2

Impact of Conversion to Compact Fluorescent Lighting, and other Energy Efficient Devices, on Greenhouse Gas Emissions

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Abstract
Selecting appropriate boundaries for energy systems can be as challenging as it is important. In the case of household lighting systems, where does one draw these boundaries? Spatial boundaries for lighting should not be limited to the system that consumes the energy, but also consider the environment into which the energy flows and is used. Temporal boundaries must assess the energy system throughout its life cycle. These boundary choices can dramatically influence the analysis upon which energy strategies and policies are founded.

This study applies these considerations to the "hot" topic of whether to ban incandescent light bulbs. Unlike existing light bulb studies, the system boundaries are expanded to include the effects incandescent light bulbs have on supplementing household space heating. Moreover, a life cycle energy analysis is performed to compare impacts of energy consumption and greenhouse gas emissions for both incandescent light bulbs and compact fluorescent light bulbs. This study focuses on Canada, which not only has large seasonal variations in temperature but which has announced a ban on incandescent light bulbs.

After presenting a short history and description of incandescent light bulbs (ILBs) and compact fluorescent light bulbs (CFLBs), the notion that a ban on ILBs could alter (or even increase) greenhouse gas (GHG) emissions in certain regions of Canada are introduced. The study then applies a life cycle framework to the comparison of GHG emissions for the ILB and CFLB alternatives. Total GHG emissions for both alternatives are calculated and compared for the provinces of Canada and again a physical rebound effect sometimes occurs. Finally, the policy and decision making implications of the results are considered for each of these locations.

1. Introduction

While there is no question that a switch from incandescent light bulbs (ILBs) to compact fluorescent light bulbs (CFLBs) will produce comparable artificial lighting for a reduced amount of energy, it is much less clear that the switch will have a beneficial impact on greenhouse gas (GHG) emissions. Light bulbs are essentially space heaters and thus contribute to space heating and lighting, which are two of the greatest energy requirements for buildings and houses. Regions with different climates and energy sources will realize a range of environmental impacts due to a switch from ILBs to CFLBs. In this study, the impacts of substituting ILBs for CFLBs, on greenhouse gas emissions, in different regions of Canada are assessed. While most greenhouse gases are not "air pollution" in the strictest sense, since they occur in great abundance in nature, anthropogenic contributions to the environment of such gases is believed to influence not only the climate and ocean chemistry at present but may play a greater, and detrimental role, in future.

Although ILBs and CFLBs serve the same purpose, to provide light, they have different histories and properties. Humphry Davy invented the first incandescent light in 1802 after sending an electrical current through a thin strip of platinum and noticing that it produced both light and heat (Bowers, 1995). This discovery was key to the invention of our modern day ILB by Thomas Edison (Bowers, 2002). Modern ILBs consist of a filament of tungsten wire and inert gas contained within a glass bulb. The inception of CFLBs began with Alexandre Edmond Becquerel, who was the first person to put fluorescent substances in a gas discharge tube (Bowers, 2002). Although early experiments in the late 19th and early 20th centuries produced lights that varied in the colour spectrum, most were unfit for practical purposes as they did not emit white light. It wasn't until the 1920's when ultraviolet light was converted into a more uniformly white-colored light that CFLBs became a feasible alternative to ILBs. Modern CFLBs contain mercury vapour and low-pressure inert gas and are coated with a fluorescent powder to convert ultraviolet radiation into visible light.

When it comes to energy consumption for a specific light emissivity, ILBs and CFLBs have diverging properties. As many have pointed out, ILBs are essentially electric space heaters that give off a small portion of their energy (up to 10%) as light, the remainder being converted in various ways to heat energy; indeed, most of the visible light will itself ultimately become heat in the environment. CFLBs use between 20 to 25% of the power of an equivalent incandescent lamp for the same light output (Coghlan, 2007). This simple energy efficiency comparison is sometimes enough to justify using CFLBs instead of ILBs. As a result, many countries have started, or are in the process of, restricting the use of ILBs and promoting the usage of CFLBs.

On the forefront of the phasing out of ILBs for CFLBs are countries such as Brazil, Venezuela, and Australia. Brazil and Venezuela were the earliest countries to introduce legislation to phase out ILBs in 2005, while Australia is attempting to prohibit ILB use by 2010. The Canadian government has followed suit and committed to banning the sale of ILBs by 2012 (NRTEE, 2009). This topic has also garnered support from most environmental groups. The notion that using more energy efficient light bulbs is good for the environment is almost irresistible. Electricity generation is the single largest source of artificial greenhouse gas emissions, accounting for over 21% of all emissions. Hence, intuition would suggest that anything that will result in a reduction in electricity use should also reduce artificial greenhouse gas emissions.

Recent concerns over global climate change have highlighted the need to reduce our "carbon footprint." While energy conservation is a crucial measure for accomplishing this goal, the present authors wish to detail the change in total and net GHG emissions associated with a switch from ILBs to CFLBs.

1.1 Switching Light Bulbs and GHG Emissions

In Canada, the excess heat produced by interior ILBs is not entirely wasted, at least not during the cooler months between Fall to Spring. Drawing a system boundary around the common household, the light bulb emits energy in the form of light and waste heat. Both of these contribute to the space heating load during the winter months in cold climates. Therefore, electrically heated homes that replace ILBs with CFLBs will simply use additional direct electrical energy to make up for the loss in heat. Essentially, total energy savings, and subsequent impacts on global warming, for these houses could be negligible.

For residences that use other space heating systems (e.g., natural gas and oil), an increase or decrease in GHG emissions result when these homes burn larger amounts of these fuels in order to make up the additional space heating requirements caused by switching from ILBs to CFLBs. If home thermostats are left at the same temperature, the space heating system will have to work harder to supplement the loss of waste heat energy provided by the inefficient light bulbs. Depending on regional supply mix characteristics and types of household space heating, this may cause a net increase or decrease in GHG emissions for the household. The key to these impacts, to whether there is an increase or a decrease, is how the compensating electrical energy is generated, thus requiring a further expansion of the system boundaries.

In many places, a net reduction in GHG emissions will be observed. Burning fossil fuels directly to heat homes is about three times as efficient as using fossil fuels to generate electricity for the regional power grid and then distributing the electricity from that grid to heat the home. Therefore, Canadian provinces that rely heavily on fossil fuels to generate electricity and to heat homes, such as Alberta and Saskatchewan, would benefit twofold from switching from ILBs to CFLBs; energy would be saved and there would also be a reduction in GHG emissions.

In contrast, a substitution from ILBs to CFLBs would likely result in an increase in GHG emissions in provinces such as Quebec or British Columbia, where virtually 100% of the electricity generated is by non-GHG emitting technologies (i.e., hydropower), and where homes are typically heated by natural gas or oil. The overall energy consumption would be less than before, but the switch from a 'clean' regional electricity supply mix to a fossil-fuel generating residential space heating system would be less environmentally friendly.

But predicting the net GHG emissions due to this light bulb switch is not straightforward for all Canadian provinces. In the province of Ontario, electricity generation is provided by a variety of sources, some of which generate GHGs, such as coal and natural gas, and some of which do not, such as hydro or nuclear. In this case the situation is much more complex and the impact of a switch from ILBs to CFLBs on GHG emissions depends on what electricity generation sources are turned off, or throttled down, with the energy savings that are achieved.

But while the light bulb switch may have adverse impacts during the cold months, in the summer, the heat from incandescent light bulbs is indeed wasted and represents an extra heating load that often is removed by air conditioning. It doubly makes sense to replace interior lights with compact fluorescent ones in the summer, across the entire country and it makes sense to replace exterior lights with fluorescent ones during all seasons. However, in Canada the summer season is approximately four months long. Therefore, it may not necessarily make sense to have a national ban on incandescent bulbs; reductions in GHG emissions for one region of the country may be cancelled out by increases in another.

2. Light Bulb Life Cycle Analysis Methodology

The first goal of this study is to critically analyze the life-cycle impacts of switching from ILBs to CFLBs in the following provinces of Canada: British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland. The framework for a comparison of GHG emissions for the ILB and CFLB scenarios requires the a model to link household life cycle energy used for space heating, space cooling and lighting with GHG emissions in order to compare the impacts of switching from ILBs to CFLBs. This is achieved in four main steps: First, energy and GHG emissions characteristics for the fabrication and disposal phases of incandescent and compact fluorescent light bulbs are estimated. Second, total energy used for household space heating, space cooling and lighting is determined using an equivalent planning period. Next, these life-cycle energy requirements are converted to GHG emission equivalents using specific energy source GHG intensities (e.g., natural gas, heating oil, and electricity) for the particular household locations. Finally, the net difference in GHG emissions due to switching from ILBs to CFLBs is compared.

The planning period of the life cycle energy analysis (LCEA) corresponds to the greater design life of the two light bulbs. System boundaries for the LCEA are specified in each life cycle phase as follows: (1) Fabrication Phase: material extraction, material production, and light bulb manufacturing; (2) Operation Phase: space heating energy, space cooling energy and lighting energy; and (3) Disposal Phase: light bulb scrapping. To simplify the model formulation, light bulb transportation energy requirements are not included within the LCEA.

The total energy expenditure of the system over the equivalent planning period can be estimated, taking into account the energy of the fabrication, operation and decommission stages. Symbolically this can be represented:

$$E = F + H + C + L + D \tag{1}$$

where:

- F = Total energy required to fabricate the bulbs,
- H =Total heat energy produced by household light bulbs during cold weather,
- C = Total heat energy produced by household light bulbs during warm weather,
- L = Total amount of energy produced in generating light, and
- D = Disposal energy required.

These terms are discussed in more detail in the following sections.

2.1 Fabrication and Disposal Phases

The fabrication stage includes material extraction, material production and light bulb manufacturing. Disposal involves the total energy required to scrap and deposit the light bulb. To avoid double counting and "reinventing the wheel," unit energy requirements for the fabrication and disposal phases of a light bulb are adopted from Gydesan and Maimann (1991) (see Table 1). Gydesan and Maimann calculate the unit energy requirements for the fabrication phase by determining the material content of the light bulb and multiplying this value by the energy content found in the corresponding material. As for unit disposal energy requirements for the disposal phase, Gydesan and Maimann advise that "no quantitative calculation has been made of the energy consumption needed for scrapping the lamps, but a qualitative assessment support that it is negligible compared to the energy consumption during the operation phase." Therefore, it is assumed that the disposal energy per bulb is equal to zero.

	ILBs	CFLBs
Wattage Equivalency (W)	60	15
Operational Lifetime (hours)	1000	8000
Fabrication Energy Per Bulb (kWh)	0.15	1.4
Disposal Energy Per Bulb (kWh)	0	0

Table 1. Light Bulb Characteristics (Gydesan and Maimann, 1991).

Applying these values with the number of replacements required throughout the planning period, the total energy required in the fabrication and disposal stages can be calculated using the following formulas:

$$F = \sum_{j=1}^{M} e_F \tag{2}$$

$$D = \sum_{j=1}^{M} e_D \tag{3}$$

where, F = total energy required to fabricate the light bulbs (kWh); e_F = fabrication energy requirement per light bulb (kWh); M = number of light bulbs requiring replacement or disposal throughout the planning period; D = total energy required to dispose of the light bulbs (kWh); and e_D = disposal energy requirement per light bulb (kWh).

2.2 Operational Phase - Space Heating Energy

Total energy required to heat a household can be found by performing an energy balance based on conservation of energy. In a household, differences between indoor and outdoor temperatures promote heat transfer through the building envelope by conduction. In cold weather, indoor temperatures are greater than the outdoor environment. As a result, energy is lost through the building envelope to the outdoor environment; to counteract this heat loss, heating systems such as a natural gas furnace, heating oil furnace, or electrical baseboards are installed to provide energy to maintain a constant indoor temperature. During cold days, heat wasted by inefficient light bulbs directly supplements the space heating component.

Thus, by defining the building envelope as the system boundary, a crude estimate of the annual energy required to maintain a household at a constant temperature during cold days (H) involves subtracting the annual heat energy gains by interior lighting (H_L) from annual building envelope heat energy loss during cold days (H_{BE}), such that:

$$H = H_{BE} - H_L \tag{4}$$

where (4) is measured in kWh.

Average Canadian households located in different provinces vary in building size, envelope thermal resistance, and climate. These regional differences provide unique energy consumption rates for the average local household. Assuming that the majority of Canadians maintain average indoor temperatures around 18°C (Valor et. al., 2001), a common building science unit, degree-days, can be used to estimate energy losses and gains through the building envelope. Heating Degree-Days (HDD) and Cooling Degree-Days (CDD) are quantitative units that add up the differences between the mean daily temperature and the average indoor temperature of 18°C over an entire year. For example, if three average outdoor daily temperatures were 12°C, 16°C and 10°C, the total HDD for those three days would be 16 K·days (i.e., 6 + 2 + 8).

Thermal resistance of a building envelope is key to determining a household’s heat loss or gain. A building envelope is effectively a membrane that separates indoor and outdoor environments whose primary function is to control heat flow through the use of thermal insulation. Regional climates make for different insulation resistance requirements (i.e. R-values). To estimate building envelope heat loss, HDD and CDD are combined with the building envelope thermal resistance and surface area by the following relationship (in kWh):

$$H_{BE} = \sum_{i=1}^{n} \left(\frac{A_i}{R_i} \right) HDD \tag{5}$$

where n = total number of different surface areas; A = surface area i of the building envelope area (m^2); R = building envelope surface area i thermal resistance ($m^2 \cdot K$)/W; and HDD = heating degree-days (K·day).

A light bulb emits all of the energy it consumes as heat or light. While the primary function of a light bulb is to provide a source of light for the resident, all of this energy supplements the space heating energy required to maintain a constant temperature within the household. Waste heat energy is emitted from the light bulb while light energy also contributes to space heating as the building walls and components absorb the light and convert it to heat. Total heat energy produced by household light bulbs during cold weather can be estimated (in kWh) as follows:

$$H_L = \alpha_H \sum_{i=1}^{n} 8.76\, P_i t \tag{6}$$

where α_H = percentage of year requiring heating; n = number of light bulbs in an average household; P = power required to operate light bulb i (W); and t = percentage of time the light bulb is turned on throughout an entire year.

2.3 Operational Phase - Space Cooling Energy

Total energy required to cool a household can also be found by performing an energy balance. In warm weather, high outdoor air temperatures can produce an uncomfortable indoor environment; a household air conditioning system is often installed to provide comfort for occupants by lowering the indoor air temperature.

However, in contrast to space heating energy requirements, heat energy produced by light bulbs during warm days increases the total space cooling energy required. Thus, by again defining the building envelope as the system boundary, a crude estimate of the annual energy (in kWh) required to cool a household during warm days (C) involves adding the annual heat energy gains by interior lighting (C_L) with annual air conditioning energy requirements (C_{AC}), such that:

$$C = C_{AC} + C_L. \tag{7}$$

The annual energy requirements of an air conditioner are dependent on cooling degree-days, outdoor design temperatures, and energy efficiency ratings. Natural Resources Canada (2004b) uses the following formula to estimate space cooling energy requirements (in kWh):

$$C_{AC} = \frac{Q \cdot CDD}{(T_d - 18)0.9\, EER} \cdot \frac{24}{1000} \tag{8}$$

where Q = basic air conditioning cooling capacity (Btu/h); CDD = cooling degree-days (K·day); T_d = air conditioning design temperature (°C); and EER = air conditioning energy efficiency rating.

In summer months, the energy consumed by a light bulb will be transferred to the household and will add this energy to the space cooling load. Using the same rationale in determining equation (6) above, the total heat energy (in kWh) produced by household light bulbs during warm weather can be estimated by:

$$C_L = \alpha_L \sum_{i=1}^{n} 8.76\, P_i t \tag{9}$$

where α_C = percentage of year requiring cooling; n = number of light bulbs in an average household; P = power required to operate light bulb i (W); and t = percentage of time the light bulb is turned on.

2.4 Operational Phase - Lighting Energy

Energy is consumed by ILBs and CFLBs to produce visible light. The amount of electricity 9in kWh) used for home lighting (L) is estimated using the following formula:

$$L = \sum_{i=1}^{n} 8.76\, P_i t \tag{10}$$

where n = number of light bulbs in an average household; P = power required to operate light bulb i (W); and t = percentage of time the light bulb is turned on.

3. GHG Intensities

There are five main energy sources for Canadian electricity: coal, natural gas, oil, nuclear and hydroelectric. There is a small amount of wind-powered generation that is increasing in importance but at this point represents less than 1% of Canadian electricity generation. Each source has its exclusive GHG intensity (emissions per unit of electricity): coal has the highest GHG intensity; oil has about 75% of the emissions of coal; gas has about half of the coal GHG intensity; and nuclear and hydroelectric sources are assumed to be non-GHG-emitting sources. Strictly speaking there are life-cycle greenhouse gas emissions for nuclear and hydroelectric generation as well. Though there is no consensus figure on these, estimates are of the order of 10 grams of CO_2 per kWh. In any event these are much lower than the additional life cycle emissions from burning of fossil fuels, which are also not considered. Only GHG emissions from operation are considered, since these are well known.

Manufacturing and disposing light bulbs requires energy. Producing this energy often involves burning fossil fuels. As a result, any light bulb produced or scrapped may produce GHG emissions. To simplify the analysis and draw from existing literature, GHG intensities used to fabricate and dispose of ILBs and CFLBs are taken from Gydesan and Maimann (1991). Although light bulbs come from different suppliers and often manufactured half-way across the globe, it is assumed for simplicity that the electricity supply mix used in their paper is common for all light bulbs used in Canada.

During the operational phase, natural gas and oil are two common forms of energy used to heat the average Canadian household. For simplicity, these GHG intensities are assumed to be constant across Canada. Space heating using electricity, on the other hand, has varied GHG intensities due to its dependence on the regional electricity supply mix. For example, Quebec will have a low level of average space heating GHG intensity primarily because it relies on electric baseboards or forced air electric furnaces for space heating.

During the operational phase of a light bulb, GHG emissions will be different for the Canadian provinces, as the electricity generation supply mix (and the corresponding GHG intensities) varies by province. For example, in the province of Alberta electricity generation is predominantly fueled by coal. Hydroelectric power is nearly the exclusive source of electricity in Quebec, and Ontario is between the two: it controls sources of hydro, coal, natural gas and a small amount of oil along with a baseline load of nuclear power to provide electricity. Average GHG intensity per region can be estimated by dividing regional GHG emissions by total electricity generated by the specific energy source (Environment Canada, 2007). As a result, Alberta has a high average GHG intensity for electricity generation while Quebec is very low and Ontario is moderate.

To assess the difference in GHG emissions involved in using ILBs and CFLBs, GHG intensities (in the form of g CO_2 eq/kWh) for each life-cycle phase are multiplied by corresponding fabrication, space heating, space cooling, household lighting and disposal energy requirements to estimate total GHG emissions using the following formula:

$$G = \eta_i F + \eta_i H + \eta_i C + \eta_i L + \eta_i D \tag{11}$$

where η_i = GHG intensity as a function of the main energy source (g CO_2 eq/kWh). Equation (11) is measured in g CO_2 equivalents.

4. Results

The analytical model developed above is applied to determine total life cycle energy requirements from the fabrication, operation (space heating, space cooling and lighting) and disposal phases of a light bulb within a household located in each of the provinces of Canada.

For this study, the typical design life of a CFLB is assumed to be 8000 hours (Gydesan and Maimann, 1991). The light bulbs are also assumed to operate only 4 hours per day. Using these two values, the life-cycle planning period is determined to be 5.5 years. To compare an ILB on the same timeline, the ILB is assumed to be replaced eight times throughout the planning period. Adopting the data from Gydesan and Maimann (1991), life-cycle energy requirements for the average ILB and CFLB (neglecting space heating relationships introduced earlier) fabrication and disposal stages are determined (see Table 2).

	ILBs	CFLBs
Fabrication Stage (kWh)	32	37
Operational Phase (kWh)	Varies by Province	Varies by Province
Disposal Stage (kWh)	0	0

Table 2. Light Bulb Life-Cycle Energy Requirements.

Fig 1 estimates the total life cycle energy requirements throughout the entire planning period assuming only the lighting energy requirements from the operational phase. Looking at lighting energy alone, significant savings in energy consumption are realized when switching from ILBs to CFLBs.

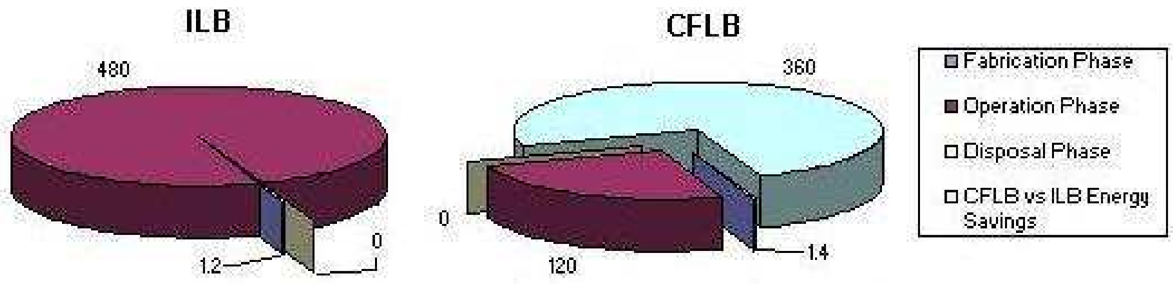

Fig. 1. Life-Cycle Energy of ILBs vs CFLBs (units in kWh).

However, the analysis that follows expands the system boundaries from their research to include space heating, cooling and total lighting energy requirements to assess the overall environmental impacts of switching from ILBs to CFLBs. Energy requirements for both ILB and CFLB scenarios, including space heating considerations, are estimated for Canadian provinces using (4) to (10). The majority of the data has been assembled from Government of Canada sources (See the Tables in Appendix A). Total operational energy estimates for ILBs and CFLBs in the average provincial household are presented in Table 3.

	BC	**AB**	**SK**	**MN**	**ON**
ILB Yearly Household Energy (E_{ILB}) (kWh)	15,100	21,300	24,700	22,900	19,000
CFLB Yearly Household Energy (E_{CFLB}) (kWh)	14,700	20,800	24,100	22,200	17,900
	QC	**NB**	**NS**	**PE**	**NL**
ILB Yearly Household Energy (E_{ILB}) (kWh)	18,900	19,200	18,300	19,400	18,900
CFLB Yearly Household Energy (E_{CFLB}) (kWh)	18,300	18,800	17,700	18,900	18,500

Table 3. Yearly Household Heating and Lighting Energy Requirements for Various Canadian Provinces.

Converting these energy requirements to GHG emissions using (11), total household GHG emissions for the selected provinces while using either ILBs or CFLBs were calculated in Table 4. Again, aggregation of data regarding regional GHG intensities came from a number of Government of Canada sources (See Tables in Appendix A).

	BC	AB	SK	MN	ON
Net GHG Emissions from the Light Bulb Switch (G_{net}) (kt CO_2 eq)*	1690	-8470	-2430	407	-5460
Annualized Net GHG Emissions from the Light Bulb Switch (G_{net}) (kt CO_2 eq)	**309**	**-1550**	**-443**	**74**	**-997**
Residential GHG Emissions over Planning Period (kt CO_2 eq)*	22100	40200	8820	5750	104000
Percentage Change from Residential Emissions	+7.7%	-21.1%	-27.5%	+7.1%	-5.2%
	QC	NB	NS	PE	NL
Net GHG Emissions from the Light Bulb Switch (G_{net}) (kt CO_2 eq)*	1450	-389	-1670	-22	110
Annualized Net GHG Emissions from the Light Bulb Switch (G_{net}) (kt CO_2 eq)	**265**	**-71**	**-305**	**-4**	**20**
Residential GHG Emissions over Planning Period (kt CO_2 eq)*	23700	2850	5460	1270	1430
Percentage Change from Residential Emissions	+6.1%	-13.7%	-30.6%	-1.7%	+7.8%

* Note: The life cycle planning period is 5.5 years

Table 4. Household Life-Cycle Heating and Lighting GHG Emissions for Various Canadian Provinces.

4.1 Sensitivity Analysis

A sensitivity analysis was carried out to assess the influence of uncertain model parameters on total and net GHG emissions. Each parameter was increased and decreased by 50% in 25% increments and the model was run again with the new values to determine total and net GHG emissions due to these changes. Differences in GHG emissions between different provinces were also noted.

4.1.1 Total GHG Emissions

The following parameters were found to be the most sensitive when assessing total GHG emissions:

- Percentage daily light bulb operation
- CFLB operational lifetime, and
- number of private dwellings occupied by usual residents.

The following parameters were found to have moderate sensitivity when assessing total GHG emissions:

- Average indoor wall height
- heated area
- minimum thermal resistance for the walls and floor, and
- average electricity GHG intensity

Those parameters that had the minimum impact on GHG emissions were:

- average number of household light bulbs
- minimum thermal resistance for the roof
- percentage of year requiring heating, and
- air conditioning design temperature

GHG emissions were relatively insensitive to the following parameters:

- Percentage of indoor household light bulbs
- percentage of outdoor household light bulbs
- air conditioning EER
- ILB operational lifetime
- light bulb fabrication energy
- percentage using central and portable A/C systems, and
- basic air conditioning cooling capacity

4.1.2 Net GHG Emissions

The parameters that had significant impact on net GHG emissions were:

- average number of household light bulbs
- percentage of indoor household light bulbs
- percentage daily light bulb operation
- private dwellings occupied by usual residents
- percentage of year requiring heating, and
- average electricity GHG intensity had significant sensitivity.

The percentage of outdoor household light bulbs had only moderate impact on net GHG emissions while the percentage of the year requiring cooling had only a slight impact on net GHG emissions. All other parameters were deemed to be insensitive towards net GHG emissions.

Almost all of the air conditioning parameters influenced the total and net GHG emissions for Ontario (i.e., air conditioner EER, percentage of year requiring cooling, percentage using central and portable AC systems, basic air conditioning cooling capacity, and air conditioning design temperature); the other provinces were generally insensitive to these parameters since air conditioning is not as heavily used.

5. Critical Reflections

As expected, there is an overall household reduction in life-cycle energy consumption for each province when switching from ILBs to CFLBs (see Table 4). However, the energy saving is not as substantial as a first impression might have suggested. The electrical energy saved when using efficient light bulbs is generally offset to some extent by the increased space heating energy requirements. The results also indicate that the fabrication and disposal phases of a light bulb do not have a substantial impact on the total energy consumption or GHG emissions of a light bulb (these phases generally less than 0.5% of the total life cycle energy consumption). Rather, the greatest impact is observed in the operational phase (greater than 99% of the life-cycle energy consumed by a light bulb comes from the operational phase).

Total GHG emissions caused by the light bulb "switch", on the other hand, were strikingly different. As shown in Table 4, net GHG emissions decreased in many provincial households that switched from ILBs to CFLBs. Many provinces 'switched' from a high to a low GHG-emitting space heating energy source. But the marginal decrease differed for each province. For example, the decrease in Ontario was much smaller than in Alberta, even though Ontario has nearly four times the population. Meanwhile, some provinces experienced a switch in the opposite direction to that experienced by the majority of the provinces. British Columbia, Manitoba, Quebec, and Newfoundland-Labrador all experience a net increase in GHG emissions resulting from the light bulb switch.

Alberta is an example of a compelling case for making a switch from ILBs to CFLBs. The GHG intensity of electricity generation in the province is very high (861 g CO_2/kWh) while the GHG intensity associated with home heating is relatively small (approximately 220 g CO_2/kWh). Hence, providing partial heating for a home using inefficient ILBs is much worse for the environment in terms of GHG emissions. This same explanation can be used for households located in provinces such as Saskatchewan, New Brunswick, Nova Scotia, and PEI that also experienced a net decrease in GHG emissions.

Quebec represents the opposite extreme. In Quebec, the majority of homes are heated using electricity that has an average GHG intensity of 8 g CO_2/kWh. For these homes, it makes virtually no difference to GHG emissions if interior ILBs are replaced with CFLBs in months when home heating is required. At the same time, the homes will be no less expensive to heat. Only in the summer months will Quebec's switch from ILBs to CFLBs result in less electricity consumed and have a negligible effect on GHG emissions.

However, the situation is different for the increasing plurality of Quebec homes that are heated with oil and natural gas. The GHG intensities associated with space heating using natural gas (approximately 220 g CO_2/kWh) or oil (approximately 315 g CO_2/kWh) are much higher than those associated with electrical space heating; a portion of which is provided by light bulbs. In these homes, switching from ILBs to CFLBs will result in some energy savings but will also result in the use of a different mixture of energy types that have a higher overall GHG intensity. As Table 4 shows, if all homes in Quebec were required to switch from ILBs to CFLBs there would be an increase of 265,000 tonnes in CO_2 emissions in the province, equivalent to the annual emissions from almost 50,000 automobiles. In fact, this amount will increase in future as homes move away from electric space heating to cheaper and more efficient fossil fuel sources! Again, this same argument can be used for households located in provinces such as British Columbia, Manitoba and Newfoundland-Labrador who also experienced a net increase in GHG emissions.

In Ontario, the situation is less straightforward. The GHG intensity of electricity generation is moderate (220 g CO_2/kWh) and comparable to the GHG intensity of space heating using natural gas, which is the predominant heating source in the province. A warmer climate in the summer months, compared to Quebec and Alberta, helps to tip the balance slightly in favour of switching from ILBs to CFLBs, if reduction in CO_2 emissions is the goal.

The opportunity for greater reduction of GHG emissions in Ontario exists but would require coordination with provincial bodies that control the electricity generation sector. Ontario has a large variety of electricity generation sources and the way that they are managed is complex. Nuclear power accounts for about 50% of Ontario's electricity generation and it is run at close to 100% output 24 hours per day providing most, but not all, of the base load electricity requirements for the province. Coal, natural gas, a small amount of oil, and hydro are used to provide the balance of base load requirements and electricity generation supplies are adjusted to meet demand, a practice the industry refers to as "load following." Wind power generation is relatively small but the grid accepts whatever energy it can provide.

In a province like Ontario it is not so much the average GHG intensity of electricity generation that matters but rather the forms of electricity generation, which are turned off with the energy saved by switching from ILBs to CFLBs. Ideally, coal generation would be turned off with the energy that is saved. At present, however, there is no regular pattern in how the Ontario electricity system responds to load changes from one day to the next, at least in terms of what forms of electricity generation are switched off. For maximum environmental benefit one would like to see hydro capacity kept constant and coal electricity generation turned off. However, most of Ontario's hydroelectric generation is not capable of 24/7 operation and many dams need to be switched off during the late evening and in the middle of the night to allow an inventory of water to build up, thus allowing them to be used to meet peak demand in the middle of the day.

In Ontario, consumers pay a fixed price for electricity depending on their usage. The largest electricity producer is the provincially owned Crown Corporation, Ontario Power Generation, and it receives a fixed price for the electricity that it generates depending on rates determined by the Ontario Energy Board, their regulating body. Many private electricity generators, most of whom run natural gas fired plants, receive the market price. Economics, therefore suggests that the best value for the taxpayer would occur if the natural gas generators were turned off in response to a reduction in demand, since this is generally the most expensive source of generation. However, this does not generally happen in isolation. At times of low demand, which can occur in the Spring and Fall periods of the year in a climate like Ontario's, hydro-electricity is sometimes used to follow electrical loads, which from a GHG emissions perspective, is the worst case scenario if the aim is to use more efficient CFLBs to reduce greenhouse gas emissions. In the absence of better information, the average GHG intensity for the provincial electricity generation grid was used in these calculations. However, it should be recognized that Ontario has potential to improve GHG emission reductions when switching from ILBs to CFLBs if this emission reduction goal is factored into operation of the diverse mix of generation facilities. In the absence of a price for carbon there are no economic drivers to encourage electrical generation utilities to manage their diverse generation sources in such a way as to turn off those that have the highest GHG emissions when electricity demand drops.

5.1 Sensitivity Implications

Of the parameters that were sensitive to total GHG emissions, most of their sensitivity can be explained with common sense: the longer a light bulb operates, the greater its total GHG emissions; and with a greater number of households comes higher emissions. There is also rationale behind CFLB and ILB operational lifetime varying in sensitivity. The CFLB operational lifetime is sensitive because the model planning period is based on this parameter. The ILB operational lifetime is insensitive due to the insignificant impact that light bulb fabrication has on the total GHG emissions throughout the planning period.

Sensitivity regarding net GHG emissions is slightly more difficult to explain. It is easy to understand that the number of household light bulbs and private dwellings occupied by usual residents will increase the marginal difference between GHG emissions associated with ILBs versus CFLBs – these parameters clearly exacerbate the net difference in GHG emissions. The percentage of indoor household light bulbs is directly related with the impacts light energy has on supplementing space heating energy during the colder months. Since space heating energy consumption is directly related to the percentage of year requiring heating, the effects a CFLB has on increasing the load of a space heating system during varying periods of 'cold' months may have a direct impact on net GHG emissions depending on how the electricity is generated and how the home is heated. Altering the GHG intensities involved in electricity generation for each province will also impact the net difference in GHG emissions: there are regions where electrical heating from light bulbs is effectively "switched off" and replaced with space heating energy sources other than electricity that have higher or lower GHG intensities.

As for the net GHG emissions, sensitivity involving the air-conditioning parameters are unmistakable in Ontario since it is one of the few provinces where the use of air-conditioning is prevalent.

5.2 Common Misconceptions

A number of readers have an intuitive feeling that the findings from this research are just plain wrong. While many arguments against the study may be defensive "gut reactions," two common disputes have been raised when interpreting the validity of this research: 1) the savings in electricity by switching from ILBs to CFLBs ultimately reduces fossil-fuel based electricity generation; and 2) the electricity generated in each province is fungible – electricity grids are interconnected and a savings in one area result in a decreased load in another area. Addressing both of these arguments enlightens the readers to the further intricacies discovered while modeling this light bulb "switch". A discussion of these items follows.

5.2.1 "Saving electricity reduces fossil-fuel based electricity generation"

This argument revolves around the notion that the electricity saved must be in the form of coal-fired electricity generation. But this assumption is not correct – different regions can throttle down different sources of electricity generation when experiencing a lighter load demand. It is the type of electricity generating source that is turned off with the electricity that you save by using CFLBs, specifically for each region that matters.

This point is easily illustrated. Ontario is complex and thus has no coherent pattern for throttling down generating sources in response to load reduction. For instantaneous changes, coal fired generation is generally used because it responds the fastest to demands for load increase or reduction. However, the savings one finds in switching from ILBs to CFLBs are systematic ones, more like current day to day fluctuations that are largely driven by the weather. If you look at these day to day fluctuations and compare one day to the next, between the hours of 6 PM and midnight (when people tend to use their lights), sometimes hydroelectricity is throttled down, sometimes coal is, sometimes gas fired electricity is throttled down and sometimes all three.

Examining one month's worth of data from the Ontario Independent Electricity System Operator (IESO), from April 7th to May 8th of 2008, to see how the electricity system deals with load reductions was fascinating: nuclear generation stayed the same (as one would expect - being baseload), coal generation decreased by 43%, natural gas generation decreased by only 10% and hydro-electric generation by 47%. Using the same approach as Environment Canada (2007), this means that the incremental GHG intensity for Ontario approximately equals (if you assume that this one month stretch is representative): 0.43 X 900 g CO_2/kWh (for coal) + 0.10 X 500 g CO_2/kWh (for natural gas) + 0.47 X 0 g CO_2/kWh (for Hydro) = 437 g CO_2/kWh. This incremental value, when compared to Environment Canada's (2005) Ontario GHG intensity of 220 g CO_2/kWh, would actually result in a yearly residential GHG reduction of approximately 1980 kt CO_2 i.e; a substantial decrease in GHG emissions for Ontario.

In Alberta, the situation is clear – reducing coal-based electricity generation is the only option and therefore the above statement remains true.

Although electricity is fungible, in Quebec, it is hard to make a compelling argument that using CFLBs will result in a coal fired electricity generating station being shut down in New Brunswick or New York State or elsewhere. The ability to transmit electricity from one jurisdiction to the next is limited by simple physics (e.g., transmission losses when transporting electricity great distances) not to mention politics (e.g., difficulties in trying to build new transmission lines). In addition, most electricity trading goes on during the day, when loads are highest, and not during the late evening when people use their home lighting the most. Understanding the incremental electricity savings and the type of electricity generation that would be subsequently throttled down is not so cut and dried as one would expect. It is complicated, which is another important point that we make in this study.

5.2.2 "Electricity supply is fungible"

Many arguments in favour of CFLBs have to do with the philosophical belief that reductions in load will manifest themselves in less use of fossil fuels, and this has been addressed to some extent in the previous section. There are arguments that electricity is fungible (sort of like money) – so that electricity generated by a particular source in one province can be swapped with another in an adjacent province or US state. However, understanding the electricity export/import situation in different provinces is complicated.

Many permutations involving "what ifs" are generated when including electricity exporting/importing from adjacent provinces/states. For example, one argument involves the potential export of electricity from Alberta to British Columbia if the existing demand from BC is higher than the province's generating capability. In such a case, using ILBs will cause greater GHG emissions in BC because it may have to import electricity from nearby Alberta, which is generated exclusively by fossil fuels with a high GHG intensity. But if electricity is fungible, then Alberta may also import electricity from BC. This means there is a possibility that any electricity load reduction that results from switching to CFLBs in Alberta, could result in diminished imports from BC, since that electricity will be more expensive than in-province fossil generated electricity. If that were the case then switching to CFLBs in Alberta could have no impact on GHG emissions at all in the absence of a provincial government policy mandating the import of clean electricity from BC, even if it is more expensive. In other words, in the absence of a substantial carbon penalty, or government policy, there are no economic drivers to shut down coal fired electricity generation in response to load reduction because, whatever its faults, coal fired electricity is relatively cheap. Until such time as this happens, the greenhouse gas emission reductions that could be achieved, in switching from ILBs to CFLBs, will never come close to being realized in a country like Canada, with a relatively cold climate and relatively clean electricity generation.

6. Future Research

Some questions can be raised towards the validity of the unit energy requirements for the fabrication and disposal phases of a light bulb, as the values and assumptions used to estimate these values may be outdated and/or obsolete. Gydesan and Maimann (1991) indicate that their fabrication data was taken from a source dated back to 1979. At the same time, the assumption that there are no disposal phase energy requirements may be incorrect. Gydesan and Maimann (1991) explain that increased energy requirements may be needed for properly handling the mercury that remains an issue during the disposal of CFLBs. In their analysis, they assume that the light bulbs are disposed via an incinerator and that all mercury is emitted to the environment. The latter is one consequence of switching from ILBs to CFLBs that is outside of the scope of this work. ILBs can be disposed of in ordinary household waste while CFLBs require an infrastructure to manage their disposal and manage mercury pollution. In the absence of such an infrastructure and strict adherence to them, one consequence of a mandated switch from ILBs to CFLBs would be an increase in environmental mercury pollution.

Another item that may need further review is the energy and GHG emissions involved in the transportation phase. Light bulbs are also manufactured in many places across the globe – each with different local electrical generation supply mixes and varying distances to ship the light bulb from the manufacturer to the consumer. Exporting of manufactured goods from half way around the world could provide the foundation for substantial energy requirements and GHG emissions involved in the transportation phase. Additional research in this area is recommended.

Finally, additional research involving the importing/exporting of electricity across provincial, state or country boundaries in response to load changes is crucial for understanding the impact of switching from ILBs to CFLBs on GHG emissions. Bans of ILBs are largely based on the mistaken impression that the energy saving realized in switching from ILBs to CFLBs will result in the switching off of coal fired generation because of the fungible nature of electricity. This is simplistic, will only occur in some jurisdictions and his highly dependent on the nature of electricity generation available and the nature of the electricity market. Where market forces drive the dispatch of electricity generation, the electricity savings that result in switching from ILBs to CFLBs will generally result in the most expensive forms of generation being turned off first and this is usually not coal fired generation, if more expensive generation is also part of the mix.

Understanding these mechanics could have significant impacts on future decision-making and policies for Canadian homeowners and even business-owners as carbon-based currencies become popular in the future. Including this analysis is out of the scope of this study, but should be carried out before policy is executed.

7. Conclusions

Decisions that are made regarding the future of energy use, conservation and demand management or even the optimal blend of supply mix are interdisciplinary and complex by nature. The metrics used to evaluate the decision have to be compatible with the choices themselves and cannot be skewed towards either.

In summary, switching from ILBs to CFLBs may not always result in an environmentally friendly outcome, especially in cold climates. While the intention to reduce electricity consumption is noble, the "switch" from electrical and fossil-fuel based space heating may drive up GHG emissions in certain regions. While we agree with the paradigm of reducing overall demand, the core contribution of this research highlights the greater need to reduce demand from higher GHG intensive energy sources.

We are entering the age of carbon consequences where measuring, reporting and addressing carbon emissions will become commonplace. It is time to rethink how we use current energy supplies by eliminating fossil fuel-based energy and begin to encourage energy from sustainable sources.

If we only generated electricity in Canada by burning coal, with a GHG intensity of approximately 900 g/kWh, our model predicts that almost 14 million tonnes of CO_2 per year would be avoided in Canada if every household switched from using ILBs to CFLBs. However, our electricity generation is relatively clean in Canada and instead our model, together with our assumptions, predicts only a reduction of 2.7 million tonnes.

In this case, a Canadian-wide ban on ILBs is not an ideal strategy to reduce national GHG emissions. Although the ban will result in a reduction in net Canadian GHG emissions there are provinces that will see and increase in GHG emissions due to the light bulb switch (i.e., BC, MB, QC, and NL). Only certain Canadian locations would benefit most from this light bulb paradigm shift (i.e., AB, SK, ON, NB, NS, and PE); locations where the switch between space heating and lighting energy results in lower net GHG emissions.

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9. Appendix A

Table I - Average Household Energy Characteristics

Average Household Indoor Wall Height (m)	2.5
Average Number of Household Light Bulbs[a]	26.4
Percentage of Indoor Household Light Bulbs[a]	89%
Percentage of Outdoor Household Light Bulbs[a]	11%
Percentage Daily Light Bulb Operation	17%
Average Indoor Temperature[b] (°C)	18
Air Conditioning EER[c] (Btu/h/W)	8.9

a = Natural Resources Canada (2000)

b = Base temperature to calculate HDD and CDD; and (Valor et al., 2001)

c = NRC (2006b)

Table II - Light Bulb Characteristics

	ILBs	CFLBs
Wattage Equivalency[a] (W)	60	15
Efficiency[b]	0.1	0.3
Operational Lifetime[c] (hours)	1000	8000
Fabrication Energy Per Bulb[c] (kWh)	0.15	1.4

a = Natural Resources Canada (2004a)

b = General Electric Company (2007)

c = Gydesen and Maimann (2000)

Table III - Household Energy Characteristics for Canadian Provinces

	BC	AB	SK	MB	ON	QC	NB
Private Dwellings Occupied by Usual Residents[u]	1,642,715	1,256,192	387,160	448,766	4,554,251	3,188,713	295,871
Main Heating Energy Source[v]	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Electricity	Electricity
Percentage of Households Heated by Natural Gas[v]	60%	97%	89%	62%	70%	5%	0%
Percentage of Households Heated by Electricity[v]	32%	2%	5%	33%	18%	70%	60%
Percentage of Households Heated by Oil[v]	6%	0%	3%	2%	9%	18%	22%
Percentage of Households Heated by Other[v]	2%	0%	0%	3%	1%	7%	17%
Heated Area[a] (m^2)	133	112	112	112	139	105	116
Surface Area - Roof[b] (m^2)	133	112	112	112	139	105	116
Surface Area - Floor[b] (m^2)	133	112	112	112	139	105	116
Surface Area - Walls[b] (m^2)	115	106	106	106	118	102	108

Table III - Household Energy Characteristics for Canadian Provinces

	BC	AB	SK	MB	ON	QC	NB
Predominant Administrative Zone[z]	A	B	C	C	A	B	B
Minimum Thermal Resistance-Roof[c] ($m^2 \cdot K/W$)	5.4	5.8	5.6	7	5.6	7	7
Minimum Thermal Resistance-Walls[c] ($m^2 \cdot K/W$)	2.1	2.1	2.1	3.1	2.1	3.1	3.1
Minimum Thermal Resistance-Floor[c] ($m^2 \cdot K/W$)	1.08	1.08	1.08	1.08	1.6	1.08	1.08
Heating Degree Days[x] (K·day)	2879	4884	5546	5717	3719	5022	4846
Cooling Degree Days[x] (K·day)	49.9	68.8	184.1	197.4	436	121.4	35.2
Number of HDD Days in 2007[x]	327	338	314	305	254	311	342
Number of CDD Days in 2007[x]	36	27	47	58	111	54	22

Table III - Household Energy Characteristics for Canadian Provinces							
	BC	AB	SK	MB	ON	QC	NB
Percentage of Year Requiring Heating	90.1%	92.6%	87.0%	84.0%	69.6%	85.2%	94.0%
Percentage of Year Requiring Cooling	9.9%	7.4%	13.0%	16.0%	30.4%	14.8%	6.0%
Percentage Using Central and Portable A/C Systems[w]	16.6%	30.2%	30.2%	30.2%	73.7%	31.1%	7.9%
Basic Air Conditioning Cooling Capacity[e] (Btu/h)	21900	19100	19100	19100	22700	17700	19700
Air Conditioning Design Temperature[f] (°C)	25	29	32	31	30	29	26
Average Electricity GHG Intensity in 2005[t] (g CO_2 eq/kWh)	17	882	822	14	220	9.1	394

a = Total floor space of a dwelling excluding the basement and the garage (NRC, 2005a)
b = Assume the heated area is 1-storey and shaped as a square.
c = MNECH (1997) and Haysom (1998), based on Administrative Region and main heating energy source.
d = Environment Canada (2005)

e = NRC, 2005b
f = NRC (2004b)
h = NRC (2005a) and Snider (2006)
t= Environment Canada (2007)
u = Statistics Canada (2007)
v = Snider (2006)
w = NRC (2005a)
x = Environment Canada (2005), based on weather stations central to population mass
y = NRC (2005a) and Snider (2006)
z = NRC (2004d) based on highest population concentration and Degree-Day Zones table from Chapter 1, Part 2.

Table IV - Light Bulb Life Cycle Energy Requirements

Total Planning Period Timeline (years)	5.5	
	ILBs	CFLBs
Number of Replacements per Planning Period	8	1
Total Energy Consumption in Fabrication Stage[a] (kWh)	1.2	1.4
Total Energy Consumption during Operational Phase (kWh)	480	120
Total Energy Consumption in Disposal Stage[a] (kWh)	0	0
Average Light Bulb Manufacturing GHG Intensity[a] (g CO_2 eq/kWh)	850	

a = Gydesen and Maimann (2000)

Table V - Average Household GHG Emission Characteristics

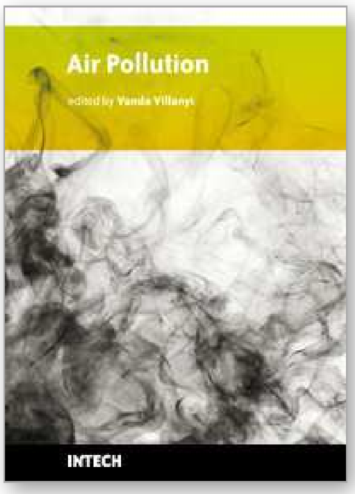
Natural Gas Heat of Combustion (kJ/mol)	802
Molar Mass of CO2 (g/mol)	44
Natural Gas GHG Intensity (g CO2 eq/kWh)	198
Heating Oil GHG Emissions[b] (g CO2 eq/L)	2680
Heating Oil Energy Intensity[c] (MJ/L)	38.2
Heating Oil GHG Intensity (g CO2 eq/kWh)	253
Natural Gas Furnace Efficiency[d]	81.00%
Heating Oil Efficiency[d]	78.00%
Electric Heating Efficiency[d]	100.00%

a = based on heat of combustion of Natural Gas when water is a vapour

a = EIA (2007)

b = NRC (2004c)

c = Mid-efficiency for Natural Gas and Oil NRC (2004c)



Air Pollution

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Although the climate of the Earth is continually changing from the very beginning, anthropogenic effects, the pollution of the air by combustion and industrial activities make it change so quickly that the adaptation is very difficult for all living organisms. Researcher's role is to make this adaptation easier, to prepare humankind to the new circumstances and challenges, to trace and predict the effects and, if possible, even decrease the harmfulness of these changes. In this book we provide an interdisciplinary collection of new studies and findings on the score of air pollution.

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