Benchmarking of Energy Savings Associated with Compact Fluorescent Lighting in Homes

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ABSTRACT

Energy efficient compact fluorescent (CF) lamps are becoming more commonly available in the marketplace for homeowners. The replacement of energy efficient lamps in homes would certainly reduce the electrical energy use and power demand; however, it would also affect the space heating and space cooling energy needs.

Benchmarking tests were performed at two identical full-size research houses located at Canadian Centre for Housing Technology (CCHT). Compared to conventional incandescent, CF lighting reduced electricity demand by about 77% and energy use by about 67%. During the heating season, the reductions in the lighting energy use were almost offset by an increase in the space heating requirements. The lighting energy is utilized as internal gains for the house. The results showed that 83% to 100% of lighting energy consumption contributed to the internal gains. During the summer season with cooling systems, the reduction in lighting energy also reduced the cooling loads. About 80% of the lighting energy internal gains add to the house cooling demand.

The 'take back' effect, interaction of lighting with other loads, significantly alters the potential estimates of overall cost savings associated with lighting. During the heating season, CFL lighting reduces the internal gains compared to conventional lamps and, therefore, increases the heating loads. In the summer season, the CFL lighting reduces the cooling loads. Overall, compact fluorescent lighting positively contributes to energy and cost savings in residential buildings.

Introduction

In recent years, due to substantial reductions in the incremental costs associated with energy efficient lighting fixtures, their use in housing has become more prevalent. The use of these energy efficient lighting fixtures influences the need for house heating and cooling.

There are a number of field studies available for retail and commercial buildings showing the increase in the need for heating and the reduction in the cooling loads associated with the replacement of conventional lighting with the energy efficient lighting (NBI 2003). Residential use of lighting is different than the retail and commercial sectors. There is a selective use of lamps/fixtures in houses depending on occupants needs. A literature search conducted as part of this study did not show any authorative information on the overall impact of the use of compact fluorescent lamps on overall energy efficiency. Energy simulation models do consider the effects of internal gains associated with lighting and its implications. However, the effects of internal gains are aggregated with all other appliances in the house. To help understand the 'net' impact of the compact fluorescent lighting in housing, Natural Resources Canada developed a detailed field research plan along with the validation of the internal gains model associated lighting energy use.

This paper presents the results of the benchmarking study conducted during the heating and cooling seasons along with validation of the internal gains model associated with lighting energy use in houses. Based on the inter-dependence effects, the overall impacts of compact fluorescent lamps (CFL) in housing applications have been determined for various major population centres.

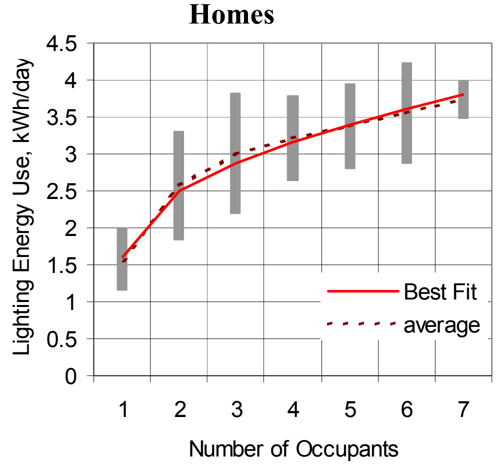
Average Lighting Energy Use in Canadian Homes

Over the years, there have been a number of detailed housing surveys. From a set of 134 highly monitored houses (NRCan 1997), the following profiles were generated to define lighting energy use in housing. Data also showed that lighting energy use accounts for about 5% to 8% of the annual utility costs in cold climate regions. Table 1 and Figure 1 show the typical lighting energy use profile for Canadian homes.

Table 1. Lighting Energy Use in Canadian Homes

No. of Occupants	Average Lighting Energy Use, kWh/day	Standard Deviation, kWh/day
1	1.6	0.4
2	2.6	0.7
3	3	0.8
4	3.2	0.6
5	3.4	0.6
6	3.5	0.7
7	3.7	0.3

Figure 1. Profile of Lighting Energy Use in Canadian Homes



The data analysis for Alberta and Ontario houses (each consisting of more than 40 houses) showed that the average lighting energy use for Alberta was about 0.6 kWh/day more than that for Ontario. Analysis also showed seasonal variations in lighting energy use – up to 4.1 kWh/day during the winter and 2.8 kWh/day during the summer months. For the purpose of the benchmarking study, the lighting energy use is assumed to be about 3.4 kWh/day.

Test Facility

The Canadian Centre for Housing Technology (CCHT) facility provides a unique opportunity for verifying the difference between two different types of technologies[1]. Features of these research houses are as follows:

- Each house is a typical 2-storey wood-frame house, with 210 m^2 of livable area, set on a cast-in-place concrete basement, with style and finish representative of current houses available on the local housing market.

[1] Visit the website http://www.ccht-cctr.gc.ca/ for a full description of the facility.

- These houses are built to meet the R-2000 Standard[2] with a construction package that includes tight, well-insulated assemblies, low-e argon-filled sealed glazing units. Both these houses have a high efficiency sealed combustion condensing gas furnace, a power-vented conventional gas hot water heater and a heat recovery ventilator. The furnace, water heater and gas fireplace are all vented through the wall, eliminating the need for chimneys.
- The research houses also feature standard sets of major appliances typically found in North American homes. Human activity is automatically simulated by operating appliances, lighting and other equipment according to an identical schedule in both houses. The simulated occupancy system is also used to monitor energy performance.
- The standard comparison showed that these houses perform almost identically, within 0.3%, of each other. Ideally, these houses provide excellent opportunity to verify competing technologies (CCHT 2005).

Baseline Tests

Incandescent Lamp and CFL Characteristics

Each lamp was subjected to laboratory testing for the voltage, power, light intensity, power factor (PF), volt-amps reactive, volt-amps and harmonics. The following are typical observations:

- The difference in published rating and measured wattages of the compact fluorescent and conventional incandescent lamps ranged by about ±1.2 W or about ± 4%. The manufacturers' ratings of the power demand for lamps were good and reliable for the energy calculations.
- The power factor of the compact fluorescent lamps ranged from 0.56 to 0.59. The incandescent lamps had a power factor of 1.0.
- The mean values of the whole-house power factor for the Reference and Test houses are close – indicating that overall, the power factor is not an issue. When observed, the minimum value of PF differed by about 0.06 or about 7% - indicating that CFL lamps do have lower PF especially when they start up.

Baseline Tests with Incandescent Lighting

The Test and Research houses were set up and operated with identical conditions to develop a full profile for the reference. As shown in Figure 2, the lighting power demand for both houses followed identical patterns of power draw with less than 0.4% difference.

Although, the normal lighting energy use was 3.4 kWh/day, it was increased to 10.2 kWh/day with conventional lamps. The target was to obtain a difference of 7.0 kWh/day with CFL lighting. The main reason for increasing the lighting load by three times to 10.2 kWh/day was to have accurately measurable change in the lighting energy use per day. Our sensitivity analysis for the whole house energy monitoring showed that the electrical energy use

[2] For more information on R2000 Standard, visit http://oee.nrcan.gc.ca/r-2000/

measurements were within ±1% when the daily difference was above 5 kWh/day. The baseline test results are as follows:

- **Heating Season:** Two sets of baseline tests were conducted during the month of March 2004 using incandescent lighting in both houses. The measured data showed that daily energy consumption associated with lighting was within 0.05 kWh per day or about 0.5% and seemed to be within the acceptable measurement limits. The space heating energy use, measured in terms of furnace natural gas consumption, showed that both houses were relatively closely operating. The difference in the furnace energy consumption for two houses was about 5 MJ per day or about 1.2%. This again found to be within the measurement accuracy of gas flow meters.
- **Cooling Season:** During the month of July 2004, for a period of eight days tests were conducted to determine baseline cooling loads using incandescent lamps in both houses. The measured air-conditioning system energy performance showed that the net energy removed by the air conditioning system in the reference and test houses were within the measurement accuracy of maximum of 4% difference, or about 8 MJ/day.

Figure 2. Baseline Profile of Incandescent Lighting Power Demand for Reference and Test Houses

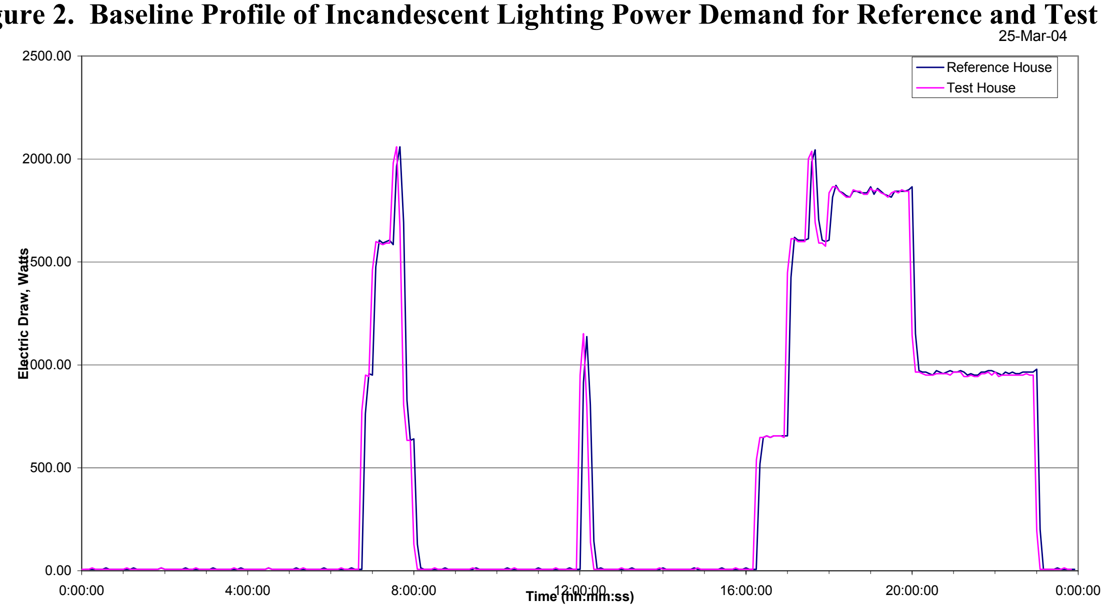


Figure 3. Profile of CFL and Incandescent Lighting Power Demand for Reference and Test Houses

Compact Fluorescent Lamp Tests

The Test house was retrofitted with compact fluorescent lamps. About 31 incandescent lamps were replaced with a similar lumen output CF lamp. For example, a 9-Watt CF lamp replaced a typical 40-Watt incandescent. Figure 3 shows the typical daily profile of the Test and Reference house lighting profiles.

Heating Season

Table 2 shows the measured data of lighting energy use and the space heating energy requirements for the Test and Reference houses. The lighting energy use in the Reference house with conventional lighting ranged from 10.74 to 10.83 kWh/day with an average of about 10.77 kWh/day. This was close to the baseline results. The lighting energy in the Test house with CFL lighting was about 3.44 to 3.49 kWh/day with an average of about 3.47 kWh/day.

Table 2. Measured Results of Lighting Energy and the space Heating Energy Use in Test and Reference Houses

	Daily Lighting Consumption (kWh)		Lighting Energy Savings	Furnace Gas Consumption, MJ		Space Heating Energy Impacts
Date	**Reference House**	**Test House**		**Reference House**	**Test House**	
26-Mar-04	10.80	3.45	68.0%	145.1	156.7	-7.9%
27-Mar-04	10.82	3.47	67.9%	104.7	125.0	-19.3%
28-Mar-04	10.80	3.47	67.9%	106.3	130.1	-22.5%
15-Apr-04	10.83	3.49	67.8%	95.2	112.2	-17.8%
16-Apr-04	10.75	3.46	67.8%	83.2	103.9	-24.9%
17-Apr-04	10.80	3.48	67.8%	89.7	113.3	-26.3%
18-Apr-04	10.77	3.47	67.8%	91.2	121.4	-33.1%
30-Dec-04	10.74	3.49	67.5%	359.2	389.0	-8.3%
31-Dec-04	10.78	3.49	67.7%	251.8	278.6	-10.7%
01-Jan-05	10.79	3.46	67.9%	223.0	246.2	-10.4%
02-Jan-05	10.79	3.48	67.8%	430.6	469.4	-9.0%
03-Jan-05	10.76	3.48	67.7%	281.9	315.1	-11.8%
04-Jan-05	10.75	3.49	67.5%	280.1	305.2	-9.0%
05-Jan-05	10.58	3.44	67.4%	342.4	372.4	-8.8%
average	**10.77**	**3.47**	**67.8%**	**206.0**	**231.3**	**-15.7%**

The space heating energy use varied depending on the outdoor conditions. The space heating requirements ranged from 83 to 430 MJ/day representing about 15% to about full (100%) space heating load for the house. The 14-day test period covered the full range of the heating loads enabling the comparison of the effects of energy efficient lighting. The data analysis showed the following trends:

- The compact fluorescent lighting in the Test house reduced the daily electricity consumption by about 7.3 kWh. This accounted for about 67.8% of the daily lighting energy use.
- The space heating energy use increased to compensate for the reduction in the lighting energy use. The space heating energy use increased by 11.5 to 38.8 MJ/day with an average of about 25.3 MJ/day. This ranged from 8% to 33% of the daily space heating load.
- The reduction in lighting energy use was almost offset by an increase in the space heating requirements.

Cooling Season

For the cooling season, tests were conducted using the calibrated CF and incandescent lamps and the same lighting schedule. Tests were conducted during the August 10 to August 30, 2004 for a period of 21 days during which daily maximum outdoor temperatures ranged from 20 ^{o}C to 29.3 ^{o}C. Test results are shown in Table 3. The following trends were observed:

- The air conditioning systems energy consumption reduced by about 2.1 to 3.8 kWh per day depending on the ambient conditions. On average, the difference in the air-conditioning energy loads was about 3.1 kWh per day for the test period.

- The energy analysis showed that about 78% of the internal gains due to lighting add to cooling loads.
- The air conditioning system operated from about 330 to 830 minutes per day (5.5 to 13.8 hours per day) in the Reference house and about 200 to 752 minutes per day (3.3 to 12.5 hours per day) in the Test house. Use of CF lighting reduces the ON time run of the cooling equipment by 20% or more.
- The tests showed that the CFL lighting provides savings of 7.3 kWh per day along with reduction in the air-conditioning load by 3.1 kWh per day. This amounts to a total reduction in electrical energy use by about 10.4 kWh per day for the test period.

Table 3. Measured Results of Lighting Energy and the Space Cooling Energy Use in Test and Reference Houses

	Lights and Receptacles Daily Electrical Consumption (kWh)				A/C & Furnace Daily Elect. Consumption (kWh)		
Date	Reference House	Test House	Difference		Reference House	Test House	Difference
14-Aug-04	10.8	3.4	7.3		20.8	18.1	2.6
15-Aug-04	10.7	3.4	7.3		23.8	20.5	3.2
16-Aug-04	10.7	3.5	7.2		25.7	22.4	3.3
17-Aug-04	10.8	3.4	7.4		24.7	21.3	3.4
18-Aug-04	10.7	3.4	7.3		27.0	24.1	2.9
19-Aug-04	10.8	3.4	7.4		25.7	22.7	3.0
20-Aug-04	10.8	3.4	7.3		19.7	15.8	3.8
21-Aug-04	10.7	3.4	7.3		18.9	16.7	2.1
22-Aug-04	10.8	3.5	7.4		20.2	16.7	3.6
23-Aug-04	10.7	3.4	7.3		18.8	16.4	2.4
24-Aug-04	10.8	3.4	7.4		17.4	14.9	2.5
25-Aug-04	10.7	3.4	7.3		22.6	18.8	3.8
26-Aug-04	10.8	3.4	7.3		28.1	24.8	3.3
27-Aug-04	10.7	3.4	7.3		29.7	26.0	3.7
28-Aug-04	10.8	3.4	7.4		34.8	31.5	3.3
29-Aug-04	10.8	3.5	7.3		17.2	13.9	3.2
30-Aug-04	10.7	3.4	7.3		16.6	13.3	3.3
Average	10.8	3.4	7.3		23.0	19.9	3.1

Potential Energy Savings with Compact Fluorescent Lighting

One of the key questions is - what is the overall impact of the energy efficient compact fluorescent lighting compared to conventional incandescent lighting in homes located in different climates? Using the energy analysis program, we developed a range of house archetypes and evaluated them for 33 different weather locations - 11 in Canada and 22 in the U.S (NRCan 2005b). The following lists assumptions for energy analysis:

- A typical two-storey house with 186 sqm (about 2,000 sqft) of heated floor area. The thermal archetype based on the age (representative size, insulation levels, airtightness and heating, hot water, ventilation and cooling systems), location and type of the house. Each house is maintained at about 21 ^{o}C (main floors) and 19 ^{o}C (storage and basement rooms) during the heating season. During the cooling season, the house is maintained at 25 ^{o}C.

- Conventional lighting energy consumption is 3.4 kWh/day. Although, the lighting energy consumption generally varies throughout the year depending on the length of the days and a presumption about outdoor and indoor daylight levels.

Table 4. Estimates of Annual Energy and Cost Savings Associated with CFL in Typical New Homes

	Options		Annual Energy Impacts				Annual Cost Savings			
Location	Baseline Lighting	CFL Lighting	Savings in Lighting Energy	Impact on Space Heating		Savings in Space Cooling	Heating Season Cost Savings	Heating +cooling seasons savings per year	Cost Savings with Lighting only (without 'Take Back')	Ratio of A/B
	kWh/day	kWh/day	kWh/year		Unit	kWh		A	B	
Canadian Locations										
Vancouver, BC	3.40	2.53	318	-21.6	m3	49	$ 9	$ 12	$ 20	62%
Edmonton, AB	3.40	2.53	318	-27.9	m3	38	$ 19	$ 22	$ 26	84%
Saskatoon, SK	3.40	2.53	318	-25.2	m3	59	$ 18	$ 24	$ 29	83%
Winnipeg, MB	3.40	2.53	318	-25.9	m3	61	$ 8	$ 11	$ 19	59%
Toronto, ON	3.40	2.53	318	-23	m3	63	$ 16	$ 22	$ 27	80%
Ottawa, ON	3.40	2.53	318	-23.9	m3	53	$ 16	$ 21	$ 27	76%
Montreal, QC	3.40	2.53	318	-182.4	kWh	54	$ 8	$ 12	$ 20	60%
Quebec City, QC	3.40	2.53	318	-184.2	kWh	55	$ 8	$ 12	$ 20	59%
Saint John, NB	3.40	2.53	318	-25	L	60	$ 5	$ 9	$ 24	38%
Halifax, NS	3.40	2.53	318	-22.4	L	52	$ 15	$ 20	$ 31	63%
St. John's, NF	3.40	2.53	318	-29.6	L	40	$ 8	$ 11	$ 28	40%
U.S. Locations										
Fairbanks, AK	3.40	2.53	318	-28.6	m3	18	$ 25	$ 27	$ 38	71%
Phoenix, AZ	3.40	2.53	318	-5	m3	84	$ 24	$ 31	$ 27	118%
Los Angeles, CA	3.40	2.53	318	-5.1	m3	72	$ 36	$ 44	$ 38	116%
San Francisco, CA	3.40	2.53	318	-13.7	m3	34	$ 32	$ 36	$ 38	94%
Denver, CO	3.40	2.53	318	-18.2	m3	37	$ 17	$ 20	$ 26	79%
Washington, DC	3.40	2.53	318	-16.1	m3	44	$ 17	$ 20	$ 24	83%
Miami, FL	3.40	2.53	318	0	m3	96	$ 27	$ 35	$ 27	130%
Orlando, FL	3.40	2.53	318	-1.2	m3	90	$ 27	$ 34	$ 27	126%
Atlanta, GA	3.40	2.53	318	-12	m3	57	$ 19	$ 23	$ 24	95%
Honolulu, HA	3.40	2.53	318	0	m3	101	$ 53	$ 70	$ 53	132%
Chicago, IL	3.40	2.53	318	-18	m3	38	$ 18	$ 21	$ 27	80%
New Orleans, LA	3.40	2.53	318	-5.2	m3	76	$ 22	$ 28	$ 25	114%
Boston, MA	3.40	2.53	318	-19.5	m3	32	$ 28	$ 32	$ 37	86%
Detroit, MI	3.40	2.53	318	-17.7	m3	38	$ 18	$ 21	$ 27	81%
Minneapolis, MN	3.40	2.53	318	-19.8	m3	33	$ 16	$ 18	$ 25	73%
New York, NY	3.40	2.53	318	-17	m3	40	$ 38	$ 43	$ 45	95%
Columbus, OH	3.40	2.53	318	-17.8	m3	39	$ 18	$ 21	$ 26	81%
Portland, OR	3.40	2.53	318	-18.6	m3	33	$ 14	$ 16	$ 22	72%
Houston, TX	3.40	2.53	318	-4.8	m3	78	$ 27	$ 34	$ 29	117%
Madison, WI	3.40	2.53	318	-19.7	m3	34	$ 18	$ 21	$ 28	77%
Seattle, WA	3.40	2.53	318	-20.8	m3	25	$ 10	$ 12	$ 20	59%

- Replacement of five conventional incandescent fixtures with compact fluorescent fixtures. Based on this scenario, five fixtures with 77 W incandescent lamps used for three hours per day are replaced with CFL of 19 W. The reduction in daily lighting energy use is about 0.87 kWh.
- Used the annual average residential unit energy costs for electricity and natural gas for the year 2005 for different locations (StatCanada 2006, US-EIA Database 2006).

Using the above assumptions, detailed house models were generated using the HOT2000 energy analysis software (NRCan 2005a). Table 4 summarizes the energy analysis results on an annual basis. The following trends were noted:

- The electrical energy savings are about 318 kWh per year with CF lighting. The reduction in lighting energy consumption is about 26%. The electrical demand savings associated with lighting is about 0.29 kW with CF lighting.
- For heating dominated regions, the increase in the annual space heating energy consumption is about 0.6% to 1.7%.
- For the cooling dominated regions, the reduction in the space cooling energy use ranged from 4% to 9.5% for the CF lighting. The reduction in "ON" time operation of cooling equipment ranged from 15% to 22%.
- The 'take back' effect, interaction of lighting with other loads, significantly reduces the potential estimates of overall cost savings associated with lighting. For example, for a new house located in Vancouver without air-conditioning, the estimated energy cost saving is about $9 (includes lighting cost savings and additional expenditure for the space heating). If the lighting benefits were only considered, the electricity cost reduction amounted to $20. Similarly, for Miami, with the air-conditioning system, the potential energy cost saving is about $35; whereas, if only lighting energy reductions were considered, the electricity cost reduction amounted to about $27.
- Most lighting supplier and manufacturers, advertise the energy savings associated with CF lamps only on the basis of the reductions in annual electricity use associated with the lamp. In heating dominated climate, there is a significant 'take-back' effect associated with compact fluorescent lamps. The analysis showed that the 'take-back' effect could reduce the cost benefits up to 40%. In exactly opposite spectrum, in the cooling dominated climates, the 'additive' effects can increase the savings up to 30%. These analyses indicate the importance of interactive or realistic evaluation of CF lighting benefits in Canadian and the US homes.
- Assuming the cost of five CF lighting fixtures of about $40, the simple payback period for CF lamping is two to six years.

Summary and Conclusions

Compact fluorescent lighting can create significant energy and cost savings in houses. These are based on the reduction in electrical power demand and annual energy use; increase in the space heating loads to offset the reduction in lighting energy; and reduction in the cooling energy use.

The CCHT houses provide a unique research and test facility to accurately determine the impact of conventional incandescent and energy efficient compact fluorescent lighting on the performance of a whole house. The measured power draw for the incandescent and compact fluorescent lamps compared well with manufacturers' specifications.

The energy efficient lighting systems do affect the space conditioning requirements. During the heating season, the compact fluorescent lighting reduces the internal gains thereby increasing the space heating energy use. The CCHT test showed that 83% to 100% of lighting energy use offset the space heating energy use.

During the cooling season, the compact fluorescent lighting reduces the internal gains; thereby, reducing the space cooling energy use. So, during the cooling season, the lighting energy reductions and the cooling energy reductions are additive. The cost savings are positive in all climates although the interaction effects reduce savings in most cases.

References

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