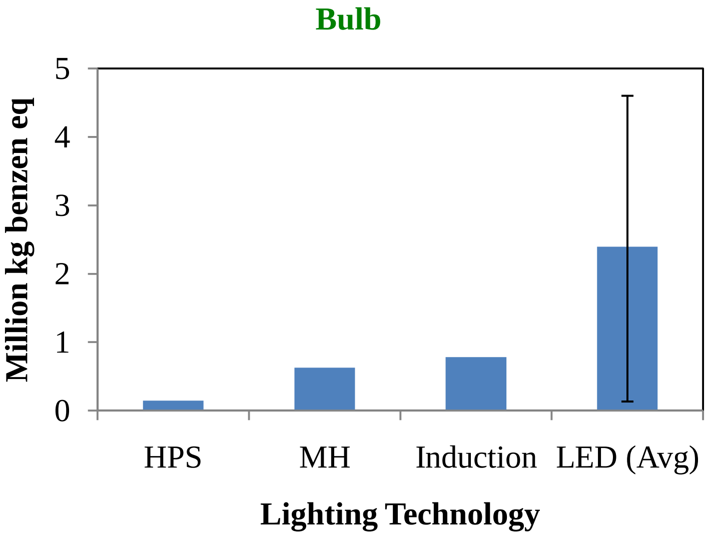
Appendix G: TRACI Output - Acidification

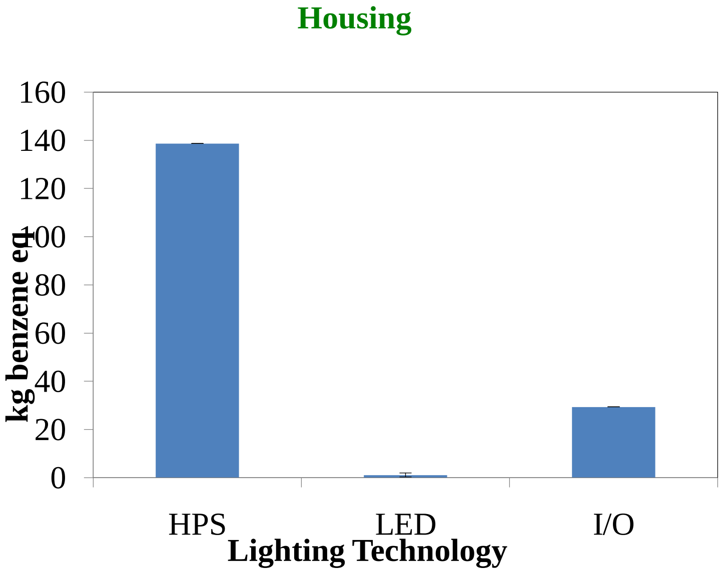


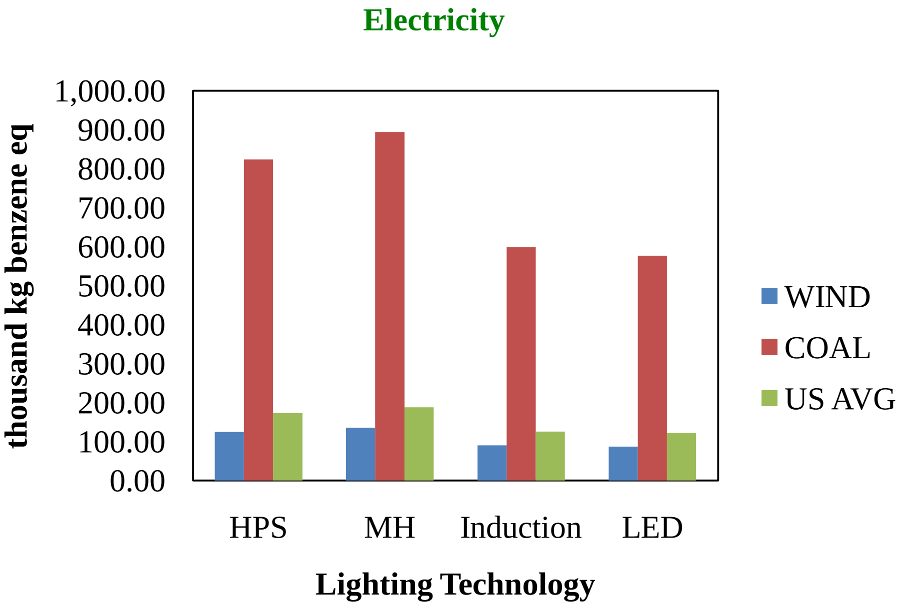




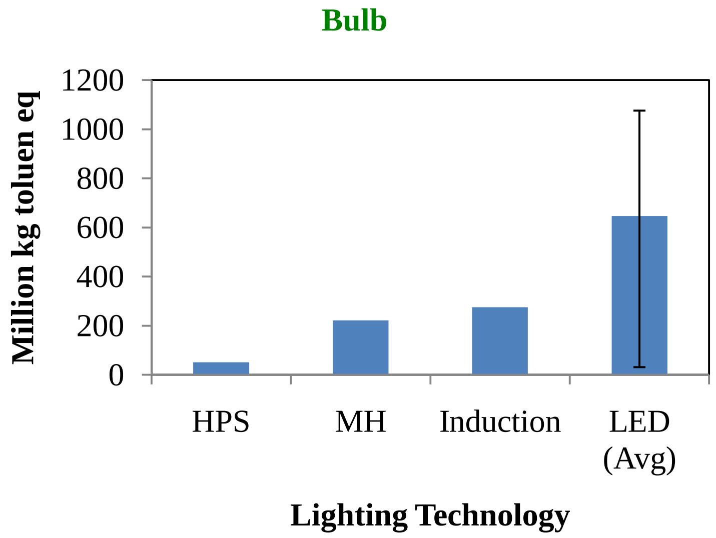
Appendix H: TRACI Output – Carcinogenics

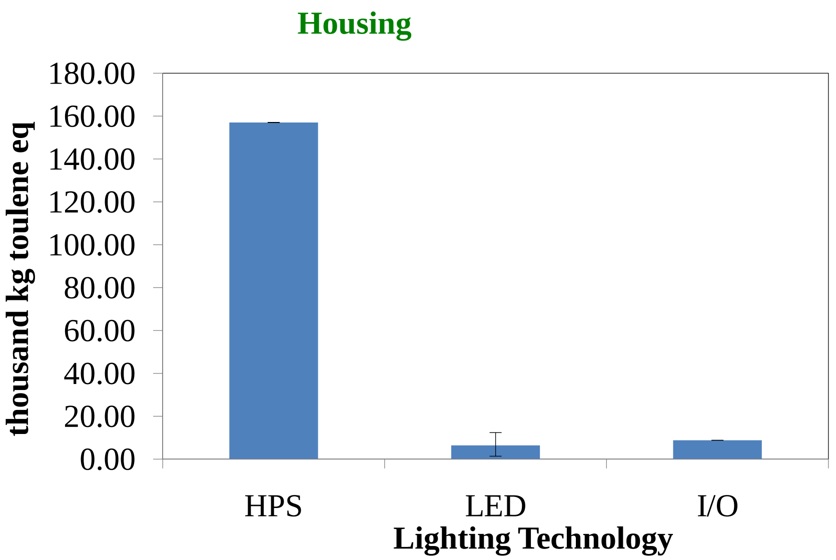


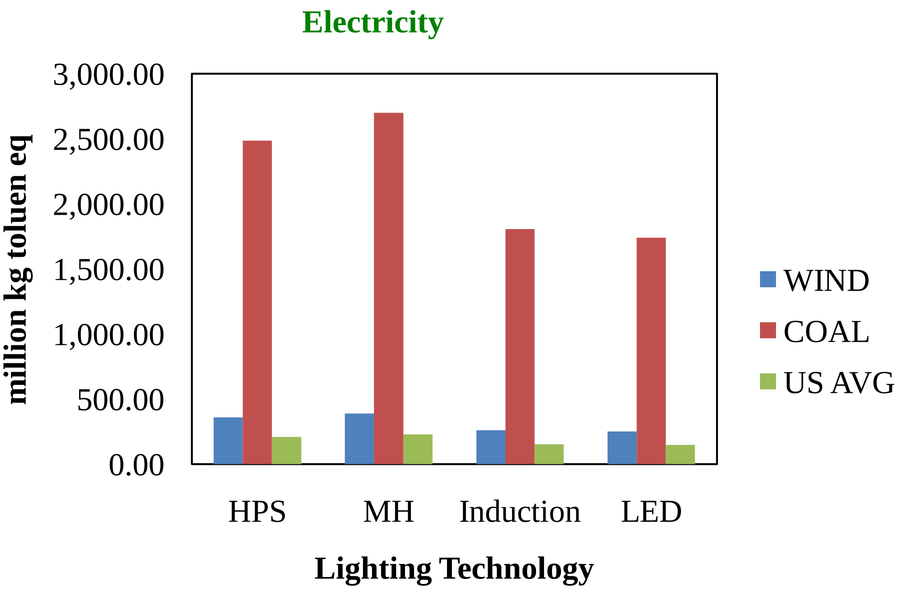




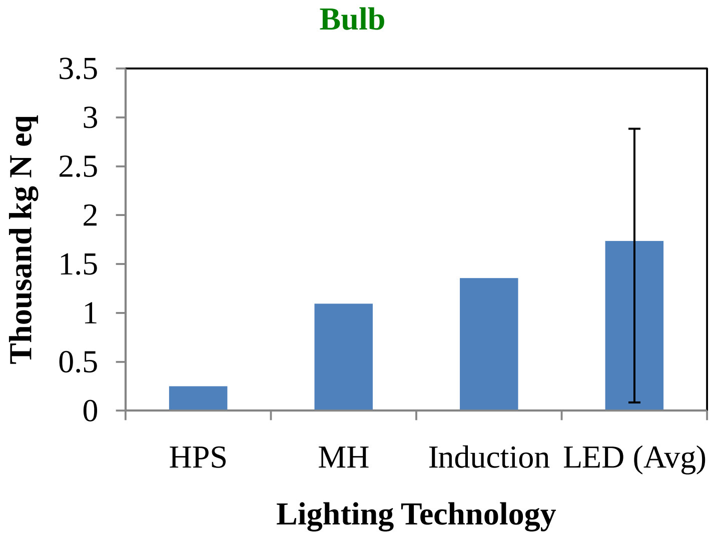
Appendix I: TRACI Output – Non Carcinogenics

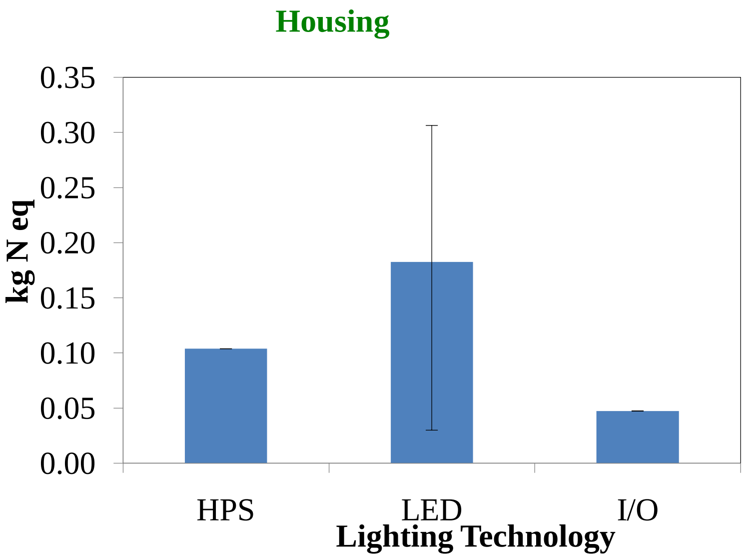


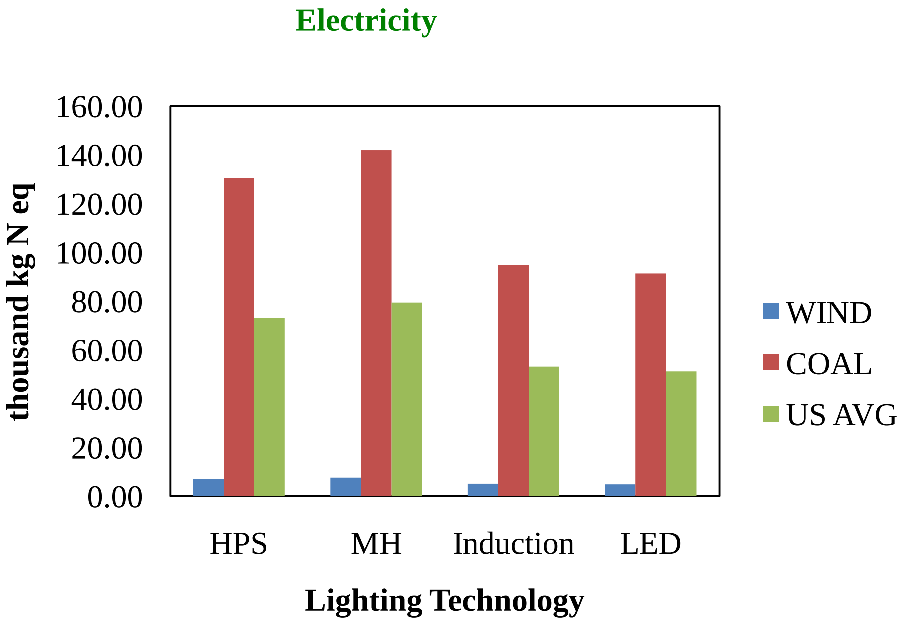




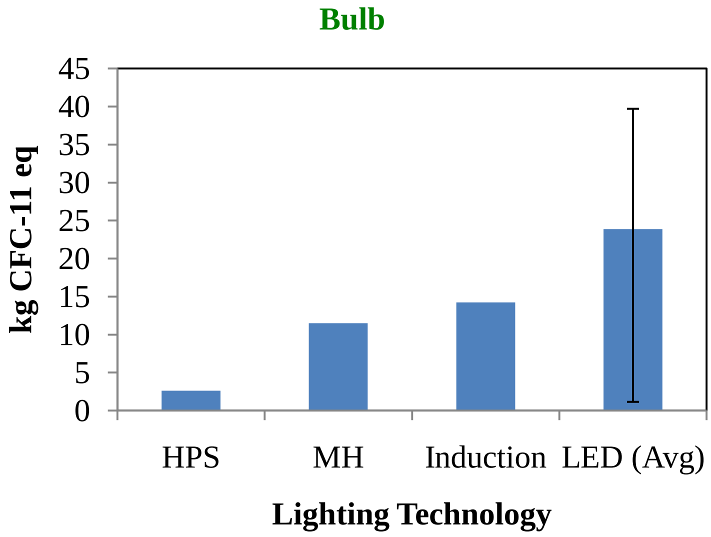
Appendix J: TRACI Output – Eutrophication

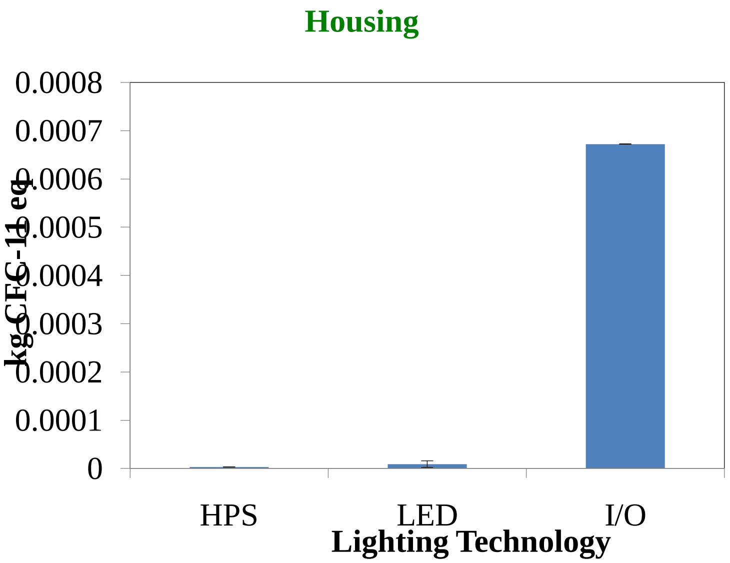


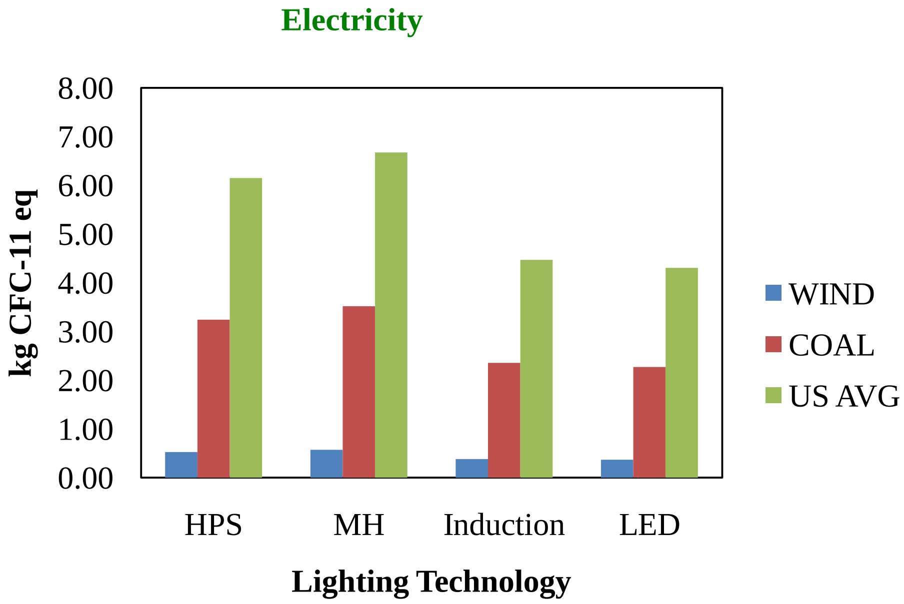




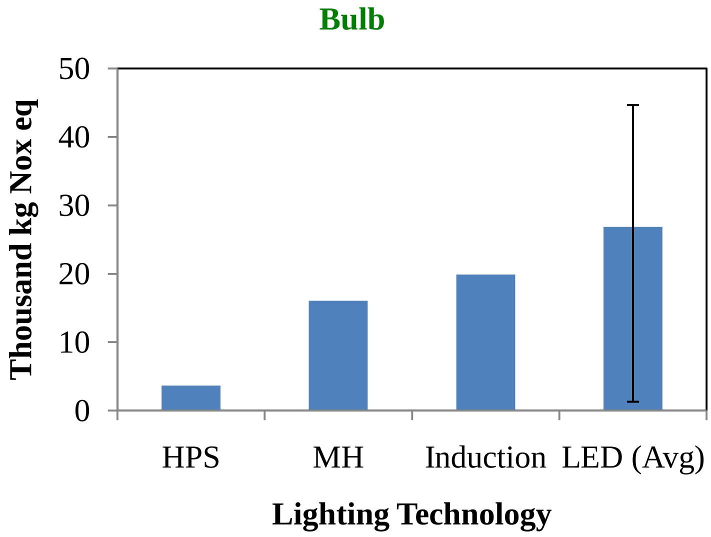
Appendix K: TRACI Output – Ozone Depletion

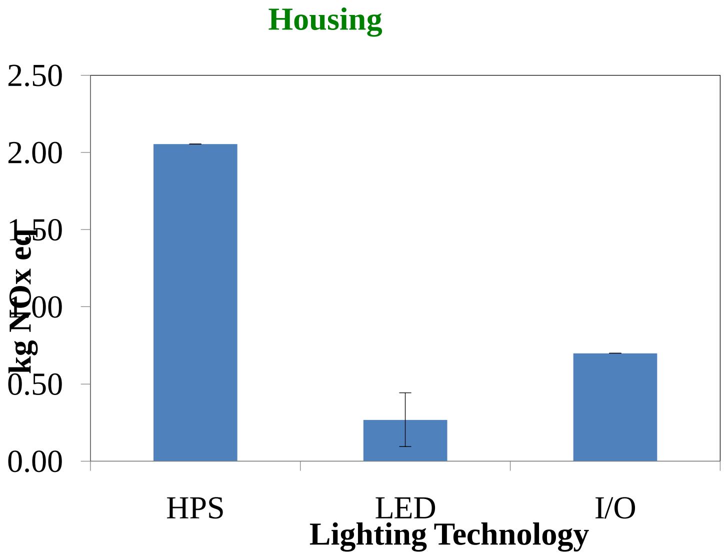


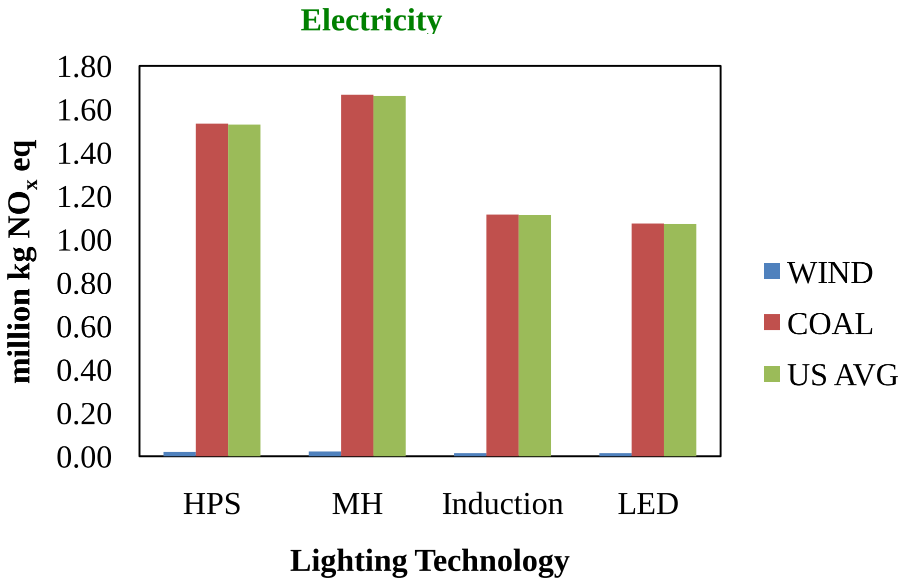




Appendix L: TRACI Output – Smog







Appendix M: Questionnaire

An accurate life cycle assessment begins with quality data. The best quality data may be collected as a requirement of bid submission. Few manufacturers understand or have ready access to the level of data required. Providing manufacturers with a questionnaire to fill out while they prepare their bids may address this issue.

To simplify the modeling of light fixtures, data should be collected and organized in relation to specific parts. For example, instead of providing the total weight of an aluminum alloy for the light fixture, companies should provide the specific weight used in each part, such as the housing, bracket, and lens frame. This level of detail will aid in identifying which parts cause the greatest environmental impacts.

If this level of detail is unavailable, a basic table, shown in Table 10, may be used. Note a specific alloy or type of material is requested. This allows the material to be assigned to most similar process in SimaPro.

Table 10. Basic Level Data

Material	**Weight** (kg)
6111 aluminum alloy	4.3
1060 steel alloy	3.2
Soda glass	2.5
etc	

Many materials can be formed in different manufacturing processes. The manufacturing process can greatly affect the environmental impact of parts of the same material. Aluminum, for example, may be formed in die cast, press formed, stamped or many other methods. Table 11 has been expended to include specific part names and manufacturing process.

Table 11. A Better Data Set

Part	**Material**	**Process**	**Weight (kg)**
top housing	6111 aluminum alloy	press forming	4.3
bracket	1060 steel alloy	forged	3.2
lens	soda glass	cast	2.5
etc			

Part names should be as specific as possible. The manufacturer name and location, and the model number or stock name (i.e. “Cree LED model XP14”, or “flat sheet aluminum 1/8 in. thick”) should be included.

Many companies submitting lights to the pilot program were sales representatives of manufacturers. Requests for data had to pass through these offices to reach the engineering departments of the manufacturers. Time should be allotted to allow data requests to pass through lengthy supply chains.

Confidentiality is very important to the manufacturers. Researchers should either instruct manufacturers on how to make their data generic but useful, or use a 3rd party to do this. The 3rd party could provide models of each technology averaged from many manufacturers.

The blank questionnaire in Table 12 is intended as a starting place for a research team to develop a questionnaire specific to their needs. Below the table are suggested lists of parts and materials. These may be included with the questionnaire to help companies understand the level of detail required.

Table 12. Questionnaire

Part	Model Number	Material (alloy, temper, chemical name)	Manufacturing Process	Weight (kg)
Housing				
Lens				
Bulb				
Power Supply				

Possible part names

- Bulb
- LED Assembly
- LED
- Computer Board
- Driver Board
- Decorative Cover
- Luminaire Shell
- Mounting Plate
- Aluminum U-bolt mounting bracket
- Reflector rivets
- Reflector
- Power Supply Cover
- Power Cord
- Lens
- Lens Gasket
- Dusk to Dawn Control
- Water tight connector
- Bolts for Mounting Bracket
- misc fasteners

Possible material types

- Aluminum alloy $AlMg_3$
- Aluminum alloy w/powder coating
- Printed circuit board
- EPDM
- Paint - polyester powder
- Plastic - polycarbonate
- PVC
- Silicon Rubber
- Steel - stainless
- Steel - zinc plated
- Wires

Appendix N: Southside Test Pilot Companies

The companies involved in Pittsburgh's South Side test pilot are listed below. Much of our data comes from averages of these companies' products.

ActOne
Altenae/The LED Co.
Amplex Control software
Arch Lighting Cooper LED
Bain representing American Green Light
CF Sales representing GES
CFI Associates representing Lavalux
Chips & Wafers
Clean Light/Green Light
Condor Mfg AITI
Condor Mfg USLT
Datran Corp
Dialight
Energy Resources ILS
ESPA Corp
General Electric
Geolights LDI
Gexpro
Gormley BETA
Gormley Kim
Green LED Solutions
Hite
Hite representing GE/OSRAM
Hite LEDFolio
Imbue Tech
Laface representing Acuity Brands/AEL/Visionaire/ESCO
LED waves
LeoTek
Niland Lighting
Orion
Paolicelli Roadway Lighting
Qualite
Repco II representing GE, LSI, and Lumec
ROMLite
Samudra
Solar Smart
Streetscapes Hadco
Universal Solutions
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XUS

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