CIRAIG[MC]

Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et services

FINAL REPORT

COMPARATIVE LIFE CYCLE ASSESSMENT OF LIGHT BULBS: INCANDESCENTS AND COMPACT FLUORESCENTS

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Prepared for

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EXECUTIVE SUMMARY

Hydro-Québec Distribution called upon the Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG) to conduct a comparative life cycle assessment of the incandescent and compact fluorescent light bulbs used in Québec.

More specifically, the **objectives** of this project were to: 1) establish the environmental profile of both types of light bulbs; 2) determine their *hot spots*; and 3) compare the two options based on an analysis by scenario. The aim was to assist Hydro-Québec in increasing its understanding of the impacts of the light bulbs' life cycles and provide an answer to the question of whether or not compact fluorescents should replace incandescent bulbs.

This document is the final report on the project and was submitted after a critical review. It includes a description of the study design used to conduct the comparative life cycle assessment of the light bulbs, the inventory results and the assessment and interpretation of the potential impacts.

A literature review first determined that there were few articles published on electric light bulbs. Two studies were found, one by Pfeifer (1996) reported by Bio Intelligence Service (2003) and one by Parsons (2006). Both recommend incandescent light bulbs by a ratio of 4:5. However, further analysis of these articles demonstrated the need for results that better reflected the Québec context, especially as it pertains to the grid mix, which could have a potentially significant impact on the environmental performance of the bulbs during use. In fact, neither study accounted for the crossed effect of the heat released within the homes during lighting hours. According to the **crossed effect principle**, these internal heat gains constitute either an additional load on the cooling system or a reduced load on the heating system. This aspect seems important in the Québec context considering that incandescent light bulbs generate more heat than compact fluorescents.

The review that was carried out made it possible to draw up a preliminary overview of the life cycles of the compact fluorescent and incandescent bulbs and define the methodological framework on which the LCA was based. The assessment was:

1. Adapted to the Québec context in terms of the representativeness of the data (particularly as it pertains to electricity production);
2. Designed to take into account the crossed effect of the heat generated by the light bulbs.

The **function that was studied** was *lighting (providing between 500 and 900 lumens) over a given period (10 000 hours)*. The effect of the secondary functions of the bulbs (e.g., creating a pleasant atmosphere) was not take into account, with the exception of the crossed effect of the heat generated during use, which was considered based on an analysis by scenario, as described below.

- The basic scenario does not take the heat generated during use into account as a co-product (i.e., it does not consider the heat's effect on the homes' heating and cooling systems). The environmental profile of this scenario is that of the life cycle of the light bulbs, including their various functions (e.g., lighting and heating). It therefore meets the project's two main objectives, which are to establish the profiles of the life cycles of the bulbs and identify the *hot spots* and key environmental parameters.
- The **crossed effect scenario** aims to meet the third objective of the project by "crediting" the avoided impact of an equivalent amount heat production by a heating system (or by adding the impact generated by an additional cooling process) to the life cycle of the bulbs. The environmental profile is therefore that of the main function of the light bulbs: lighting but not heating (secondary function). In order to represent the typical Québec contexts, the crossed effect was developed into various sub-scenarios.

It is also important to note that the **end-of-life scenarios** initially proposed were not examined as part of this project. Please refer to sub-section 5.2.2.

The **reference flows** for this study are the number of light bulbs required to provide between 500 and 900 lumens during 10 000 hours:

- System A: One 13- or 15-W compact-fluorescent bulb (service life: 10 000 hours);
- System B: 10 60-W incandescent bulbs (service life: 1 000 hours/bulb).

The **system boundaries** are the production, distribution, use, and end-of-life management of both types of bulbs, including the production and transport of the resources consumed and the transport and management of the waste generated.

The **primary data** was mostly collected from various light bulb manufacturers (whose products are available in Québec) through electronic questionnaires and telephone discussions. Information on the technical specifications and materials and an overview of the manufacturing and distribution processes of the most widely-sold incandescent and compact-fluorescent bulbs was requested. The data collected included information on the products sold by major manufacturers in Québec (Philips, Globe and Sylvania, especially).

Two **hypotheses** were formulated regarding the Chinese and Québec grid mixes, energy consumption during bulb production, packaging and end-of-life light bulb waste management and the distances and modes of transport engaged during the life cycles of the bulbs. These hypotheses are detailed in section 4.2.

Finally, all of the production processes for the resources consumed and waste management processes and all of the modes of transport engaged in the life cycles of the bulbs were modeled based on available **secondary data**. Because most of the systems' elementary processes were included in *ecoinvent* (http://www.ecoinvent.ch/) and to maximise the uniformity and coherence of the data used to model them, preference was given to this LCI database and it was adapted whenever possible (especially to better reflect the Québec and North American energy contexts).

Finally, the data collected was assessed based on the internationally-recognized **life cycle impact assessment** (LCIA) method, IMPACT 2002+. The results obtained were then compared with those generated using a Canadian method, LUCAS, which, in essence, arrived at the same conclusions.

The results show that the **use phase** dominates the life cycles of both types of bulbs, followed by the **production phase** during which 6 to 30% of the potential damages of the life cycle of the compact fluorescent bulb occur (this figure is only between 1 and 5% in the case of the incandescent). Distribution and end of life are negligible in both cases.

The use phase (which represents between 69 and 96% of potential damages in the case of the compact fluorescent bulb and between 93 and 99% in the case of the incandescent) is driven by **electricity consumption**, which, depending on the damage categories, is dominated by either electricity production (because of the small amounts purchased and produced from coal and industrial gas) or transmission (copper production and copper and chromium (VI) emissions seeping into the soil from the infrastructure network).

In addition, a comparison of the environmental profiles obtained for both types of bulbs would give preference to one or the other alternative based on the lighting conditions defined by:

- The number of days in the year:
  - In the warm season (when homes are not heated but could be cooled);
  - In the cold season (when homes are heated).
- The daily number of lighting hours during each season.

The crossed effect of the heat generated by the light bulbs during these lit hours was therefore considered in homes heated by electricity, gas or oil, since the crossed effect of this heat on the cooling system was negligible. It is also important to note that wood heating was not considered even though it accounts for 9% of heating in Québec. The heat generated by the light bulb does not impact this type of system because it is not controlled by a thermostat and, thus, there is no crossed effect.

The results therefore account for an annual use of one of the two types of light bulbs, which means that the environmental credit for the avoided heating is only attributed to a fraction (approximately 60%) of the 10 000 lighting hours considered per functional unit. Crediting the avoided heating during 10 000 hours of use (and therefore considering light bulb use during the cold season only) had a slight effect on the environmental profiles obtained ,but the conclusions remain the same, especially when considering an annual use of one or the other type of light bulb:

- The damages associated with the life cycle of the compact fluorescent bulb represent, depending on the damage category, between 20 and 30% of those associated with the incandescent (an average of 28%).
- Compact fluorescent lighting, rather than incandescent, therefore entails an overall reduction in damages during the warm and neutral seasons and also during the **cold season** in **homes heated by electricity**. In these homes, the credit is not significant enough to offset the damages generated by the life cycle of the light bulb (especially during the use phase) and the compact fluorescent remains the best option.
- Though the potential advantage of the incandescent bulb over the compact fluorescent was not highlighted in the case of a home heated by gas or oil, the results are mostly in its favour:
  - In **homes heated with natural gas**, incandescent bulbs are the best option when considering climate change and resources damages. In addition, though the damages to human health and ecosystem quality would give preference to the compact fluorescent, the net gain associated with the use

of this type of bulb is 5 times smaller than the net gain associated with the use of incandescents for the climate change and resources categories;

- Similarly, in **oil-heated homes**, the use of incandescent bulbs obtained, in 3 out of the 4 damages categories, a net gain that was 15 times higher than the gain generated by the compact fluorescents in the ecosystem quality damage category.

In this case, the credit manages to offset some of the damages generated by the life cycles of the bulbs. More specifically, the credit is derived from the amount of heat produced by an oil- or a natural gas-powered system and which is “avoided” and replaced with heat from less harmful electricity (the electricity consumed by the light bulbs when lit). Because this credit is greater in the case of the incandescents, their use becomes more advantageous under certain circumstances.

In fact, the profile of the **average distribution of the types of heating in Québec** is similar to that of natural gas-heated homes, though it is slightly less favourable to the incandescent. Based on these results, the province-wide use of compact fluorescent bulbs (through public policy, for example) is therefore not ideal. As previously stated, the use of incandescent bulbs could be advantageous during the cold season (approximately 55% of the year) in natural gas- or oil-heated homes (23% of homes in Québec). However, the compact fluorescent is a more appropriate choice when:

- There is no possible crossed effect – during the warmer or neutral season and during the colder seasons for wood-heated homes (9% of homes) or insufficiently insulated homes (whose set point is never reached); and when
- The environmental credit from the crossed effect does not offset the damages caused by the life cycles of the light bulbs (i.e., during the cold season in homes heated by electricity – 68% of homes).

In addition, the results of the **uncertainty analysis** that was carried out show that it is unlikely that the conclusions would be reversed for all of the studied scenarios, except for the distribution of the types of heating methods across Québec. In this case, it is in fact difficult to identify which of the two options is most probably the better choice. This confirms the earlier caveat regarding the widespread promotion of the use of compact fluorescent bulbs within the Québec energy context.

Of course, these results have certain **limitations**. Other types or models of light bulbs on the Canadian market could eventually be integrated into the study model so as to better represent compact fluorescent technology and extend the conclusions to the Canadian context. It is therefore important to avoid taking any of the conclusions out of their original context.

The conclusions also have other limitations, especially those pertaining to the applicability of the various hypotheses to the life cycles of the light bulbs used in Québec in 2006, as well as to the completeness and validity of the inventory data and the impact assessment methods that were used. Though it is very probable that these limitations will impact very few of the conclusions of the analysis, refining the data, hypotheses and/or models would reduce the uncertainty of the results, especially those for the *hot spots* in the contribution and sensitivity analyses:

- The completeness (resources and emissions not taken into account) and the validity of the data used to model the production and end-of-life phases.

- The validity of the data used to model the use phase (especially the processes and parameters in Table 5-2).
- The value of the coefficient of performance (COP) of the natural gas heating systems for which the damages to human health could lead to a preference for the compact fluorescent bulbs.
- The impact of the uncharacterized substances that could alter the conclusions for the gas- and oil-heated homes.
- The possible consequences of giving preference to a certain type of light bulb (given that this study does not assess the consequences of a significant market penetration of compact fluorescent bulbs across the province, the conclusions only provide some of the answers that should be considered in the decision-making process).

To support an eventual decision, the assessment could be refined using a consequence-based approach (consequential LCA). This type of method would quantify the environmental performance gaps between the two types of bulbs based on the different potential decisions that Hydro-Québec could make regarding the use of the electricity generated by its network. The results of the sensitivity analysis showed that the use of incandescent bulbs, even in the colder season in oil- and gas-heated homes, is probably not an ideal solution in the North American energy context (i.e., in an open system in which variations in consumption in a given region have a more or less direct impact on consumption in another).

By way of indication, the following graphs present the results that were obtained based on the average distribution of heating types in Québec homes in the provincial and North American contexts. For each context and each damage category, there are three bars. The first represents the compact fluorescent bulbs, the second the incandescents and the third is the difference between the two types of bulbs. It is important to note that all of the contributions are expressed in relative terms since they refer to the total obtained for the baseline scenario of the incandescent and therefore corresponds to a value of 100%. Also, the value of 100% differs for each energy context and damage category. For example, for the climate change category, the value is equal to 21 kg CO_2 using the Québec mixed grid but is equal to 424 kg CO_2 when using the North American mixed grid.

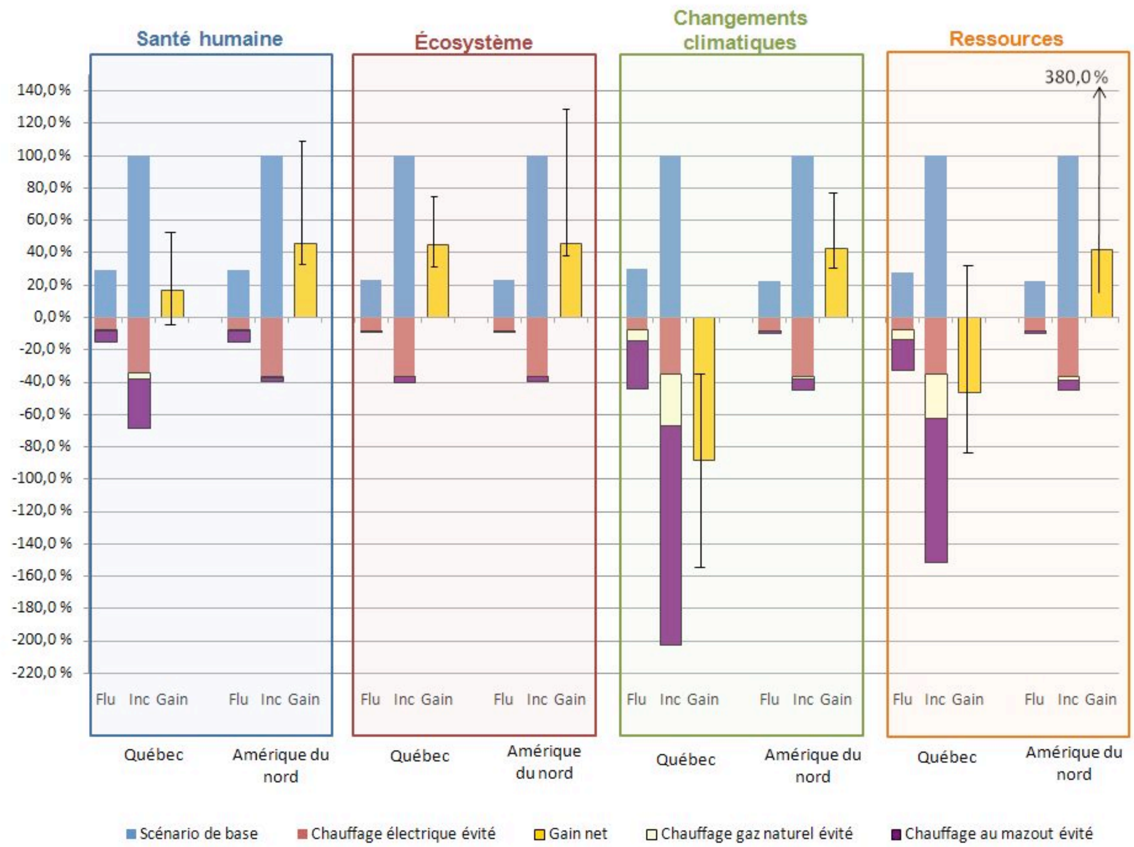

Figure 1: Damages of the crossed effect scenario based on the average distribution of heating types in Québec in the Québec and North American energy contexts

Assuming that each kWh saved could substitute for forms of energy that are more polluting or less efficient than gas or oil (thermal energy in particular), it would seem best to favour the widespread use of compact fluorescent bulbs so as to foster overall energy efficiency.

Though the compact fluorescent bulbs, in most cases, cause fewer damages than the incandescents throughout their life cycles, their production and end-of-life phases must still be improved, especially as they pertain to the electronic components and mercury they contain. The use of modular ballasts (which are not integrated and therefore reusable) and the recovery/recycling of the light bulbs at the end of their life cycles seem like suitable options. Only LCA results could quantify these potential improvements.

It is also important to note that the LCA results present the potential environmental impacts and not the actual ones, nor do they express the individual risk associated with an exposure following the accidental breakage of a compact fluorescent bulb in a closed environment or the influence of certain more or less significant parameters from the user's standpoint (e.g., interference with infrared devices, min-max functional temperatures, use with a dimmer and harmonic distortion).

A synthesis of this study is included in Annex E of this report.

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ACRONYMS AND ABBREVIATIONS

AC	Acidification
AMI	Assessment mean impact
BOD	Biological oxygen demand
CFC	Chlorofluorocarbons
CFL	Compact fluorescent lamps
CH_4	Methane
COD	Chemical oxygen demand
CIRAIG	Interuniversity Research Centre for the Life Cycle Assessment of Products, Processes and Services
CO_2	Carbon dioxide
COP	Coefficient of performance
DALY	Disability-adjusted life-years
DOC	Dissolved organic carbon
EC	Ecotoxicity
ECA	Aquatic ecotoxicity
ECT	Terrestrial ecotoxicity
EC50	Effect concentration 50%
EUA	Aquatic eutrophication
EUT	Terrestrial eutrophication
GHG	Greenhouse gas emissions
GIEC	*Groupe d'experts intergouvernemental sur l'évolution du climat* (IPCC, in English)
IEEE	Institute of Electrical and Electronic Engineers
IPCC	Intergovernmental Panel on Climate Change (GIEC, in French)
ISO	International Organization for Standardization
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LOEC	Lows observed effect concentration
LU	Land use
LUCAS	Life cycle impact assessment method used for Canadian-specific contexts
NLPIP	National Lighting Product Information Program
N_2O	Dinitrogen oxide
NOEC	No observed effect concentration
NO_X	Nitrogen oxides
OLD	Ozone layer depletion
PAF	Potentially affected fraction
PDF	Potentially disappeared fraction
PE	Polyethylene
PP	Polypropylene
PS	Photochemical smog
PVC	Polyvinyl chloride
RG_{100}	Global warming over 100 years
RU	Resource use
SAFE	*Schweizerische Agentur für Energieeffizienz* (Swiss agency for efficient energy use)
SETAC	Society of Environmental Toxicology and Chemistry

SSEE	Society for Sustainability and Environmental Engineering
SO_2	Sulfur dioxide
TOC	Total organic carbon
ToxC	Human toxicity (cancer)
ToxNC	Human toxicity (non-cancer)
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
VOC	Volatile organic compound
W	Watts
WU	Water use

1. INTRODUCTION

For many years, Hydro-Québec has been committed to energy efficiency. One of the corporation's strategies is to support the substitution of incandescent bulbs by compact fluorescents, which are believed to be more ecological given that they consume up to 75% less energy to produce the same amount of light over a longer service life.

But this apparent environmental gain generated by the compact fluorescents does not take into account the use phase of the product's life cycle. The resources consumed and the pollutants emitted during its production, distribution and end-of-life management have, until today, not been considered by Hydro-Québec when determining whether or not to promote one option over the other. This aspect appears all the more relevant given that compact fluorescent bulbs contain mercury and should be considered hazardous household waste. Also, it has often been stated that incandescents generate more heat and therefore contribute to home heating, but, in keeping with the crossed effect principle, the internal heat gains during lighting also constitute an additional load on the cooling systems (or a reduction for the heating systems) (Parent 2007). This fact seems potentially significant within the Québec context.

Hydro-Québec Distribution therefore engaged the services of the Interuniversity Research Centre for the Life Cycle of Products, Processes and Services (CIRAIG) to carry out a comparative life cycle assessment (LCA) of both types of bulbs in the Québec context. LCA is a methodological tool that makes it possible to assess the potential environmental impacts of a product or activity throughout its entire life cycle based on internationally-recognized methods. It is a holistic approach that determines the *hot spots* of a system and ensures that the implemented solutions do not simply transfer the pollutant effects from one phase of the life cycle to another or from one impact category to another.

The objectives of the study and the methodology used are detailed in chapter 3. Chapters 4 and 5 describe the results of the subsequent phases of the LCA, in keeping with International Organization for Standardization (ISO 14040 series) regulations.

The methodological framework presented in chapter 3 was established based in part on a review of the available information on the focus of this study and is summarized in chapter 2.

The LCA is detailed in Annex A, which includes a section in which the various LCA terms are defined. An overview of the results of the study is included in Annex E.

2. BIBLIOGRAPHICAL REVIEW

This chapter provides an overview of the compact fluorescent and incandescent bulbs used in Québec and a review of the studies that have been conducted on the environmental impacts of the life cycles of these two types of bulbs.

2.1 Overview of the electrical light bulbs used in Québec

According to the study by Marcon-DDM (2006), the most popular substitutive compact fluorescent in Québec is the 13-15-watt (W) *Energy Star* certified twister bulb with integrated ballast. Because it has a screw base (unlike the standard compact fluorescents with a pin cap), the twister compact fluorescent is normally considered to be equivalent to a 60 W incandescent bulb (in terms of the amount of light it provides).

As illustrated in Figure 2-1, the compact fluorescent market in Québec is dominated by three large manufacturers: Sylvania, Philips and Globe (82%). These corporations also manufacture incandescent light bulbs, though they may not necessarily be the most important manufacturers (information unavailable).

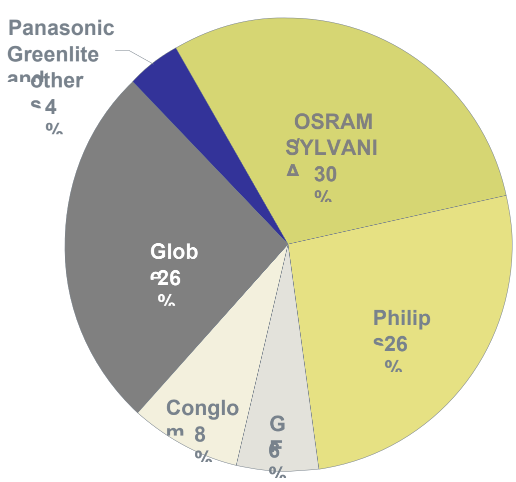
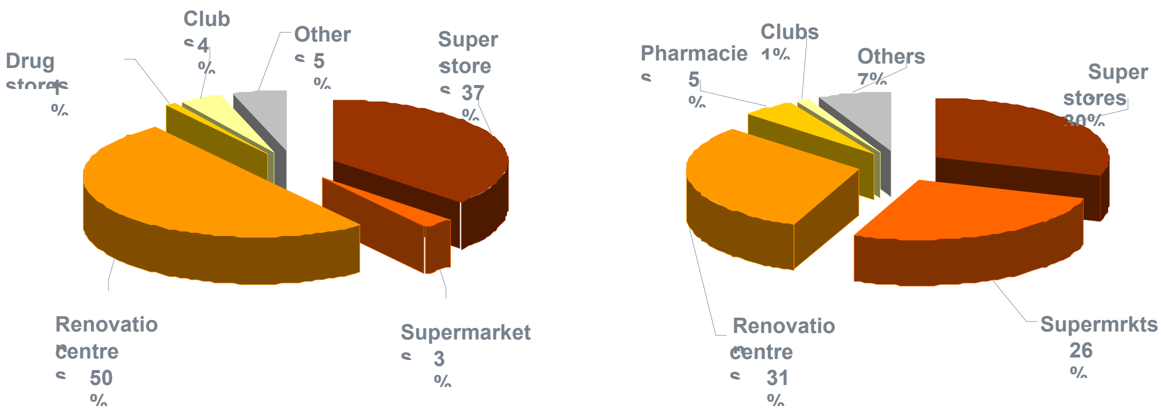


Figure 2-1: Market shares (2005) based on SECOR Conseil figures
(Hydro-Québec Distribution, 2007)

In 2004, renovation centres were important compact fluorescent bulb retailers. For the incandescents, the market was divided between superstores and renovation centres (Figure 2-2).



Compact fluorescents **Incandescents**

Figure 2-2 : Market shares of the two types of bulbs based on SECOR Conseil figures
(Hydro-Québec Distribution, 2007)

Table 2-1 summarizes the information gathered by the CIRAIG in June 2007 from various Montréal-area retailers. It presents the different types of 13- and 15-W compact fluorescents and 60-W incandescents offered by the three largest manufacturers. The bulbs listed are the most popular models, based on in-store quantities (the greater the stock, the higher the consumer demand). The table also provides the provenance (place of production) of each model and their respective specifications (lumens – amount of light) and service life.

The most widely available bulbs were *Soft White* (compact fluorescents) and *Standard* (incandescents). These two types are regarded as equivalent, especially in terms of the “quality” of the light provided (quantified based on the temperature and colour rendering index). Because the equivalence of each type of bulb to specific colours is not standardized, there may be certain variations and inconsistencies and the comparisons therefore had to be verified by the manufacturers during the data collection process.

Table 2-1 : Models available in Québec and produced by the three main manufacturers

Retailer	Manufacturer	Model	Type	Amount of light (lumens)	Service life (hours)	Provenance
Twister compact fluorescent with integrated ballast (13 or 15 W)						
Home-Depot	Philips	Marathon mini – 15 W	Day Light	950	10 000	China
Wal-Mart	Philips	Marathon mini – 15 W	Soft White	860	10 000	China
Wal-Mart	Globe	Twister mini – 13 W	Soft White	800	10 000	China
Rona Le Quincaillier	Globe	Twister – 13 W	Soft White	800	10 000	China
Rona l’Entrepôt	Globe	Twister mini – 13 W	Soft White	800	6 000	China

Table 2-1 : Models available in Québec and produced by the three main manufacturers

Retailer	Manufacturer	Model	Type	Amount of light (lumens)	Service life (hours)	Provenance
Rona Le Quincaillier	Sylvania	Twister mini – 13 W	Soft White	900	10 000	China
Rona l'Entrepôt	Sylvania	Twister mini – 13 W	Day Light Extra	850	8 000	China
Rona l'Entrepôt	Sylvania	Twister mini – 13 W	Soft White	900	10 000	China
60-W incandescent						
Home-Depot	Philips	N/A	Standard	820	1 000	Indonesia
Home-Depot	Philips	N/A	Day Light	680	1 000	Mexico
Rona Le Quincaillier	Globe	N/A	Standard	540	1 000	China
Wal-Mart	Globe	N/A	Standard	600	1 000	China
Rona l'Entrepôt	Sylvania	N/A	Standard	870	1 000	U.S.A.
Rona l'Entrepôt	Sylvania	N/A	Day Light	640	1 000	U.S.A.
Rona l'Entrepôt	Sylvania	N/A	Clear	880	1 000	U.S.A.

2.2 Environmental studies on the life cycle of light bulbs

There are few bibliographical references on the life cycle of light bulbs. Two studies were found: one by Pfeifer (1996) published by Bio Intelligence Service (2003) and another by Parsons (2006). Both concluded that the compact fluorescents are a better choice than the incandescents by a ratio of 4:5.

The Pfeifer study reports only a small amount of information, because it only examines the use phase. In addition, it is not necessarily representative from a technological standpoint because bulbs have evolved considerably since the study was published some 10 years ago (e.g., energy efficiency and the size of the ballast have been improved and the size of the bulbs themselves and the amount of mercury they contain have been reduced).

The Parsons study considers all of the phases of the life cycle and is relatively representative of the current technological context. The author concludes that compact fluorescents constitute a significantly better choice from an environmental standpoint. But the study was conducted within the Australian context, which differs from the Québec context especially in the fact that our power system is a mixed grid (the author based the findings on electricity generated from 100% coal when electricity in Québec is over 90% hydroelectric). This element is even more significant when considering the fact that electricity consumption in the use phase is, based on the results obtained to date, the main contributor to the life cycle impacts of a light bulb.

Neither study considers:

- The heat that is generated during the use phase and which contributes to home heating. Once again, this element is important in the Québec context given that incandescents generate more heat that the compact fluorescents for the same amount of light.

- The possible recovery of the bulbs at the end of their service life.

Parsons corroborated the results of a study carried out by the United States EPA (http://www.nema.org/lamprecycle/epafactsheet-cfl.pdf), but these findings are not adapted to the Québec context. Both studies affirm the low impact of the mercury contained in the compact fluorescent bulbs as compared to the impact of the coal production necessary to generate electricity during the use phase of the bulbs.

The conclusions of these studies should therefore be verified through an LCA and:

1. Be adapted to the Québec context in terms of the representativeness of the data (especially as it pertains to electricity production) and the life cycle impact assessment models;
2. Consider the heat generated by the bulbs, the various compact fluorescent recovery rates and the reuse of the materials and mercury at the end of the bulbs' service life.

Table 2-2 provides an overview of the main parameters and conclusion of the two studies.

Table 2-2 : Main parameters and conclusions of the two studies

Parameter	Parsons (2006)	Pfeifer (1996), reported by BIO Intelligence Service (2003)
Function	Lighting	Lighting
Functional unit	Provide an equivalent quantity of lumens during 8 000 hours	10 million lumen-hours
Reference flow	Incandescent: 4x 100-W/ 2000 hour bulb	Incandescent: 15.4x 60-W/ 1 000 hour bulb
	Compact fluorescent (CO): 1x 18 W/8 000 hour bulb	CF#1: 2x 15-W (600 lm)/ 8 000 hour bulb CF#2: 1.9x 13-W (650 lm)/ 8 000 hour bulb CF#3: 2.1x 11-W (600 lm)/ 8 000 hour bulb
Life cycle phases considered	Raw extraction → Manufac- → Distribution → Use → End of life	Use
Imputation rules	None	None
Hypotheses	• The compact fluorescents are manufactured in China. The incandescents, in Indonesia; • A 100-W incandescent is equivalent to an 18-W compact fluorescent in terms of lumens; • Compact fluorescent energy consumption by the manufacturer and retailer is 0.05% (of the total energy consumption) and 0.02% for the incandescents, based on the economic values of the two products; • Power system losses (transport and distribution) account for 2% of the total energy consumption; • The low power factor of the compact fluorescents is taken into account. This factor is equivalent to 0.01% of total consumption and system losses; • Both types of bulbs are landfilled at the end of their service life; • The compact fluorescent contains 5 mg of gaseous mercury; • The argon-mercury ratio in compact fluorescents is 1:500 (in terms of pressure); • The impact of the life cycle of the indium contained in the compact fluorescents is negligible; • Both types of light bulbs contain a phenol-formaldehyde based sealant; • The phosphorus does not have a significant environmental impact; • The bulbs are transported 700 km from their port of arrival to the major cities and 120 km from the disposal point to the landfill.	None

Table 2-2 : Main parameters and conclusions of the two studies

Parameter	Parsons (2006)	Pfeifer (1996), reported by BIO Intelligence Service (2003)
Use-phase electricity	100% from coal	17.4 % coal + 7.4 % gas + 16.4 % hydro + 7.8 % lignite + 40.3 % nuclear + 10,7 % oil
Data sources	• Data on electricity consumption, the power factor, harmonic distortion and the electronic circuits come from the Institute of Electrical and Electronics Engineers (IEEE) and other recognized institutions; • Data on the materials (mass and type) is from the laboratory of D. Parsons; • The technical specifications are from the manufacturers.	None
LCIA method	CML 2. Baseline 2001 Australian Toxicity Factors V1.00 Eco Indicator 99 E Australian Substances V2.01	None
Main conclusions	• Compact fluorescents are clearly superior to the incandescents from an environmental performance standpoint because they are more energy efficient (the use phase therefore dominates the impact of the life cycle of the light bulbs); • The impact of the mercury contained in the compact fluorescents is not a major issue when compared to the other environmental impacts or to the amount of mercury emitted from the coal-fired plant (that provides electricity during the use phase). The results are the same for the lead contained in the welded seams of both types of bulbs; • The electronic ballast has a significant environmental impact because of the material from which it was made and the energy used to manufacture it; • The low power factor and the high level of harmonic distortion of the compact fluorescents could have a potential impact on the electric power system.	• The compact fluorescents are clearly superior to the incandescents. The factor that adversely differentiates the incandescents is the primary energy consumed during use (95% of all of the primary energy consumed throughout the entire life cycle. Consumption during the manufacturing stage is approximately 5%); • The amounts of mercury emitted during the life cycles of the incandescents and the compact fluorescents are equivalent.

3. STUDY MODEL

The following sections describe the first phase of the LCA (determining the objects and scope) based on the ISO standards. This chapter will present the study model that defined the methodological framework to which all of the subsequent phases of the LCA had to conform.

3.1 Study objectives

3.1.1 Goal of the study

This study was conducted to assess and compare incandescent and compact fluorescent bulbs. More specifically, the objectives were to:

1. Establish the environmental profile of the life cycle of the two types of light bulbs (i.e., the documenting materials and energy consumption and the environmental discharges and assess the potential impact generated by this consumption and discharge);
2. Identify the *hot spots* (e.g., use and end-of-life management) and the key environmental parameters (e.g., electricity consumption and mercury emissions) of the life cycles of the bulbs;
3. Compare the two systems based on an analysis by scenario in order to be able to determine the strengths and weaknesses of each and the conditions under which one would constitute a better choice than the other:
    - The **baseline scenario** does not take into account the heat generated as a crossed effect during the use phase. It therefore does not consider its potential effect on the homes' heating and cooling systems.
    - The **crossed effect scenario** takes the effect of the heat released by the bulbs inside the home into account. This scenario was developed into sub-scenarios so as to represent the various typical Québec contexts.

It is also important to note that the **end-of-life scenarios** that were initially proposed were not carried out as part of this project. This choice is explained in section 5.2.2.

3.1.2 Application

The aim was to assist Hydro-Québec in increasing its understanding of the impacts of the light bulbs' life cycles and provide an answer to the question of whether or not compact fluorescents should replace incandescent bulbs.

3.1.3 Target audience

The results of this comparative study are to be used by Hydro-Québec and are also for public disclosure. Because these results support comparative affirmations meant to be disclosed to the public, a critical review was carried out by a committee of interested parties (see sub-section 3.2.8).

3.2 Scope of the study

3.2.1 Functions, functional unit and reference flows

The LCA was not carried out on the products but on one of several functions that these products ensure. The assessment therefore aims to determine the amount of products necessary to fulfill the studied function, thus ensuring the comparability of alternative options that perform differently. The functional unit represents the quantification of the studied function, and the reference flow makes it possible to link a system's performance to the functional unit (i.e., they represent the amount of product necessary to fulfill the function expressed by the functional unit).

The following paragraphs detail the function, functional unit and reference flows for this study.

3.2.1.1 Functions

The main function of the product system in this study is as follows:

Lighting (providing an amount of light) for a given period

The systems are multifunctional because 1) they release a certain amount of heat that could possibly be recovered during use; and 2) they have other secondary functions such as creating a pleasant atmosphere and providing an amount of light that could lessen the symptoms of seasonal depression.

These secondary functions must also be taken into account so as to ensure the functional equivalence of the two compared systems. However, it is important to note that:

- For feasibility and simplicity reasons, only the heat generated by the bulbs was taken into account. The other secondary functions were not. The impact of the life cycle of the bulbs is therefore entirely attributable to light and heat. This hypothesis seems reasonable given the small presumed contributions of the other secondary functions to the total impact and the presumed equivalence, especially in terms of the quality of the light provided by the two bulbs that were compared (see section 2.1).
- The heat generated is considered to be a function only if it is viewed as a co-product (and especially as a "recovered" sub-product) and therefore as a consumed resource that will help lessen heating needs. If, however, the heat generated leads to increased cooling, then this must be considered as a "waste" to be managed.

The treatment for this secondary function is described in sub-section 3.2.3.

3.2.1.2 Functional unit

The quantification of the function being studied is based on the amount of lumens provided during a given period. The functional unit that was select is defined as follows:

Providing between 500 and 900 lumens during 10 000 hours

The use of an interval rather than an exact value when quantifying the amount of light provided was chosen so as to remain in keeping with the foreseen application: suggesting that Hydro-Québec clients replace their incandescent bulbs with compact fluorescents (based on the bulbs' environmental performances). It is therefore important that the result reflect the replacement of a 60-W incandescent bulb by an equivalent compact fluorescent available on the market and the fact that we presume that the consumer will not be affected by a difference of some hundred lumens.

3.2.1.3 Reference flows

The reference flows for this study are the number of light bulbs required to provide between 500 and 900 lumens during 10 000 hours. They are as follows:

- System A: 1x 13- or 15-W compact fluorescent bulb (service life: 10 000 hours);
- System B: 10x 60-W incandescent bulbs (service life: 1 000 hours/bulb).

The reference flows can also include the total amount of electricity consumed by each bulb during their service lives.

3.2.2 Product system boundaries and description

The boundaries of the system determine the phases, process and flows considered in the LCA. They must include: 1) all of the activities related to the attainment of the objectives of the study and which are therefore necessary to fulfill the function being studied; and 2) all of the process and flows that make a significant contribution to the potential environmental impact.

The following paragraphs provide a general description of the systems studied and determine the processes and flows that were initially included and excluded and the temporal and geographic boundaries. These initial boundaries were refined and revised after data inventory collection (as described in chapter 4).

3.2.2.1 General description of the systems

Figure 3-1 details the boundaries of the product systems studied. Note:

- It is a complete cradle-to-grave assessment that takes all of the phases of the life cycles of the bulbs into account;
- That the secondary functions, with the exception of the heat generated in winter, are not taken into account.

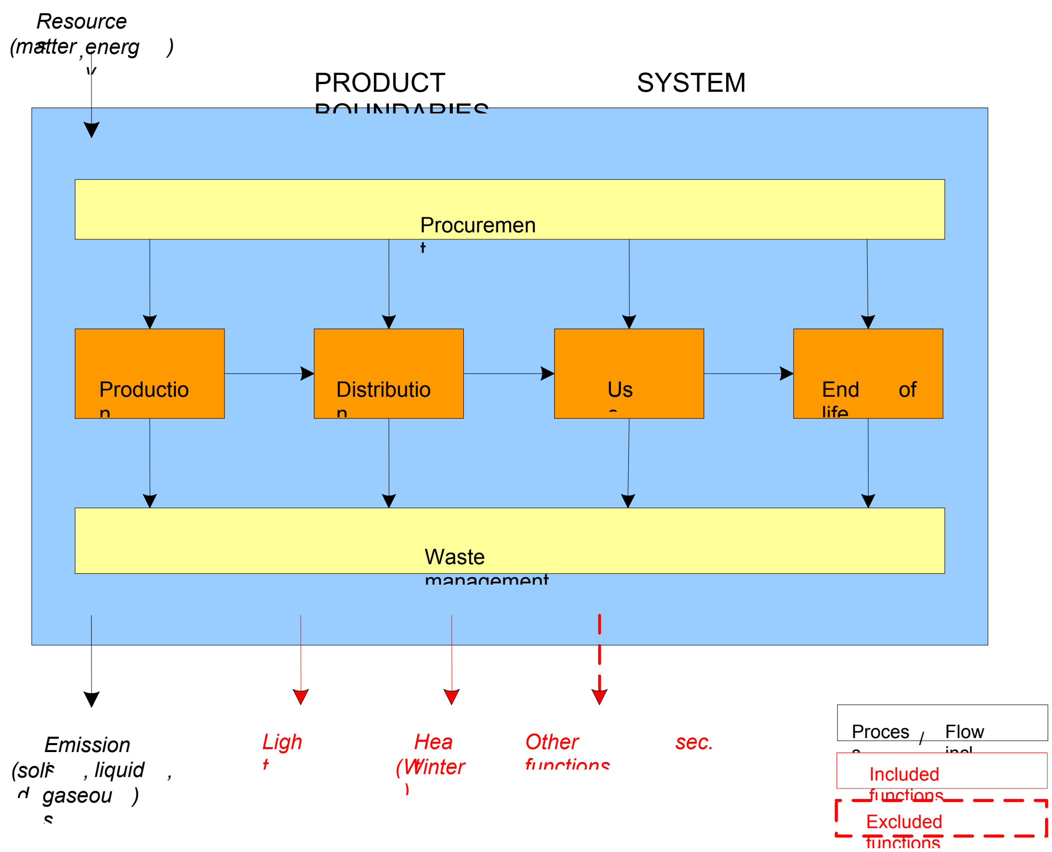


Figure 3-1 : Boundaries of the system being studied

The following paragraphs describe the main processes of the systems (more detailed descriptions are in chapter 4).

The **production** sub-system pertains to the various phases that occur during the manufacturing and packaging of both types of bulbs. It therefore corresponds to the operations of the equipment and infrastructure involved in light bulb production.

The **distribution** sub-system pertains to all of the various types of transport for the finished products from the manufacturing sites to the distribution centres (retailers). It also includes the handling and stocking of the products by the retailers (and wholesalers and any other intermediary, if applicable).

The **use** and **end-of-life** sub-systems pertain to the use and elimination of the light bulbs at the end of their service lives, including the methods of transport engaged between the retailers, users and waste management areas, respectively.

Finally, the **procurement** and **waste management** sub-systems respectively, for each of the four aforementioned sub-systems, pertain to all of the activities having to do with:

- Resource procurement (water, energy, chemicals and materials) including the extraction, treatment and transformation of the natural resources and the transport required to reach the use sites (i.e., the bulb production, distribution, use, and end-of-life management sites).
- The transport and treatment of the waste generated during one or the other of these life cycle phases, taking into account the possible types of reclamation (reuse, recycling, use for energy purposes, etc.).

3.2.2.2 Processes and flows initially included and excluded and inclusion criteria

When conducting an LCA, it is not necessary to quantify the inputs and outputs that will have only a small impact on the broad conclusions of the study. Therefore, in keeping with the guidelines set out by the SETAC (1997) and ISO 14044 (2006):

- The human activities and construction, maintenance (upkeep and repairs) and dismantling of the capital assets are normally excluded from the systems. However, certain commercial LCA databanks, including *ecoinvent* (www.ecoinvent.ch), include the capital assets in a summary way and are able to show that these secondary processes are not always negligible. They should therefore be considered whenever possible. For this study, no data on the construction, maintenance or dismantling of the capital assets, daily transport of the employees, business trips or any other of the activities of the manufacturers have been integrated into the model. The model only takes into account the processes associated with the construction, maintenance and dismantling of the capital assets that are included in the *ecoinvent* modules;
- The initial identification and selection of the processes in the system studied are generally based on information and data (primary and secondary) that is available and relatively easily accessible;
- Following the first data collection phase, certain physical inclusion criteria (mass or energy contribution) can be used to assess the potential influence of the missing data on the results or to help focus the assessment and interpretation efforts on the elements that have a reactive effect on the environmental impacts. The physical inclusion criteria can be set to a certain percentage of the total inventory (1%, for example) but should not be applied to the inputs and outputs that present a recognized environmental impact (i.e., the substance must be kept in the inventory no matter the amount, given its environmental relevance). In this study, no elementary flow was excluded based on these criteria. All of the raw data (study-specific and the data obtained from Hydro-Québec and light bulb manufacturers) and secondary data (from a generic databank) was taken into account in the inventory, regardless of the physical amounts that it represented.

Table 3-1 provides an overview of the processes initially included within the system boundaries

Table 3-1 : Processes initially included in the LCA of the two types of light bulbs (baseline scenario)

Life cycle phase	Sub-phases/processes
Production	1. Assembly and packaging
Distribution	1. Transport
	1. Between the production site and the shipping port (truck)
	2. Intercontinental (boat)
	3. Receiving port and receiving/shipping centre(s) (train)
	4. Between the receiving/shipping centre(s) and retailers (truck)

Life cycle phase	Sub-phases/processes
	2. Handling and stocking
Use	1. Transport between the distribution and use sites
	2. Use (10 000 hours)
End of life	1. Transport between the use and landfill sites
	2. Landfilling
Procurement	1. Production and transport of the resources required in the production, distribution, use and end-of-life phases of the life cycles of the light bulbs
	1. Raw materials (materials and components)
	2. Packaging materials
	3. Electricity and combustibles
	4. Other material resources consumed (in the end-of-life phase, for example)
Waste management	1. Transport and management of the waste generated during the production, distribution, use and end-of-life phases of the life cycle of the bulbs
	1. Production waste
	2. Packaging waste
	3. Other types of waste generated

3.2.2.3 Geographic boundaries

The geographic boundaries impact various aspects in LCA because:

- The resources involved may come from various regions of the world;
- The infrastructure (e.g.: transport, production, energy production and power) and waste management systems differ from one region to another;
- The environment's sensitivity to different pollutants varies from one geographic zone to another.

This study focuses on the distribution, use and end-of-life phases in the Québec context of light bulbs manufactured in China. The processes associated with energy and raw materials procurement and with the management of the waste generated during one of the aforementioned phases can take place anywhere in the world.

3.2.2.4 Temporal boundaries

The temporal boundaries of an LCA pertain to:

- The period defined by the functional unit and which takes the production, distribution, use (service life) and end-of-life management of the products into account;
- The period during which the substances in the inventory have an effect.

For this study, the period defined by the functional unit corresponds to 10 000 hours of lighting. The temporal boundaries are therefore defined by the production and distribution periods of the number of light bulbs required to provide 10 000 hours of light and by the length of the use phase of the bulbs during their service lives and the duration of their end-of-life management phases. Note:

- Certain processes included within these boundaries may generate emissions during a longer period. For example, landfilled waste releases emissions (biogas and leachate) over a period of time whose extent (several decades to over a century or even a millennium) depends on the design and operation of the burial cells and how these emissions are modeled.
- The reference year is 2006. The study therefore constitutes a static LCA that is representative of the situation in 2006.

The life cycle impact assessment (LCIA) of the substances included in the inventory must be considered over an undefined period of time (i.e., it must take the entire extent of the environmental persistence and effect of these substances into account). However, different modeling options to curb the uncertainty of the results are sometimes warranted. This is the case for the potential effect of the amount of greenhouse gas emissions, which could be quantified over a period of 20, 100 or 500 years, while an undefined period of time is normally used to quantify stratospheric ozone layer depletion, any toxic or ecotoxic effects and other impacts. The models and hypotheses used in the LCIA are presented in sub-section 3.2.6 and in Annex B.

3.2.3 Imputation approach

As stated earlier, the use of light bulbs generates heat that can be reclaimed (see paragraph 3.2.1.1). This heat is considered in two distinct scenarios:

1. The heat generated by the light bulb is a **co-product** when it is linked to a reduction in heating needs (electrical or other). It is then taken into account as a "credit" to the life cycle of the light bulb, since it offsets the impact of an equivalent amount of heat by the heating system. This type of credit ensures a certain functional equivalence between the two systems being compared and leads to a fairer attribution of the impact of the light bulb to the function being studied (i.e., generating light).
2. The heat generated by the bulb is **waste** that must be treated when it increases cooling needs. It must then be taken into consideration and the impact associated with an additional treatment (cooling) must be added to the life cycle of the light bulb.

3.2.4 General hypotheses

This sub-section presents the general hypotheses on the life cycles and the characteristics and technical parameters of the light bulbs.

3.2.4.1 Life cycle of the light bulbs used in Québec in 2006

- Sylvania, Philips and Globe are the three main compact fluorescent and incandescent light bulb manufacturers;
- Both types of light bulbs are manufactured in China;
- The specifications provided by the manufacturers are representative of the light bulbs that are used;
- The secondary functions are negligible, with the exception of the heat generated in winter;
- The light bulbs are landfilled at the end of their service life and all of the mercury contained in the compact fluorescents is therefore released into the air.

3.2.4.2 Characteristics and technical parameters

- In terms of the amount of light provided, a 60-W incandescent bulb is equivalent to a 13- or 15-W compact fluorescent. Therefore, though the light flux varies significantly between the different light bulb types and models (see Table 2-1), it is, in practice, considered to be equivalent for these two types of bulbs;
- A 60-W incandescent bulb has a service life of 1 000 hours; a 13- or 15-W compact fluorescent has a service life of 10 000 hours;

- Approximately 90% of the energy consumed by the two types of light bulbs is ultimately released into the ambient air (95% of the energy consumed is released as heat and 95% of the heat that is released is emitted into the ambient air);
- The low power factor of the compact fluorescents is not taken into account, even though it can increase energy consumption by between 5 and 7% (Olivier, 2007);
- In the case of the compact fluorescents, the decrease in lumens over time is not taken into consideration. This reduction does not impact the service life or electricity consumption of the bulb.

3.2.5 Life cycle inventory (LCI) data

This sub-section provides an overview of the data sources that were used and the data quality requirements that were implemented. These requirements made it possible to direct the data collection process and validate the information used in the study.

3.2.5.1 Data sources

This LCA aims to provide environmental data on the life cycle of the two types of bulbs used in Québec. It was therefore carried out in a way that relied mostly on the available **raw data** (i.e., the data pertaining to a sample of supposedly representative models of the two types of light bulbs). This raw data was essentially collected from various light bulb manufacturers whose products are sold in Québec.

The missing, incomplete or difficult to access data was completed with hypotheses and **secondary data** (i.e., generic or theoretical data available in the literature and international LCA databases). Given the number of sub-systems generally involved in the life cycle of products and services, there remains a balance between the efforts invested to obtain primary data and the enhanced quality of the study.

Among the available secondary data, some life cycle inventory (LCI) databanks are recognized by the international scientific community, especially the European *ecoinvent* database (www.ecoinvent.ch), which is the most complete LCI databank available and largely surpasses other commercial databases from a quantitative (number of included processes) and qualitative (quality of the validation processes, completeness of the data, etc.) aspect.

3.2.5.2 Data quality requirements

The reliability of the results and the conclusions of the LCA depend on the quality of the inventory data that is used. It is therefore important to ensure that the data meets certain specific requirements that are in keeping with the objectives of the study.

The ISO standard stipulates that the requirements pertaining to the quality of the data should at least ensure **validity**, which, in this case, consists in its representativeness of age, geographic provenance and technological performance. All of the data used should therefore be representative of:

- The period defined by the temporal boundaries, the year 2006 (see paragraph 3.2.2.4) ;
- Of the geographic context in which the studied systems occur (see paragraph 3.2.2.3) ;
- The technological characteristics of the elementary process(es) that it describes.

The LCI databases that are currently available are more or less representative of the context in which the studied systems occur. These databases present the technological averages that, for the most part, are representative of the European context. They can, however, be adapted in as much as the data that they contain is sufficiently disaggregated and that the information available allows for it. For example, some European data on the production or transformation of various materials refers to other data (for required energy production, for example). This data can then be replaced by energy production data that is specific to the context of the study, thus increasing the geographic representativeness of the European geographic data available on the production or transformation of materials.

Therefore, though most of the generic data modules used for this study were taken directly from the *ecoinvent* database, several of these modules were adapted in order to enhance their representativeness of the products and contexts being examined. Especially for the activities that take place in Québec (distribution, use and end-of life phases), the *ecoinvent* modules were adapted by replacing the European grid mix with:

- The Québec grid mix for the foreground processes (i.e., the processes that are directly linked to the studied system – electricity consumption during use and the end-of-life management of the light bulbs);
- The North American grid mix for the background processes (i.e., all of the processes directly or indirectly related to the foreground processes – all of the resources consumed to produce the electricity for the use and end-of-life management phases). The North American grid mix, in this case, is more appropriate considering the fact that procurement and the management of the elements generated during the various phases of the life cycle do not only occur in Québec.

All of the foreground processes that occur in Québec (excluding the various methods of transport) require background processes that are adapted to the North American energy context.

Because production is carried out in China and that the exact procurement processes are unknown and possibly integrated into the world market, the European modules were used *as is* without any modifications. The estimated electricity consumption on light bulb production sites was modeled based on the Chinese grid mix (as presented by the International Energy Agency), which itself was modeled based on non-adapted European modules.

Though ISO does not currently recommend any particular method for data **completeness** and **precision**, the following should be considered:

- The data must be collected in a way that ensures that it is as disaggregated as possible (aggregations by technology type or sectors should be avoided).
- The data should be documented (metadata) in keeping with the best available practices.

Applying these recommendations will eventually lead to the assessment of the completeness and precision of the data used in LCA.

3.2.6 Life cycle impact assessment (LCIA)

It was initially proposed that a life cycle impact assessment (LCIA) be carried out based on the Canadian method, LUCAS (Toffoletto *et al.*, 2005). But the inventory data on the production of the electronic components of the compact fluorescent bulbs was only available through Empa (www.empa.ch) and only the flows characterized and aggregated into impact categories according to the IMPACT 2002+ method (Jolliet *et al.*, 2003) were obtained from this source.

It was therefore decided to base the LCIA on this last, internationally recognized method and to verify whether the use of LUCAS brings about variations in the results. Table 3-2 details the impact categories considered by each of the methods. These impact categories are presented in Annex B.

In addition, the LUCAS method is currently limited to the characterization phase (i.e., to the conversion and aggregation of the inventory results according to their contribution to each of the impact categories). Therefore, unlike IMPACT 2002+, LUCAS does not convert the characterized results into damages. Though the conversion of the impacts into damages introduces an additional uncertainty, the analysis of four damage categories in relation to over ten impact categories simplifies the interpretation of the results.

Note: These categories do not cover all of the environmental impacts associated with human activities (e.g., noises, odours, radiation and electromagnetic fields).

Table 3-2 : IMPACT 2002+ and LUCAS damage and impact categories: a comparison

IMPACT 2002+		LUCAS
Damage category	**Impact category**	**Impact category**
Human health (HH)	Carcinogenic effects	Carcinogenic effects
	Non-carcinogenic effects	Non-carcinogenic effects
	Respiratory effects caused by inorganic substances	None
	Ionizing radiation	
	Ozone deterioration	Ozone depletion
	Photochemical oxidation	Photochemical smog
Ecosystem quality (EQ)	Aquatic ecotoxicity	Aquatic ecotoxicity
	Terrestrial ecotoxicity	Terrestrial ecotoxicity
	Acidification/terrestrial eutrophication	Terrestrial eutrophication
	Land use	None
Climate change (CC)	Global warming	Global warming
Resources (R)	Non-renewable energies	Fossil fuels
	Mining	Mining
No link with a damage category	Aquatic acidification	Aquatic acidification
	Aquatic eutrophication	Aquatic eutrophication

3.2.7 Calculation method

When all of the required data has been obtained and the associated flows have been standardised in relation to the functional unit that was selected, it is possible to model the product system using commercial LCA software. The SimaPro software, developed by Pré Consultants (www.pre.nl), was used to calculate the inventory and assess the potential environmental impacts associated with the inventoried emissions.

3.2.8 Critical review

The critical review is a process used to verify whether the LCA satisfies international standards. Critical reviews of LCA are generally optional, except in the case of comparative affirmations that are to be made public. An LCA conducted to support a comparison that will be made public requires special attention given the risks associated with the incorrect interpretations of the results by the various stakeholders. The critical review also enhances the credibility of the assessment.

Because the results of this study will be made public, a critical review was carried out by an expert committee whose members possess the expertise necessary to validate the hypotheses, data and processes used to conduct our study. The committee was made up of:

- Pascal Lesage, Eng jr, Ph. D., LCA consultant for Sylvatica, committee chairman;
- Sylvain Lavigne, Eng., GE Canada Lighting, industry representative;
- Gilles Meunier, Eng., Energy Efficiency and Services, Hydro-Québec, energy use specialist;
- Sylvain St-Amour, OSRAM SYLVANIA, industry representative.

The expert opinion of Bret Hamilton of the Vermont Energy Investment Corporation was also informally solicited.

As stipulated in ISO 14 040, the objectives of the critical review were to ensure that:

- The methods used to carry out the LCA are in keeping with the ISO 14 040 and 14 044 standards;
- The methods used to carry out the LCA are scientifically and technically sound;
- The data used is appropriate and reasonable given the objective of the study;
- The interpretation of the results reflects the limitations that were identified and the objectives of the study;
- The report is transparent and coherent.

In addition to these objectives, the critical review includes an in-depth verification of certain key results and of the product system model created with the SimaPro LCA software. The results of the review (comments, committee questions and CIRAIG responses) are in Annex D.

3.2.9 LCA applications and limitations

This study aims to enhance Hydro-Québec's understanding of the environmental impacts of the life cycles of the two types of light bulbs used in Québec. Other types and/or models of light bulbs available on the Canadian market could eventually be integrated into the study model so as to better represent compact fluorescent technology and extend the conclusions to the Canadian context. The conclusions of this study must therefore not be taken out of their original context.

The results of the LCA may be used to:

- Identify the significant environmental aspect of the two types of bulbs used in Québec;
- Target the strengths and weaknesses of each of the options according to the different scenarios so as to be able to identify the conditions under which one option is better than the other.

The main limitations of the conclusions are:

- The applicability of the various hypotheses on the life cycle of light bulbs used un Québec in 2006;
- The completeness and validity of the inventory data given:

  - The risk of omitting important flows due to a lack of data because the system boundaries are based on information provided by the manufacturer and all of the available generic data;
  - The validity of the data used considering the quality of the sample of raw data that was collected (small sample with great variations) and the temporal, geographic and technological representativeness of the generic data that was used.
- The completeness and validity of the LCIA methods, especially because they do not cover all of the substances that contribute to the various impact categories nor all of the environmental impacts associated with human activities (e.g., noise, odours, radiation, electromagnetic fields).
- The quantitative assessment of the possible consequences in order to advocate one type of bulb over the other (to support an eventual decision). Because this study does not cover all of the consequences of a significant penetration of compact fluorescents on the Québec market, the conclusions only provide some of the answers that must be considered in the decision-making process.

The sensitivity of the results and conclusions to most of these limitations are assessed in chapter 5.3.

It is also important to note that the LCA results present the potential (and not the actual) environmental impacts. They do not express the individual risk associated with an exposure caused by the accidental break of a compact fluorescent in a closed environment or the effect of certain parameters that are more or less important from the user's perspective (e.g.: interference with infrared devices, min-max operating temperature, use with dimmer, harmonic distortion, etc.).

4. LIFE CYCLE INVENTORY ASSESSMENT (LCIA)

This chapter presents the second phase of the LCA: the inventory assessment. It describes the data collection methodology and data sources, details the product systems and hypotheses and provides an assessment of the inventory results for each type of light bulb.

4.1 Collection methodology and data sources

The **raw data** was essentially collected from various manufacturers whose products are sold in Québec. The collection process was conducted using a questionnaire (sent via e-mail) and telephone discussions. The information requested aimed to obtain technical specifications, the list of materials and an overview of the manufacturing and distribution phases of the most popular models of the two types of bulbs. This information is detailed in Annex C. The names of the people who were involved in raw data collection and the mode of transmission of the data provided are also identified for each manufacturer that was contacted.

Because the environmental profile of the studied systems must be as representative as possible of the light bulbs used in Québec, it was initially suggested that only the data on the biggest selling light bulb models of the three largest manufacturers on the Québec compact fluorescent market (Sylvania, Philips and Globe) be considered. The main incandescent manufacturers in Québec are unknown, but the products of the various manufacturers are presumed to be relatively similar for this type of bulb.

Given the relatively large amount of missing (information that manufacturers did not provide) or somewhat uncertain data (given the variability of the data provided by the various manufacturers), all of the information collected was taken into account in the modeling phase.

Hypotheses were formulated for energy consumption during light bulb production, packaging and end-of-life waste management, and for some of the distances and modes of transport involved in the life cycle of the bulbs. These hypotheses are detailed in the following section (4.2).

Finally, all of the consumed resources and waste management production processes and all of the modes of transport involved in the life cycle phases of the bulbs were modeled based on available **secondary data**. A summary table of the secondary data that was used is presented in Annex C of this report.

Because most of the elementary processes in the studied system are included in the *ecoinvent* LCI database and to maximize the uniformity and coherence of the data used to model them, *ecoinvent* was preferred and adapted whenever possible (especially as it pertains to the North American energy context, as discussed in paragraph 3.2.5.2). Also, the processes without equivalents in the *ecoinvent* database were modeled based on proxy data. This way of compensating for the missing data lessens the technological representativeness of the results.

4.2 Description of the product systems and the hypotheses for the LCA model

The systems (the included elementary processes) were established based on the information provided by the manufacturers, various hypotheses and available generic data.

The following paragraphs describe the elementary processes that were included and excluded from the systems and the hypotheses used to calculate the inventory. A complete list of these processes is in Annex C.

4.2.1 Production phase

Little information was gathered from the manufacturers regarding the various light bulb production phases. It essentially consists in the production of the glass tube/globe, base screw and electrodes/filament, in the assembly of the various components and in the packaging of the finished product.

More specifically, in the case of the incandescent bulb:

- Producing the globe consists in several glass cutting, heating, blowing and cooling processes. Once the inside of the globe is made, it is then coated with a layer of silica. Certain technical specifications may also be stamped onto the outside.
- Producing the screw base consists in moulding the metal sheath (tinplate) and soldering (with or without a lead-based braze) with an electric contact (copper). The screw base also includes a black glass insulator.
- Assembling the product then involves:
  - Introducing a tungsten filament attached to the light bulb's wiring (copper), which is then connected to a glass rod;
  - Aspirating the air contained in the globe and filling it with a mix of argon and nitrogen;
  - Sealing the globe and screw base after connecting the internal wiring of the globe to the connection pin in the base (copper).
- Finally, packaging the light bulb involves inserting it into a cardboard box (primary packaging that contains one or several light bulbs). No details were provided regarding the product's secondary and tertiary packaging.

The production processes of a compact fluorescent are similar. However, with compact fluorescents:

- The inside surface of the tube is made of phosphor;
- The screw base also includes a plastic base (PVC or PBT) and an electronic ballast, which explains why this type of light bulb weighs some two or three times more than the incandescent (on average, based on the data);
- The light bulbs are filled with argon and mercury.

Because the various steps are not detailed and because no generic data of a sufficient quality was obtained regarding the manufacturing of the light bulbs, this step of the life cycle essentially accounts for the production of the main materials contained in the finished products. These materials are listed in Table 4-1, the details of which were obtained from the various manufacturers presented in Annex C.

Table 4-1 : Main materials contained in a light bulb

Component	Material	Mass [b] (g)	
		A- C. fluorescent	B- Incandescent
Tube/Globe	Glass surface	25.15	22.75
	Coating: phosphor (A) or silica (B)	0.95	0.81
Screw base	Metal sheath (tinplate)	2.35	1.71
	Connection pin (copper)	1.00	0.10
	Electrical contact (copper)	5.67	0.90
	Soldering (with or without lead-based braze)	0.66	0.63
	Lead (soldering)	0.36	0.43
	Insulator (black glass)	4.97	3.33
	Base (PVC or PBT)	12.83	n/a
Ballast [c]	Electronic ballast	16.90	n/a
Electrodes/Rod	Rod (glass)	1.20	3.30
	Filament (tungsten)	4.36	0.11
	Internal wiring (copper)	n/a	0.17
Sealant	Glue (no details)	2.73	1.59
Gas fill	Argon	0.017	0.074
	Mercury	0.003	n/a
	Nitrogen	n/a	0.004
Packaging	Cardboard	26.03	23.18
TOTAL MASS		**95.46**	**55.80**

NOTES:
[a] This list of materials is taken from the quantitative data that was collected. Certain sources report: **1)** the **presence of other materials**, especially the ink sometimes applied to the outside of the globe and the coating on the tube and electrodes; **2) possible alternatives to these materials**, especially to the gas fills (using krypton rather than argon), the composition of the internal wiring (with an alloy that also contains iron and nickel) and to the metal sheath (made of aluminum or copper rather than tinplate). No quantitative data of sufficient quality was obtained on the materials (supplementary or alternative).
[b] Average mass based on the data collected (see Annex C).
[c] Though only the mass of the ballast was provided by the manufacturer, the electronic components were modeled based on the weight obtained in the lab of the ballast of a Philips 15-W compact fluorescent bulbs. These weights are presented in Annex C.

The production of the actual amounts of consumed materials (taking production losses into account) and of all the other resources used to operate the production equipment and infrastructure is considered, except for on-site energy consumption. This energy consumption is estimated to be 10% of the raw energy[1] required to produce the resources consumed on site (24.172 and 0.864 MJ for the compact fluorescents and the incandescents, respectively) and is equally distributed between three types of systems: electricity, natural gas and oil (hypotheses).

In addition, though raw data on the amount of sealant contained in both types of bulbs was obtained, no details on the type of sealant or its contents were given. Because no generic data on this type of product was found, this process was not taken into account in the inventory. It is interesting to note that, according to the study by Parsons (2006), the sealant may contain phenol-formaldehyde.

The various resources are transported to the production sites by truck over an average estimated distance of 1 000 km.

[1] Energy consumed, including the energy to power the extraction, transport, refining and other phases.

Finally, because the total waste generated during production (materials losses, chemicals, atmospheric emissions, liquid effluents) is not known, the bulbs' transport and management (elimination or other) are not taken into account.

4.2.2 Distribution phase

According to the information received from the manufacturers, two types of light bulbs are made in China (exact location unknown) and follow a relatively similar route. As described in Annex C, the light bulbs are generally transported:

1. From the production site to the shipping port (mode and distance not mentioned). Transport is presumed to be by truck over an average estimated distance of 200 km);
2. Between the shipping and arrival ports (transport by boat over an average distance of almost 10 000 km):
    a. Shipping ports are generally located on China's east coast (Xiamen, Guangzhou, Shanghai and Fuzhou).
    b. The arrival port for all of the manufacturers is Vancouver.
3. From Vancouver to Montréal (transport by train over an average distance of almost 5 000 km), though one manufacturer (Globe Electric) mentioned that the bulbs were transported by train to Toronto and then sent to Montréal by truck (this exception is not taken into account in the inventory).
4. Between the distribution centre(s) (shipping/receiving) in Montréal and the various Québec retailers (transport by truck over an average estimated distance of 200 km).

The distances were estimated using information from the World Shipping Register (for maritime transport), Via Rail (for rail transport) and Google (for truck transport). No data was obtained on the handling and stocking of the bulbs in the distribution centres or retail stores. These phases are therefore not taken into account. They essentially involve electricity consumption and generate packaging waste (secondary and tertiary) and are possible negligible.

4.2.3 Use phase

The phase includes the transport of the light bulbs to retailers and consumer homes, the generation of primary packaging waste and electricity consumption during use.

Because the distance between the homes and retailers is unknown and the fraction of the transport that is attributable to the light bulbs is difficult to assess (and is potentially negligible), the process is not considered in the inventory.

Once again, the average distance between the homes and retailers and landfill sites in Québec is not known but estimated at 50 km (transport by truck). The primary packaging (cardboard) is supposed to be 33% recycled and 67% landfilled (according to Natural Resources and Wildlife Québec, 2005).

In keeping with the functional unit, electricity consumption is calculated for 10 000 hours for each system:

- System A: 1 light bulb * 13 W (representative of the most popular models sold in Québec) * 10 000 hours = 130 kWh ;
- System B: 10 light bulbs * 60 W * 1 000 hours = 600 kWh.

As previously stated (sub-section 3.1.1), the baseline scenario does not take into account the heat generated by the light bulbs, while the crossed effect scenario considers the heat to be an additional load on the cooling system or a reduced load on the heating system. The impact of an equivalent amount of heat that the heating system does not have to produce can be credited to the life cycle of the light bulb, (environmental bonus) while an additional process can be added to take into account the extra load on the cooling system. The crossed effect scenario was developed into sub-scenarios so as to represent the various typical Québec contexts. The following paragraphs describe the method and hypotheses used to model these sub-scenarios.

4.2.3.1 Parameters of the crossed effect scenario

The crossed effect scenario is essentially based on an estimate of the number of lighting hours during three typical seasons in Québec:

- The cold season, during which homes are heated;
- The warm season, during which certain homes are cooled;
- The neutral season, during which homes are neither heated nor cooled.

The following table presents the hypotheses that were put forward.

Table 4-2 : Number of annual lighting hours in Québec in each season

	Days/year	Hours/day	Hours/year
Cold season: heating	200	6.7	1340
Warm season: potential cooling	43	4.7	202.1
Neutral season: no heating or cooling	122	5.7	695.4
Total	365	--	2237.5
Source: Lee (2007a&b)			

Because the study assessed 10 000 lighting hours for each of the two types of bulbs (in keeping with the functional unit), the crossed effect scenario covers 4.47 years of use.

The energy consumption of the two types of bulbs during each season was calculated based on equation 4-1.
Table 4-3 details the calculations for one year and the 4.47 years of the study.

$$Cons(kWh/year) = Cons(W) * 1kW/1000W * Days/year * Hours/day \quad \textbf{4-1}$$

Cons Electrical consumption of the bulb (kWh/year or W)

Days/year Number of days per year (in the cold, warm and neutral seasons)

Hours/day Number of lighting hours per day (in the cold, warm and neutral seasons)

Table 4-3 : Energy consumption (kWh) of the bulbs in each season

	A- C. fluorescent		B- Incandescent	
	1 year	4.47 years	1 year	4.47 years
Cold season: offset heating	17	78	80	359
Warm season: additional cooling	3	12	12	54
Neutral season: no heating or cooling	9	40	42	186
Total	29	130	134	600

During the 10 000 hours (or 4.47 years) of usage, it is presumed that 90% of the energy consumed by the light bulb is later dispersed as heat into the ambient air (see sub-section 3.2.4). This emitted heat then offsets an equivalent contribution by the heating system during the cold season and leads to additional cooling during the warm season.

The amounts of energy (heat) released into the ambient air by both types of bulbs (and which impact the heating and cooling systems) are calculated based on the equation in 4-2. Table 4-4 describes the various heating and cooling systems and their use rates in Québec.

Note: Wood heating is not taken into account even though it represents 9.1% of all heating in Québec. This is explained by the fact that the heat that is released by the light bulb does not impact wood-heated homes because the system is not controlled by a thermostat. There is therefore no possible crossed effect.

$$C(kWh) = Cons(kWh / year) * 4.47 yr * Heat / COP \qquad \textbf{4-2}$$

C	Credit for the energy that is offset for the heating system or the additional **load** on the cooling system.
$Cons$	Electricity consumption of the bulb (in the warm or cold season).
COP	Coefficient of performance of the heating or cooling system (the ratio between the amount of heat produced and the amount of energy consumed).
$Heat$	% of the energy consumed that is transmitted into the ambient air as heat (and which impacts the heating and cooling systems).

Table 4-4 : Distribution of the types of heating/cooling systems in Québec

Type of heating/cooling system	% of houses heated/cooled [c]	Coefficient of performance (COP) [b, c]
Oil-fired boiler	17.2	0.65
Natural gas-fired boiler	5.8	0.70
Electrical heating	67.9	1.00
Wood heating	9.1	0.40
Heat pump – cooling	7.0	3.1
Air conditioning	30.5	2.9
No cooling system	62.8	n/a

NOTES:
[a] The term *air conditioning* includes central, window and mobile air conditioners. An average COP was calculated based on the average COP of these types of units.
[b] Average coefficient of performance (COP)
[c] Information provided by Lee (2007b)

4.2.3.2 Modeling the crossed effect sub-scenarios

As previously mentioned, the crossed effect scenario was developed into sub-scenarios so that the various use contexts could be modeled for each type of bulb. The cases studied cover homes that are:

- Entirely heated by electricity, natural gas or oil (during the cold season); and
- Either cooled and not cooled (during the warm season);

All of the other types of heating and cooling systems listed in Table 4-4 were modeled so as to represent the average Québec home. Table 4-5 provides an overview of the various sub-scenarios.

Table 4-5: Typical homes in Québec modeled by for crossed effect scenario

<table>
<tr><th colspan="2">Sub-scenario</th><th>Lighting</th><th>Heating</th><th>Cooling</th></tr>
<tr><td>SF</td><td rowspan="2">01</td><td>C. fluorescent</td><td rowspan="2">100% electricity</td><td rowspan="8">With a cooling system</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">02</td><td>C. fluorescent</td><td rowspan="2">100% natural gas</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">03</td><td>C. fluorescent</td><td rowspan="2">100% oil</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">04</td><td>C. fluorescent</td><td rowspan="2">Based on the distribution in Québec (Table 4-4)</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">05</td><td>C. fluorescent</td><td rowspan="2">100% electricity</td><td rowspan="8">Without a cooling system</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">06</td><td>C. fluorescent</td><td rowspan="2">100% natural gas</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">07</td><td>C. fluorescent</td><td rowspan="2">100% oil</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
<tr><td>SF</td><td rowspan="2">08</td><td>C. fluorescent</td><td rowspan="2">Based on the distribution in Québec (Table 4-4)</td></tr>
<tr><td>SI</td><td>Incandescent</td></tr>
</table>

4.2.4 End of life

This phase covers the end-of-life management of the light bulbs, including the transport between consumer homes and management locations.

No light bulb recycling was taken into account and 100% of the mercury contained in the compact fluorescents is presumed to be released into the air (during collection, transport, and landfilling operations). The recycling of compact fluorescents in Québec is minimal to inexistent at the moment (RECYC-QUÉBEC, 2007). The rate of recycling sits at approximately 0.2% in the rest of Canada (Pollution Probe, 2005).

As previously stated, the average distance between consumer homes and the landfill sites in Québec is unknown but estimated to be 50 km (transport by truck).

Also, the generic data used to model light bulb landfilling underestimates (though not significantly) the damage of this phase of the life cycle (especially as it pertains to the potential leaching of the heavy metals contained in the electronic components of the compact fluorescents).

4.3 Data sources summary

Table 4-6 summarizes the data required to carry out the LCI of the light bulbs and the various data sources used (for the baseline scenario). It also provides an overview of the data that remained missing (no hypotheses or secondary data).

Table 4-6 : Required data and data sources summary (baseline scenario)

Required data		Data sources for each phase of the life cycle of the bulbs: Production	Distribution	Use	End of life
Resources consumed in each phase of the life cycle					
Electricity	○ Quantities (kWh)	○ Hypothesis: 1/3*10% of the primary energy required in pre-production	○ **Missing data**	○ Manufacturers (technical specifications of the products)	○ Generic European LCI data adapted to the energy contexts in 1) Québec (foreground processes); and 2) North American (for the background processes)
	○ Production technologies	○ Chinese grid mix modeled from generic European LCI data	○ Québec energy mix modeled from generic European LCI data (adapted to the North American energy context)		
Combustibles	○ Quantities (kg, m3, etc.)	○ Hypothesis: 2/3*10% of the primary energy required in pre-production	○ **Missing data**	○ N/A	
	○ Types	○ 1/3 natural gas; 1/3 oil			
	○ Production technologies	○ **Missing data**			
	○ Transport (distances, modes)	○ **Missing data**			
Material (material, chemicals, packaging)	○ Quantities (kg, m3, etc.)	○ Manufacturers (**incomplete data**)	○ N/A	○ N/A	
	○ Types and composition of the materials				
	○ Production technologies	○ **Missing data**			
	○ Transport (distances, modes)	○ **Missing data**			
Water	○ Quantities (m3)	○ **Missing data**	○ N/A	○ N/A	
	○ Production technologies				
Waste generated in each phase of the life cycle					
Atmospheric emissions	○ Quantities (kg, m3, etc.)	○ **Missing data**	○ N/A	○ Non applicable	○ Generic European LCI data adapted to the energy contexts in 1) Québec (foreground processes); and 2) North American (for the background processes)
	○ Type and composition				
Liquid effluents	○ Quantities (kg, m3, etc.)	○ **Missing data**	○ N/A	○ Non applicable	
	○ Types and composition				
	○ Management methods				
	○ Transport (distances, modes)				
Solid waste	○ Quantities (kg, m3, etc.)	○ **Missing data**	○ Secondary and tertiary packaging (**missing data**)	○ Manufacturers (primary packaging)	
	○ Types and composition				
	○ Management modes			○ Hypothesis: 50% landfilled, 50% recycled	
	○ Transport (distances, modes)			○ Hypothesis: 50 km by truck	
Transport of the product from one life cycle phase to another					
Transport	○ Distance	○ N/A	○ Manufacturers **(incomplete data)**	○ **Missing data**	○ Hypothesis: 50 km by truck
	○ Modes of transport				

4.4 Inventory results

This section presents the intermediate and elementary flows in the life cycles of the two types of bulbs.

4.4.1 Quantification of the primary intermediate flows

4.4.1.1 Baseline scenario

For each of the two types of bulbs, the materials and energy needs (for transport or equipment) that correspond to the energy flows were determined. These intermediate flows, which are directly involved in each of the phases of the life cycle, are presented in Table 4-7.

These flows indicate that the mass of a compact fluorescent is between two and three times higher than that of an incandescent (on average, based on the data collected). So as to remain in keeping with the functional unit, the use of one compact fluorescent rather than ten incandescents reduces the total weight of the consumed materials by 485 %.

Producing a compact fluorescent entails an energy consumption that is 64% higher than for the production of ten incandescents (presuming the energy required to produce the bulbs is equivalent to 10% of the primary energy required for raw materials production, as discussed in sub-section 4.2.1).

Seeing that the amount of waste generated in the use and end-of-life phases (cardboard packaging and bulbs) is directly related to the weights of the materials consumed during production, these intermediary flows also become less significant with the use of a compact fluorescent.

Also, because the distances covered in transport (raw materials, finished products and waste) are presumed to be the same for the two types of bulbs, the corresponding flows (in tkm) are reduced by between 370 and 791% through the use of compact fluorescent rather than incandescent light bulbs.

Table 4-7: Primary intermediate flows of the baseline scenario

Intermediate flow		**A** (C. fluorescent)	**B** (Incandescent)	**Variation** (A vs B)
1- Production				
Materials				
Body (glass)	g	25.15	227.5	-805%
Coating (phosphor)	g	0.95	0	n/a
Coating (silica)	g	0	8.1	n/a
Metal sheath (tinplate)	g	2.35	17.1	-628%
Connection pin (copper)	g	1	1	n/a
Electric contact (copper)	g	5.67	9	-59%

Table 4-7: Primary intermediate flows of the baseline scenario

Intermediate flow		A (C. fluorescent)	B (Incandescent)	Variation (A vs B)
Soldering (with or without lead)	g	0.66	6.3	-855%
Lead (soldering)	g	0.36	4.3	-1094%
Insulator (black glass)	g	4.97	33.3	-570%
Base (PVC or PBT)	g	12.83	0	n/a
Electronic ballast	g	16.9	0	n/a
Rod (glass)	g	1.2	33	-2650%
Filament (tungsten)	g	4.36	1.1	**+75%**
Internal wiring (copper)	g	n/a	1.7	n/a
Glue (unknown)	G	2.73	15.9	-482%
Argon	g	0.017	0.74	-4253%
Mercury	g	0.003	0	n/a
Nitrogen	g	0	0.04	n/a
Cardboard	g	26.03	231.8	-791%
Total – light bulb	g	95.46	558	-485%
Energy				
Transport – raw materials	tkm	0.0955	0.558	-485%
Heat – oil and gas	MJ	1.612	0.576	**+64%**
Electricity	kWh	0.224	0.080	**+64%**
2- Distribution				
Energy				
Transport (truck)	tkm	0.0191	0.112	-485%
Transport (transoceanic)	tkm	0.955	5.58	-485%
Transport (train)	Tkm	0.477	2.79	-485%
Transport (truck)	tkm	0.0191	0.112	-485%
3- Use				
Energy				
Electricity	kWh	130	600	-362%
Transport – waste	Tkm	0.001	0.012	-791%
Waste (packaging)				
Cardboard (67% landfilled; 33% recycled)	g	26.03	231.8	-791%
4- End of life				
Energy				
Transport – waste	tkm	0.003	0.016	-370%
Waste (light bulbs)				
Plastic base (landfilled)	g	12.83	0	n/a
Other landfilled components	g	56.27	321.9	-472%
Emissions				
Mercury (air)	g	0.003	0	n/a
Lead (water)	g	0.36	4.3	-1094%

4.4.1.2 Crossed effect scenario

The amounts of energy (heat) released into the ambient air by the two types of bulbs are calculated with equation 4-2 (see paragraph 4.2.3.1). Table 4-8 lists the results of the calculations for 10 000 hours (4.47 years) of lighting.

The energy consumed by the incandescent light bulbs is greater than that consumed by the compact fluorescents (+362 %) and it's use therefore creates a greater load on the cooling systems in the warm season. However, this load is credited (as an environmental bonus) in the cold season due to the fact that it offsets some of the heating.

Also, the credit for the energy that the heating system does not have to expend is approximately 20 to 30 times higher than the additional load on the cooling system because of:

- The number of lighting hours, which is higher in the cold season (1 340 hours/year as compared to 202 hours/year in the warmer season; and because of
- The systems' coefficients of performance (less than 1 in the case of the heating systems and more than one in the case of the cooling systems).

Table 4-8: Avoided energy (heating system) and additional load (cooling system) for 10 000 hours (4.47 years) of lighting

	A (C. fluorescent)	B (Incandescent)	Variation (A vs B)
Cold season: offset heat	kWh	kWh	%
Electric heating	70.3	324	-362
Natural gas heating	100	463	-362
Oil heating	108	499	-362
Warm season: additional load	kWh	kWh	%
Air conditioners	3.42	15.8	-362
Heat pump	3.65	16.9	-362

4.4.2 Quantification of the elementary flows

The intermediate (primary) flows were then converted to elementary flows using the secondary data that was collected. These elementary flows represent the flows between the environment (input flows – natural resources) and the output flows (emissions into the air, water and soil) of the product systems.

The detailed inventory results are presented in Annex C, which describes the main elementary mass flows based on the functional unit (linked to the life cycle of the light bulbs necessary to provide 10 000 hours of lighting).

Given these results, the use of a compact fluorescent bulb as compared to ten incandescents (necessary to provide the same service as a compact fluorescent), entails a significant reduction in practically all of the elementary flows. Contrary to Parsons' (2006) results, the total amount of mercury released into the air (throughout the life cycles of the two types of light bulbs) increases by 80% with the use of compact fluorescents rather than incandescents. But these results account for the fact that compact fluorescents are not recycled at the end of their service life and that the mercury they contain is entirely released into the air.

In addition, the resource consumption and atmospheric emissions associated with the life cycle of a compact fluorescent represent more or less one fifth (20% on a mass basis) of that associated with the life cycle of ten incandescents. Also, the emissions released into the water and soil by a compact fluorescent are all but negligible as compared to those of the incandescent (less than 3% on a mass basis).

But these results do not take ballast production into account, which is, however, integrated into the environmental profile and characterised and aggregated within the impact categories (as described in the next chapter). As discussed in sub-section 3.2.6, even though the input and output flows of this production are unknown and therefore not considered in the LCI, the associated impact is taken into account in the assessment.

The characterization and aggregation of these flows within the impact and damage categories makes interpreting the results easier. In Annex C, the main elementary flows are not always the same for the two systems and neither is their order in terms of mass or environmental relevance.

5. IMPACT ASSESSMENT AND RESULTS INTERPRETATION

The inventory data and the environmental impacts of the life cycles of the two types of bulbs were assessed and interpreted, in keeping with the methodological framework presented in sub-section 3.2.6.

5.1 Assessment of the baseline scenario

5.1.1 Damage/impact indicator results

The damage indicator results for each phase of the life cycles of both types of bulbs are in Annex C. Figure 5-1 details these results. There are two bars for each indicator category. The first represents the compact fluorescent (system A) and the second is the incandescent (system B). It is important to note that:

- All of the contributions are expressed in relative terms because they refer to the total obtained for the incandescent, which corresponds to a value of 100% (because the damage indicators do not have the same unit value and their results greatly differ in absolute value).
- The graph presents the uncertainty intervals, which are discussed in section 5.3.

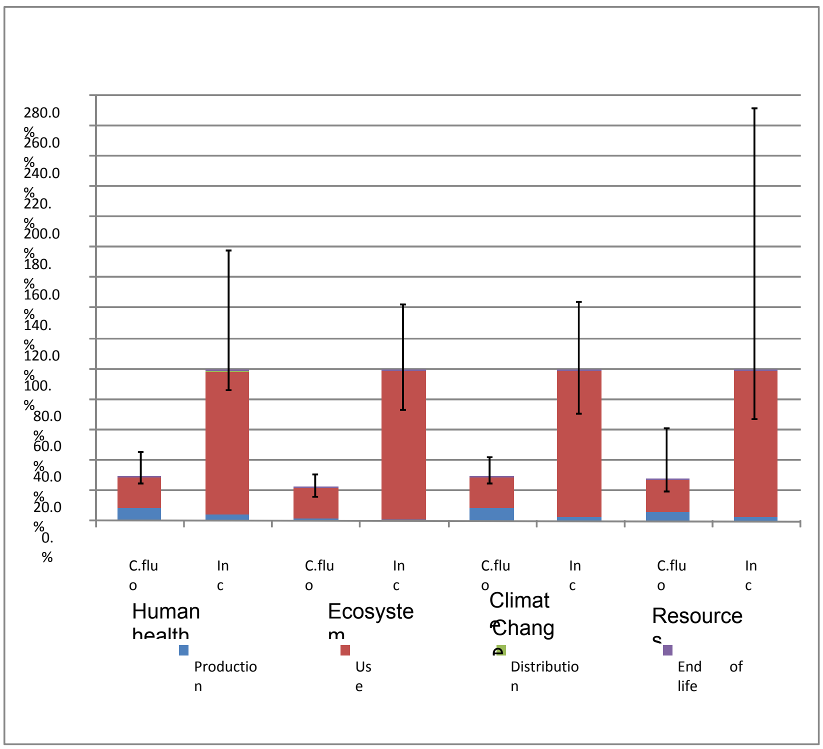


Figure 5-1 : Baseline scenario damages for both types of light bulbs

A first finding is the important contribution of the **use** phases of both types of light bulbs to each damage category. This contribution represents between 69 and 93% of potential damages in the case of the compact fluorescent and between 93 and 99% of damages in the case of the incandescent. Light bulb **production** is responsible for between 6 and 30% and 1 between and 5% of the damages for the compact fluorescent and incandescents, respectively. Distribution and end-of-life management seem negligible in both cases.

These conclusions are similar for most of the impact categories, including aquatic acidification and eutrophication. The impact indicator results (not included in the table) show that the gap between the use and production of the light bulbs differs for certain categories (relative to the gap observed for the damage indicators). Table 5-1 details the impact categories whose gap between the use and production phases is significantly different from the one observed for the damage).

Table 5-1 : Gaps in the indicator results (damage and impact) for the light bulbs' use and production phases

Damage		Impact (whose gap is different than that observed for the damage)	
Category	**Gap (%)** Use vs production	**Category**	**Gap (%)** Use vs production
A-Compact fluorescent			
Human health	39	Ionizing radiation	84 (maximum gap)
Ecosystem quality	87	Terrestrial acidif./eutroph.	36 (minimum gap)
		Land use	15 (minimum gap)
Climate change	41	None	n/a
Resources	53	Mining	**-55 (reversed gap)**
B-Incandescent			
Human health	88	None	n/a
Ecosystem quality	98	Land use	63 (minimum gap)
Climate change	93	None	n/a
Resources	93	Mining	**-44 (reversed gap)**
NOTE: A **maximum gap** indicates that the impact indicators of the use and production phases have a greater gap (as compared to the damage indicator results) while a **minimum gap** indicates that they are similar. A negative gap (**reversed**) means that the production phase contributes more than the use phase to the impact indicator. The inversion observed for mining does, however, somewhat contribute to resource damage.			

The second finding is similar to that of the inventory assessment: there is a reduction in all of the damage indicators with the use of the compact fluorescents, with the exception of:

- The production phase (all indicators increase);
- Ecosystem quality in the end-of-life phase.

The production of a compact fluorescent would be more damageable by approximately 25 to 75% than the production of 10 incandescents (necessary to provide the same service as a compact fluorescent), essentially because of the production of the electronic components (ballast). Without taking these components into account the damage of compact fluorescent production is only approximately 40 to 60% of that of the production of 10 incandescents (except in the climate change category in which the damage of both types of bulbs is almost equivalent).

The increases in the damage indicators observed in the production and end-of-life phases remain lower than the reductions observed for the other life cycle phases. A net reduction can also be observed for all of the impact indicator results.

The damage of the complete life cycle of the compact fluorescent bulb therefore represents, depending on the category, between 20 and 30% of that of the incandescents (an average of 28%). Also, the impact of the compact fluorescent is between 20 and 50% of that of the incandescents (an average of 30%).

5.1.2 Contribution analysis

The use phase results analysis shows that electricity production and transmission contributes to practically 100% of the potential damages. This conclusion is not surprising given that this phase only involves electricity consumption and the transport and management (elimination/recycling) of the cardboard packaging.

Electricity production is, in fact, the main contributor in the climate change and resources categories. For the human health category, electricity production is almost equivalent to electricity transmission, while transmission has the greatest impact on the ecosystem quality category. The following table details the key environmental parameters of the use phase.

Table 5-2: Key environmental parameters of energy consumption (low voltage) based on Hydro-Québec's energy grid mix

Damage/impact category	Process	Approx. contribution	Key parameters
Human health (HH)	Production	**< 55%**	**Coal**, **hydroelectric** (dams and run-of-river) and **industrial gas**
	Transmission	**> 45%**	**Copper** production
Ecosystem quality (EQ)	Production	> 15%	**Coal, hydraulic** (dams) and **nuclear** (to a lesser degree)
	Transmission	**< 85%**	**Copper** and **chromium(VI)** emitted into the soil
Climate change (CC)	Production	**< 90%**	**Coal** and **industrial gas** and **hydraulic** (dams) to a lesser degree and **oil**
	Transmission	> 10%	**Copper** and **iron** production, **PVC** production and elimination
Resources (R)	Production	**< 95%**	**Nuclear** production and, to a lesser degree, **coal** and **oil**
	Transmission	> 5%	**Copper**, **iron** and **PVC** production
Aquatic acidification (AA)	Production	**< 55%**	**Coal** production and, to a lesser degree, **hydraulic** (dams) and **oil**
	Transmission	**> 45%**	**Copper** production
Aquatic eutrophication (EUA)	Production	**< 65%**	**Oil** and, to a lesser degree, **hydraulic** (dams and run-of-river)
	Transmission	> 35%	**Iron** production and, to a lesser degree, **copper**

5.2 Scenarios assessment

5.2.1 Crossed effect scenario

The crossed effect of the heat released by the bulbs during lighting was considered in the case of homes heated by electricity, gas and oil (the crossed effect of the heat on the cooling system being negligible). The damages (and impacts) of the additional load on the cooling systems during the warm season are insignificant as compared to those of the credit for the energy avoided and even to those of the baseline scenarios (even without attributing a credit, the damages and impacts of cooling remain insignificant as compared to those of the rest of the life cycle). Therefore, in an effort to remain as concise as possible, only the effect of the avoided heating is presented in the following paragraphs.

The average distribution of the types of heating in Québec was also studied so as to assess the advantages of the province-wide use of the compact fluorescents (through public policy, for example).

Finally, the results consider the annual use of one type of bulb or the other and the environmental credit for the heating that is avoided is therefore only attributed for a fraction (approximately 60%) of the 10 000 hours of lighting of the functional unit. The sensitivity of the results to the attribution of a credit for offset heating during 10 000 hours of use (and therefore by considering light bulb use in the cold season only) was also assessed in paragraph 5.4.1.4.

5.2.1.1 Homes heated with electricity, gas or oil

The following figures present the damage indicator results for the various crossed effect sub-scenarios. There are three bars for each category. The first represents the compact fluorescent (system A), the second is the incandescent (system B) and the third is the difference between the two types of bulbs. Once again, 1) all of the contributions are expressed in relative terms since they refer to the total obtained for the baseline scenario of the incandescent and therefore correspond to a value of 100%; and 2) the uncertainty intervals are discussed in section 5.3.

Therefore, for a home heated with **electricity**, the compact fluorescent remains the best option when considering all of the damage categories. This result is not surprising since:

1. The credited amounts (see Table 4-8) are smaller than the amounts required for lighting (130 kWh for the compact fluorescent and 600 kWh for the incandescent); *and*
2. The credited electricity consumption (offset heating) process is identical to the electricity consumption process for lighting (in the baseline scenario).

In this case, the credit does not offset the damages of the baseline scenario and the compact fluorescent remains the best option. The impact indicators (not included in Figure 5-2) all lean towards the compact fluorescent for this sub-scenario.

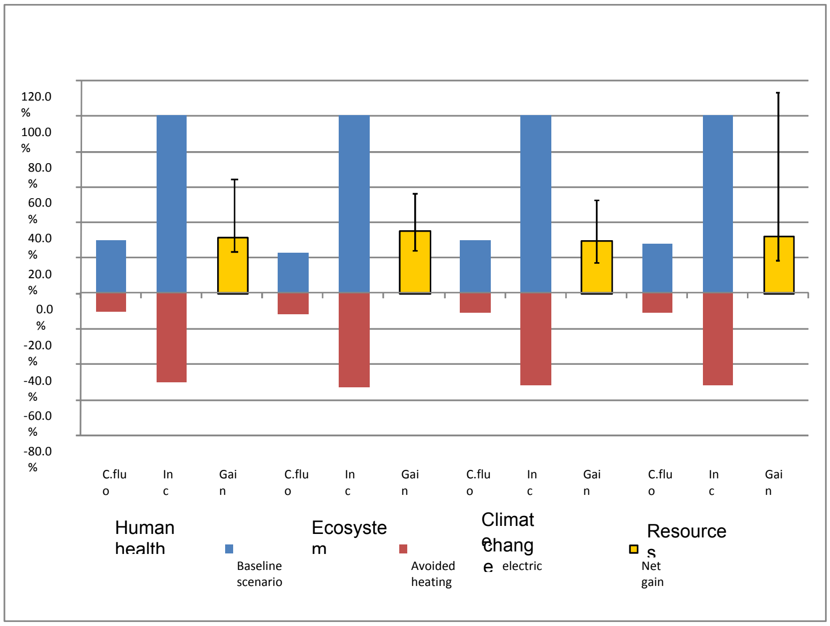


Figure 5-2: Damages of the crossed effect scenario for an electricity-heated home

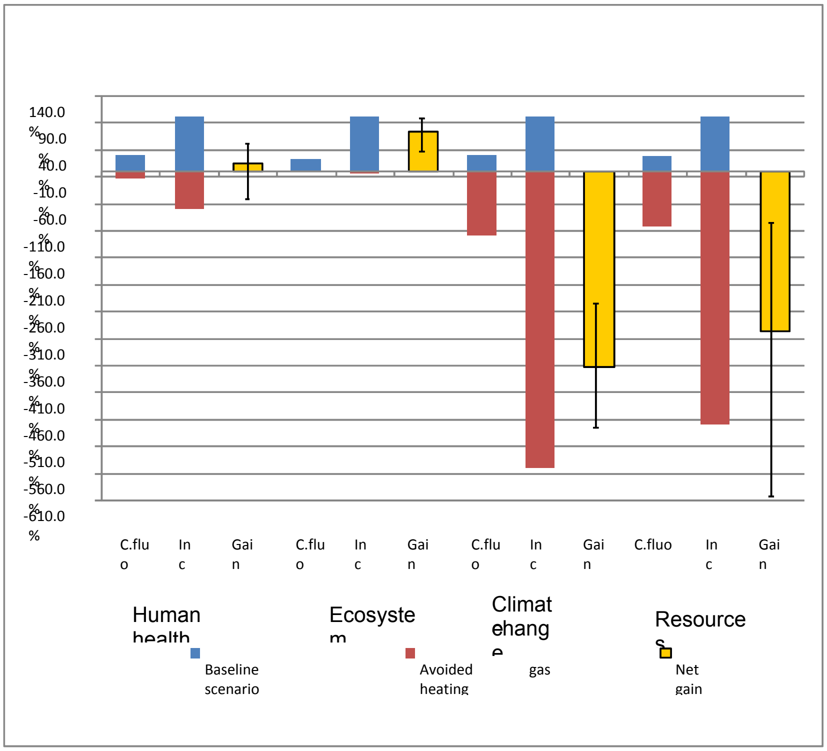


Figure 5-3: Damages of the crossed effect scenario for a natural gas-heated home

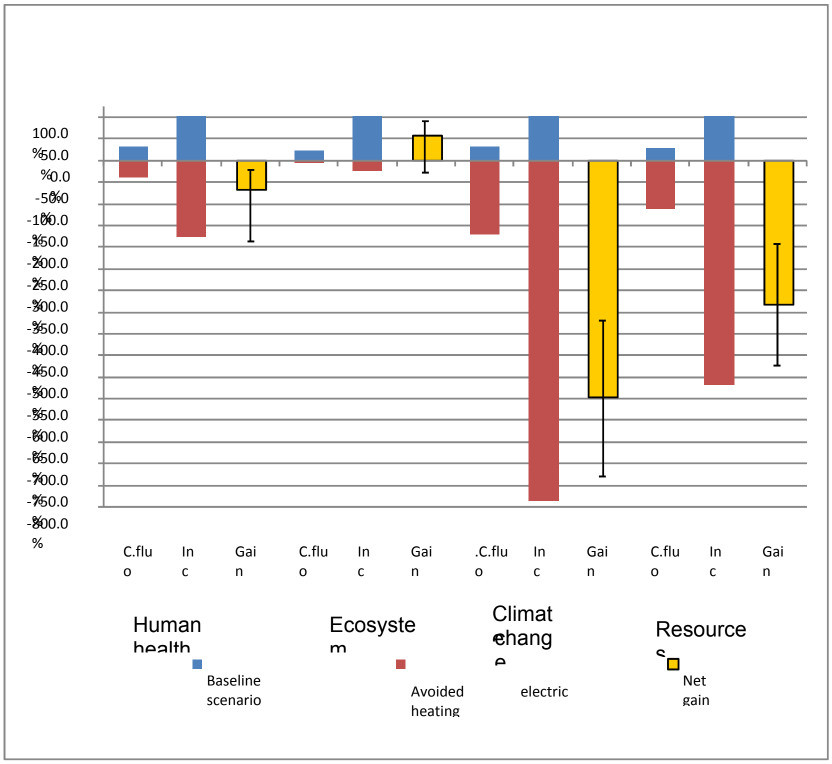


Figure 5-4: Damages of the crossed effect scenario for an oil-heated home

For homes heated with gas or oil, the amounts credited are, once again, inferior to the amounts required for lighting (Table 4-8). However, the elementary flows of the heating process (per MJ) being more numerous and/or more important (in terms of mass contribution and/or environmental relevance) than those of the baseline scenario, the credit attributed offsets certain baseline scenario damages. Specifically, the credit comes from the fact that a given amount of heat generated by an oil- or gas-powered system is "avoided" and replaced with heat produced from electricity, which causes less damages (electricity consumed by the light bulbs when lit). Because this credit is greater in the case of the incandescents, the use of this type of bulb is more advantageous under certain conditions.

Especially in the case of natural gas-heated homes, the use of incandescent bulbs is the best option when considering the climate change and resource damages. In addition, though human health and ecosystem damages would tend to favour the compact fluorescents, the net gain from using this type of bulb is more than 5 times less than the net gain of the incandescents for the climate change and resources categories.

In the same way, for oil-heated homes, the use of incandescents obtains, for three of the four damage categories, a net gain that is more than 15 times greater than the gain from a compact fluorescent in the ecosystem quality damage category alone.

Finally, Table 5-3 lists the impact categories whose conclusions are reversed as compared to those of the damage categories. The elements that could potentially lessen the interest in the use of incandescent bulbs in gas- or oil-heated homes are included in the table in bold.

Table 5-3: Impact categories (compact fluorescent vs incandescents) whose contribution is different from that of its damage

Damage		Impact categories
Category	**Most significant contributor**	
Natural gas		
Human health	Incandescent	Carcinogenic effects
		Ozone layer depletion
		Photochemical oxidation
Ecosystem quality	Incandescent	Terrestrial acidification/ eutrophication
Climate change	Compact fluo.	None
Resources	Compact fluo.	**Mining**
None	n/a	Aquatic acidification (incandescent)
		Aquatic eutrophication (compact fluorescent)
Oil		
Human health	Compact fluo.	**Non-carcinogenic effects**
		Ionizing radiations
Ecosystem quality	Incandescent	Terrestrial acidification/ eutrophication
		Land use
Climate change	Compact fluo.	None
Resources	Compact fluo.	**Mining**
None	n/a	Aquatic acidification (incandescent)
		Aquatic eutrophication (incandescent)

5.2.1.2 Average distribution of heating systems across Québec

The crossed effect of the average distribution of heating systems across Québec is presented in Figure 5-5. The profile of this scenario is similar to that of a natural gas-heated home. For this scenario, the incandescent bulb is the best option when considering the damages in the climate change and resources categories. And though the two other damage categories would favour the compact fluorescents, the net gain is lower than the one associated with the incandescents for the climate change and resources categories.

Finally, the impact categories for natural gas in Table 5-3 also apply to this fourth crossed effect sub-scenario.

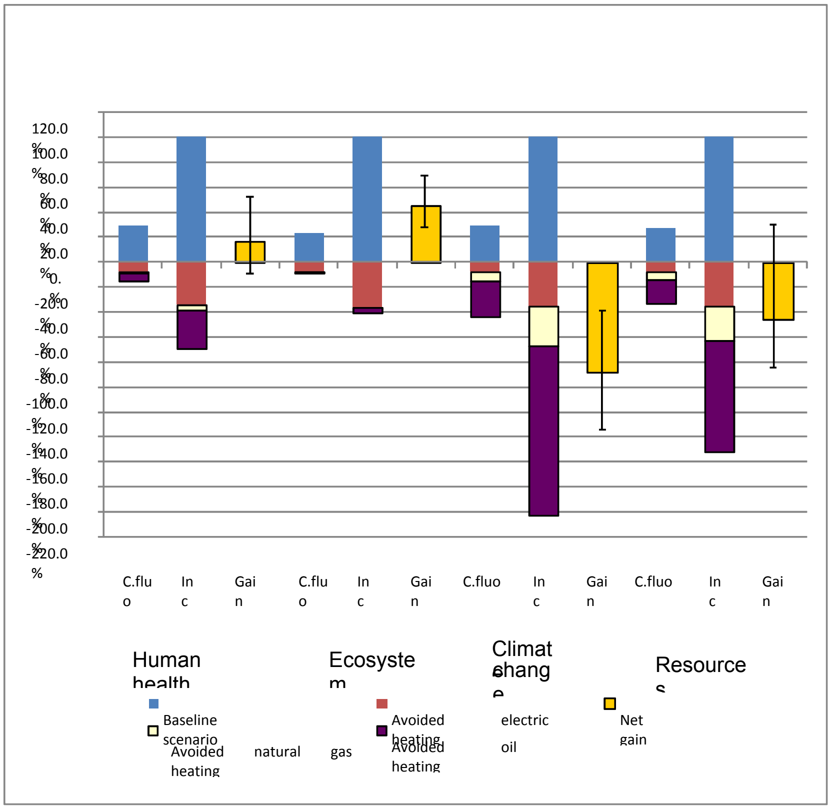


Figure 5-5: Damages of the crossed effect scenario based on the average distribution of heating systems across Québec

5.2.2 End-of-life scenarios

The end-of-life scenarios initially proposed were not carried out as part of this project.

- In light of the results of the baseline scenario, the end-of-life phase is negligible as compared to the use phase and, to a lesser degree, to the production phase of the bulbs.
- Because the baseline scenario does not consider any bulb recycling and presumes that 100% of the mercury of the compact fluorescents is released into the atmosphere, a scenario analysis taking into account the various recovery rates of the bulbs should further reduce the relative significance of the end-of-life phase given that:
  - Mercury emissions into the air would then be much less (or none at all);
  - The total impact of light bulb recycling would then be attributed in whole or in part to other product systems (recovered light bulb users). The impact of the recycling that would be attributable to the life cycle of the bulbs would normally be less than that of landfilling (which is entirely attributable to the bulbs).

However, it is important to remember that the current light bulb landfilling model underestimates, though probably not significantly, the damage of this phase of the life cycle (especially as it pertains to the potential leaching of the heavy metals contained in the electronic components of the compact fluorescent).

5.3 Uncertainty analyses

Of the thousands of individual elementary flows inventoried in the elementary processes of the various scenarios that were examined, the vast majority were taken from the *ecoinvent* data bank. Most of these flows present a variability that consists in a lognormal distribution around a specified central value (and used in the deterministic calculations) that is characterised by its standard gap. However, the variability introduced into the data by the authors of the *ecoinvent* database does not correspond to the actual variability of the processes (i.e., statistically determined based on concrete measures carried out during data collection) but is estimated by applying a pedigree to describe the quality of the data according to its origin, collection method and representativeness and is subjectively determined by databank authors. It is therefore essential to understand that the objective is to highlight the uncertain character of the conclusions and that the variability only provides a broad idea because better quality information is not available.

The variability of most of the primary data that was collected was also estimated and is presented in the table below.

Table 5-4: Primary data uncertainty hypotheses

Parameter	Supposed type of distribution	Values and hypotheses
Mass of the raw materials (except ballast)	Uniform	Average, minimum and maximum values provided by the manufacturer
Transport distance	Normal	Supposed value +/- 50 %
Total energy production	Normal	Supposed value +/-5 %
Light bulb consumption	Normal	Specified value +/-2 W
Number of days per season	Normal	Specified value +/-15 %
Number of hours of lighting per day (per season)	Normal	Specified value +/-2 hours
% of the energy consumed by the light bulb that is released as heat	Uniform	Supposed average (0,95), minimum (0,90) and maximum (1) values
% of the released heat that is dissipated into the ambient air		
COP of the heating and cooling systems	None	Deterministic (average) values specified

An uncertainty analysis was carried out because of the variability of the inventory results. The SimaPro 7.1 software made it possible to conduct a Monte Carlo type analysis (a propagation study of the variability of the inventory during calculation, which then becomes probabilistic) with 1 000 iterations. The results for the baseline and crossed effect scenarios are presented in the following sub-sections.

5.3.1 Baseline scenario

The uncertainty intervals presented in Figure 5-1 (section 5.1) show that there is no possibility that the conclusions are reversed for the baseline scenario. Therefore, based on these results, it is unlikely that the compact fluorescent would be the greatest contributor to the damage categories.

This is also confirmed by the results of the calculations carried out on the subtraction of system B (incandescent) from system A (compact fluorescent). According to these calculations, when the impact calculated for system A is greater than that of system B, the result of the iteration is positive. This result is negative if system B shows a greater impact. It is therefore possible to know the probability that a system would have a greater impact than another. The following figure graphically illustrates the result of this type of analysis.

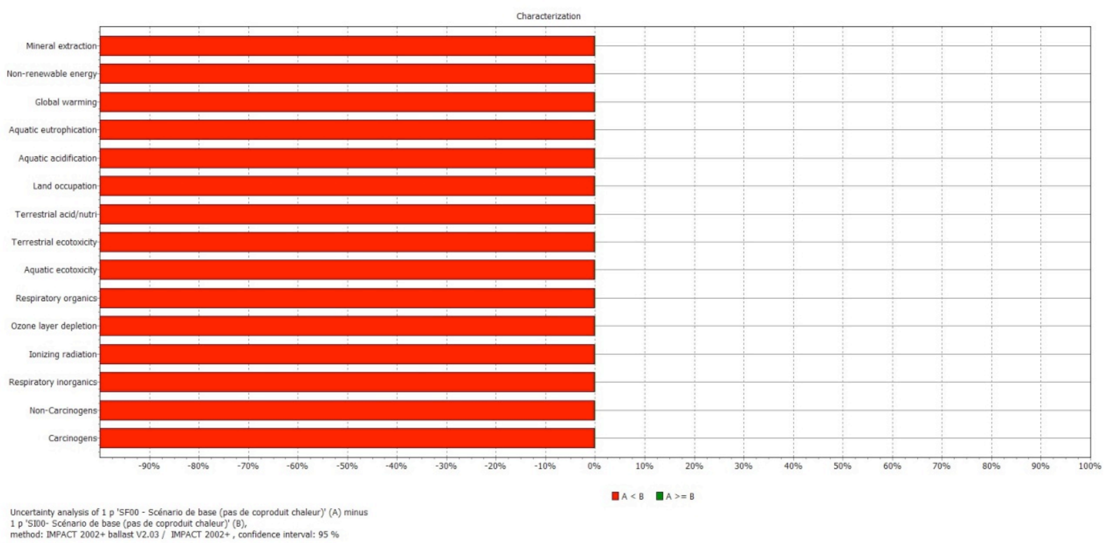


Figure 5-6: Probability of the occurrence of the result of the subtraction of the systems (A - B) for the baseline scenario

For the baseline scenario, the uncertainty analysis makes it possible to conclude that compact fluorescent lighting (and not incandescent) leads to a reduction in damages (including all impact categories).

5.3.2 Crossed effect scenario

For the crossed effect scenario, the uncertainty intervals presented in the figures in section **Erreur ! Source du renvoi introuvable.** show that the conclusions could be reversed for certain damage categories.

5.3.2.1 Electricity-, gas- or oil-heated homes

As for the baseline scenario, the uncertainty intervals in Figure 5-2 (section **Erreur ! Source du renvoi introuvable.**) show that the conclusions could not be reversed for a home heated with electricity. It is therefore improbable that a compact fluorescent would be the greatest contributor to one or the other damage category for this scenario.

This is also confirmed by the results of the Monte Carlo simulation carried out on the subtraction of the damage indicators of each of the systems (A – B). As demonstrated in the following figure, the simulation conducted on the impact indicators shows that there is a small probability of occurrence (less than 2%) for the result $A \geq B$ in the photochemical oxidation and land use categories.

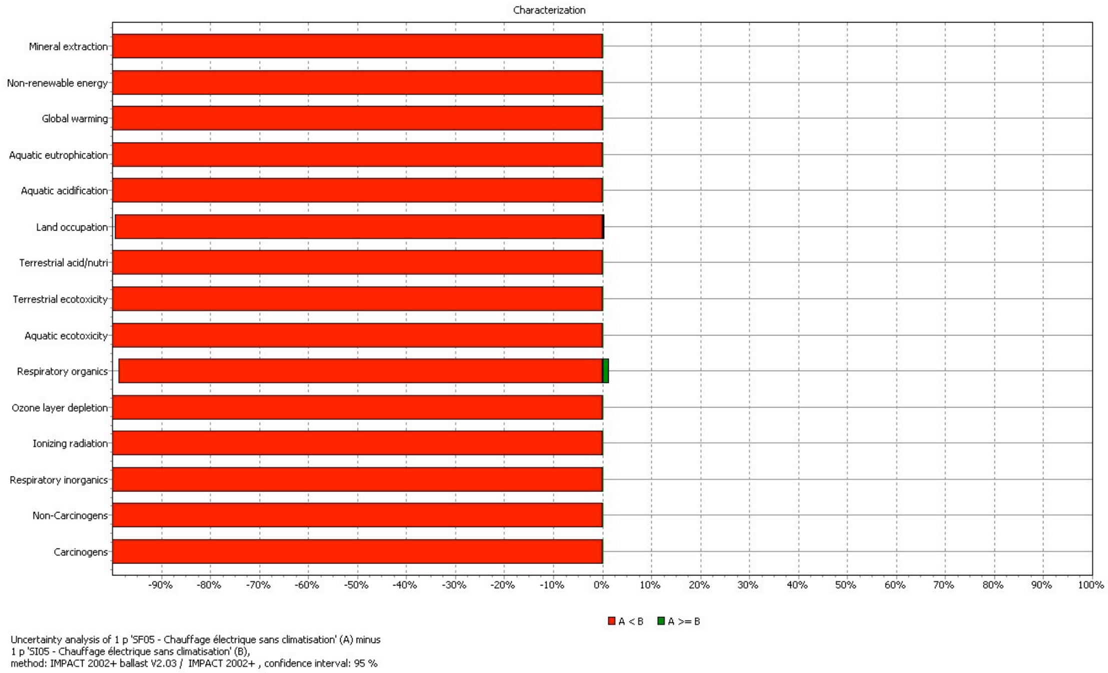


Figure 5-7: Probability of the occurrence of the result of the subtraction of the systems (A - B) for the crossed effect scenario (home heated by electricity)

For gas- and oil-heated homes (see Figure 5-3 and Figure 5-4 in section **Erreur ! Source du renvoi introuvable.**), the possible inversions all favour the incandescents, increasing their potential advantage. According to the results of the Monte Carlo simulation carried out on the subtraction of the damage indicators, the probability of the occurrence of the A ≥ B result for the categories that initially favoured the compact fluorescents remains at less than 20% for both types of heating. The Monte Carlo simulation carried out on the impact indicators is presented in the figures below.

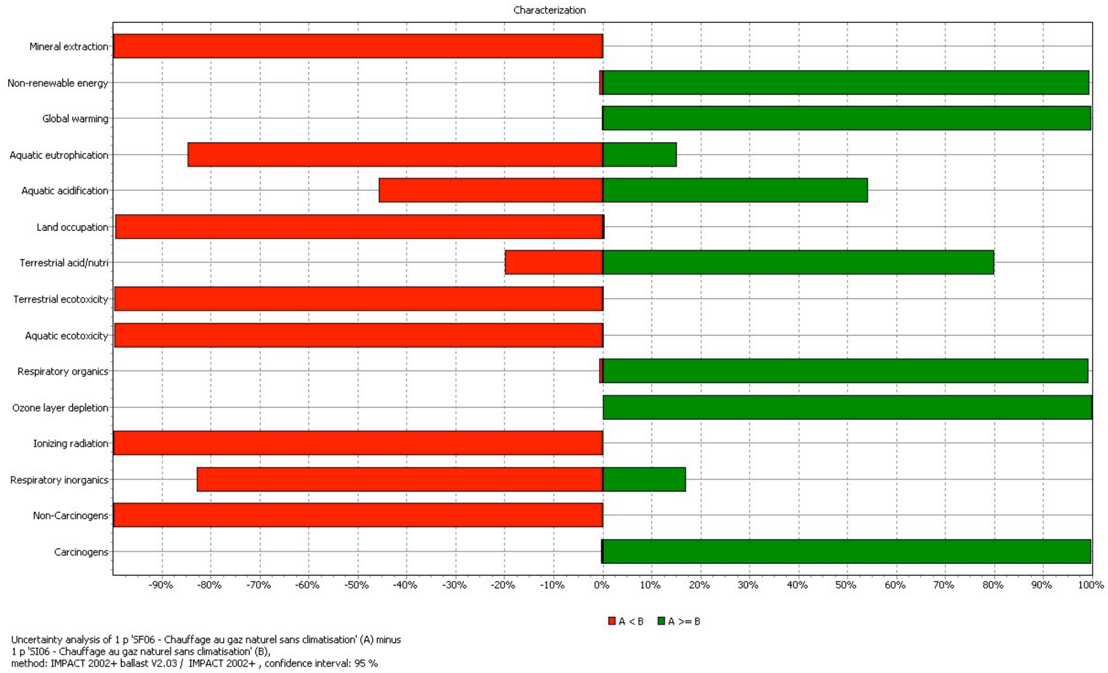


Figure 5-8: Probability of the occurrence of the result of the subtraction of the systems (A - B) for the crossed effect scenario (home heated by natural gas)

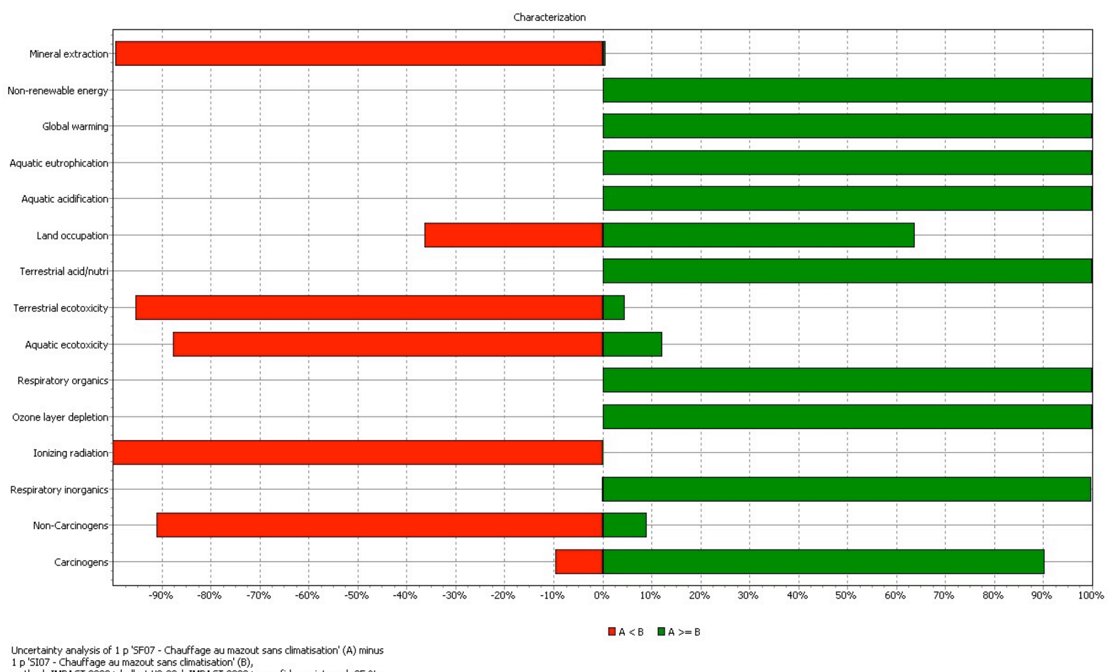


Figure 5-9 : Probability of the occurrence of the result of the subtraction of the systems (A - B) for the crossed effect scenario (homes heated with oil)

5.3.2.2 Average distribution of heating systems in Québec

In the scenario that represents the average distribution of the types of heating in Québec, the uncertainty intervals in Figure 5-5 (section **Erreur ! Source du renvoi introuvable.**) show that:

- The compact fluorescents are the best option when considering all of the damages except climate change;
- The net gain from the incandescents in the climate change category can be smaller than that of the compact fluorescent in other damage categories.

For this scenario, it is therefore difficult to determine which of the two options is best. This is also confirmed by the Monte Carlo simulation results of the subtraction of the damage indicators (as detailed in the following figure).

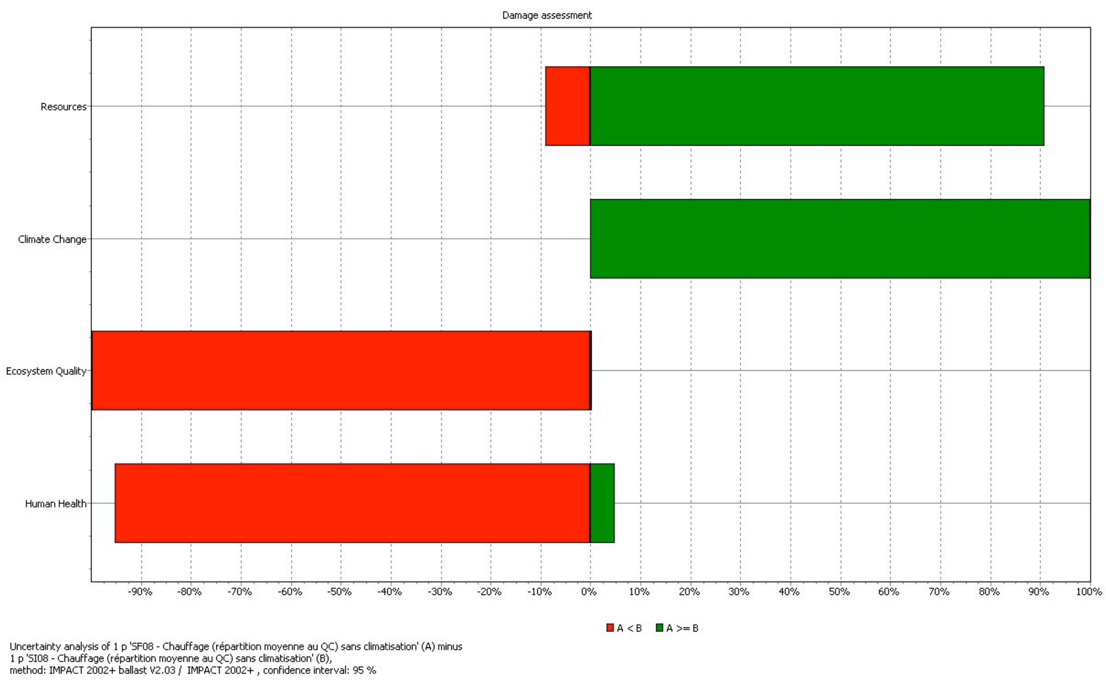


Figure 5-10: Probability of the occurrence of the result of the subtraction of the systems (A - B) for the crossed effect scenario (based on the average distribution of heating systems in Québec)

5.4 Sensitivity analyses

As discussed in the previous section, several parameters used when modeling the systems introduce a certain degree of uncertainty, especially in the choice of hypotheses, in the generic data modules and in the impact (and damage) assessment models used. The results are linked to these parameters and their uncertainty is therefore transferred to the conclusions.

To test the robustness of certain parameters, sensitivity analyses were carried out and the values of the uncertain parameters were replaced with different but probable values. The range of variations that these results then take on demonstrates the importance of the modified parameters and the scope in which the most valid results are most probably situated.

5.4.1 Choice of hypotheses

The hypotheses of the baseline scenario essentially involve the data that was initially missing and later obtained (or not) through estimations and the value of certain technical parameters of the light bulbs, especially their service life and the consumption of the compact fluorescents (impacted by the power factor). The parameters of the crossed effect scenario involve:

- Parameters pertaining to the number of hours of lighting per season;
- The fraction of the energy consumed by the bulbs that is ultimately emitted into the ambient air (and avoids a load on the heating system);
- The fraction of the heat that is dissipated and which can be credited to the life cycle of the bulbs; and
- The value of the coefficients of performance (COP) of the heating and cooling systems (corresponding to the average values that are representative of these systems in Québec).

As detailed in the previous section (5.3), a probability distribution was linked to several of these hypotheses in order to take their uncertainty into account. In essence, the parameters that are not covered in the uncertainty analysis, besides the missing data that was not obtained from estimates, pertain to service life, the increased consumption of the compact fluorescents given their low power factor, the value of the COP and the fraction of the heat credited to the light bulbs.

The results of this sensitivity analysis carried out on the hypotheses are presented in the following paragraphs.

5.4.1.1 Estimation of the missing data

The results are relatively insensitive to on-site energy consumption (types and amounts), packaging and light bulb waste management and to the various transport distances (resources to the production site, light bulbs to the shipping ports, light bulbs to the retailers, light bulbs and waste to the waste management sites). Attributing a probable value to these parameters, which were initially presumed to be of no effect, had little impact on the environmental profiles of the two types of bulbs.

Sensitivity analyses were not carried out on the parameters that were not fulfilled by the estimations (presumed to have no effect). They essentially pertain to the various resources consumed and to the waste generated during the production and distribution phases of the light bulbs and their transport from the retailers to the consumers' homes. However, these parameters could potentially have little effect on the results, with the exception of those of the production phase (resource and waste that was not considered). The completeness and validity of the data used to model this phase are, in fact, quite uncertain and the contributions could therefore be increased.

5.4.1.2 Hypotheses on the technical parameters

As mentioned in paragraph 3.2.4.2, the low power factor of the compact fluorescent was not taken into account, though it could increase energy consumption by between 5 and 7%. An increase in consumption of over 10% (17 W) does not impact the conclusions of the LCA. The relative damage of the life cycle of the compact fluorescents is therefore only slightly greater (it represents between approximately 30 and 35% of that of the incandescent).

In the same way, the 5 000-hour service life of the compact fluorescents (as compared to 10 000) does not impact the conclusion, though it does reduce the gap of the damages of both types of light bulbs.

5.4.1.3 COP selection

Given that the damages (and impacts) of the cooling systems are negligible as compared to those of the life cycle of the light bulbs, the conclusions are normally insensitive to the value of the COP of the cooling systems. The environmental profiles based on COP between 1 and 10 confirm this hypothesis.

Regarding the heating systems (gas and oil), the average COP seem to be quite weak as compared to the values currently found in the literature. An increase in the COP entails a reduction in the credit attributed for the heating that is avoided and therefore an increase in the damage of the two types of bulbs. The increases observed with a COP equal to 1 do not impact the environmental profiles. Comparing the systems provides conclusions that are similar to those previously obtained, with the exception of the human health category for which the gap between the two types of bulbs is greater. Therefore, in the case of a gas-heated home, this damage category would favour the compact fluorescents whereas in the case of an oil-heated home, it would favour the incandescent.

5.4.1.4 Attribution of the credit for the offset heating

The fact that home lighting would be entirely ensured by one type of bulb means that the environmental credit for the offset heating is only attributed for a fraction (approximately 60%) of the 10 000 hours of light considered by the functional unit. But attributing a credit for the heating that is offset during the 10 000 hours of use (and therefore considering light bulb use in the cold season only) only slightly changes the environmental profiles that are obtained in the following ways:

- For homes heated by electricity, the conclusions remain the same, though the gap between the two types of bulbs is reduced (the damages of the compact fluorescent represent between 35 and 85% of those of the incandescent);
- For homes heated with natural gas, the gap between the two types of bulbs varies very little, with the exception of the human health category, which makes the incandescent a better choice. Given that this damage category initially favoured the compact fluorescent, this result would foster the use of incandescents during the cold season in gas-heated homes.
- For homes heated with oil, the gap between the two types of light bulbs varies in a way that is similar to that of homes heated with gas. In this case, however, the relative contribution of the incandescent to the damages to human health is only slightly smaller.

5.4.2 Choice of generic data

The assessment of the sensitivity of the results to the choice of generic data should help prioritize the elements that are potentially more sensitive (i.e., whose data are of lesser quality and/or whose contribution to the potential impact seems more important). As indicated in Table 5-5, these elements are usually taken from the data modules used to quantify (besides the production phase whose completeness and validity are rather uncertain) the use phase processes and parameters in Table 5-2.

The effect of the grid mix powering the light bulbs during their use phase was examined as part of this study. On one hand, the purchase of electricity (from coal, especially) was omitted from the Québec grid so as to assess the impact of importing within the network (hypothesis: a closed system). On the other hand, to consider the fact that North American grids are more or less inter-connected, the Québec grid was replaced with the average North American grid mix (hypothesis: open system).

5.4.2.1 Effect of electricity imports on Québec's power system

Omitting the purchase of non-hydroelectric power from the Québec grid mix changes the relative contribution of the various electricity production and transmission systems but does not change the overall conclusions on the best light bulb option. Electricity consumption during the use phase remains the main contributor to the life cycle of both types of bulbs.

5.4.2.2 Impact of the North American grid mix

Relying on the North American grid mix, which is mainly based on coal and natural gas, clearly changes the conclusions. In this case, the credit attributed for the heat that the gas and oil systems do not have to produce no longer offsets the baseline scenario damages. The compact fluorescent therefore becomes the best option for all of the scenarios, since its damage represents between 20 and 25% of that of the incandescents (for all scenarios). Only some impact categories indicate that the incandescent is the best option: ozone depletion (for gas and oil heating), photochemical oxidation and aquatic eutrophication (for oil only). By way of indication, Figure 5-11 details the results for heating based on the average distribution across Québec.

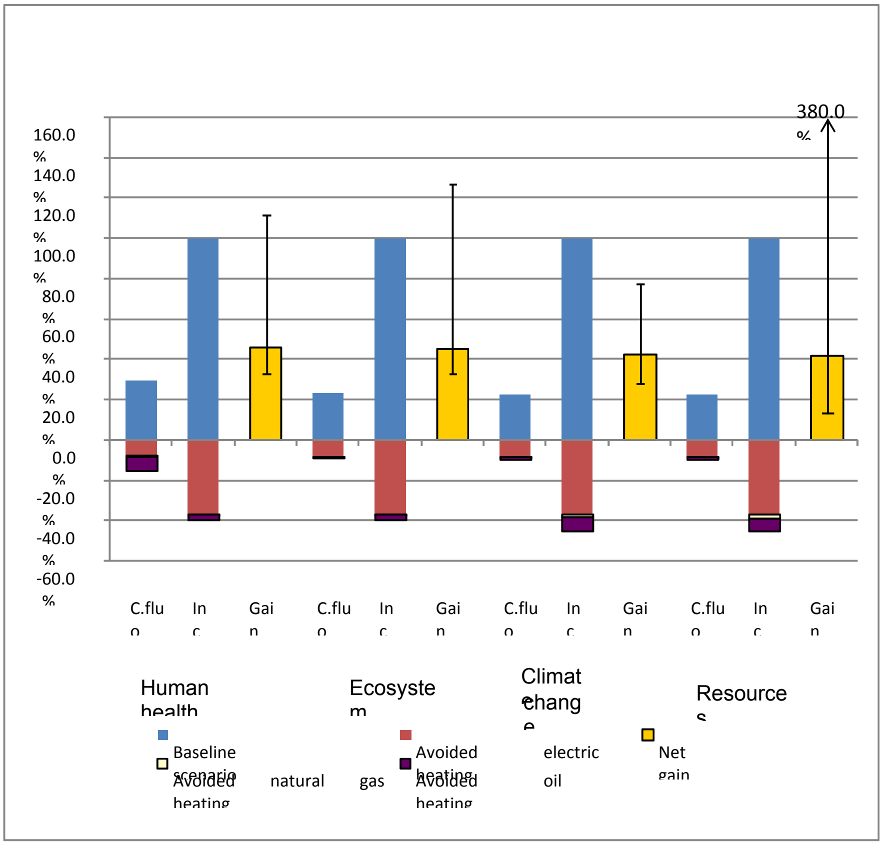


Figure 5-11: Damages of the crossed effect scenario based on the average distribution of heating systems in Québec in the North American energy context

These results demonstrate the importance of considering the possible consequences of promoting one type of bulb over another. The use of incandescent bulbs, even during the cold season in homes heated with natural gas or oil, is not the solution for the North American energy context (i.e., an open system in which the variations in consumption per region effect consumption in another region). In other words, the energy conservation associated with the substitution of incandescent bulbs by compact fluorescents is also better when it can be used or exported to replace thermal energy production (or, in general, energy that is less efficient than gas or oil systems).

5.4.3 Comparison of LCIA methods

As presented in sub-section 3.2.6, the LCIA was based on the IMPACT 2002+ method and designed to verify the sensitivity of the results to the selected assessment method (by comparing it to the results obtained using LUCAS).

Though IMPACT 2002+ is less adapted to the Canadian context than LUCAS, there are no scientific inconsistencies for the impacts with global repercussions and whose assessment models are the same, regardless of the place of emission or resource extraction (global warming, ozone depletion, abiotic resource and water use). But because a given area's environmental conditions have an effect on regional (photochemical smog, eutrophication, acidification) and local (human toxicity, ecotoxicity, land use) impacts, the characterization models used for these impacts must normally take the characteristics of the receptor into account. Applying more than one LCIA method therefore makes it possible to verify whether the variability of these receptor areas and characterization models has a significant effect on the conclusions.

The indicator category results using LUCAS, depending on the scenarios, would favour the same type of bulbs as IMPACT 2002+, but not for the carcinogenic effects categories in the case of homes heated with oil, for which IMPACT 2002+ would recommend incandescents (while LUCAS gives preference to the compact fluorescents).

5.5 Limitations of life cycle inventory analysis and assessment

The limitations of the inventory analysis are essentially brought about by the incomplete and only somewhat valid inventory itself. Several processes initially included in the life cycle of the bulbs had to be excluded or estimated during data collection, mainly due to a lack of information. The inclusion of and/or increase in the representativeness of these processes in the inventory would most certainly alter the results of the analysis but probably not to the degree to which the conclusions would be reversed. The excluded and estimated processes are basically the same for the two systems and/or pertain to elements that seem to have little effect on the results (following the contribution and sensitivity analyses). For reference, Table 5-5 presents the data quality indicators used for the LCA. This assessment makes it possible to ascertain the reliability of the data in light of its potential impact on the results obtained (in terms of their contributions to the impacts). The criteria used to qualify the data are detailed in Table 5-6.

Table 5-5: Qualifying the data

Intermediate flux	Potential contribution to the impact	Data quality	
		Quantity	Process
1- Production			
Materials			
Body (glass)	3	2	3
Coating (phosphor)	3	2	4
Coating (silica)	3	2	4
Metal sheath (tinplate)	3	2	3
Connection pin (copper)	3	2	3
Electric contact (copper)	3	2	3
Soldering (with or without lead)	3	2	3
Lead (soldering)	3	2	n/a
Insulator (black glass)	3	2	4
Base (PVC or PBT)	3	2	3-4
Electronic ballast	5	2	3-4
Rod (glass)	3	2	3
Filament (tungsten)	3	2	3
Internal wiring (copper)	3	2	3
Glue (unknown)	3	2	5
Argon	3	2	4
Mercury	3	2	4

Table 5-5: Qualifying the data

Intermediate flux	Potential contribution to the impact	Data quality	
		Quantity	Process
Nitrogen	3	2	4
Cardboard	3	2	3
Other resources (undetermined)	3	5	5
Energy			
Transport – raw materials	1	4	3
Heat – oil and gas	3	4	3
Electricity	3	4	2
Transport – production waste	1	5	5
Waste and emissions			
Production waste (undetermined)	3	5	5
2- Distribution			
Energy			
Transport (truck)	1	2	3
Transport (transoceanic)	1	1	1
Transport (train)	1	1	2
Transport (truck)	1	2	2
Energy consumption – handling and stocking	1	5	5
Waste (packaging)			
Secondary and tertiary waste (if applicable)	1	5	5
3- Use			
Energy			
Transport (light bulbs to consumers)	1	5	5
Electricity	5	1	2
Transport – waste	1	4	2
Waste (packaging)			
Cardboard (67% landfilled; 33% recycled)	1	1	3
4- End of life			
Energy			
Transport – waste	1	4	2
Waste (light bulbs)			
Plastic bases (landfilled)	1	1	3
Other components (landfilled)	1	1	4
Emissions			
Mercury (air)	1	4	n/a
Lead (water)	1	4	n/a

Note: The **quality of the *quantity* data** refers to the reliability of the amounts of inventoried materials and energy and the transport distances and amount of waste based on their fates (primary intermediary flows). The **quality of the process data** refers to the geographic and technological validity of the generic data modules that were selected (intermediary and elementary secondary flows). Finally, the potential contribution to the impact refers to the potential effect that the data will have on the results (given the results of the contribution and sensitivity analyses).

Table 5-6: Data qualification criteria

Points	Qualification criteria – *quantity* data
1	Relatively reliable specific data or information that varied little from one manufacturer to another
2	Rather uncertain specific data or information that varied from one manufacturer to another
3	Data estimated from other sources

4	Data grossly estimated
5	Missing data
Points	**Qualification criteria – *process* data**
1	Ground or generic data with good geographic and technological representativeness of the selected process
2	Generic data partly adapted to the energy/technological context
3	Incomplete data (the process is only partially represented) or whose geographic and technological representativeness is unknown
4	Data whose geographic and technological representativeness is inadequate / The data is not easily accessible, another processes is used to approximate the figures (proxy)
5	Missing data
Points	**Qualification criteria – potential contribution to the impact**
1	Potentially small or negligible contribution (does not impact the results)
3	Potential contribution
5	Significant potential contribution

The results presented in the previous sections (5.1 to 5.3) are based on the calculations conducted using the models of the IMPACT 2002+ impact assessment method. The damages (and impacts) that are assessed are only potential damages (and impacts) since they are based on a model (and therefore a simplified version) of the real environment. The results of the LCIA are relative expressions that do not predict the effects on the final impacts for each category, the exceeded thresholds, safety margins or risks. These results should therefore not constitute the only basis for any comparative affirmations that are to be made public since additional information is required in order to remedy certain limitations of the LCIA itself.

More importantly, the interpretation of the characterization results cannot be based only on the results obtained (on the substances for which the database provides methods and characterization factors that convert the inventoried elementary flows into impact categories or damages). In fact, many elementary flows (357) could not be converted into category indicator results because no characterisation factor was available. They were not taken into account in the impact and damage assessment. Also, these uncharacterized elementary flows are the same for both types of bulbs and the majority tend to weaken with the use of compact fluorescents (over 90% for the baseline scenario and electricity-heated homes; over 80% for gas-heated homes; over 65% for oil-heated homes). Their impacts, which would be assessed if the characterization factors were available, are therefore similar and would either support the results (in the case of the baseline scenario and homes heated with electricity) or reverse them (in the case of homes heated with oil or gas).

6. CONCLUSION

This project aimed to establish the environmental profiles of the compact fluorescent and incandescent bulbs used in Québec and determine their *hot spots*. It was also conducted to identify the conditions under which one option is better than the other considering the crossed effect of the heat emitted during the use phase of the bulbs, since these heat gains in homes lead to lesser loads on the heating systems.

6.1 Environmental profiles of the compact fluorescent and incandescent bulbs

The results indicate that the use phase dominates the life cycles of both types of bulbs, followed by the production phase, which is responsible for between 6 and 30% of the damages potentially associated with the life cycle of the compact fluorescent and only 1 to 5% of the damages in the case of the incandescent. The distribution and end-of-life phases are negligible in both cases.

Use, which represents between 69 and 93% of the potential damages in the case of the compact fluorescent and between 93 and 99% in the case of the incandescent, is dominated by electricity consumption. Depending on the damage categories, this consumption is driven either by the production of electricity itself (especially because of the small amounts purchased and produced from coal and industrial gas) or by its transmission (copper production and the emissions of copper and chromium VI in to the soil by the network infrastructure).

6.2 Conditions favouring one option over the other considering the crossed effect of the heat

When considering the environmental benefit of the crossed effect of the heat released during use, it is also necessary to consider the possible consequences, on a global scale, of promoting one type of bulb over another. Replacing incandescents by compact fluorescents would bring about savings of energy that could then be used for purposes other than lighting. The uses that these energy savings will be put towards make it possible to more appropriately determine the type of bulb that should be promoted.

…in the Québec energy context

If the saved energy is not used for other means (and therefore if it is possible to consider that a surplus of water would not be run through the turbine), then using the Québec energy grid mix as a basic hypothesis to assess the impact of electricity is warranted. The comparison of the environmental profiles that are obtained for both types of bulbs would then dictate the better choice according to the lighting conditions. The compact fluorescent is proven to be a better choice than the incandescent when:

- There is no possible crossed effect – in the warm or neutral season (approximately 45% of the year) and in the cold season for wood-heated homes (9% of homes in Québec) or in inadequately insulated homes (in which the set point of the thermostat is never reached); and

- When the environmental credit brought about by the crossed effect does not offset the damages associated with the life cycle of the bulbs (in the cold season for homes heated with electricity – 68% of homes).

In this case, with the use of compact fluorescents, there is a decrease in all of the damage indicators except for:

- The production phase (all of the indicators increase);
- Ecosystem quality in the end-of-life phase.

Therefore, though the compact fluorescent often generates fewer damages than the incandescent throughout its life cycle, the production and end-of-life phases should be enhanced, especially the electronic components and mercury that they contain. LCA results could quantify the potential improvements linked to the different enhancement options, including the use of modular ballasts (which are not integrated and therefore reusable) and the recycling/recovery of light bulbs at the end of their life cycles.

Finally, the results also demonstrated that the use of incandescents could still be advantageous in the cold season (approximately 55% of the year) in oil- or gas-heated homes (23% of homes in Québec), especially considering climate change and resource use. Though the potential advantage of the incandescent is not entirely clear for ecosystem quality and human health damages, the large-scale promotion of the compact fluorescents should still be avoided in the Québec energy context.

…in a more global energy context

If, however, the electricity surplus makes it possible to substitute a less efficient form of energy for a gas- or oil-fired heating system (especially thermal energy), the compact fluorescent is a better choice for all heating types. Based on the results of the sensitivity analysis, the use of incandescents is 4 to 5 times more damageable that the use of compact fluorescents in the North American energy context (in an open system in which consumption variations in one region have a more or less direct impact on consumption in another region). In this context, to enhance global energy efficiency, it is best to use compact fluorescents.

This assessment should therefore be refined through a consequence-driven approach (or consequential LCA). This would make it possible to quantify the gaps in environmental performance of the two types of bulbs in the North American energy context and take the various possible consequences that could eventually be linked to energy savings in Québec into account.

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ANNEXE A : MÉTHODOLOGIE D'ANALYSE DU CYCLE DE VIE (ACV)

Le contenu de cette annexe est compris dans le fichier suivant :
« Pi33_Rptfin_2008-04-24_Annexe_A »

ANNEXE B : MÉTHODES D'ÉVALUATION DES IMPACTS DU CYCLE DE VIE (ÉICV)

Le contenu de cette annexe est compris dans les fichiers suivants :
« Pi33_Rptfin_2008-04-24_Annexe_B » et
« Pi33_Rptfin_2008-04-24_Annexe_B-2 »

ANNEXE C: DONNÉES, HYPOTHÈSES ET RÉSULTATS

Le contenu de cette annexe est compris dans le fichier suivant :
« Pi33_Rptfin_2008-04-24_Annexe_C »

ANNEXE D: RAPPORT DU COMITÉ DE REVUE CRITIQUE ET RÉPONSES DU CIRAIG AU COMITÉ

Le contenu de cette annexe est compris dans les fichiers suivants :
« Pi33_Rptfin_2008-04-24_Annexe_D-1 » et
« Pi33_Rptfin_2008-04-24_Annexe_D-2 »

ANNEXE E: FICHE SYNTHÈSE DE L'ÉTUDE ACV

Le contenu de cette annexe est compris dans le fichier suivant :
« Pi33_Rptfin_2008-04-24_Annexe_E »