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An Investigation into Light Bulb Sustainability

James Chen

York Pan

Andrew Renison

University of British Columbia

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James Chen

York Pan

Andrew Renison

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Dr. Carla Paterson

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Abstract

This article presents a triple bottom line assessment of 3 different options of lighting for use in the new SUB. A triple bottom line takes in to account social economical and environmental impacts of the choices. Much data on the usage part of the life cycle of the light source is readily available, however this does not cover energy consumption during manufacture or recycling; furthermore, there is even less information about the social impacts during these phases. For each lighting source, this report examines the manufacturing, usage and disposal stages in the life cycle of the lighting options. While there are transparency issues surrounding some of these stages, quantifiable data will be used when possible, and qualitative analysis when appropriate. With the different stages of the lifecycle for each option assessed, it is recommended that a combination of lighting options be used. Fluorescent tubes should be used for large open areas, small rooms such as closets should use incandescent or LEDs, and areas such as bathrooms should use LEDs or CFLs. A further cost analysis can be carried out based on these suggestions, but overall environmental and social factors should play a key role in determining the best options for specific uses.

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Glossary

Wafer: A thin slice of semiconductor material, such as a silicon crystal, used in the fabrication of integrated circuits and other microdevices.

LIST OF ABBREVIATIONS

CRI – Color Rendering Index

LED – Light-Emitting Diode

LCA – Life Cycle Analysis

CFL – Compact Fluorescent Lamp

SSL – Solid State Lighting

WTEF – Waste-to-Energy Facility

Introduction

As the new SUB aims to be designed with the goal of having a minimal ecological footprint, there are many aspects that need to be examined. This report looks at sustainable options for lighting, with three options being considered. CFLs, LEDs, and incandescent light bulbs are the focus of this report, and each will be examined in the production, operation, and disposal stages of its life cycle. As energy consumption is well known during the operation of these various lighting methods, attempts are made to focus more on the production and disposal stages.

Incandescent Light Bulbs

Incandescent light bulbs are the oldest kind of bulb on the market today. They are also the kind of bulb that people are most familiar with. They produce light by running a current through a wire filament and heating up the filament to incandescence. The bulb itself is evacuated and partially filled with an inert gas to prolong the life of the filament. Less than 10% [1] of the energy dissipated by the bulb is given off as visible light, and the rest is given off as heat. This would indicate that incandescent bulbs are a poor candidate as a sustainable choice, however there are a number of positive factors which must be considered in a triple bottom line assessment that qualify incandescent bulbs to be a candidate. The following sections will go into detail and quantify some of the properties of incandescent light bulbs.

Manufacture

Incandescent bulbs are the original light bulb; therefore the manufacturing processes for them are the most established and optimized. This is reflected by the low initial cost for this kind of bulb when compared to alternative bulbs for the same lighting application. Incandescent bulbs have remained relatively unchanged in their production since the design became practical enough for commercialization in the early 1900s [2].

The main materials that go into an incandescent bulb are glass and metal for the base [3]. There are no toxic substances used in the construction of an incandescent light bulb. Incandescent bulbs do not require an electronic ballast in their construction. The energy it takes to produce one incandescent bulb is 0.29 kWh [3].

A quick search reveals that most bulb manufacturers are based in mainland China or Taiwan, but there are a few manufacturers based in North America still selling incandescent bulbs. Buying from North American sources has two benefits. First it cuts down on shipping distance, which lowers energy consumed in the life cycle of the bulb, and secondly, manufacturers in North America must follow government regulated guidelines that control working conditions for workers.

If purchasing from a manufacturer in Asia, the carbon emission due to shipping must be added. According to carbonfund.org, CO_2 emissions when shipping with sea freight is 0.0273 g/(kg km) shipped [4]. The distance from Taiwan to Vancouver is 9570km [5] and each bulb has 26.37g [6] or .0264kg of material in it. This equals to 6.89g of co2 for every bulb shipped from Asia to Vancouver.

Operation

Incandescent bulbs have been in use for the longest amount of time, and as such, standard bases and fittings have been designed around the incandescent bulb. The E26 form factor is the standard light bulb that fits in most sockets and lamps in homes and small commercial applications in the United States. For compatibility, other light bulbs are made in such a way to mimic the E26 form, even if it makes the bulbs much more complicated, ie: CFL and LED bulbs.

The light produced by incandescence is the kind of light people are most familiar with and is most favoured by most people. This preference is reflected in the average CRI rating of incandescent light bulbs being among the highest of any bulbs, ~97, slightly higher for halogen filled bulbs [1].

The average efficacy of incandescent bulbs in lumen/W varies from 8-25, and are rated from 750 – 2500 operational hours. The amount of co2 emitted by the bulb due to energy consumption is 73kg over the lifetime of one bulb lasting 1000 hrs [6].

Disposal

Of the major types of light bulbs in this report, incandescent bulbs have the shortest life span, thus they must be disposed of most frequently. Incandescent bulbs do not offer much incentive to be recycled; they contain no toxic materials and can be disposed of safely. They also do not have enough recoverable material to be worth the energy expenditure to be recycled.

Recycling programs in Vancouver like those organized by Rona and Home Depot only take CFL bulbs and make no mention of incandescent bulbs. As incandescent bulbs are being phased out in favour of other alternatives, it is unlikely that any recycling programs will start any time soon.

Compact Fluorescent Lamps

The majority of the knowledge disseminated to the public about new CFLs, when compared to traditional, incandescent lights, is the increased longevity of CFLs during use. What is less known is the energy consumption during production of the fluorescent lamps, proper recycling methods and energy loss during disposal, and what constitutes as a holistic LCA of a CFL. When examining the production of a CFL, there are boundaries in obtaining accurate data and general knowledge about manufacturing practices. For one, the manufacturers themselves rarely disperse such information, and furthermore, such information is rarely tabulated. The second issue is where one decides to set limits on the scope of such an assessment. What is considered the "cradle" and "grave" in an LCA will affect the various energy inputs that are taken into account. For the purposes of this report, the production and disposal phases will be the primary focus in this triple-bottom assessment, since the in-service energy savings of CFLs are well known. When comparing the in-service use of a CFL to an incandescent light bulb, for example, it is known that the life of a CFL is approximately ten times longer (10,000 hours) than an incandescent light bulb [6], although this value changes and will be discussed later on, and the power requirements for a CFL are less than that for an incandescent [6]. For purposes of examining the production of fluorescent lights, specifically CFLs, it is necessary to briefly introduce the method of operation and components of the lamp itself.

Manufacture

Fluorescent lighting is already widely used in offices, classrooms, and large public areas within buildings. They are manufactured in numerous shapes, the most commonly seen is that in the slender, tubular form. More recently, CFLs are being used for private home use and in small office spaces. Fluorescent lights' mode of operation is different in many aspects to that of incandescent light bulbs. Fluorescent lights are known as "tubular discharge lamps" [1], that contain a small amount of mercury and are filled with argon gas, and require a ballast to ensure proper start-up and consistent lighting. During operation, electrons from the cathode located at one of the ends of the bulb are emitted and collide with the vapour mercury electrons, which radiate ultraviolet light. The phosphorus coating on the inner surface of the bulb then converts this ultraviolet radiation to visible white light. The ballast that is located at the base of the fluorescent bulb is a circuit board that contains a multitude of electrical components; some ballasts are made up of 24 components [6], which significantly increases the overall number of different metallic compounds present in a CFL. With this basic understanding of the working principle of a CFL, the two important issues are the presence of mercury in tube of the light, and the lead and arsenic that are released into the environment during production of the circuit board for the ballast. Fluorescent lights contain approximately 5 mg of mercury, although several newer brands of CFLs contain as little as 3.6 mg [1]. The problem during the production of

CFLs, with regards to the mercury content, is the health hazards posed to the workers in the manufacturing plants. Almost all of the CFLs bought in North America are manufactured in China [8], where production standards are not as stringent. Worker conditions are less regulated, and health and safety regulations can vary dramatically from one factory to another. In one documented case, 68 out of 72 factory workers required hospitalization form mercury poisoning in a factory located in Foshan, China, and in a similar incident in Jinzhou, China, 121 out of 123 factory workers had mercury levels in excess of the allowable amount, with some extreme cases where mercury levels were 150 times the allowable amount [8]. While these are some of the rarer cases that have been reported, high production rates of CFLs compounded with an absence of industry-wide health and safety regulations would not cause one to doubt that there are similar issues many factories and their workers face.

In addition to these social problems that fluorescent lights pose, there are also environmental issues in the production stages that merit consideration. In one study that compared CFLs to incandescent lights, the amount of lead and arsenic released into the environment was examined. Table 1 below shows illustrates these values for a typical incandescent light bulb and CFL. The numbers have been standardized in terms of 10,000 hours of in-service use for giving off approximately 1,600 lumens of light. This number is decided based on the average amount of light that a bulb or lamp needs to produce to be a viable product, and does not have anything to do with the color of light produced, which will be discussed later.

Table 1. Arsenic and Lead Emissions for Production of Incandescent and CFL lights [6]

	Arsenic Emissions (mg)			**Lead Emissions (mg)**		
	Airborne	*Waterborne*	*Soil*	*Airborne*	*Waterborne*	*Soil*
Incandescent 100 W	0.639	1.002	0.011	0.79	1.091	0.073
CFL 23 W	0.507	7.19	0.002	1.434	34.6	0.012

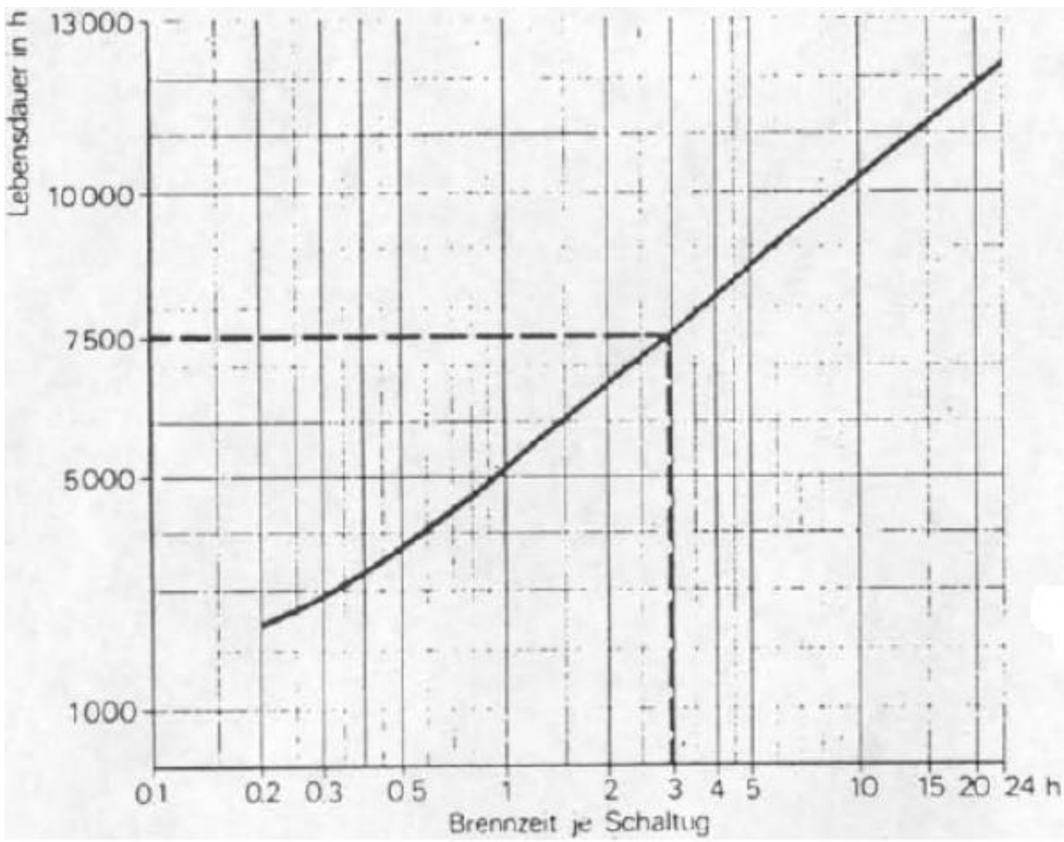
It is apparent that arsenic emissions for CFL production are higher than for incandescent bulb production, with the majority of emissions waterborne. Lead emissions in CFL production are significantly higher than for incandescent light bulb production, and similar to arsenic emissions, the majority is waterborne emissions.

Another aspect that should be considered is the weight of CFLs and CO_2 emissions for transportation costs. An average CFL has a mass of approximately 95 grams [6]. Based on the above values for CO_2 emissions associated with sea freight of 0.0273 g/(kg km) and an estimated shipping distance from Shanghai to Vancouver of 10,700 km, the carbon dioxide emissions for shipping one CFL equals to 27.75 grams.

Operation

Although there are a many different types of CFLs, most have an average of 10,000 hours per bulb. However, one important issue is the decrease in lifetime with an increase of cycling, or turning the lights on and off. The higher the frequency of cycling, the lower the lifetime of the CFL. Graph 1 below shows this linear relationship.

Graph 1. Lifetime of CFLs as a function of hours per activation [8]



The x-axis is the number of hours the CFL remains on, i.e. cycle time, in hours, and the y-axis shows the total lifetime of the CFL in hours. As this clearly shows, CFLs are better put to use in areas where there is no constant cycling. In a small office, where there would be a higher frequency of cycling than say in bathrooms, CFLs would not be as long lasting and energy efficient.

In regard to CO_2 emissions, CFLs, on average, emit 184 kg CO_2 per 10,000 hour lifetime [6]. Ninety-nine percent of this comes from the user end, in the form of electricity required to generate power for lighting the CFLs, with the remaining CO_2 emissions coming from production and shipping.

One important aspect during the use of CFLs, especially in comparison to traditional incandescent bulbs, in the discomfort that people can experience due to the “whiteness” of the light. The CRI rating of CFLs is lower than incandescent, and is usually around 80. Many people who are sensitive to such light do not prefer this option, and in some cases where people experience hypersensitivity to light, this is a considerable problem for extended exposure.

Disposal

A main concern with the disposal of CFLs is the mercury content of such a light source. With approximately 5 mg of mercury in each bulb, and a lack of proper recycling centers for CFLs, the worst case scenario is disposal into a landfill where all the mercury content seeps into the surrounding area once the tube breaks. One option for proper disposal in Vancouver would be utilizing the Burnaby Waste-to-Energy Facility (WTEF). With a carbon injection system installed into the WTEF, one of the first in North America [9], mercury emissions can be reduced and controlled. This would allow proper disposal of CFLs, with minimum mercury emissions into the environment during disposal.

LED

LEDs are commonly used in quantity to form SSL systems as a common efficient lighting method. However, merely including the production of the materials and LED components can already cancel out the energy savings during the usage.

Manufacture

A table that summarizes energy consumption during the production of LED is included below.

Table 2. LED Chip Production Energy Consumption [10]

	Energy Consumption
LED growth reactor system	11kWh
LED growth auxiliary equipment	11kWh
LED bake and auxiliary equipment	5kWh
Post-processing	20kWh
Facility systems	19kWh
Total	66kWh

The energy consumption is calculated based on the assumption that individual LEDs are of size 1mm by 1mm, allowing 2000 dies from a single wafer.

Also, the above numerical values are obtained from adding up each step of energy used during the production of LED. A sample table of energy consumption in process steps is included below in Table 3.

Table 3. Energy Consumption during Manufacturing Process [10]

Process Step	Single Wafer System (kWh)
Temperature ramp-up and stablilization	0.25
n-GaN	0.43
InGaN grading	1.2
Barriers and wells	1.88
p-GaN	0.37
Post-anneal	0.59
Temperature cool down	0.018
Total	3.7

The standards for LEDs have been well established. In Europe, no toxic materials are generated during the production of LEDs. Thus, the main environmental issue for manufacturing is carbon pollution in China, since most of LEDs are produced in China. The carbon pollution occur because of the energy consumption while producing LEDs and shipping to worldwide. Carbon pollution usually declines during a recession, but CO_2 pollution increased by 2 percent last year, most of the increase coming from China [11].

Operation

LEDs are commonly used in quantity to SSL systems as a common efficient lighting method. A simple comparison can clearly demonstrates how efficient SSL systems.

An incandescent bulb emits only 10% of the electricity, with the other 90% as waste heat. CFLs produce 5 times of light given the same amount of electricity, which means, for the same amount of light, CFLs provide 80% reduction in power consumption. A common alternative lighting method is to use LEDs in quantity to form SSL systems, which have the potential to produce 10 to 15 times of light given the same amount of electricity as incandescent bulbs, which means, given the same amount of light, SSLs provide 90% to 93% reduction in power consumption [10].

The main environmental issue of using LEDs is light pollution, which could lead to social problems, such as depressed immune systems and increase in cancer rates such as breast cancer [12]. Well established industrial standard and regulation are in need.

Disposal

LEDs have a long life time, and last about ten times as long as CFLs [13]. LEDs usually stop functioning due to the limit of the number of switching on, which is usually around a few thousand times. Because of the well established standards, LEDs do not have toxic materials generated during disposal. Thus, limited information about environmental problems during the disposal of LEDs can be found. Also, as a relatively new lighting method, more efficient disposal methods are under development.

Conclusion and Recommendations

As have been discussed, the various lighting options all have their advantages and disadvantages, so some sacrifices will have to be made when choosing the best options. What is important to recognize is that any sacrifices made in the name of sustainability ought to be minimised while maximising the output for each option. Thus a combination of options should be used. Table 4 below shows a basic comparison highlighting several factors that can help in determining what the best options are for the various parts of the new SUB. Large areas may want long, fluorescent tube lighting that consume less energy and last longer than incandescent light bulbs. Small offices may not want to use CFLs due to frequent on and off cycling. Bathrooms may be able to use LEDs or CFLs since lights are kept on a long periods of time, and motion sensors can be used to reduce energy consumption during off peak hours. Since people do not spend relatively long periods of time in the bathroom, the appearance of these lights is not of great importance. Janitorial closets may best be served by use of a single incandescent light bulb, in order to minimise full reliance of CFLs for lighting purposes. Study lamps for personal lighting in study areas for students would likely best be fit with incandescent light bulbs or LEDs, since there would be frequent on and off cycling, and this would reduce the amount of CFLs used and thus reduce the amount of mercury requiring recycling. Students who spend extended periods of time in study areas might experience fatigue from the appearance of harsh lighting and may experience light irritation.

Table 4. Baseline Comparison between lighting options

	Incandescent	CFL	LED
Cost (as this varies greatly, average baseline ratio is used)	1	three to ten times Incandescent	three to twenty times Incandescent
Life	700-1000 hrs	10000-20000 hrs	100000 hrs (usually 10 times of CFL)
Power (lumens/watt)	10	50	100-150
Application Requirements	none	lifetime decreases with shorter on/off cycles	lifetime decreases with shorter on/off cycles
Manufacturing Process	Less complex	more complex (ballast assembly)	most complex (13 general process steps)
Contains Mercury	No	Yes	No
Appearance	Pleasing	can be harsh on eyes	can be harsh on eyes
Disposal	Frequent disposal due to short operational lifetime	Limited recycling centers, mercury issues, can use WTEF	No known toxic chemicals released during disposal

While these lighting options have all been discussed, and social, environmental, and economical factors have been taken into account, natural lighting should be used as much as possible. Alternatives to lighting should be taken advantage of, such as inner walls painted white to increase room brightness and large rooms situated at corners of the building to maximise natural light intake should be utilized. With the acknowledgement that many rooms and areas in the new SUB will need additional lighting, this report has attempted to outline the best lighting options, and serves as a guideline in which to choose the most effective means for light bulb sustainability.

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