Techno-Economic Assessment of Solar Technologies and Integration Strategies for the Canadian Housing Stock

by

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DALHOUSIE UNIVERSITY

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Signature of Author

To:

My husband, Omid, who is the happiness of my life

My parents, who cherished me in every step of my life

My sister and brother, who are my best friends for life,

Without their love and support it could never be done

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ABSTRACT

Energy security is probably one of the most challenging issues around the world. Therefore, the focus on methods of decreasing energy consumption and consequently its associated greenhouse gas (GHG) emissions is intensified by policy decision makers. Residential buildings are one of the potential sectors that can reduce its energy consumption in various ways, such as: improving thermal characteristics of the building, using more energy efficient appliances and using renewable energy resources. Among these methods, integration of solar technologies to buildings provides one of the substantial opportunities for reducing energy consumption and the associated GHG emissions in Canada's residential sector. Therefore, this research work was conducted to assess the impact of solar technologies and solar technology integration strategies on the end-use energy consumption and the associated greenhouse gas (GHG) emissions in Canadian residential sector by using a new state-of-the-art end-use energy and GHG emissions model of the Canadian residential housing stock.

The new Canadian residential end-use energy and emissions model that is used in this project incorporates a 17,000 house database developed using the latest data available from the Energuide for Houses database, Statistics Canada housing surveys, and other available housing databases, and utilizes an advanced building energy simulation program as its simulation engine. A new neural network methodology is incorporated into the model to estimate the socio-economic and demographic dependencies of the energy consumption of discretionary end-uses such as appliances, lighting and domestic hot water, while a new approach is used to incorporate occupancy, appliance, lighting and domestic hot water load profiles into the model. A new method is used to calculate the GHG emissions from electricity consumption used in the residential sector based on the actual electrical generation fuel mix and the marginal fuel used in each province as a function of time of the year.

Each solar technology is added to the eligible houses to examine the interrelated effects of integrated solar technologies and practices on the housing stock. The objective is to conduct realistic assessments of the cost effectiveness, energy savings and GHG emission reduction benefits of integrated solar technologies for the entire Canadian housing stock (CHS) as well as for different regions, house type, and fuel types. The integrated solar technologies and practices that are assessed include passive solar with added thermal storage and motorized blinds, solar DHW system, and photovoltaic electricity and heat generation systems.

This project provides a comprehensive techno-economic and emissions assessment of integrated solar technologies and practices, and will be useful for developing national and regional policies and strategies related with integrating solar energy into the residential sector.

LIST OF ABBREVIATIONS AND SYMBOLS USED

a	Latent heat coefficient
A	Area
AB	Alberta
ACSH	Annual cost save due to energy saving for each house
AL	Appliances and lighting
AT	Atlantic region (provinces: New Brunswick, Newfoundland and Labrador, Nova Scotia, Prince Edward Island)
ATCCH	Average tolerable capital cost per house
ATCCU	Average tolerable capital cost per upgrade unit
b	Latent heat coefficient
b_0	Incidence angle modifier coefficient
b_1	Incidence angle modifier coefficient
BC	British Columbia
BIPV/T	Building integrated photovoltaic / thermal system
BOC	Bank of Canada
$\bar{c}$	Average specific heat capacity
C_{eff}	Effective heat capacity
C_l	Heat capacity in liquid phase
C_P	Specific heat capacity
C_s	Heat capacity in solid phase
CFC	Complex fenestration construction
CHS	Canadian housing stock
CHREM	Canadian Hybrid Residential End-use Energy and Emission model
CMHC	Canadian Mortgage and Housing Corporation
COP	Coefficient of performance
CPC	Compound parabolic collector
CSDDRD	Canadian Single-Detached & Double/Row Housing Database
CSTU	Cost of undertaking the upgrade for a house
CWEC	Canadian Weather for Energy Calculations

DG	Double glazed
DHW	Domestic hot water
D/R	Double/Row
e	The fuel cost escalation rate per interest period
E	Energy savings per period for each fuel type
$E_{T,ref}$	Effective irradiance on the module
EGHD	EnerGuide for Houses Database
EIF	Emission intensity factor
F	Fuel price per amount for each fuel type
F_R	Collector heat removal factor
g	Sensible heat generation rate
$\bar{g}$	Heat generation rate over the control volume
G	Radiation incident upon the collector
GHG	Greenhouse gas
h	Enthalpy
H_{ref}	Reference insolation
i	Interest rate per interest period
I_L	Light generated current
I_D	Diode current
I_{mp}	Maximum power point current
I_{sh}	Shunt current
Isc	Short-circuit current
IEA	International Energy Agency
LiBr	Lithium bromide
m	Number of different fuels used in a house
$\dot{m}$	Mass flow rate
M	Mass
MB	Manitoba
n	The number of interest periods
$\overrightarrow{n_s}$	Outward drawn normal unit vector
N	Number of solar panels in surface

NB	New Brunswick
NF	Newfoundland and Labrador
NG	Natural gas
NH	Number of houses that received the upgrade
NRCan	Natural Resource Canada
NS	Nova Scotia
OCAR	Open-cycle absorption refrigeration
OEE	Office of Energy Efficiency
OT	Ontario
PCM	Phase change material
PE	Prince Edward Island
PR	Prairies region (provinces: Alberta, Manitoba, Saskatchewan)
PV	Photovoltaics
PV/T	Photovoltaic / thermal system
$\dot{Q}$	Heat transfer
QC	Quebec
r	Flow rate correction coefficient
$\vec{r}$	Heat transfer direction
Rs	Series resistance
R_{sh}	Shunt resistance
ref	Reference condition
SC	Space cooling
SD	Single-detached
SDHW	Solar domestic hot water
SG	Single glazed
SH	Space heating
SHGC	Solar heat gain coefficient
SK	Saskatchewan
t	Time
T	Temperature
$\bar{T}$	Average temperature of control volume

T_a	Ambient temperature
T_c	Heat exchanger outlet temperature
T_{c-1}	Heat exchanger inlet temperature
T_i	Collector inlet temperature
T_o	Collector outlet temperature
T_s	Tank temperature
T_{s-1}	Tank inlet temperature
TACS	Thermally activated cooling system
TCC	Total capital cost
TCCH	Tolerable capital cost of the retrofit for each house
TCU	Total cost of upgrade
TG	Triple glazed
TIC	Total investment cost
TMC	Transparent multi-layer construction
TNUU	Total number of upgrade unit
TTCC	Total tolerable capital cost
U_L	Collector overall loss coefficient
UA	Overall heat loss coefficient
V	Control volume
V_{mp}	Maximum power-point voltage
Voc	Open-circuit voltage
VLT/VT	Visible light transmittance
yr	Year
α	Empirical coefficient
β	Empirical coefficient
γ	Empirical coefficient
ζ	Angle of incidence of solar radiation upon the collector
η	Efficiency
κ	Incidence angle modifier
λ	Conductivity
ρ	Density

$(\tau\alpha)_n$ Normal-incidence transmittance-absorptance

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CHAPTER 1 INTRODUCTION

Increasing energy consumption and associated GHG emissions along with rising fossil fuel prices impose major challenges on energy policy decision makers around the world, and Canada is no exception to this trend. Although, Canada is one of the least densely populated countries in the world, its rigorous climate, the energy intensive nature of the country's industries, and the large distances between population centers result in a relatively high per capita energy use. According to The World Bank, in 2008 Canadians consumed 8 tonnes of oil equivalent per capita, which is more than four times of the world average (The World Bank, 2012). This amount of energy consumption accounts for about 23 tonnes of associated GHG emissions per year (The World Bank, 2012) which shows an increase by 23% above the 1990 level whereas Canada under the 1997 Kyoto Protocol on global climate change, made an international commitment to reduce its GHG emissions to six percent below the 1990 level by the period of 2008-2012 (Environment Canada, 2010).

According to the Office of Energy Efficiency of Natural Resources Canada, in 2007 Canadian households were responsible for 16% of the total national end-use energy consumption and 15% of the total GHG emissions (OEE, 2007) (Figure 1.1). Consequently, any national policy to reduce energy consumption and the associated GHG emissions must address the residential sector energy consumption to be effective.

To reduce energy consumption and GHG emissions in the residential sector different strategies can be considered such as using renewable energy resources, improving end-use energy efficiency, improving envelope and windows characteristics, and introducing alternative energy conversion technologies, such as cogeneration systems that have higher efficiencies and produce lower GHG emissions compared to conventional technologies. Among strategies that can be utilized, integration of solar technologies to buildings provides one of the substantial opportunities for reducing energy consumption and GHG emissions in Canada's residential sector.

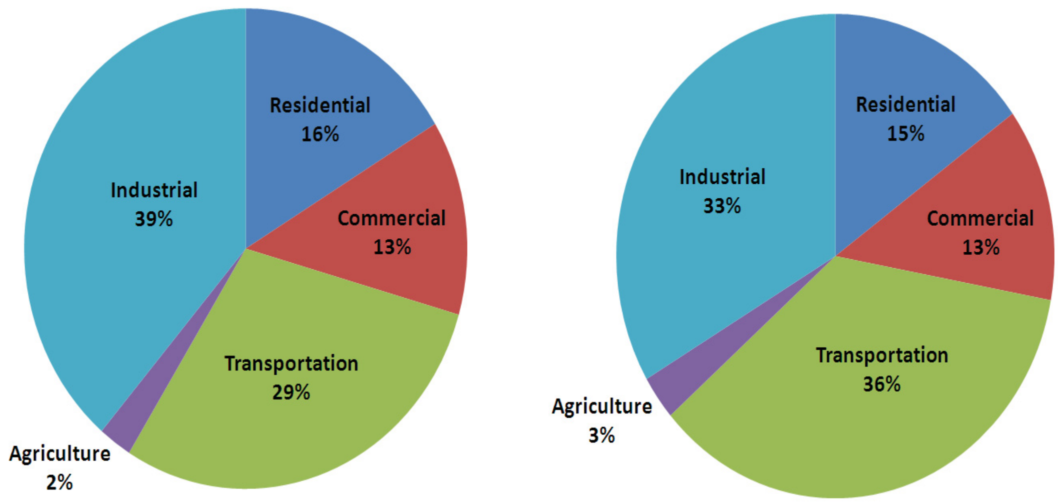


Figure 1.1 Canada a) Energy consumption, b) GHG emissions by sector (OEE, 2007)

Therefore, this research work was conducted to assess the techno-economic impact of a variety of solar energy technologies on the end-use energy consumption and GHG emissions by the Canadian housing stock. Due to the wide range of solar technologies available, as well as the types and sizes of buildings, construction characteristics, and climatic conditions in Canada, the prediction of the techno-economic performance of solar technologies require the use of detailed computer tools[1].

To address this problem, the new Canadian Hybrid Residential End-use Energy and Emission model (CHREM) (Swan, et al. 2008, Swan, 2010, Swan, et al. 2011) was used to investigate the impact of solar technologies on the energy consumption and Greenhouse Gas (GHG) emissions for the Canadian housing stock (CHS). CHREM is based on the Canadian Single-Detached and Double/Row Database (CSDDRD) (Swan, et al., 2009b, Swan, 2010), which was developed using the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys, and other available housing databases, and utilizes the ESP-r building energy simulation program (ESRU, 2009) as its simulation engine.

[1] Two comprehensive review papers focusing on building stock models and computer tools for stock modeling were recently published (Kavgic et al., 2010, Swan and Ugursal, 2009a); therefore a review is not included here.

1.1 Overview of the CHREM

The CHREM consists of six components that work together to provide predictions of the end-use energy consumption and GHG emission of the CHS. These components are (Swan, et al. 2008, Swan, 2010, Swan, et al. 2011):

- The Canadian Single-Detached & Double/Row Housing Database (CSDDRD),
- A neural network model of the appliances and lighting (AL) and domestic hot water (DHW) energy consumption of Canadian households,
- A set of AL and DHW load profiles representing the usage profiles in Canadian households,
- A high-resolution building energy simulation software (ESP-r) that is capable of accurately predicting the energy consumption of each house file in CSDDRD,
- A model to estimate GHG emissions from marginal electricity generation in each province of Canada and for each month of the year,
- A model to estimate GHG emissions from fossil fuels consumed in households.

The flow diagram of CHREM is shown in Figure 1.2.

The CSDDRD is a subset of the EnerGuide for Houses Database (EGHD), which is culmination of over 200,000 requested home energy audits collected from 1997 through 2006 (SBC 2006) by Natural Resources Canada (NRCan). The EGHD does not include apartments or mobile home dwelling types. However, it does account for single-detached (SD) and double/row (D/R) houses, representing 80% of the CHS (OEE, 2006).

1.2 Solar technologies for the residential sector

Solar energy is currently used for water and space heating, space cooling and generating power for residential buildings. There are a variety of technologies available for solar thermal and power generation in the residential sector such as solar collectors, photovoltaic cells and thermal mass, as summarized in Table 1.1. Since the goal of this project is studying the impact of adopting solar technologies on the residential energy consumption and GHG emissions in the Canadian residential sector, as well as their cost effectiveness, it is necessary to identify solar technologies that are potentially feasible within the Canadian context. To identify the suitable solar technologies for the Canadian residential sector, first the literature on the performance and feasibility of solar technologies are reviewed. Based on the findings of this review, a set of solar technologies identified to be potentially feasible for the Canadian residential sector, and which are evaluated in detail in Chapter 4, are presented in the following section.

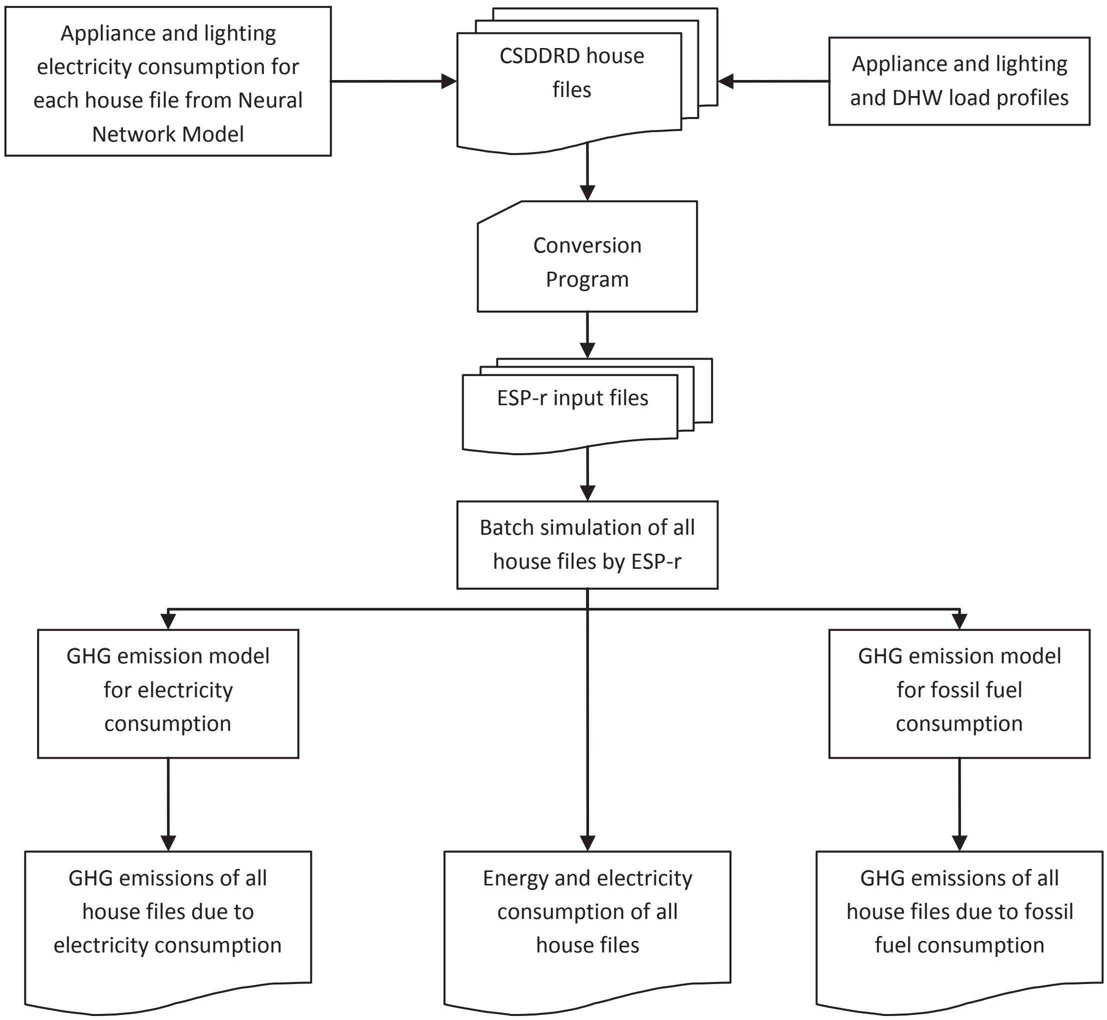


Figure 1.2 Flow diagram of CHREM

1.2.1 Solar domestic hot water system

Water heating is one of the most cost-effective usages of solar energy. In addition to heating domestic hot water, solar water heaters can also be used in applications such as car washes, hotels and motels, restaurants, swimming pools, and laundromats.

Table 1.1 Available solar technologies

1. Solar water heating
   - a. Using flat plate collector
     - i. Thermosyphon
     - ii. Active
   - b. Using evacuated tube
     - i. Thermosyphon
     - ii. Active

2. Solar space heating
   - a. Passive
     - i. Direct gain systems
       - 1. Changing windows area
       - 2. Changing windows type
       - 3. Shading devices
         - a. Fixed internal or external shading (Venetian blind)
         - b. Fixed external shading (overhang)
     - ii. Indirect gain
       - 1. Trombe wall
       - 2. Thermal distributed mass
       - 3. Phase Change Materials (PCM)
     - iii. Isolated gain
       - 1. Sunspace
   - b. Active
     - i. Active solar space heating
       - 1. Liquid based
         - a. Flat plate collector
         - b. Evacuated tube
         - c. Concentrating collector
       - 2. Air based
     - ii. Controlled internal and external shading devices

3. Solar Space Cooling
   - a. Thermally activated cooling systems (TACS)
     - i. Solar absorption cooling system
     - ii. Solar desiccant technology

4. Photovoltaics
   - a. PV electricity generation
   - b. Photovoltaic thermal (PV/T) system
     - i. Building Integrated photovoltaic thermal (BIPV/T) system

Solar domestic hot water (SDHW) systems can be classified into two categories: passive (or thermosyphon) and active systems. Active systems have circulating pumps and controls, while passive systems do not. Having pumps allows active systems to operate year round without the danger of freezing. Also, the hot water storage tank does not have to be close the collector. Depending on whether household water is heated directly in the collector or via a heat exchanger, solar water heating systems can be characterized as either direct (also called "open loop") or indirect (also called "closed loop").

There are a variety of designs for a solar water heater. In general, it consists of four main components, as shown in Figure 1.3:

1. Solar collector, which converts solar radiation into useable heat,
2. Heat exchanger/pump module, which transfers the heat from the solar collector into the water,
3. Storage tank to store the solar heated water,
4. Auxiliary heater to provide supplementary energy, in case there is insufficient or no solar energy to cover the entire load.

Besides those components, many solar water heater systems use a small photovoltaic module to power the pump needed to circulate the heat transfer fluid through the collectors. The use of such module allows the solar water heater to operate even during a power outage.

There are basically three types of thermal solar collectors: flat-plate, evacuated-tube and concentrating.

- Flat – plate collector:
  Flat-Plate collectors comprise of an insulated, weatherproof box containing a dark absorber plate under a transparent cover. Water or heat conducting fluid passes through pipes located below the absorber plate and is heated during this course. Flat-plate collectors are the most common solar collector type and they dominate the market. In all countries, except China, they represent about 90% of the market of covered solar collectors (Henning, 2004). The most popular application of flat-plat collector is domestic hot water production.

- Evacuated tube collectors:
  Evacuated tube collectors are made of a series of modular tubes, mounted in parallel, whose number can be increased or reduced as hot water delivery needs change. There are three main types of evacuated tube collectors (sometimes also referred to as Solar Tubes).
  1. Glass-Glass
  2. Glass-Metal

3. Water-in-Glass

Evacuated tube collectors represent about 10% of the market of solar collectors in International Energy Agency (IEA) countries. In China, this collector technology is the dominating one (Henning, 2004).

Evacuated tubular solar collectors have a substantially lower heat loss coefficient than standard flat plate collectors and therefore have promise as a means of supplying heat at temperatures above 100°C. The performance of evacuated tubular collectors could also be superior to that of flat plate collectors for lower-temperature operation due to their favourable incidence angle response and higher efficiency during periods of low irradiation and ambient temperature. However, the relatively higher cost of this type of solar collector is its disadvantage.

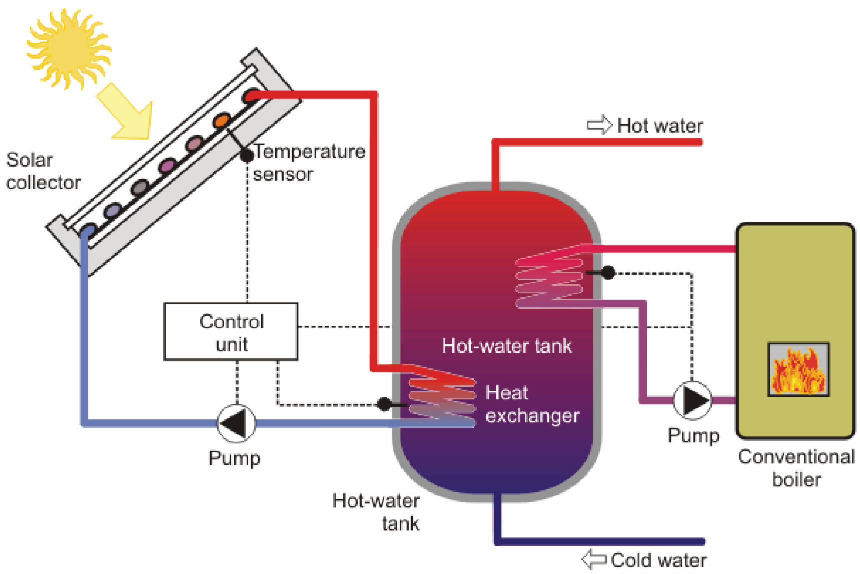


Figure 1.3 Schematic of a typical domestic hot water system (Volker Quaschning, 2009)

- Concentrating solar collectors:

  A concentrating collector utilizes a reflective parabolic-shaped surface to reflect and concentrate the sun's energy to a focal point where the absorber is located. To work effectively, the reflectors must track the sun. These collectors can achieve very high temperatures (150-800˚C (Duffie, et al. 2006)) because the beam solar radiation is concentrated on a small area. Concentrating collectors have been used to make steam that spins a turbine-generator set in a solar power station. Due to their high cost and high temperature range, this type of collector is not suitable for SDHW.

1.2.2 Solar space heating

There are two basic types of solar space heating systems: passive solar heating and active solar heating. Passive solar space heating takes advantage of the solar heat gain through design features, such as large south-facing windows, and materials in the floors or walls that absorb heat during the day and release that heat at night when it is needed most. A sunspace or greenhouse is a good example of a passive system for solar space heating.

1.2.2.1 Passive systems

1.2.2.1.1 Direct gain systems

Direct gain is a passive heating technique generally used in cold climates. It is the most common, simple and effective approach. The basic principle is that sunlight is admitted into the living spaces, directly through openings or glazed windows, to heat the walls and floors and thereby the air inside. In the northern hemisphere, the glazed windows are generally located facing south to receive maximum sunlight during winter.

In terms of energy performance, windows play a dual role, allowing solar gains to offset the heating loads during the heating season while adding to building loads during the cooling season. Windows also represent a major source of heat loss in winter, as their insulating value is much lower than that of the surrounding walls.

One way of achieving better performance with windows is by using advanced glazing systems. Using more than one pane for the window and high-performance low-emissivity (low-e) coated glazing, which provides better thermal performance than clear glass, can dramatically improve the energy performance of the house.

To study the effect of windows on the heating and cooling energy requirement[1] of a building, the following factors should be considered:

i. Area of windows:

   There are not adequate studies focusing on the impact of window size and its orientation for cold climates. A study about the influence of window size on the energy balance of low energy houses by Persson, et al. (2006) studied 20 terraced houses in southern Sweden which were well insulated and had modern triple-glazed windows with low-e coated glazing. To model these houses a dynamic building simulation tool, was used. The results indicate that the size of the energy efficient windows does not have a major influence on the heating demand in the winter, but is relevant for the cooling need in the summer. This suggests that instead of the traditional way of building passive houses which recommended

[1] 'Space heating/cooling energy requirement' is the amount of energy required to maintain the temperature of a house at the required level. It does not include the efficiency of the space heating/cooling equipment.

decreasing size of northern windows since they are a source of heat losses rather than solar gain, it is possible to enlarge the window area facing north and get better lighting conditions if high efficiency windows are used.

ii. Type of windows:

Three properties are integral to evaluating glazing energy performance: insulating performance (U-factor), solar heat gain coefficient (SHGC), and visible light transmittance (VLT or VT). The ideal properties depend on the local climate, building type, and design. For instance, while a low U-factor (less heat loss) is most important in a cold climate; a low SHGC (less solar heat gain) is a priority where overheating is a concern. Visible transmittance is important when daylight is incorporated into the building design.

There are three fundamental approaches to improve the energy performance of glazing products (Carmody, et al. 2007):

- Alter the glazing material itself by changing its chemical composition or physical characteristics. An example of this is tinted glazing.

- Apply a coating to the glazing material surface. Reflective coatings and films were developed to reduce heat gain and glare; and more recently, low-emittance coatings have been developed to improve both heating and cooling season performance. Low-e coatings can combine the advantages of a reduced U-factor and SHGC while maintaining high levels of visible light transmittance.

- Assemble various layers of glazing and control the properties of the spaces between the layers. This strategy includes the use of two or more panes or films, low conductance gas fills between the layers, and thermally improved edge spacers.

Previous studies show that gas-filled, low-e double glazed windows are the most cost effective choice for cold climate (Sullivan, et al. 1987, Karlsson, et al. 2001, Barry, et al. 2007).

iii. Window shading:

Solar gain through the glazing is commonly the largest and most variable heat gain in buildings and has major implications on energy consumption and peak cooling loads. Without appropriate solar gain control strategies, building peak cooling loads and increased cooling energy can offset any benefit from thermally improved envelopes. Control of solar gain is not only necessary in highly glazed, poorly insulated buildings, but is critical in the design of new energy efficient residential and commercial green buildings.

Shading devices such as operable slat-type louver blinds, roller blinds, drapes, overhangs, and retractable awnings are simple but effective devices, yet their impact on peak cooling loads and annual energy consumption is not thoroughly studied.

Shading devices can be classified into two categories:

- Exterior shading devices:

  The best place to shade a window is on the outside, before the sun strikes the window (Carmody, 2007). The most common approach is using an overhang. Overhangs are most effective at mid-day for the sun facing walls (south walls, in the northern hemisphere). For sun-facing windows, overhangs can be sized to block out much of the summer sun but still permit lower-angled winter sun to enter. Compared to other types of shading devices, overhangs have the advantage of reducing heat gain and glare without diminishing the view.

  Overhangs may be fixed, operable, and/or portable. Examples include roof eaves, awnings, and Bahama shutters (top-hinged louvered shutters typically propped open with wooden dowels). Fixed overhangs offer perceived longevity and low maintenance at the expense of flexibility. Although adjustable devices allow the user to fine tune the amount of shade or direct sunlight, they require more maintenance. Portable fixtures generally provide flexibility and longevity plus some personal involvement with installation and removal. Overhangs may be inappropriate for sites with restrictive regulatory guidelines.

  Previous studies on the effect of fixed overhangs on the cooling and heating energy requirements show that depending on the building location and the climate, the annual cooling energy requirement can be reduced by up to 23% (Farrar-Nagy, et al. 2000, Nikolaou, et al. 2007, Beausoleil-Morrison, 2009), heating energy consumption can be increased by up to 1.5% (Purdy et al. 2001) and annual energy consumption can be reduced by up to 9% (Nikolaou, 2007).

- Interior shading devices:

  Most homeowners use some form of interior window treatment, such as drapes, blinds, or shades. The major disadvantage of internal devices is that, regardless of how reflective they are made, they trap heat on the interior of the glass so they may cause overheating during the summer. However, they can reduce heat energy requirements during the winter.

  The Venetian blind is thought to have grown in popularity for its technical improvements over cloth shading systems. The following three advantages over cloth drapes are often cited: 1) greater durability, 2) easier operation, and 3) more economical.

Blinds can be used internally or externally. Metal window blinds are often used outside to protect against theft, temperature, vision, bad weather and fire (in fire-prone areas). Often these blinds are machine-operated, rather than hand operated.

Previous studies on the effect of blinds and their position on the heating and cooling energy requirements of a building show that existence of the blind can reduce energy consumption of the building (Lomanowski, et al. 2007, 2009, Laouadi, et al. 2008, Galasiu, et al. 2009). It was also found that the optimum blind position is the outdoor side blind in terms of reducing the cooling energy requirement (Lomanowski, et al. 2007, 2009) and indoor blind in terms of reducing the heating energy requirement (Lomanowski, et al. 2009).

1.2.2.1.2 Indirect gain systems

In case of indirect solar gains, heat enters the building through windows and is captured and stored in thermal mass (e.g water tank, masonry wall) and slowly transmitted indirectly to the building through conduction and convection.

Thermal mass enables building materials to absorb, store, and later release significant amounts of heat. Buildings constructed of concrete and masonry have a unique energy-saving advantage because of their inherent thermal mass. These materials absorb energy slowly and hold it for much longer periods than do less massive materials. This delays and reduces heat transfer through a thermal mass building component, leading to two important results:

1. There are fewer spikes in the heating and cooling requirements, since mass slows the response time and moderates indoor temperature fluctuations.
2. Thermal mass can shift energy demand to off-peak time periods when utility rates are lower. Since power plants are designed to provide power at peak loads, shifting the peak load can reduce the number of power plants required.

Three strategies are used to store the heat in the building interior surfaces:

i. Thermal storage wall (also called the Trombe wall)
ii. Distributed thermal mass
iii. Phase Change Materials (PCM)

i) Trombe wall

In cold climates, as long as the number of sunny days is sufficiently large, Trombe walls provide a potential to reduce energy consumption for heating as well as cooling. The Trombe wall system (Figure 1.4) consists of a south facing massive wall (in the northern hemisphere), which is commonly painted black for maximum solar absorption and a single or double glazed glass cover. The wall also forms part of the structural support for the building. Solar energy passes through the glass cover and is absorbed on the darkened wall surface. This energy is trapped, in a way similar to the heat in a greenhouse, as glass is opaque to thermal radiation. The wall, which is usually of brick or concrete construction, stores that heat and conducts it to the living area. Heat is transferred from the back face of the wall to the room by convection and radiation. In additions, vents are located at both the top and the bottom of the wall. Cooler room air, drawn through the bottom vents, is heated as it passes up the duct and then delivered into the room through the top vents. This convective heat transfer-called "thermo-circulation"- provides a direct heat path to the room, while the heat conducted through the wall exhibits a thermal delay. Ideally these two heat paths could be matched to provide comfortable living conditions throughout the day. The wall can also be operated without vents at all, in which case it is commonly called a thermal storage wall.

Numerous studies on the operation and performance of Trombe wall type thermal storage wall passive systems have been conducted (detailed literature and references can be found in Appendix A). From the literature, it was found that the optimum thickness of the Trombe wall is around 25-35 cm, depending on the latitude of the site the building is located. Trombe wall modification by means of changing its geometry, using composite materials and solar chimney can increase its efficiency by 20%.

ii) Distributed thermal mass

Numerous studies show that thermal mass can reduce cooling and heating energy consumption, and help to maintain the indoor temperature around the desirable set point.

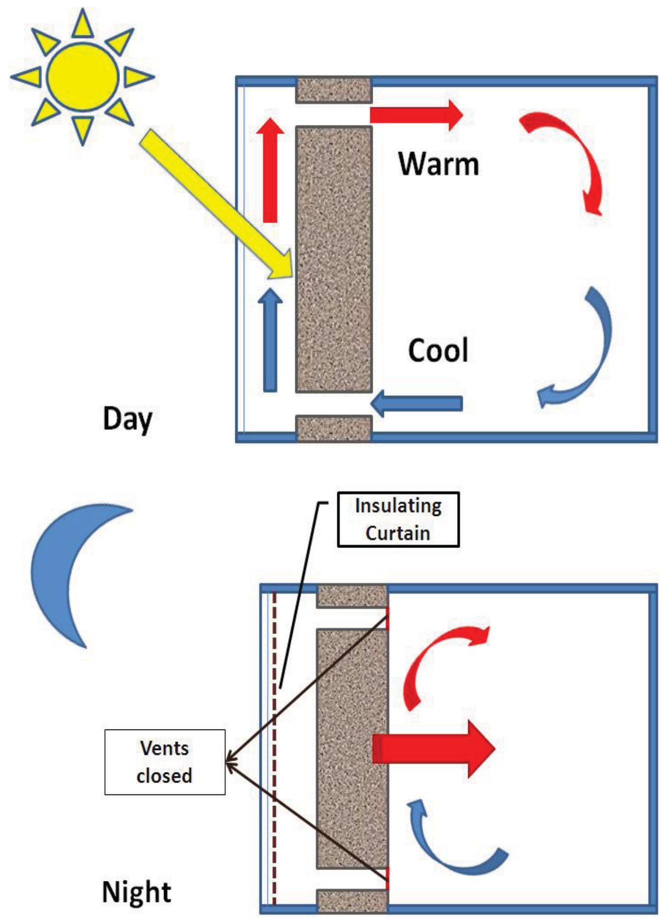


Figure 1.4 Schematic of Trombe wall during a day and a night in winter

Experimental and simulation studies conducted to evaluate the effect of high thermal mass on cooling energy consumption of buildings in warm climates in the US (Burch, et al., 1984 for Maryland, Ruud, et al., 1990 for Florida, and Brown, 1990 for New York), Kenya (Ogoli, 2003 for Nairobi), and Australia (Gregory, et al., 2008 for Callaghan) found that high mass buildings consume less cooling energy than similar lightweight buildings that have similar thermal resistance, and thermal mass is more effective when positioned on the interior side of the insulation.

Studies conducted to identify the effects of thermal mass on heating and cooling energy of buildings in cold climates found similar results. Based on the results of simulation studies conducted using seven different building simulation programs for Nordic climate and modern, well-insulated Nordic buildings, Kalema, et al. (2008) reported that if high thermal mass is used instead of extra-light construction, heating and cooling energy consumption can be reduced by 4% and 30–50%, respectively. The same study found similar results for apartment buildings. A recent study on the impact of using a variety of thermal masses on the Toronto Net Zero Energy house with a lightweight construction and a highly insulated building envelope (Siddiqui, et al. 2009) found that the use of thermal mass with the Net Zero Energy house in Toronto provides reductions in the daily indoor temperature fluctuations and savings between 5-7% and 8-15% for the heating and cooling loads, respectively.

iii) Phase Change Material (PCM)

Unlike Trombe wall and thermal distributed mass which stores thermal energy as sensible heat, PCMs stores thermal energy as latent heat. Sensible heat storage causes several problems such as excessive mass and temperature fluctuations, whereas latent heat storage reduces the required mass of storage and due to isothermal process of phase change it provides a suitable means of temperature control.

According to Lane (1983), the utilization of PCMs in active and passive solar buildings has been a subject of interest since 1940s. Any PCM composite has two components: an organic or inorganic compound that undergoes a phase change transition within some desired operating temperature and a porous structure that acts as containment for the heat storage substance (Heim, et al. 2003, Heim, 2005 & 2006). In buildings this porous structure can be traditional construction materials such as gypsum, concrete or ceramic. PCMs can be impregnated to this structure and used as an internal surface lining.

Studies on thermal performance and properties of organic and inorganic compounds show that organic materials are more stable and easier to encapsulate. However, their flammability, their volume change at transition and their tendency to react with the products of hydration in concrete are some disadvantages of organic materials (Hawes, et al. 1993, Farid et al. 2004, Tyagi, et al. 2007).

Experimental and simulation studies conducted to evaluate the effect of adding PCMs for heat storage to a passive solar house on energy savings for cold and mild climates show that adding a PCM as inside wall lining can save energy up to 15% (Peppio, et al. 1991, Siddiqui, et al. 2008) and reduce the maximum room temperature by about 4 ˚C during the day time (Athienitis, et al. 1997). It was also found that the melt temperature that is 1-3 ˚C above the average room temperature provides the most optimal heat storage (Peppio, et al. 1991). The results of study on the Net Zero Energy House in Toronto show that the optimum concentration of the PCM in the envelope building is around 40% (Siddiqui, et al. 2008)

1.2.2.1.3 Isolated gain systems:

When thermal barriers are placed between the interior spaces and the solar-heated thermal storage, the heat flow from the storage into the building can be controlled. This type of passive system is an isolated-gain system. An isolated-gain solar system is basically an indirect-gain system except that a distinct separation (insulation or physical separation) exists between the thermal storage and the interior space. The most common isolated-gain passive solar home design is a sunspace.

There are extensive studies on the sunspace energy analysis and its design and modeling (detailed literature and references can be found in Appendix A). From the literature it was found that the energy performance of a sunspace can be the same as an insulated wall. However, sunspace offers a living space with attractive environmental characteristics.

It was also found that adding sunspace to the building, especially on the south side, increases indoor temperatures significantly during both the cold and the hot periods, resulting in potential overheating over the warm period, while low-emissivity double glazing provides a slight improvement over single glazing in terms of energy performance.

These and other similar studies indicate that adding sunspace to a building has the potential to improve the energy performance of the building.

1.2.2.2 Active systems

1.2.2.2.1 Active solar space heating

Active solar space heating systems involve the mechanical collection, transport, and storage of heat by elements separate from the building structure itself. The system components in active solar space systems are the same as SDHW systems with addition of a distribution system. There are two basic types of active solar heating systems based on the type of the fluid—either liquid or air—that is heated in the solar energy collectors. Liquid-based systems heat water or an antifreeze solution in a "hydronic" collector, whereas air-based systems heat air in an "air collector."

Solar liquid collectors are most appropriate for central heating. They are the same as those used in solar domestic water heating systems. Flat-plate collectors are the most common, but evacuated tube and concentrating collectors are also available.

Solar air heating systems use air as the working fluid for absorbing and transferring solar energy. Air collectors start producing heat earlier and continue to do so later in the day than liquid systems, so they may produce more usable energy over a heating season than a liquid system of the same size (DOE, 2008). Also, unlike liquid systems, air systems do not freeze, and minor leaks in the collector or distribution ducts will not cause significant problems, although they will degrade performance. However, air is less effective heat transfer medium than liquid, so solar air collectors operate at lower efficiencies than solar liquid collectors.

A major barrier for large-scale thermal solar systems is the high costs compared to conventional systems. Solar systems for SDHW require collector areas in the range of 3-5 m^2 for a typical single family household. The collector area required for DHW and space heating is considerably larger. Hence, the costs of these systems are more challenging.

There are extensive studies on energy performance of solar thermal systems, its modeling and optimization in the past few decades. These studies cover a wide range of countries and climatic regions, from the prairies of Canada (e.g. Stewart, et al., 1992) and Sweden (Nordell, et al., 2000) to Northern Greece (Argiriou, et al., 1997) and rural Lithuania (Sateikis, et al., 2006), as well as a wide variety of solar and other system combinations, such as solar-wind, solar-geothermal. These studies show that solar heating systems can provide a substantial portion of the space heating requirement of buildings, especially when used in combination with other renewable energy systems such as wind or geothermal, and the economic feasibility depends on the climate, costs and economic conditions.

1.2.2.2.2 Controlled internal and external shading devices

Shading devices can be either fixed or moveable. Fixed systems are commonly used for solar shading, while operable systems are more common to control thermal gains, protect against glare, and redirect daylight. The use of fixed blind systems generally requires higher energy consumption than moveable blind systems because as they decrease the cooling load and cooling energy use, they also reduce the possible benefit for heating with solar gain when there is a heating load. Moveable systems follow the dynamic exterior thermal and luminous conditions. Manually operated systems are generally low energy efficient and unreliable.

A simulation study examined the impact of manual control (lowered/retracted) of window blinds on annual energy consumption of a single south-facing room in Toronto, Canada (Newsham, 1994). Four blind control strategies were considered: 'permanent' (always closed), 'none' (always open), 'manual' (based on solar thermal gain and illumination), and '7 months' (blinds always closed April - October, and always open November - March). The study found that a blind system by itself, without a proper control, could result in an increase in energy consumption.

Automated shading systems reduce energy use and control interior conditions without relying on occupants. Automated systems can achieve savings in both cooling loads and lighting energy. Automated blinds have better thermal and daylighting performance than both fixed blinds and manually controlled blinds. Automated systems close automatically when the indoor light level or temperature exceeds the control set point and re-open later to admit useful light.

An experimental study in Montreal shows that the use of automated Venetian blinds can decrease the energy cost by 30% during the winter and by 50% during the summer (Rheault, 1990). However, automatic systems can produce discomfort in occupants who dislike the feeling of not having personal control over the system. Also, automated devices are often high-maintenance, and therefore expensive, solutions. Other studies conducted in a variety of climatic conditions found similar results. In an extensive experimental study conducted at a full-scale demonstration facility in Oakland, California over a 1.5 year period to assess the energy saving potential of automated Venetian blinds operated in synchronization with daylighting controls concluded that an integrated system could achieve energy savings of 7-15% and 19-52% for cooling and lighting energy, respectively, compared to a fixed 45° angle setting of the blinds (Lee et al., 1998). Utilizing a sophisticated adaptive controller incorporating fuzzy logic and genetic algorithm capable of prediction and adapting to user behaviour and room characteristics for the integrated operation of blinds, electric lighting, and HVAC systems in an occupied office building in Lausanne, Switzerland, Guillemin et al. (2001) achieved a reduction in energy consumption of 25% over 94 days in winter compared to a conventional system. In a similar study conducted in Manglore, South India, Kurian et al. (2008) found that fuzzy-based blind and artificial lighting control could achieve 20-80% of annual energy savings compared to the base case of manual blind systems without daylighting control. Similarly, Kim, et al. (2009) found that for an office building in Seoul, South Korea, optimal control of blind systems based on heat gain and daylight outperforms manual control.

1.2.3 Solar space cooling

1.2.3.1 Thermally activated cooling systems (TACS)

Cooling and refrigeration can be accomplished using thermally activated cooling systems (TACS) driven by solar energy. The TACS available for solar-driven cooling include absorption systems and desiccant systems.

1.2.3.1.1 Solar absorption cooling system

Absorption technology demands high temperatures (at least 88˚C) and collectors capable of producing them are evacuated-tube and concentrating solar collectors (House-energy, 2009). However, recent study by Johnson (2011) shows that the absorption chiller can be run at lower temperatures (about 70˚C) and the coefficient of performance (COP) of the system will not drop dramatically.

The refrigerant–absorbent pair suitable for solar absorption cooling systems is water–lithium bromide (LiBr) because of the lower generator temperatures needed (90–120˚C). These temperatures can be achieved with compound parabolic collectors (CPCs) and evacuated tube collectors that are both stationary and therefore are easier to install and operate than parabolic trough collectors (Florides, et al. 2002).

Over the past decades, considerable research has been devoted toward developing efficient and economic solar driven absorption refrigeration systems. In 1961, Chinnapa (1961) proposed solar energy to power a cooling system. Since then, solar-powered absorption cooling system has been discussed frequently. Two approaches have been taken to solar operation of absorption coolers. The first is to use continuous coolers, similar in construction and operation to gas- or steam-fired units, with energy supplied from the solar collector, storage or auxiliary systems whenever conditions in the building dictate the need for cooling (Collier, 1979, Haim, et al. 1992, Hawlader, et al. 1993, Ameel, et al. 1995). The second is to use intermittent coolers similar in concept to that of commercially manufactured food coolers. Intermittent coolers have been considered for refrigeration, but those work in solar air conditioning are commonly based on continuous cycles (Chinnapa, 1961, Duffie, et al. 2006).

There are two types of continuous absorption solar cooling systems: open-cycle absorption refrigeration (OCAR) and closed-cycle. The OCAR has three distinct advantages: 1) simplicity of the collector, 2) improved thermodynamic performance, 3) improved adaptability to solar energy (Collier, 1979). These systems are more cost effective than closed-cycle and work at lower temperatures (Ameel, et al. 1995). Therefore the OCAR systems are suitable for solar cooling systems.

There are extensive studies on development, performance and optimization of absorption cooling systems for hot and mild climates (Collier, 1979, Haim, et al. 1992, Hawlader, et al. 1993, Ameel, et al. 1995, Ghaddar, et al. 1997, Hammad, et al. 1998, Florides, et al. 2002, Assilzadeh, et al. 2005, Syed, et al. 2005, Mazloumi, et al. 2008). The results of these studies show that while the technology works best in dry and hot climatic conditions, it is economically uncompetitive unless combined with domestic water heating.

1.2.3.1.2 Solar desiccant technology

Desiccant cooling systems combine sorptive dehumidification, heat recovery, evaporation and heating to create a cooling process which can offer energy savings compared to conventional air conditioning systems. Waste heat or solar energy can be used for the required regeneration of the sorbents in the dehumidifier, leading to further energy savings.

Studies on desiccant cooling systems demonstrate that these systems provide a techno-economically feasible solution for hot and humid climates provided that the cooling system is integrated with space heating and solar domestic hot water systems (Davangere, et al. 1999, Henning, et al. 2001, Mavroudaki, et al. 2002, Halliday, et al. 2002, Gommed, et al. 2007).

Simulation studies conducted using Canadian conditions also show that solar thermal desiccant cooling and dehumidification systems provide a potential in reducing expensive peak power requirements in Canadian summer months using a clean, sustainable energy source. For example, a simulation study conducted by Haddad et al. (2008) to evaluate a conventional vapour compression based cooling system and a desiccant evaporative cooling system installed in an R-2000 house located in Halifax, Ottawa and Calgary using actual weather data files for the year 2001 for the period June 1st – August 31st indicate that when the desiccant evaporative cooling system is used without solar energy, there is a significant reduction in electricity consumption associated with residential space cooling (30% for Halifax and 53% for Calgary), while the use of solar energy for regeneration of the desiccant wheel can provide a significant portion of the auxiliary thermal energy needed. However, the operation of the solar system increases the electricity consumption of the cooling system due to the operation of circulation pumps of the solar system, which can significantly reduce or completely eliminate the potential of the desiccant system as a peak shaving technology. Simulation study of a solar thermal liquid-desiccant air-conditioning system for eight days in July using Toronto, Ontario weather data indicate that storage of desiccant allows a smaller solar collector array to meet the fresh air dehumidification demand (Jones et al., 2008).

1.2.4 Photovoltaics

Photovoltaics (PV) is a solar power technology that uses solar cells (solar photovoltaic arrays) to convert energy from the sun into electricity. Since the output of a single cell is not sufficient to satisfy a practical load, cells are grouped together to form "PV modules" that may in turn be arranged in "solar arrays" (also known as "solar panels"). Solar arrays are increasingly incorporated into the roof or walls of buildings as a principal or auxiliary source of electrical power. Although the systems are not cost competitive with conventional energy systems, they are attractive for pollution-free generation of electricity. Due to advances in technology and a consequent decrease in manufacturing costs, as well as generous government subsidies, the photovoltaics market has significantly expanded all over the world, especially in the US, Europe and Japan. The global production of photovoltaic cells has annually grown at the rate of 30–45% since 2000, and this growth is expected to continue: the global solar electrical capacity in 2000 was 1 GW and is anticipated to increase to 140 GW by 2030 (Zahedi, 2006).

PV systems can be categorized as off-grid or grid-connected. An off-grid system is suitable for remote residential or commercial buildings far from the existing electricity grid, and requires a battery for keeping a balance between electricity supply and demand. On the other hand, a grid-connected system can extract further electricity if needed from the utility grid, and excess electricity can be delivered to the grid (NRCan, 2002; Zahedi, 2006). Therefore, it does not need a battery unit and thus is less expensive compared to the off-grid system. Although off-grid systems were dominating the photovoltaic market at the beginning of 1990s, the production of grid-connected systems rapidly grew and exceeded the off-grid in 1998 primarily due to generous feed-in tariffs for PV electricity (Hass, 2003).

PV cells suffer from a drop in efficiency with the rise in temperature due to increased resistance. To solve this problem and to utilize the otherwise wasted thermal energy, PV thermal (PV/T) systems were developed. In these systems, heat is carried away by the thermal part of the system, keeping temperatures lower and consequently lowering resistance. When such systems are integrated into the building façade, they are referred to as BIPV/T (Building Integrated Photovoltaic Thermal system).

1.2.4.1 PV electricity generation

Experimental and simulation studies conducted to evaluate the techno-economic performance and GHG emissions of the PV systems for warm and cold climates in Japan (Udagawa, et al. 1997 for Tokyo, Takuma, et al. 2006 for Northern Kyushu), in Belgium (Verbeeck, et al. 2005, for Luven) and in Canada (Kikuchi, et al. 2009 for Ottawa, Toronto, Montreal, Calgary and Vancouver) found that by using a stand-alone PV system, the energy consumption and GHG emissions can be reduced by up to 17% and 19%, respectively. However, it is not a cost effective solution to save energy in residential buildings. To increase the performance and cost effectiveness of a PV system, it can be combined by a SDHW which can reduce energy consumption by 50% for a total collector and PV array area of 40 m2 for a residential building.

1.2.4.2 Photovoltaic thermal (PV/T) systems

A PV-Thermal (PV/T) collector produces electricity and serves as a thermal absorber, simultaneously generating useful heat and power, with higher electrical efficiency than standard PV arrays due to the lower cell temperature that reduces electrical resistance (Duffie, et al. 2006).

PV/T collectors can be flat plate or concentrating, and are classified according to the type of the working fluid used (water or air) (Charalambous, et al. 2007), while PV/T applications can be classified as grid-connected and autonomous. In this work, the emphasis is on grid-connected systems.

The research on PV/T collectors started during the mid-1970's, with the main aim of increasing energy efficiency. Domestic application was regarded as the main market. Initially the focus was on glazed collectors; both air-type and liquid-type, but soon the idea of an unglazed PV/T collector combined with a heat pump also received attention. In the beginning of the 1990s, large PV facades started to receive attention and the issue of ventilating these in order to reduce the PV temperature, quickly lead to the idea that this heat could also be used, especially for space heating (Zondag, 2008).

There are extensive studies on the performance, development, optimization and modeling the PV/T systems. Comprehensive reviews of the literature on PV/T development were done by Zondag (2008) and Charalambous, et al. (2007). A brief review of the literature on the performance of PV/T collectors is presented here.

As indicated by Zondag (2008), the first work on a flat-plate PV/T-liquid system analyzed a silicon array mounted inside a stationary flat-plate thermal collector with a lead-acid battery as the storage element for residential heating concluded that the system was technically feasible and cost effective (Wolf, 1976). The research on PV/T liquid was continued in USA, Japan, Norway, Germany, Israel, China and Cyprus. These studies (e.g. Kalogirou, 2001, Chow, et al. 2006) concluded that glazed PV/T systems for domestic hot water heating are a promising application for residential buildings. Following the 'Solar One' house, which was built in 1973/1974 at the University of Delaware (Boer et al. 2003), research on the PV/T-air systems continued in the US at the MIT and Sandia Laboratories. In Canada, Conserval Engineering developed the PV SOLARWALL system with Bechtel and CANMET (CANMET, 2009) and conducted thermal and electrical performance measurements and testing. The results of this work showed that combining PV panels with the SOLARWALL thermal panel can produced higher total combined solar efficiencies than either of the PV or thermal panels on their own (Hollick, et al. 1998).

1.2.4.2.1 Building integrated photovoltaic thermal (BIPV/T) system

BIPV/T systems are a special application of PV/T systems where the solar panels are integrated into the building envelope, as part of the walls or roof. These systems present a feasible alternative for preheating of ventilation air, especially for buildings with a large ventilation demand (Zondag, 2008). However, Zodang (2008) points out that since this is required only during the heating season, it is worthwhile to look for summer application of the heat as well. For domestic applications, as well as for utility applications with a large tap water demand, the heat may be used for the heating of water through a heat exchanger. For unglazed BIPV/T applications, the thermal efficiency will be low and care should be taken to optimize the integration of the BIPV/T into the HVAC system as a whole, which requires good design tools. The optimization of the system will strongly depend on climate. Since large majority of the previous studies have been done in Europe and USA and for the non-residential applications of BIPV/T, the results cannot give accurate performance estimation for the Canadian climate. However, in an extensive simulation based study, Pelland et al. (2006) evaluated the electricity generation potential of building integrated photovoltaics (BIPV) in Canada on a countrywide basis and for each of the provinces, as well as for a few municipalities featuring as case studies. In order to estimate the electricity generation potential of buildings in Canada, a conservative methodology developed by the International Energy Agency Photovoltaic Power Systems Programme (Task 7) was applied. The analysis shows that photovoltaics could meet a substantial fraction of annual electricity consumption in Canada, particularly in the residential sector, where about 46% of current needs (53 out of 114.8 TWh per year) could be provided by photovoltaics. For commercial and institutional buildings, photovoltaics could provide about 15-17% of total consumption (131.7 TWh per year). For the combined residential and commercial/institutional building stock, about 29% of the yearly 246 TWh used could be supplied by PV. This corresponds to a total installed capacity of about 73 000 MW, and to about 23 Megatonnes of avoided GHG emissions per year.

Two numerical models, a steady state and a transient model, were developed for open-loop air-based BIPV/T systems by Candanedo, et al. (2008, 2009a, b). The predictions of the models were compared to the experimental data from the PV/T system located at Concordia University (Diarra, et al. 2008). This BIPV/T channel was built to simulate a section of the roof at EcoTerra demonstration house (Candanedo, 2009b). It was found that the transient model, which includes thermal capacity effects of the PV, follows experimental measurements better than the steady state model. However, the transient model is probably not necessary for system design as it does not significantly improve average accuracy. The sensitivity analysis conducted as part of these studies evaluate the effect of air flow rate, insulation level, bottom strapping and top strapping on the performance of a BIPV/T. It was found that increasing the airspeed, addition of wood strapping on the bottom or on the top increase thermal energy output by up to 15%. However, adding insulation does not improve the PV performance significantly.

Studies conducted for climates other than Canada to evaluate the feasibility and effectiveness of the BIPV/T provide similar results. For example, extending the ESP-r software capability to simulate the façade- and roof-integrated photovoltaic modules, Clarke et al. (1997) studied the efficiency improvements to be expected from hybrid PV systems under different European climate regimes, and found that the combined efficiency, electrical and thermal, increase the PV performance by up to 50%.

1.2.5 External shading effect

External shading may decrease or increase the energy requirement of a building depending on building characteristics and environmental conditions. A potential benefit of shading for adjacent structures is decreasing the cooling energy requirement. Negative consequences of shading include the loss of natural light for passive or active solar energy applications and the loss of warming influences, which increase the heating energy requirement during the cold season. Factors influencing the impact of shading are site-specific such as the latitude and climate, as well as the direction, number, size and distance of neighbouring structures. Although potentially significant, the impact of neighbouring structures on the heating and cooling energy requirement of houses is often neglected in building energy analysis.

Due to the potentially substantial effect of shading due to neighbouring structures on the energy requirement of buildings, a case study was conducted to analyze this effect for a typical building in Canada. This case study intends to quantify the magnitude of the effect of site shading on the energy requirement of residential buildings in Canada using a representative two-story detached house. Site shading effects of neighbouring buildings and trees on annual heating and cooling energy requirements are evaluated using ESP-r. The effects of the orientation, distance and size of the neighbouring object on heating and cooling energy requirement are investigated for four major cities (Halifax, Toronto, Calgary, Vancouver) representing the major climatic regions in Canada (Atlantic, Central, Prairies, Pacific). The detailed study is presented in Appendix B (Nikoofard, et al. 2011).

1.3 Solar technologies selected for detailed evaluation

Based on the review presented in the previous section, the following solar technologies that show techno-economic potential for the Canadian residential sector are selected for detailed evaluation:

- Solar domestic hot water heating

  As discussed earlier, active SDHW systems are designed to operate year round without any danger of freezing, while thermosyphon systems cannot be operated during the cold season. Similarly, direct systems are also not suitable for a cold climate. Therefore, in this project active indirect systems are considered.

  While flat plate and evacuated tube collectors are suitable for SDHW applications, evacuated tube collectors are currently not manufactured in Canada. Therefore, SDHW systems that utilize flat plate collectors are studied in this work.

- Solar space heating

  a. Passive

     As shown in the review conducted in the previous section, direct gain passive solar systems, i.e. window systems, can effectively be used in cold climates. Two characteristics of windows play an essential role in solar thermal performance: the area and the glazing characteristics of the windows. As well, adding internal and/or external shading devices to windows also have a direct impact on their performance. Base on a study by Beausoleil-Morrison (2009), Venetian blinds has better energy performance than overhang. Therefore, the effect of the size and type of windows and Venetian blinds as a shading device, are studied in this project.

     Storage of solar energy in the form of heat is another type of passive solar technology for space heating. As discussed in the previous section, the technologies available for storing solar thermal energy are primarily the Trombe wall, thermal distributed mass and/or PCMs. A recent study by the Canadian Mortgage and Housing Corporation (CMHC) quoted by Athienitis (2009) concluded that Trombe wall is not an efficient technology for Canada. However, literature shows that thermal distributed mass has a reasonable performance in Canada. For applying thermal distributed mass to an existing building, it is necessary to change the construction of whole wall. In other words, in reality the selected wall(s) should be reconstructed which is not practical. Therefore, thermal distributed mass is not considered in this study.

     As concluded in the literature, PCMs have a reasonable performance in Canada and do not have the practical problem as distributed mass.

Therefore, PCMs is considered as storage technology for passive solar houses in this study. Available PCMs in the market for retrofit are stand-alone units which are modeled in this study. However, to simulate the performance of these units they are treated as if they are incorporated into the floor.

b. Active

The results of previous studies indicate that air based solar space heating systems are less efficient than liquid based systems, but they do not have the problem of freezing in cold climates. It was concluded from the literature that due to the large collector area needed, active space heating systems are not a cost effective solution and their performance is not satisfactory unless combined with the SDHW. Therefore, active space heating systems is not considered in this work.

Controlled shading devices are another type of active solar space heating system. Controlling shading devices allows the benefit of shade in summer and insulation layer at night in winter. According to the literature, the use of automated Venetian blinds decreases energy consumption in both winter and summer. Therefore, the use of controlled Venetian blinds is considered in this work.

- Solar space cooling

  Energy consumption for space cooling in Canada is only 2% of total energy consumption of the residential sector (OEE, 2007). Also, based on the results of previous studies, solar space cooling systems are not a cost effective option. Therefore, the solar space cooling is not considered in this work.

- Photovoltaics

  Based on the literature, a PV system may reduce energy consumption by up to 50% depending on the climate. But, it is not a cost effective technology for most climates if government subsidies did not exist. It should however be noted that the price of PV modules has decreased by a factor of 50% over the past 12 years, and further and substantial reductions are expected (Enerdata, 2012). Thus, the economic feasibility of PV systems is expected to improve over the next decade. Currently, in the absence of government subsidies, it is generally necessary to use PV panels that have thermal energy collection capability, i.e. BIPV/T, to justify the cost of PV systems. However, due to lack of time only the PV system is modeled in this work.

The selected solar technologies which are studied in this project are summarized in Table 1.2.

Table 1.2 Selected Solar Technologies

1. Solar water heating (using flat plate solar collector)
    a. Active (forced circulation)
2. Solar space heating
    a. Passive
        i. Direct gain systems
            1. Changing windows area
            2. Changing windows type
            3. Shading devices
                a. Fixed internal or external shading (Venetian blind)
        ii. Phase change materials (PCMs)
    b. Active
        i. Controlled internal and external shading devices (Venetian blind)
3. Photovoltaics
    a. PV electricity generation

1.4 Techno-economic assessment of solar technologies and integration strategies for the Canadian housing stock

For policy makers it is crucial to have a reliable techno-economic assessment of integration of new technologies to the residential sector. A correct estimation of solar technologies impact on the annual energy consumption and the GHG emissions along with required capital investment for each technology can provide a guideline to new regulations that reduces energy consumption while it is cost effective.

While several small scale studies have been conducted to evaluate the technical and/or economic feasibility of solar technology application in the Canadian residential sector (Stewart, et al. 1992, Newsham, 1994, Hollick, et al. 1998, Polland, et al. 2006, Kikuchi, et al. 2009), none of these studies have the depth or breadth proposed in this work. The residential energy and emissions model that is used in this work consists of close to 17,000 houses representative of the CHS, and is based on a comprehensive building energy simulation program capable of sub-hourly time steps analysis which is required to accurately simulate the performance of solar technologies.

Due to the substantial regional differences in climate, primary fuel availability, fuels used in electrical generation, as well as the construction, heating/cooling equipment and appliance characteristics, the suitability and feasibility of policy tools and strategies that involve solar technologies differs dramatically in Canada from region to region. Therefore, there is a need to conduct an in-depth study and analysis of potential policy tools and strategies involving solar technologies for the different regions of the country in order to identify those that are most effective for each region to help achieve Canada's commitments to reduce its energy consumption and GHG emissions.

Based on the presented background this dissertation develops:

- A techno-economic assessment of solar technologies for different regions of the country,
- A systematic framework to select candidate houses in each region for each solar technology evaluated,
- New or adapting existing simulation models of solar technologies, and
- Capital cost investment model for solar technologies that reflect the present worth of money for each upgrade based on different penetration rate, money interest rate, and fuel cost escalation rate and payback period.

1.4.1 Objectives

The major objectives of this thesis are the following:

1- Examining the interrelated effects of integrated solar technologies on the housing stock,
2- Conducting realistic assessments of the cost effectiveness, energy savings and GHG emissions benefits of integrated solar technologies,

To investigate the impact of these solar technologies on the annual energy consumption and the GHG emissions production for the CHS, each solar technology and practice scenario is applied to CHREM. Thus, the objectives of this study are achieved through the following steps:

1. Developing new models or adapting existing models for the selected solar energy technologies into the building simulation engine ESP-r and CHREM,
2. Assessing the economic feasibility of solar technology upgrade scenarios,
3. Assessing the feasibility of solar technology upgrade scenarios in terms of greenhouse gas emissions reductions,
4. Assessing impact of these technologies on energy consumption and emissions using sensitivity analysis.

1.4.2 Outline of the Dissertation

This dissertation presents the technical and economical feasibility of integrating selected solar technologies to the CHS using the CHREM. The dissertation is organized as follows:

> Chapter 2 presents the overall methodology that is used to evaluate the techno-economic feasibility of upgrade scenarios.
>
> Chapter 3 presents a detailed modeling strategy of selected solar technologies, including the required input data by ESP-r. It also presents the methodology to select the eligible houses that can be upgraded for each upgrade scenario.
>
> Chapter 4 is divided into two major parts. First part presents the parametric study that has been conducted for each upgrade scenario. This parametric study provides the suitable input data for batch simulations. Based on the selected parameters, batch simulations for the entire Canadian housing stock were conducted and the techno-economic feasibility of each upgrade was evaluated.
>
> Chapter 5 concludes the dissertation with a summary of the research contributions. A list of recommendations is provided for future work.

CHAPTER 2 METHODOLOGY

The methodology that is used in carrying out this research is depicted in Figure 2.1 and consists of the following steps.

2.1 Model development/adaption for solar technologies

ESP-r contains models for most of the solar technologies that are of interest in this work. For those technologies that there is no model in ESP-r, models were developed using the existing features and component models in ESP-r. A detailed review of the modeling technique used for each selected solar technology is presented in Chapter 3.

2.2 Parametric study

Before applying each selected solar technology upgrade scenario to the CHREM, a parametric study is required. This analysis determines the specific variables which have significant effect on the energy performance of the upgrade. However, some upgrades do not need the parametric study due to technology complication, existing standards and previous studies on their performance.

To conduct the parametric study, a one-storey detached house commonly found in Canada is used as the "case study house", which was first modeled and simulated without any upgrade to provide the "base case" energy requirement. Then, the upgrade was added to the model and a series of simulations were conducted to determine the energy performance of the upgrade with a variety of parameters. Therefore, the parameters that result in a better energy performance of the house are selected to be considered in batch simulation of the CHS.

The case study house was selected from the CSDDRD based on its main features (i.e. number of storeys, floor area, envelope characteristics, and space heating/cooling equipment) such that the design of the test case house is one that is commonly encountered across the country. The level of thermal insulation is in conformance to the building code.

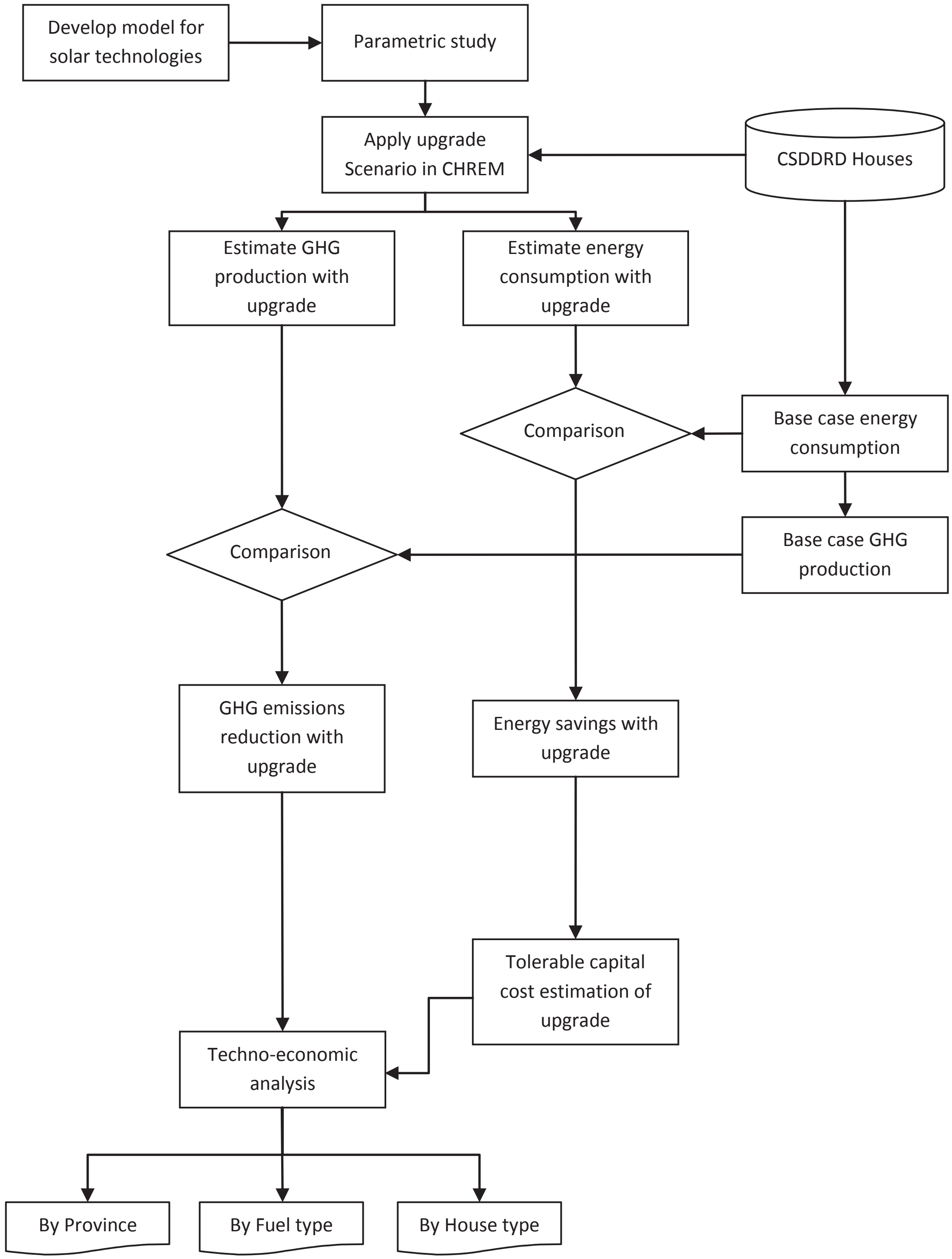


Figure 2.1 Flow diagram of the overall methodology that is used in this study

Since the effect of each upgrade integration on heating and cooling energy requirement varies substantially based on the climate and the geographical location of a house, five cities, namely Halifax, Quebec, Toronto, Calgary and Vancouver, were selected to represent the five major climatic regions in Canada, namely Atlantic, Quebec, Ontario, Prairies and Pacific.

The weather data files used in the simulations are from the Canadian Weather Year for Energy Calculation (CWEC) files (Numerical Logics, 2010). These files are 'typical year' weather files which are obtained by concatenating twelve Typical Meteorological Months selected from a database of, in most cases, 30 years of data. The months are chosen based on statistical criteria (representing mostly solar and dry bulb temperature). The climatic characteristics of selected cities are summarized in Table 2.1.

Table 2.1 Climatic characteristics of selected cities

City	Latitude	Longitude	HDD (Based on 18˚C)	CDD (Based on 18˚C)
Halifax	44˚ 54’ N	63˚ 34’ W	4031	105
Quebec city	46˚ 48’ N	71˚ 24’ W	5202	133
Toronto	43˚ 41’ N	79˚ 24’ W	3570	359
Calgary	51˚ 6’ N	114˚ W	5108	40
Vancouver	49˚ 11’ N	123˚ 10’ W	2926	44

The parameters examined for each selected solar technology upgrade scenario is presented in detail in Chapter 4.

2.2.1 Case study houses

To conduct case studies in order to identify the parameters to be used in stock level evaluation of energy efficiency measures, two “case study houses” were used.

2.2.1.1 Window modification house

To assess the impact of window type and area on the energy requirement of a house, it is necessary to select a well-insulated house for case study. This condition decreases the uncertainty of window influence on energy requirement of the house because in a well-insulated house window heat losses dominate the building envelope heat losses. Also, a well insulated house is a better representative of Canadian houses. Therefore, in this study the selected house has a higher level of insulation compared to the house selected for the shading effect analysis.

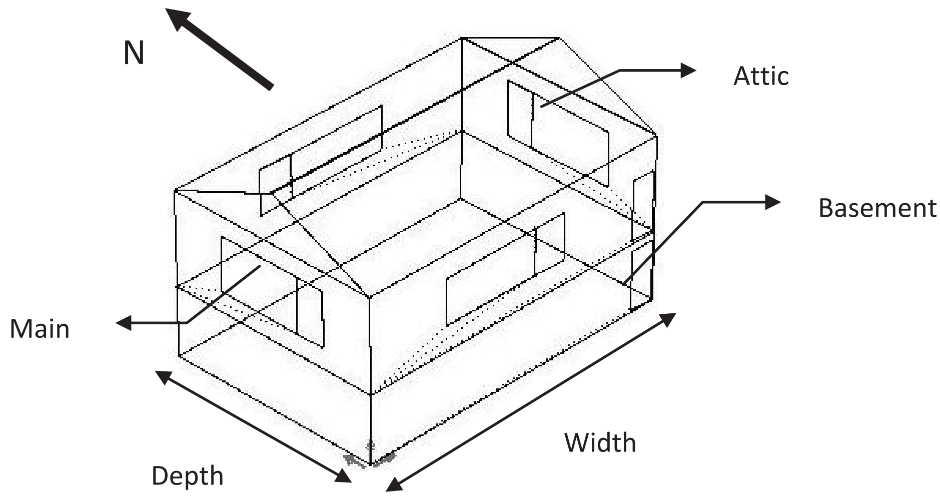


Figure 2.2 Case study house for window modification

Table 2.2 Characteristics of the "case study house" for window modification

Built year	1981
Floor-Area (m^2)	96
Width (m)	12
Depth (m)	8
Height (including attic) (m)	7.5
U-value above-grade walls ($W/m^2.K$)	0.226
R-value above-grade walls ($ft^2.{}^{\circ}F.h/BTU$)	25
U-value ceiling ($W/m^2.K$)	0.132
R-value ceiling ($ft^2.{}^{\circ}F.h/BTU$)	43
U-value basement walls ($W/m^2.K$)	0.877
R-value basement walls ($ft^2.{}^{\circ}F.h/BTU$)	6.5
U-value basement floor ($W/m^2.K$) (no insulation)	5
Front side	South

The one-storey test case house is composed of an above-grade storey, a conditioned basement and a non-conditioned attic. Since the attic is not intended to have airflow exchange with other zones, it is intentionally vented using large openings. The air flow networks (AFN) capability of ESP-r is used to estimate the airflow through these vents[1]. It is occupied by four adults, and has a set of appliances including a refrigerator, washer and dryer, dishwasher and TV[2]. The thermal characteristics of the house are given in Table 2.2, while Figure 2.2 shows the geometry.

2.2.1.2 Venetian blind house

Since the main effect of shading is on cooling energy requirement, a house with cooling system is required for this case study. Therefore, a house which has a cooling system was selected for the Venetian blind parametric study.

The case study house is a one-storey house composed of an above-grade storey, a conditioned basement and a non-conditioned attic. It is occupied by four adults, and has a set of appliances including a refrigerator, washer and dryer, dishwasher and TV. The thermal characteristics of the house are given in Table 2.3, while Figure 2.3 shows the geometry.

The modeling process and assumptions are similar to the case study house of window modification.

2.3 Indoor temperature control

Three thermal zones representing the basement, the attic and the living space were used to model the house in the ESP-r energy simulations. In the thermal model, the living space and basement are conditioned by the HVAC system while the attic is “free floating” in response to the thermal contact with the other zones and the outdoors. The space heating and cooling temperature set-points were specified as 21 and 25°C, respectively. As shown in Table 2.4, to consider occupant behavior and different climates in Canada five control periods are defined (Swan, 2010). The contact between the basement zone and the ground is modeled with the BASESIMP model (Beausoleil-Morrison and Mitalas 1997) and the

[1] For more details on modeling the attic and AFN please refer to Swan (2010).

[2] The number of occupants is based on the CSDDRD input data which is typical occupancy for Canadian residential houses.

air infiltration is modeled with the AIM-2 model[1] (Walker, et al. 1990). To simplify the model, windows are placed at the geometric center of the walls. This is a reasonable assumption based on the findings of Purdy and Beausoleil-Morrison (2001). It is assumed that there is no obstruction around the house to block solar gain.

Table 2.3 Characteristics of the "case study house" for Venetian blind

Built year	1955
Floor-Area (m^2)	102
Width (m)	12.4
Depth (m)	8.2
Height (including attic) (m)	6.3
U-value above-grade walls (W/m^2 K)	1.22
R-value above-grade walls	4.7
U-value ceiling (W/m^2 K)	0.192
R-value ceiling	29.5
U-value basement walls (W/m^2 K)	1.351
R-value basement walls	4.2
Number of windows	4 (one each side)
Window area (m^2)	6
Window type	Clear glass double glazed with 13 mm air gap
Front side	West

Table 2.4 Five periods space heating and cooling available

Period	Date	Space heating available	Space cooling available
1	Jan1 – Apr 1	✓	
2	Apr2 – Jun 3	✓	✓
3	Jun 4 – Sep 16		✓
4	Sep 17 – Oct 7	✓	✓
5	Oct 8 – Dec 31	✓	

2.4 Estimation of the annual energy savings and the reduction in GHG emissions for each solar technology upgrade scenario

As shown in Figure 2.1, each selected solar technology upgrade scenario is applied to CHREM and the resulting annual heating and cooling energy consumption is compared with the base case heating and cooling energy consumption to determine the heating and cooling energy savings due to the retrofit. The annual GHG emissions with each solar

[1] The AIM-2 model calculates the infiltration rate for each time step. The implementation can be found in Beausoleil-Morrison (2000) and Wang et al. (2009).

technology are compared to the base case GHG emissions to determine the GHG emission reduction due to each solar technology retrofit.

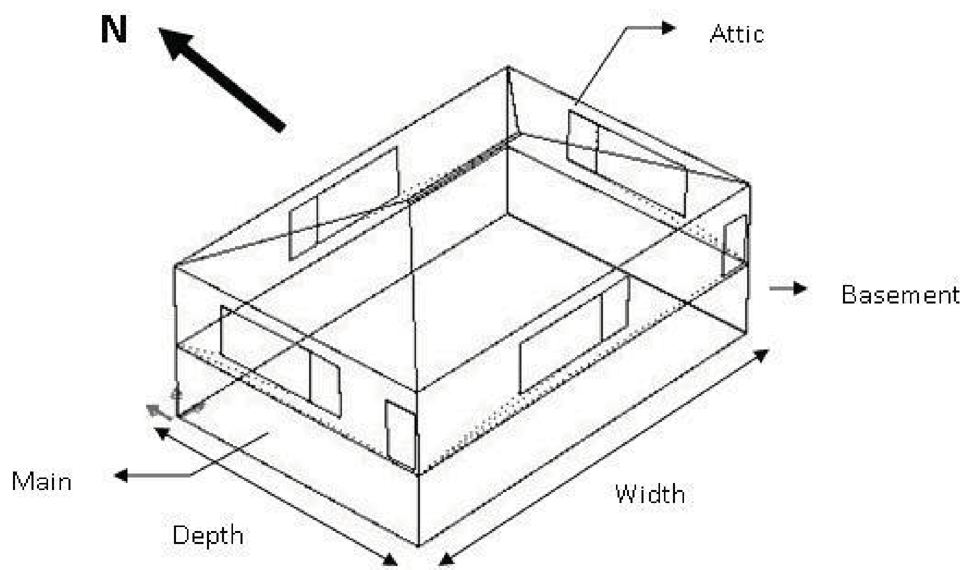


Figure 2.3 Case study house for Venetian blind

Since cooling energy savings is an important issue for retrofits like shading devices, the occupant interventions such as controlling window openings/closings, blind operations and thermostat set-points are considered in the model. To deal with controlling window openings/closings, CHREM considers a conservative regime which assumes two cases, no space cooling (SC) system exists and SC system exists. If no SC system exists, the windows may be opened when the zone temperature is greater than the ambient temperature, and both temperatures are above the heating set-point. If a SC system does exist, the preceding remains true, and the windows will close if the zone temperature rises above the cooling set-point (Swan, 2010).

To determine the annual energy savings and the reduction in GHG emissions associated with each solar technology upgrade scenario, first it is necessary to identify the houses that could receive the upgrade. Thus, for each solar technology scenario, the houses in the CSDDRD are screened to determine which house is eligible to receive the upgrade (the eligibility criteria for each technology are explained in Chapter 3).

In reality not all house owners are willing to upgrade so a penetration level is required to reflect the percentage of eligible houses that would be upgraded. Also, to assess the impact of occupant behaviour these houses shall be selected randomly. To study the impact of penetration level and occupant behavior on energy savings and GHG reduction, the results of at least three different penetration levels have to be compared. For example, 10%, 30% and 50% of eligible houses could be selected randomly and simulated. However, this method has two disadvantages:

1- Since the houses are selected randomly, it is not possible to compare the impact of two different upgrade scenarios for the same penetration level.
2- Since the houses for each penetration level is selected once, the results are subject to change by selection of another group of houses for the same penetration level and upgrade scenario. Therefore, the results of different penetration levels for the same upgrade scenario are not comparable and not reliable for energy policy decision making. However, this method would be appropriate if the occupant behaviour for only one upgrade was the scope of work.

To get more precise results which are suitable for this work, two approaches can be used. The first approach is to select houses randomly for each penetration level for a number of iterations. The mean value and the standard deviation of those iterations give a better estimation of the results. The second approach is upgrading all eligible houses and scaling the results to each penetration level. Comparing those results shows that the scaled results are in the range of mean ± standard deviation values for each penetration level. Therefore, for the purpose of this study, the second approach is suitable and it was used.

Once the houses to receive a given upgrade are identified, those house files are modified to reflect the upgrade, and another ESP-r batch simulation is conducted. The resulting energy consumption reflects the energy savings associated with the given upgrade. Thus, the annual energy savings associated with the upgrade is determined by subtracting the energy consumption with upgrade from the base case energy consumption.

Once the annual energy savings with the upgrade is determined, the GHG emission reductions are calculated based on the fuel type used at each dwelling. These emissions include those due to on-site fuel combustion and the emissions directly attributable to electricity production, inclusive of transmission.

The GHG emissions are calculated using GHG emission intensity factor (EIF) which is the level of CO_2e emitted per unit input energy. While the GHG EIF is constant for on-site fuel combustion, it varies with province for electricity generation. To generate electricity a combination of base and marginal power plants is used, which uses different fuel sources. The energy savings associated with the given upgrade has a direct impact on the marginal load. Therefore, the base case GHG emissions due to the electricity consumption of the CHS are calculated using the average GHG EIF of the regional electricity generation and the changes due to the upgrade is calculated using the marginal GHG EIF of the regional electricity generation. The available annual and monthly GHG EIFs for different provinces of Canada are shown in Table 2.5 (Farhat and Ugursal, 2010).

Table 2.5 Average and marginal GHG EIFs and transmission/distribution losses for Canadian provinces (Farhat and Ugursal, 2010)

Electrical generation characteristics		Canadian provincial GHG EIF (CO_2e per kWh)									
		NB	NF	NS	PE	QC	OT	AB	MB	SK	BC
Annual $EIF_{Average}$		433	26	689	191	6	199	921	13	789	22
Annual $EIF_{Marginal}$		800	22	360	6				1	225	18
Monthly $EIF_{Marginal}$	Jan					23	395	825			
	Feb					0	352	825			
	Mar					0	329	795			
	Apr					0	463	795			
	May					0	501	795			
	Jun					0	514	780			
	Jul					0	489	780			
	Aug					0	491	780			
	Sep					0	455	780			
	Oct					0	458	795			
	Nov					0	379	825			
	Dec					4	371	825			
Transmission and distribution losses		6%	9%	4%	6%	4%	6%	4%	12%	6%	3%

2.5 Estimation of the tolerable capital cost for each energy efficiency upgrade scenario

Since some of the solar technologies considered for upgrade are still in early phases of commercialization, it is not possible to estimate realistic total investment costs. Consequently, it is not possible to conduct a conventional economic feasibility analysis.

Thus, an alternative approach to conventional economic feasibility analysis is adopted here which involves the calculation of "tolerable capital cost" of the upgrades. "Tolerable capital cost" is the capital cost that one is able to pay based on the annual savings, the number of years allowed for pay-back, and the estimated annual interest and fuel cost escalation rates. Thus, to estimate the tolerable capital cost of each upgrade a reverse payback analysis is conducted as follows:

1. The annual fuel and electricity savings for each upgrade is estimated ($).
2. A realistic cost of money (interest rate) for residential customers borrowing money to finance the retrofit is assumed.
3. A realistic fuel cost escalation rate for fuels and electricity is assumed.
4. A realistic payback period that would be acceptable for the residential customer is assumed.
5. A reverse payback analysis is conducted to determine the tolerable capital cost of the upgrade for each house (TCCH) that will result in the assumed payback period:

$$\mathrm{TCCH} = \mathrm{ACSH}\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] \quad \text{where } i \neq e \tag{2.1}$$

where:

$$\mathrm{ACSH} = \sum_{j=1}^{m}(F * E)_j \tag{2.2}$$

where:

TCCH = The tolerable capital cost of the retrofit ($)
n = The number of interest periods (year)
i = The interest rate per interest period (%)
e = The fuel cost escalation rate per interest period (%)
ACSH = The annual cost save due to energy saving per in a uniform series, continuing for n periods ($)
E = Energy saving per period for each fuel type (depends on fuel type kg, litre, kWh)
F = Fuel price per amount for each fuel type ($/amount)
m = Number of different fuels used in a house

It should be noted that in this approach the additional installation and maintenance cost of the upgrade over and above that of the replaced system is assumed to be included in the TCC as a present value of the installation and the annual maintenance cost over the lifetime of the upgrade.

The interest rates used in the analysis are based on the Bank of Canada Prime Rate (BOC 2012), which was 1% in September, 2010. Thus, for the sensitivity analysis, interest rates of 3%, 6% and 9% are used. These numbers were selected based on the range of consumer loan's rate.

The predicted fuel cost escalation rates for each fuel type are extracted from National Energy Board of Canada (NEB, 2012) and Energy Escalation Rate Calculator (WBDG, 2012) for the medium rates. Therefore, a set of low, medium and high rates are selected as shown in Table 2.6.

Table 2.6 Real fuel escalation type for each fuel type

	Low (%)	Medium (%)	High (%)
Electricity[1]	2	6	10
Natural gas[2]	2	5	8
Light fuel oil[2]	6	10	14
Propane[2]	2	5	8
Mixed wood[3]	3	6	9

1- Electricity escalation rates are extracted from National Energy Board of Canada (NEB, 2012)
2- Fuel cost escalation rates are extracted from Energy Escalation Rate Calculator (EERC) (WBDG, 2012)
3- Wood escalation rate is based on the money interest rate as there is no source for its escalation rate

The payback period is selected based on the social demand as 2, 6 and 10 years.

Table 2.7 Fuel prices in each province

	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[1] (cents/kWh)	12.41	15.23	14.3	13.36	7.7	12.65	8.36	14.42	17.22	8.27
Natural gas[2] (cents/m^3)	N/A	N/A	45.3	46.04	47.91	28.96	33.41	27.92	20.31	42.8
Light fuel oil[3] (cents/litre)	104	97.2	100.8	108.1	109.8	117.2	107.7	107	N/A	115.7
Propane[4] (cents/litre)	N/A	N/A	96	116.5	95.4	65.9	85.9	N/A	79.9	78.9
Wood[5] ($/tonne)	156.25	156.25	156.25	218.75	159.38	187.5	162.5	156.25	312.5	150

1- Electricity prices are extracted from Hydro-Quebec (Hydro-Quebec, 2011)
2- Natural gas prices are extracted from Statistics Canada handbook (Statistics Canada, 2011)
3- Heating oil prices are extracted from Statistics Canada Handbook (Statistics Canada, 2011)
4- Propane prices are extracted from Nova Scotia department of energy (Nova Scotia Department of Energy,2011)
5- Wood prices are gathered from local companies

2.6 Fuel prices

For each province, fuel prices for natural gas, residential heating oil, electricity and propane were obtained to calculate the energy cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 2.7.

2.7 Evaluation of the economic feasibility of upgrade scenarios

It is not practical or useful to report the tolerable capital cost for each house in CSDDRD, or for that matter within the CHS because from a macro level of interest, data on individual houses have no utility. Thus, to evaluate the economic feasibility of the solar technology upgrade scenarios, two indicators, namely, "average tolerable capital cost per house" (ATCCH) and "average tolerable capital cost per upgrade unit" (ATCCU) are used. These indicators are calculated by dividing the total tolerable capital cost for each scenario (i.e. interest rate, fuel cost escalation rate and payback period) by number of houses or by number of upgrade units (e.g. window area for window modification upgrade):

$$\mathrm{ATCCH} = \mathrm{TTCC} / \mathrm{NH} \tag{2.3}$$

where:

TTCC = total tolerable capital cost as a result of the upgrade ($)

$$\mathrm{TTCC} = \sum_{i=1}^{NH} \mathrm{TCCH}_i \tag{2.4}$$

where:

NH = number of houses that received the upgrade

$$\mathrm{ATCCH} = \mathrm{TTCC} / \mathrm{TNUU} \tag{2.5}$$

where:

TNUU = total number of upgrade unit

2.8 Increase in value of houses due to solar technology upgrades

It is certain that adding solar technology upgrades to a house increases its market value; however, the estimation of the increase in market value due to such upgrades is not straight forward due to a number of reasons including buyer perception and sophistication, market forces, and energy prices. Due to the complex nature of the impact of upgrades on the market value of a house this issue was not considered in this work. Nevertheless, the reader needs to be aware that in addition to the advantages of solar technologies addressed here, i.e. the reduction in energy consumption and GHG emissions, part of the economic consequence of solar technology upgrades is the increase in market value of a house.

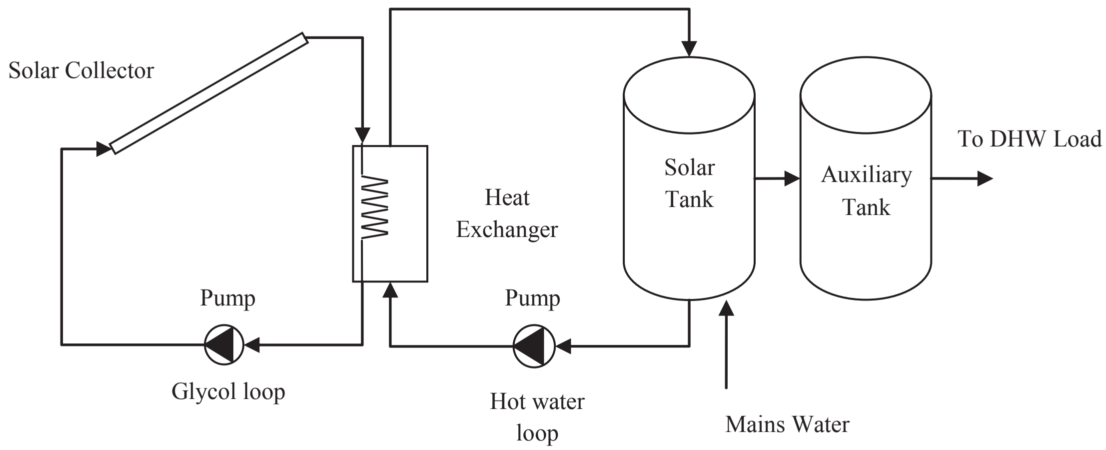
CHAPTER 3 MODELING OF SELECTED SOLAR TECHNOLOGIES

In Section 1.3, a set of solar technologies, given in Table 2.6, were identified to be suitable for the CHS based on the results of a literature review and the suitability of the technologies for the northern climate of Canada. In the following sections, the methodologies used for modeling the selected solar technologies within the ESP-r environment are presented.

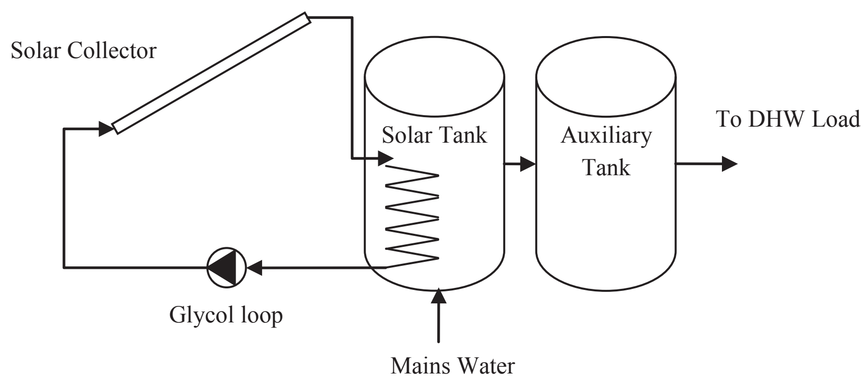
3.1 Solar domestic hot water system

As discussed in Section 1.3, the most suitable SDHW heating technology for the CHS is the forced circulation (active) type systems utilizing an anti-freeze solution (commonly propylene glycol-water) with flat plate collectors. The three commonly encountered architectures for active SDHW systems are shown in Figure 3.1. While all three architectures are similar and employ an auxiliary tank equipped with an auxiliary heat source to provide heating when there is not enough solar energy to meet the demand, they differ in the way the heat is transferred from the glycol loop to the DHW. Among these three systems, only the solar-tank in system 3 contains water-glycol mix which is not practical in reality and very expensive in case of capital cost and maintenance. Therefore, in this work, systems 1 and 2 are evaluated for the CHS.

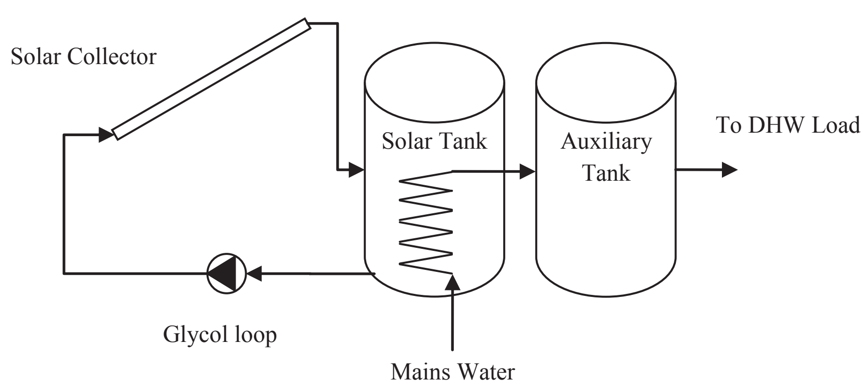
All components of the SDHW heating systems given in Figure 3.1 can be modeled using the standard component models available in the ESP-r software. Also, ESP-r provides the connectivity and control algorithms required to simulate the performance and operation of the selected SDHW heating systems. To determine the suitable input values for the SDHW heating systems, it is appropriate to review the modeling of two main components of the system, namely, the flat plate collector and the tank with an immersed coil (used in systems 2 and 3 in Figure 3.1),



a) System 1



b) System 2



c) System 3

Figure 3.1 Solar domestic hot water systems to be modeled

As described in Thevenard et al. (2006) and Haddad et al. (2007), in modeling the glycol-water loops of the SDHW systems in ESP-r, the physical properties of the water-glycol mixture need to be determined using a separate subroutine based on the glycol mass fraction in the mixture, and input into the ESP-r model since the ESP-r modeling environment was originally designed to model systems that use either water or moist air as the working fluid.

Similarly, it is necessary to estimate the temperature of the mains water entering the SDHW system in order to determine the amount of energy collected by the solar collector as well as the amount of energy required to heat the DHW. Haddad et al. (2007) modified the method developed by Moore (1986) to estimate the mains water temperature based upon estimating first the average ground temperature and the ground temperature amplitude for a given location as a function of the heating degree days and the annual average temperature, and then estimating the monthly mains water temperature based on these parameters and an empirical depth amplitude modifier. Haddad et al. incorporated their model into ESP-r and this model is used in this project.

3.1.1 Modeling of the flat plate solar collector

The flat plate collector model that is used in this work is the empirical model developed for and incorporated into the ESP-r by Thevenard et al. (2006). The model is based on an empirical solar collector efficiency equation which predicts collector efficiency (η) as a function of two parameters characteristic of the collector that are determined empirically, as well as the collector outlet and ambient temperatures, and the solar radiation incident upon the collector:

$$\eta = F_R(\tau\alpha)_n - F_R U_L \frac{(T_o - T_a)}{G} \qquad (3.1)$$

where:

F_R = collector heat removal factor (-)
$(\tau\alpha)_n$ = normal-incidence transmittance-absorptance (-)
U_L = collector overall loss coefficient (W/m^2 ˚C)
T_o = collector outlet temperature (˚C)
T_a = ambient temperature (˚C)

G = radiation incident upon the collector (W/m^2)

Since it is common to report collector efficiency as a linear or quadratic function of either the collector inlet temperature (North American practice) or the average collector temperature (European practice), Thevenard et al. transform Equation (3.1) to accommodate all four possibilities, and incorporate each one of the four modified collector efficiency functions into a separate quasi steady-state energy balance equation of the collector [1]. Thus, four quasi steady-state energy balance equations of the collector are used to model the collector performance. As an example, the energy balance equation incorporating a linear collector efficiency equation expressed as a function of the collector inlet temperature is given as follows:

$$M\bar{c}\frac{\partial T_o}{\partial t} = -\left(\dot{m}C_p - AF_RU_L\right)(T_o - T_i) + F_R(\tau\alpha)_n AG - F_RU_LA(T_o - T_a) \tag{3.2}$$

where,

M = mass of the collector and the fluid it contains (kg)
$\bar{c}$ = collector mass weighted average specific heat capacity (J/kg ˚C)
$\dot{m}$ = the flow rate through the collector (kg/s)
C_p = collector fluid heat capacitance (J/kg ˚C)
T_i = collector inlet temperature (˚C)
A = gross area of the collector (m^2)
F_R = collector heat removal factor (-)

The energy balance equations for the other cases are given in Thevenard et al. (2006) and are not repeated here.

Since it is common to operate solar collectors at flow rates other than the test flow rates and since the angle of incidence of solar radiation varies at all times, correction factors are necessary to modify the collector efficiency and the energy balance equations to account for these variations.

To reflect the effects of collector flow rate and the angle of incidence of the solar radiation on collector efficiency, the use of the *flow rate correction coefficient (r)* given

[1] Considering the order of magnitude difference between the time constant of most flat plate collectors (about 90 s) and the typical time step of building simulation (15 min to 1 hour), the quasi steady-state assumption in formulating the energy balance equation is acceptable.

in Equation (3.3) and *incidence angle modifier (κ)* given in Equation (3.6) which is determined from the test data, respectively, are recommended by Thevenard et al. (2006). Both of these correction methods were developed by Duffie and Beckman (2006).

$$r = \frac{B_u}{B_t}\frac{[1-\exp(-1/B_u)]}{[1-\exp(-1/B_t)]} \tag{3.3}$$

where, B_u and B_t is defined as follows:

$$B_t = \frac{\dot{m}_t C_{p,t}}{AF'U_L} \tag{3.4}$$

$$B_u = \frac{\dot{m}_u C_{p,u}}{AF'U_L} \tag{3.5}$$

In these equations, subscripts t and u refer to the test and use conditions, respectively.

$$\kappa = 1 - b_0\left(\frac{1}{\cos\zeta} - 1\right) - b_1\left(\frac{1}{\cos\zeta} - 1\right)^2 \tag{3.6}$$

where,

b_0 and b_1 = incidence angle modifier coefficients (-)
ζ = angle of incidence of solar radiation upon the collector (degree)

However, as noted by Thevenard et al. (2006), caution needs to be exercised in using both Equations (3.3) and (3.6) since these equations can produce erroneous predictions under certain conditions: (i) when using the *flow rate correction coefficient (r)*, it is necessary to ensure that the flow in the collector tubes does not fall within the transition region between laminar and turbulent flow because the correction factor does not produce accurate predictions of the change of collector efficiency if the flow is in the transition region, (ii) the formulation given in Equation (3.6) may produce erroneous predictions of *(κ)* when the angle of incidence upon the collector is close to 90°, and for some collectors, greater than 45°.

The input data required for the collector model, as well as the recommended default values are given in Table 3.1.

3.1.2 Modeling of the tank with an immersion heater

Since two of the SDHW systems shown in Figure 3.1 employ a water tank with an immersion heater, in this work the model for this type of tank developed and incorporated into the ESP-r/HOT3000 environment by Haddad et al. (2007) is used.

Table 3.1 Input data required for the flat plat solar collector model

Input Parameter	Unit	Description/comments	Default Value (based on ESP-r)
Collector Area	m^2	Net solar collector area	2.865
Type of efficiency equation	N/A	1- If efficiency equation is in terms of inlet temperature 2- If efficiency equation is in terms of average temperature	1(North-America)
Coefficients of efficiency equation			
Constant coefficient	N/A		0.694
Linear coefficient	$W/m^2.C$	To be provided based on collector	4.85
Quadratic coefficient	$W/m^2.C^2$	testing results by the manufacturer or	0
Collector test flow rate	kg/s	user	0.038
Heat capacitance of fluid used for test	J/kg.C		4200
Incidence angle correction method		1- If correction factor correlation is used 2- If data pairs of incidence angle and associated correction factor is used	1
Coefficients of incidence angle modifier equation			
Linear term	N/A	To be provided based on collector	0.2
Quadratic term	N/A	testing results by the manufacturer or user	0
Number of data pairs for incidence angle correction	N/A	Up to 8 pairs can be entered	5
1st data pair angle	degree	User input	0
1st data pair factor	N/A	User input	1

The model assumes a fully mixed tank, an assumption supported by the location of the heat exchanger at the bottom of the tank, and is based on two separate energy balance equations, one for the tank (fluid + walls) and one for the immersed helical heat exchanger (fluid + walls), which are solved iteratively.

The energy balance for the tank is given as:

$$\left(MC_p\right)_s \frac{dT_s}{dt} = \left(\dot{m}C_p\right)_{s-1}\left(T_{s-1} - T_s\right) + (UA)_s\left(T_e - T_s\right) + \dot{Q} \quad (3.7)$$

and, the energy balance for the heat exchanger is given as:

$$\left(MC_p\right)_c \frac{dT_c}{dt} = \left(\dot{m}C_p\right)_{c-1}\left(T_{c-1} - T_c\right) - \dot{Q} \tag{3.8}$$

where,

T_c = heat exchanger outlet temperature (˚C)
T_{c-1} = heat exchanger inlet temperature (˚C)
T_s = tank temperature (˚C)
T_{s-1} = tank inlet temperature (˚C)
M = tank or heat exchanger mass (kg)
C_p = specific heat capacity of the tank or heat exchanger (J/kg˚C)
UA = overall heat loss coefficient of the tank (W/˚C)
$\dot{Q}$ = heat transfer (J/s)

The heat transfer between the heat exchanger and the tank is determined using empirical correlations developed by Manlapaz and Churchill (1981) for the flow inside the tube (assuming laminar flow) and by Taherian and Allen (1998) for the natural convection flow outside of the helical coil.

The input data required for the tank with immersion heater model, as well as the recommended default values are given in Table 3.2.

Table 3.2 Input data required for a tank with immersed coil

Input Parameter	Unit	Description/comments	Default Value (based on ESP-r)
Mass of tank (fluid + walls)	kg	User input	200
Specific heat of the tank	J/kg.C	User input	4200
Mass of heat exchanger (fluid + tubes)	kg	User input	10
Specific heat of the heat exchanger	J/kg.C	User input	4200
Tank UA	W/C	Overall heat loss coefficient of the tank; user input	5
Total length of tube	m	Total length of tube of heat exchanger; user input	10
Inside diameter of the tube	m	User input	0.012
Outside diameter of the tube	m	User input	0.014
Tube wall thermal conductivity	W/m.C	User input	300
Diameter of curvature of coil helix	m	User input	0.5
Heat exchanger height	m	User input	0.5
Diameter of tank shell	m	User input	0.5
Coil type	N/A	1- Horizontal 2- Vertical Helix	1

3.1.3 Methodology to select houses eligible for SDHW system retrofit

There are two criteria that need to be satisfied simultaneously to establish the suitability of a house for a SDHW system retrofit:

1. The presence of a roof with significant surface area facing the correct direction with the correct tilt angle.
2. The presence of a DHW system with storage tank.

Therefore, the following selection rules are used to identify houses for SDHW system retrofit. It should be noted that all rules must be simultaneously satisfied.

1. Slope of the roof: the tilt angle of the collector has a significant effect on the performance of the collector. The optimum solar collector tilt angle depends on the latitude of the site at which house is located. The optimum slope angle varies between latitude -10˚ and latitude + 15˚ (Iqbal, 1979). Since roof slope is not specified in CSDDRD, reflecting the commonly encountered roof angles in the CHS, it is assumed in CHREM that all houses with attic/gable roof have a run:rise relationship of 5:12, which corresponds to a slope of about 23° (Swan, 2010). It is assumed in this work that the solar collector is installed directly on the roof, i.e. at an angle of 23˚, to avoid the construction of additional structures to attach the solar collectors to the roof. This assumption results in less than optimum thermal performance of the solar collector, however it is a reasonable assumption considering the magnitude of the additional structural work needed on the roof to accommodate a different inclination angle for the solar collector.

2. Orientation of the roof: in the northern hemisphere, the maximum average insolation occurs on a surface facing towards the equator. Therefore, houses with the roof orientated toward the south, south-west or south-east (i.e. houses that have a ridgeline running east-west) are considered.
   Since the ridgeline is not specified in CSDDRD, it was assumed that the ridgeline runs parallel to the longer of either the house width or side length (Swan, 2010). It should be noted here in case of SD houses, flat and hip roofs are not considered because flat roofs are not sloped and hip roofs do not have two parallel straight edges at the top and bottom of the roof, thus a collector cannot be mounted on a hip roof as shown in Figure 3.2.
   In the case of DR, as shown in Figure 3.3 with a hip roof on the right or the left and, and a ridgeline of more than 4 m, it is possible to mount a collector.

3. Roof area: Commonly, the maximum collector area for a residential building is not more than 6 m^2 (Thermo Dynamics Ltd, 2009). The roof area of all houses in CSDDRD are larger than this value, therefore there is no limitation regarding the roof area.

4. Existence of a DHW system with storage tank: to install the solar storage tank, auxiliary tank and other SDHW system accessories such as pipes and pumps, a basement is required. However, there are houses in CSDDRD which have DHW system without any storage tank which does not need basement. Therefore, the existence of a DHW system with storage tank is required to make sure there is a basement to install storage tanks.

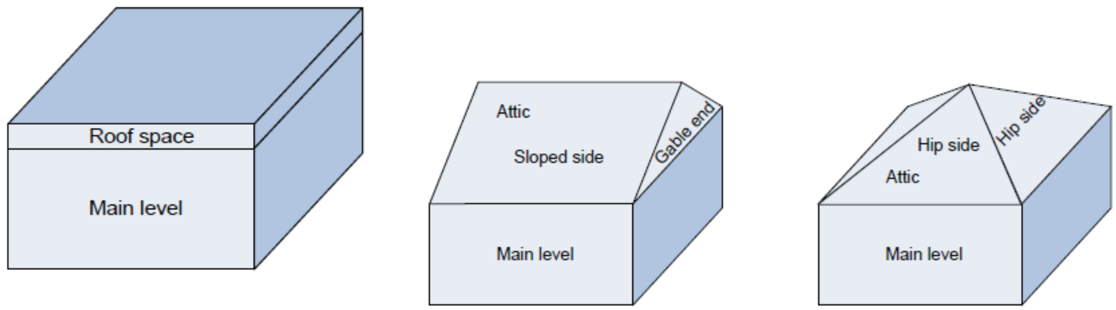


Figure 3.2 Roof space or attic configurations (a) flat roof space, (b) gable type attic, (c) hip type attic (Swan, 2010)

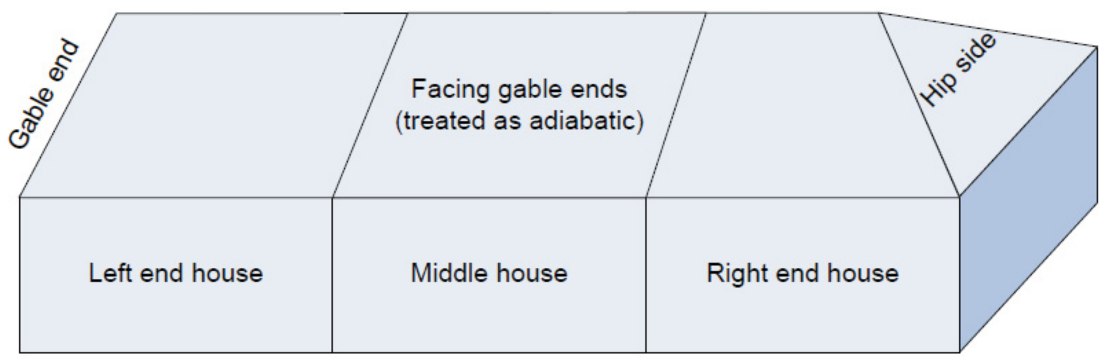


Figure 3.3 DR type houses with gable and hip type attics (Swan, 2010)

3.2 Solar space heating

As it was concluded in section 1.3, three solar space heating technologies are suitable for the Canadian climate:

- Fixed shading devices to control direct solar heat gains through windows,
- Movable shading devices to control direct solar heat gains and losses through windows,
- Phase change material (PCM) to store solar heat gains during the day and release it to the house during the night.

In addition to these three technologies, increasing the south facing window area and changing window type is also evaluated to identify economically feasible window area enlargement and thermal characteristic modification options.

3.2.1 Modeling of fixed and movable shading devices

As concluded in section 1.3, two technologies are suitable for solar shading of houses in Canada:

- Fixed Venetian blind
- Movable Venetian blind

To accurately model fixed and movable Venetian blinds the new component, "Complex Fenestration Construction (CFC) model" added to ESP-r by Lomanowski (2008) to model Venetian blinds, is used. A review of the CFC model is presented below.

3.2.1.1 Modeling of Venetian blinds

Since there is no significant wavelength overlap between solar (short-wave) and thermal (long-wave) radiation, the analysis of the energy performance of windows with shading devices is carried out in two steps: solar and thermal analysis. Solar analysis determines the solar energy fluxes that include transmission, absorption and reflection at each glazing layer, whereas in thermal analysis, the absorbed quantities are considered as energy source terms to establish the energy balance at each layer.

3.2.1.1.1 Solar analysis

Determining the optical properties of a glazing/shading system requires the calculation of the effective solar optical properties of the shading layer and considering its interaction with the glazing layer(s).

The effective solar optical properties of a slat-type blind (i.e. Venetian blind) are estimated based on a simplified model developed by Kotey et al. (2009) that uses slat geometry, slat material optical properties, and direction and type (beam or diffuse) of incident radiation as model parameters. The slat material optical properties are assumed to be independent of the angle of incidence and the slats are assumed to transmit and reflect solar radiation diffusely. The estimation of the solar optical properties of a Venetian blind layer is carried out in two steps. First, the slats are assumed to be flat with negligible thickness, and then a correction is applied to consider slat curvature. This correction prevents the model from over-predicting blind transmission when the solar profile and slat angles are aligned.

The amount of incident solar flux that is absorbed, reflected and transmitted in each layer is calculated based on the extended multi-layer model of Wright et al. (2006). The model establishes a balance of solar flux components for each layer including beam-beam fluxes, diffuse-diffuse fluxes and beam-diffuse fluxes. Thus, the model provides full detail concerning the quantities of the reflected, transmitted and absorbed solar radiation. The method is general enough to allow for introduction of incident solar radiation both on the outdoor side and indoor side of the window (Lomanowski, 2008).

Since the solar optical properties of each layer are calculated explicitly, this approach gives the CFC model the flexibility to vary the properties of each layer, such as slat angle, at any time step.

3.2.1.1.2 Thermal analysis

The CFC model considers one dimensional heat transfer through the center-of-glass, neglecting the edge and frame effects. The absorbed solar energy fluxes obtained from the solar analysis of the CFC model are used as an energy source term, which is then transmitted via conduction, convection and long-wave radiation inward and outward. Presence of a shading layer changes the long-wave radiation exchange and convective heat transfer behaviour.

Radiant heat transfer coefficients between any pair of surfaces of a window and Venetian blind system, including diathermanous and opaque surfaces, are calculated using a method developed by Wright (2008). This method is based on a set of exchange factors which provide the fraction of the radiant energy emitted by surface i that reaches surface j by direct radiation and all possible reflections.

When a shading layer such as a Venetian blind is added to a glazing system, the nature of convective heat transfer is highly dependent on the position of this layer (i.e. indoor, outdoor or between-the-glass), i.e. the boundary conditions. For instance, airflow around the outside blind is dictated by the outdoor conditions whereas for indoor blinds, ventilation and temperature conditions influence the flow. To predict the center-of-glass convective heat transfer for between-the-glass shading layer, the model developed by Huang et al. (2006) is used. This model accounts for the presence of the blind by applying a modification factor to the slat width, which effectively increases the cavity spacing. The convective heat transfer for a shading layer that is exposed to an indoor environment is predicted as a function of the distance from the tip of the blind slats to the glass surface using the model developed by Wright (2008).

When the blind is placed on the outside of the shading/glazing system, convection heat transfer takes place on both sides of the blind slats as well as the outdoor glass surface. Therefore, the external convective heat transfer coefficient which is supplied by the user or calculated based on wind speed and direction, surface orientation and temperature condition, is applied as an approximation to the front and back of the blind as well as the outdoor glass surface. It is assumed that the interaction between the blind and outermost glass surface is ignored. This is a valid assumption as an outside blind is exposed to forced convection. Essentially, the blind is assumed to have no influence on the air flow at the outdoor glass surface and the outermost cavity is considered fully vented. This assumption may cause errors during calm sunny conditions when the solar radiation absorbed in the outdoor blind is not readily rejected back to the ambient due to low convective heat transfer rates thus creating a hot zone adjacent to the window (Lomanowski, 2008).

The Venetian blind control which has been added into ESP-r by Lomanowski (2009) is an independent control from building and plants control. Currently, there are three types of control available for Venetian blinds: 1 - slat angle control, 2 - shade retract/deploy (this is the shading on/off type of control) and 3 - schedule for both slat angle and shade retract/deploy. This control can be defined along with building and plant controls.

The input data required for the CFC model, as well as the recommended default values are given in Table 3.3.

Table 3.3 Input data required for CFC model

Input Parameter	Unit	Description/comments	Default Value (based on ESP-r)
Number of glazing/shading layer	-	It can be 2 layers which represents single glazing with a shading layer to 8 layers	3
Shading layer position	-	Inside, outside or between-the-glass	outside
		Slat geometry properties	
Slat angle	degree	0 (horizontal), 90 (vertical)	45
Slat width	mm	User input	12.7
Slat spacing	mm	User input	1.058
Slat thickness	mm	User input	0.33
Distance of shading layer to glass	m	Applicable for inside and outside shading layers	0.04
Between-glass gap space	m	Applicable for between-the-glass shading layer	0.0254
		Slat solar properties	
Slat reflectivity	-	User input	0.5
Slat emissivity	-	User input	0.85
Slat transmittance	-	User input	0
Gap thickness	mm	User input	12.7
Filling gas type	-	User input	Air

3.2.1.2 Methodology to select houses eligible for shading devices retrofit

There are two criteria that need to be satisfied simultaneously to establish the suitability of a house for all types of shading device retrofit:

1- The presence of a window in the proper orientation.
2- The presence of cooling system,

Therefore, the following selection rules are used to identify houses for fixed and controlled shading device retrofit.

1- Venetian blind retrofit (fixed):
    a. Presence of a window on the west, south-west, east and south-east side of the house is necessary for this retrofit. Since in summer solar incidence angle is small in the morning and afternoon, and close to normal to the surface of western and eastern windows, an overhang is not an effective shading device. Therefore, vertical shading devices such as Venetian

blinds should be used on western and eastern sides of a house for preventing solar radiation to the zone during these periods.

   b. Existence of cooling system in the house to estimate the effect of shading device on cooling energy requirement.

2- Controlled shading device retrofit:

   a. Since the presence of shading device can be controlled in this case, all houses that have windows on any side other than north, north-east and north-west are eligible for controlled shading devices.
   b. Existence of cooling system in the house to estimate the effect of shading device on cooling energy requirement.

3.2.2 Modeling of thermal storage with phase change materials (PCMs)

As discussed in section 1.3, the most suitable thermal storage technology for retrofitting a house is PCM storage. PCMs are a type of active building elements whose thermophysical properties change in response to external thermal excitation. To model active building elements,"special materials" concept was introduced into ESP-r by Kelly (1998). The special material functions are applied to a particular node within a multi-layer construction.

To model the thermal behaviour of PCM, two numerical techniques, "Effective Heat Capacity" and "Additional Heat Source" method, were introduced into ESP-r and compared by Heim, et al. (2003) and Heim (2005). The "Effective Heat Capacity" method is based on the addition of a material capacity temperature-dependent function whereas "Additional Heat Source" method assumes that the latent heat stored or released by the PCM corresponds to some internal heat source. This heat source represents the enthalpy change of the PCM layer when the phase change process initiates (Heim, 2005). Since the "Additional Heat Source" method is unstable for time steps higher than 1 minute (Heim, 2005), the "Effective Heat Capacity" method described below is used in the ESP-r.

3.2.2.1 Effective heat capacity method

Since the PCMs during the phase change process can be in three states, namely solid, liquid and mushy (two-phase), the heat transfer process is complex. To analyze this complex process, following simplification assumptions are made (Athienitis, et al. 1997, Heim, et al. 2003, Heim, 2005):

1- The PCM composites are treated as a body of uniform equivalent physical and thermal properties - principally specific and latent heat, density and thermal conductivity.
2- The heat transfer process across the PCM composite is considered to be one-dimensional.

The transient heat conduction with variable thermo-physical properties is given by:

$$\frac{\partial}{\partial t}\rho(T)h(T) = \nabla.[\lambda(T)\nabla T(\vec{r},t)] + g(\vec{r},t) \tag{3.9}$$

where,

t = time
T = temperature
ρ = density
h = enthalpy
λ = conductivity
$\vec{r}$ = heat transfer direction
g = sensible heat generation rate

When:

$$\frac{\partial \rho}{\partial t} \approx 0 \text{ and } \frac{\partial h}{\partial t} = \frac{\partial h}{\partial T}\frac{\partial T}{\partial t} = C_{eff}(T)\frac{\partial T}{\partial t} \tag{3.10}$$

Equation (3.9) becomes:

$$\rho(T)C_{eff}(T)\frac{T(\vec{r},t)}{\partial t} = \nabla.[\lambda(T)\nabla T(\vec{r},t)] + g(\vec{r},t) \tag{3.11}$$

where,

C_{eff} = effective heat capacity

For the nonlinear equation (3.11), the Kirchhoff transformation (Ozisik, 1980) is used to remove the temperature dependent effective heat capacity outside the differential operator by defining a new dependent variable:

$$\upsilon = \int_{C_s}^{C_l} C_{eff}(T)dT$$

where,

C_s = the heat capacity in solid phase
C_l = the heat capacity in liquid phase

Therefore, equation (3.11) can be rearranged:

$$\rho(T)C_{eff}(T)\frac{\partial T}{\partial \upsilon}\frac{\partial \upsilon}{\partial t} = \nabla.\left[\lambda(T)\frac{\partial T}{\partial \upsilon}\nabla\upsilon\right] + g(\vec{r}, t) \tag{3.12}$$

In this method, the calculation process of phase changes is controlled by both temperature and total latent energy. The effective heat capacity exists only in the transition state, when the material almost isothermally stores or releases energy in the form of latent heat. This method is illustrated in Figure 3.4.

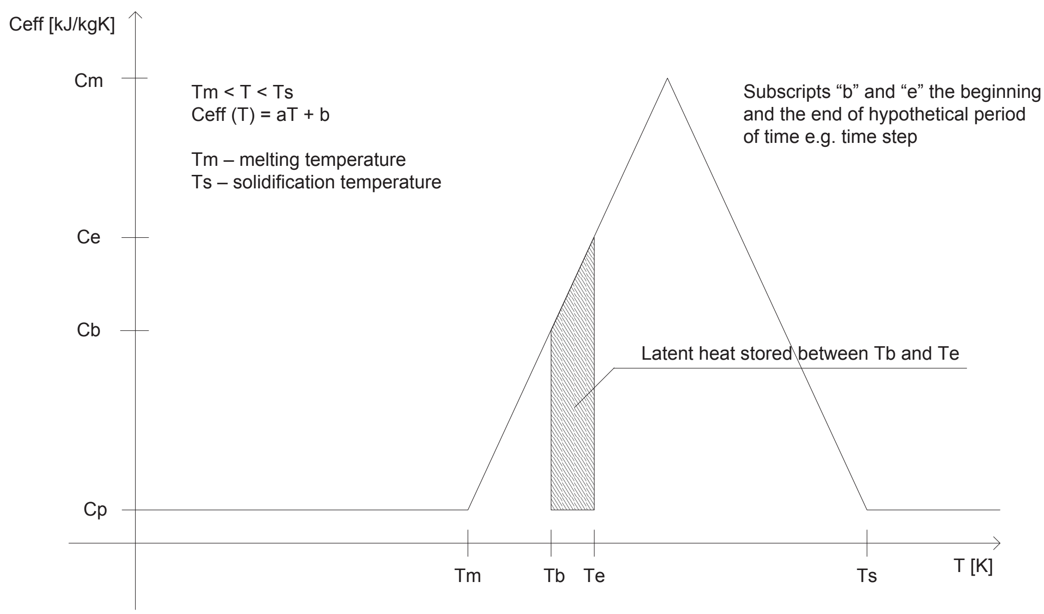


Figure 3.4 Graphical representation of "Effective Heat Capacity Method" (Heim, 2005)

According to Nakhi (1995), the control volume method can be adapted to describe the physical elements of the materials with variable thermophysical properties such as PCM. By integrating equation (3.12) over a small polyhedron control volume, V, and applying the mean value theorem and divergence theorem, with a homogeneous material and a uniform boundary at each surface, the control volume formulation is obtained (Heim, et al. 2003, Heim, 2005):

$$\rho(\bar{T})C_{eff}(\bar{T})V(\bar{T})\frac{\partial\bar{T}}{\partial t} = -\lambda_s(T)\frac{\partial T}{\partial n_s} + V(\bar{T})\bar{g} \quad (3.13)$$

where,

$\bar{T}$ = the average temperature of V
$\bar{g}$ = the heat generation rate over the control volume
$\overrightarrow{n_s}$ = the outward drawn normal unit vector

The input data required for the PCM model, as well as the recommended default values are given in Table 3.4.

Table 3.4 Input data required for PCM model

Input Parameter	Unit	Description/comments	Default Value (based on ESP-r)
Melting temperature	˚C	User defined	20
Solidification temperature	˚C	User defined	21
Conductivity in solid phase	W/m.K	User defined	0.4
Conductivity in liquid phase	W/m.K	User defined	0.8
Specific heat	J/kg.K	User defined	1000
Latent heat member a	$J/kg.K^2$	*	5000
Latent heat member b	J/kg.K	*	10000

* Note: The latent heat specific heat capacity is assumed to be a linear function of temperature in mixed-phase zone:
C_{eff}=aT+b (a=latent heat coefficient [J/kg/K^2], b=latent heat coefficient [J/kg/K])

3.2.2.2 Modeling of PCM in the houses

As described in Heim and Clarke (2003), the ESP-r control volume approach adapted to describe the physical elements of the PCM model using ESP-r's zones and networks elements is used in this work. This method allows the adoption of variable thermophysical properties (Nakhi 1995). Spaces, described by geometry, construction and operational data, are interconnected using network models that describe any air and moisture flowpaths. The complete numerical model, together with boundary conditions and imposed control, is then passed to the central solver.

The PCM material is assumed to replace the top layer of the entire first floor construction of each house. The second floor construction is left untouched not to change the structural loads of the house. This approach is used to ensure that the PCM retrofit will not compromise the structural integrity of the house.

The thermal behaviour of the PCM material was described in section 3.2.2. Thus, the PCM material stores and releases heat passively (i.e. without active control) based on the temperature in the zone (zone temperature control as described in section 2.3), and the melting and solidification temperatures of the material.

3.2.2.3 Methodology to select houses eligible for PCM storage

Presence of a window on the south, south-east and south-west sides is the only criterion that needs to be satisfied to establish the suitability of a house for a PCM storage retrofit. In winter the most solar heat gain is achieved through the south window and it is possible to store this excessive solar heat gain in PCM storage.

3.2.3 Modeling of window area enlargement and window thermal characteristic modification

As windows have transparent construction with low insulation, they are the main source of solar heat gain and heat loss from buildings. Changing window area and modifying the window type changes solar heat gain and heat losses from the building. Therefore, enlarging window area and modifying window type should be evaluated jointly.

To evaluate the trade-off between changing window area and type, modeling is conducted in three steps:

1- Enlarging window area with fixed window type
2- Changing window type with fixed window area
3- Compare the effect of different window areas with different window types on solar heat gain and heat loss to select the proper combination and apply it to eligible houses

To evaluate the effect of window area enlargement on the heating and cooling requirements of a selected house, the area of windows on the south, south-west and south-east side is increased to cover 80% of wall area in increments of 10%.

In the CHREM three window parameters available in the CSDDRD were used to describe the thermal and optical properties of the windows. These are glazing type, coating, and gap-width/fill-gas (Swan, et al. 2009c). Each window type is described in the CSDDRD with a three-digit code, as shown in Table 3.5.

Since using the same digit to represent both the gap-width and the fill gas is not appropriate for the current assessment, a fourth digit is added to the code to separate fill gas and gap size. Therefore, each window type is described with a four-digit code in this work. The coding key for constructing each window type is summarized in Table 3.6.

Table 3.5 Window parameters with the three-digit code used in CSDDRD

Code digit value	Glazing type (digit 1)	Coating* (digit 2)	Gap width and Fill gas (digit 3)
0	-	Clear Glass	13 mm – Air
1	Single Glazed (SG)	Low_e (0.04**)	9 mm – Air
2	Double Glazed (DG)	Low_e (0.10**)	6 mm – Air
3	Triple Glazed (TG)	Low_e (0.20**)	13 mm – Argon
4	-	Low_e (0.40**)	9 mm – Argon

* The low-e coating is applied to the gap facing side of the innermost glazing layer
** The numbers show the emissivity of the glazing

Table 3.6 Key code of window parameters

Code digit value	Glazing type (digit 1)	Coating* (digit 2)	Fill gas (digit 3)	Gap width (digit 4)
0	-	Clear Glass	Air	13 mm
1	Single Glazed (SG)	Low_e (0.04**)	Argon	9 mm
2	Double Glazed (DG)	Low_e (0.10**)	-	6 mm
3	Triple Glazed (TG)	Low_e (0.20**)	-	-
4	-	Low_e (0.40**)	-	-

* The low-e coating is applied to the gap facing side of the innermost glazing layer
** The numbers show the emissivity of the glazing

According to a study by Swan et al. (2009c) which considered center of glass properties from 51 possible window types, there are only 25 window types in the CSDDRD. Therefore, the effect of these window types on the heating and cooling energy requirement of residential buildings is evaluated to find the most energy efficient window type.

Table 3.7 shows all window descriptions in the CHREM with both the original CSDDRD code and the modified four-digit code used here. Since ESP-r calculates the window thermal and solar properties at each time-step, the approximate SHGCs and U-values for each window type are presented only for comparison purposes.

Since Canada has a heating dominated climate, the low emissivity coating is applied to the outside of the inner glazing layer to reduce the long-wave radiation exchange between the glazing layers and the surroundings.

According to literature (Purdy & Beausoleil-Morrison 2001, Mitchell, et al. 2003 and Carmody, et al. 2007) frame type can have a significant effect on the energy requirement of the building. Since the window area listed in CSDDRD corresponds to the "roughed-in" window area, it has been divided proportionally to consider both center-of-glass and frame. CHREM assumes that center-of-glass occupies 75% of the roughed-in-area which is a reasonable assumption based on Mitchell, et al. (2003) and Carmody, et al. (2007). Although in reality the frame surrounds the aperture area, the frame area was placed to the right-hand-side of the aperture area to simplify the model since this simplification does not significantly alter the energy requirement (Swan, 2010). An illustration of the CHREM window representation is shown in Figure 3.5.

There are six frame types represented in CSDDRD. Window frames is upgraded to a better insulated frame to improve the efficiency of windows.

To evaluate the effect of window and the frame type on heating and cooling requirements of a selected house, all windows are upgraded step by step to the most advanced window available in the market.

Currently the transparent multi-layer construction (TMC) approach is used in CHREM model to estimate the optical and thermal properties of windows. Two approaches can be used in ESP-r to estimate the optical and thermal properties of windows in simulating window performance. The TMC approach, which contains solar optical properties for center of glass system (i.e. transmission, reflection and layer absorption) at normal incidence and 5 off-normal incidence angles, is suitable for simulating windows without external shading, while the CFC approach, which calculates solar optical properties at run-time based on the normal incidence values, provides more accurate results when there is external shading. Since in this work the impact of external shading on the energy consumption of CHS is assessed, the optical and thermal properties of windows are estimated using the CFC approach. Although the CFC approach was primarily developed for modeling window shading devices, it can be used as an alternative way of modeling unshaded glazing without relying on optical property data imported from a third party tool such as Window 5.2 (LBNL, 2001).

The input data for windows are given in

Table 3.8.

Table 3.7 CHREM window database

Digits 1-3 (CHREM)	Glazing layers	Coating	Fill gas	Gap size	Digits 1-4 (modified)	SHGCs	U-value (W/m^2K)
100	SG[1]	Clear Glass			1000	0.86	5.91
200	DG[2]	Clear Glass	Air	13 mm	2000	0.76	2.73
201	DG	Clear Glass	Air	9 mm	2001	0.76	2.88
202	DG	Clear Glass	Air	6 mm	2002	0.76	3.17
203	DG	Clear Glass	Argon	13 mm	2010	0.76	2.57
210	DG	Low_e (0.04)	Air	13 mm	2100	0.52	1.70
213	DG	Low_e (0.04)	Argon	13 mm	2110	0.52	1.36
220	DG	Low_e (0.10)	Air	13 mm	2200	0.64	2.10
223	DG	Low_e (0.10)	Argon	13 mm	2210	0.64	1.99
224	DG	Low_e (0.10)	Argon	9 mm	2211	0.64	2.10
230	DG	Low_e (0.20)	Air	13 mm	2300	0.73	2.21
231	DG	Low_e (0.20)	Air	9 mm	2301	0.73	2.33
233	DG	Low_e (0.20)	Argon	13 mm	2310	0.73	2.10
234	DG	Low_e (0.20)	Argon	9 mm	2311	0.76	2.21
240	DG	Low_e (0.40)	Air	13 mm	2400	0.73	2.44
243	DG	Low_e (0.40)	Argon	13 mm	2410	0.73	2.27
244	DG	Low_e (0.40)	Argon	9 mm	2411	0.73	2.38
300	TG[3]	Clear Glass	Air	13 mm	3000	0.68	1.82
301	TG	Clear Glass	Air	9 mm	3001	0.68	1.98
320	TG	Low_e (0.10)	Air	13 mm	3200	0.58	1.48
323	TG	Low_e (0.10)	Argon	13 mm	3210	0.58	1.36
330	TG	Low_e (0.20)	Air	13 mm	3300	0.65	1.53
331	TG	Low_e (0.20)	Air	9 mm	3301	0.65	1.64
333	TG	Low_e (0.20)	Argon	13 mm	3310	0.65	1.42
334	TG	Low_e (0.20)	Argon	9 mm	3311	0.65	1.48

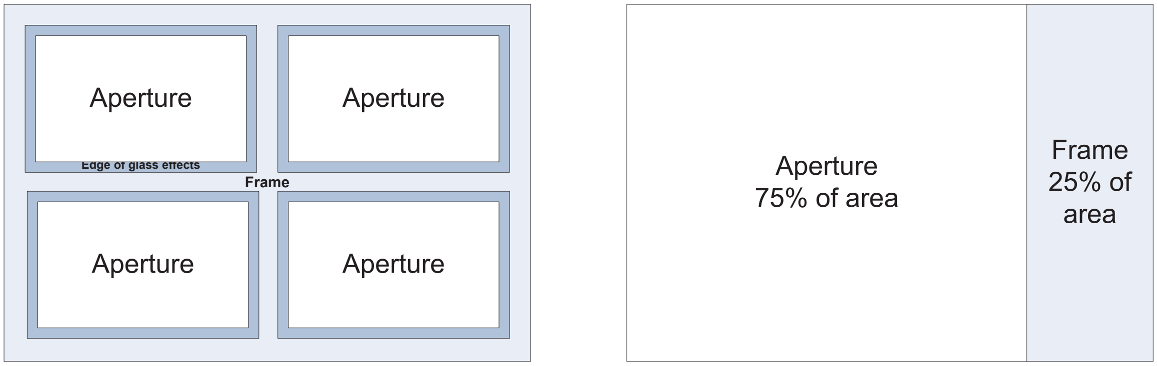


Figure 3.5 Window aperture and frame relationships for (a) the realistic layout showing the aperture, frame, and "edge of glass effects", and (b) the CHREM modeling representation (Swan, 2010)

Table 3.8 Input data required for a window

Input Parameter	Unit	Description/comments
Window area for each side	m	User input
Orientation of windows	-	1..8 (starting at south and rotating counter clockwise)
	Windows construction	
Glazing type	-	1- single glazed (SG), 2- double glazed (DG), 3- triple glazed (TG)
Coating	-	0- clear glass, 1- Low-e (0.04), 2- Low-e (0.10), 3- Low-e (0.20), 4- Low-e (0.35)
Gap width and fill gas	mm	0- 13 mm – air, 1- 9 mm – air, 2- 6 mm – air, 3- 13 mm – argon, 4- 9 mm – argon
Frame material	-	0- Aluminum, 1- Wood, 2- Vinyl, 3- Fiberglass

The required values to describe the optical and thermal properties of windows in ESP-r as well as their default values are given in Table 3.9.

.

Table 3.9 Optical and thermal properties of center-of-glass

Input Parameter	Unit	Description/comments	Default Value (based on ESP-r)
Construction material properties			
Thermal conductivity	W/m.K	-	1.05
Density	kg/m^3	-	2500
Specific heat	J/kg.K	-	750
Glazing layer thickness	mm	-	3
Gap thickness	mm	-	9
For each glazing layer			
Normal solar optical properties			
Front reflectance	-	-	0.071
Back reflectance	-	-	0.071
Transmittance	-	-	0.775
Normal optical visible properties			
Front reflectance	-	Currently not used	0.08
Back reflectance	-	Currently not used	0.08
Transmittance	-	Currently not used	0.881
Normal long wave radiative properties			
Front emissivity	-	-	0.84
Back emissivity	-	-	0.84
Transmittance	-	-	0
Gas mixture properties			
Molecular mass of gas mixture	g/gmol	-	29
a coefficient – gas conductivity	W/m.K	-	0.0023
b coefficient – gas conductivity	$W/m.K^2$	-	$0.79x10^{-4}$
a coefficient – gas viscosity	$N.sec/m^2$	-	$0.325x10^{-5}$
b coefficient – gas viscosity	$N.sec/m^2.K$	-	$0.498x10^{-7}$
a coefficient – specific heat	J/kg.K	-	1000
b coefficient – specific heat	$J/kg.K^2$	-	0.0147

3.2.3.1 Methodology to select houses eligible for window modification

Window enlargement:

The window area to wall area ratio for windows in the proper orientation is the only criterion that needs to be satisfied to establish the suitability of a house for window area enlargement retrofit. The following selection rules are used to identify houses for window area enlargement retrofit:

1- Orientation: since in winter the most solar heat gain is through windows facing toward south, houses with the windows on the south, south-east and south-west is considered for this retrofit.
2- Window area to wall area ratio: Houses with window area to wall area ratio less than 50% is considered for this retrofit.

Window type:

Type of window on each side is the only criterion that needs to be satisfied to establish the suitability of a house for window type retrofit. Therefore, the following selection rule is used to identify houses for window type retrofit.

1- Type of window on each side: since the goal of this retrofit is modifying the thermophysical properties of the window, houses with single glazed, double, glazed and clear triple glazed windows are eligible to be upgraded.

3.3 Photovoltaics

As it was discussed in section 1.2.4, photovoltaic systems can be used for electric power generation only (PV systems) or for electric and thermal power generation (BIPV/T). Since in this work only PV system is considered, the commonly encountered architecture for the PV systems is shown in Figure 3.6.

All components of PV systems given in Figure 3.6 can be modeled using the component models available in ESP-r software. Also, ESP-r provides the connectivity and control algorithms required to simulate electrical flow networks that are required for PV system modeling. In this work the PV model incorporated into the ESP-r by Mottillo (2006), described in the next section, is used.

3.3.1 Modeling of PV systems

PV arrays are characterized by their current vs. voltage curve (I-V curve). Knowing the operating point of the array, power delivered by the array can be calculated from its voltage and current. Since irradiance and temperature have a high impact on the I-V curve, a PV model defines a relationship between current and voltage of the array.

The PV model implemented in ESP-r by Mottillo, et al. (2006) is based on an equivalent one-diode circuit model (WATSUN-PV model) proposed by Thevanard (2005) and shown in Figure 3.8. In this model, it is assumed that the insolation gained by cells in the PV array does not exceed 1000 W/m^2 and it does not change with temperature (Thevenard, 1992).

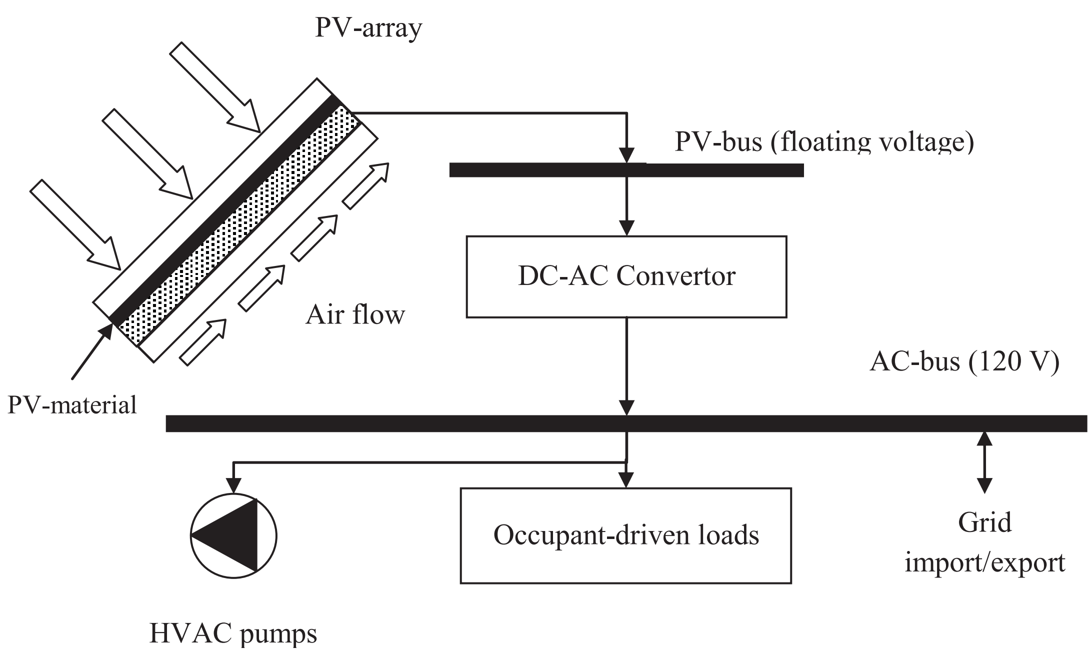


Figure 3.6 PV system

This model is based on three characteristics of module's I-V curve at the reference condition of temperature and insolation, namely maximum power point, the open circuit voltage and the short circuit current. At other conditions, the reference curve is transformed and shifted according to new conditions of insolation and temperature.

According to Kelly (1998), PV systems are modeled in ESP-r as an active material which can be located as any node inside a multi-layer construction. The PV array temperature is equal to this node temperature and the solar radiation reaching the PV-cell is equal to solar radiation incident on the glazing system (Thevenard, 2005).

WATSUN-PV model calculates short-circuit current, Isc, and open-circuit voltage, Voc, based on empirical calculations as follows (Mottillo, et al. 2006):

$$I_{sc} = I_{sc,ref} \frac{E_{T,eff}}{E_{ref}} \left[1 + \alpha\left(T_c - T_{c,ref}\right)\right] \quad (3.14)$$

$$V_{oc} = V_{oc,ref}\left[1 - \gamma\left(T_c - T_{c,ref}\right)\right].\max\left\{0,1 + \beta \ln\left[\frac{E_{T,eff}}{E_{ref}}\right]\right\} \tag{3.15}$$

where:

ref	= reference conditions
$E_{T,ref}$	= effective irradiance on the module (W/m^2)
T_c	= cell temperature (˚C)
α and γ	= empirical coefficients (/˚C)
β	= empirical coefficient (-)
E_{ref}	= 1000 W/m^2
$T_{c,ref}$	= 25 ˚C

The maximum power, P_{mp}, is given as follows:

$$P_{mp} = I_{mp,ref}.V_{mp,ref}\left(\frac{I_{sc}.V_{oc}}{I_{sc,ref}.V_{oc,ref}}\right) \tag{3.16}$$

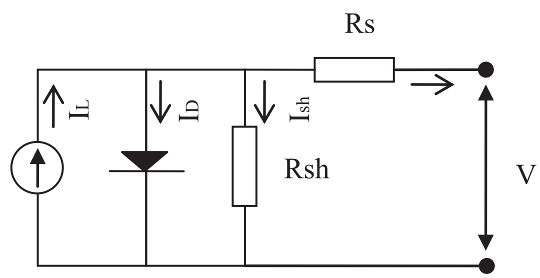


Figure 3.8 Equivalent one-diode circuit

where:

I_L	= light generated current (A)
I_D	= diode current (A)
I_{sh}	= shunt current (A)
Rsh	= shunt resistance (Ω)
Rs	= series resistance (Ω)
V	= voltage (V)

In Equation (3.16) it is assumed that the maximum power point voltage, V_{mp}, and the maximum power point current, I_{mp}, vary proportionally with the short circuit and open circuit voltage.

3.3.1.1 Integration of PV systems into CHREM

To model PV systems for each house in CHREM the following consideration and assumptions were made.

Modeling of the PV module in ESP-r

There are two different approaches to model a roof-mounted PV module in ESP-r:

1- The PV module can be modeled as a roof construction, which means that the air gap between the PV and the roof is modeled as a layer of a multi-layer construction.
2- The PV module can be modelled as a separate zone with a very small thickness attached to the roof. In this case the air gap between top and bottom layer has to be modeled by an air-flow network.

Modeling first case is easier for batch simulations, but results in lower than realistic PV efficiencies because of the higher temperatures reached in the air gap due to neglecting the air-flow that increases the heat transfer rate. The second approach requires more work for coding but it includes the air-flow network for the air gap, therefore its predictions are more realistic. Also, this approach is more suitable for the modelling of BIPV/T systems in future work. Therefore, in this work, the second approach is used in modeling the PV modules.

PV materials and area

Mainly two groups of material are used in the manufacture of PV modules:

1- Amorphous-Silicone (a-Si)
2- Crystalline-Silicone (Cr-Si), which includes mono-Si and poly-Si.

PV modules of both types can be modeled in ESP-r. A recent study by Numerical Logic Inc. (NLI) (Numerical logics Inc., 2010), which compared the efficiency of 278 commercially available PV modules found that the efficiency of a-Si PV modules is around 6% while the efficiency of Cr-Si modules is around 12%. However a-Si modules are less expensive than Cr-Si modules. Thus, there is a trade off between the efficiency and cost of the two types of PV modules.

Due to its higher efficiency, a smaller Cr-Si module is needed for the same load compared to an a-Si module, and depending on unit costs, the total cost may or may not be higher. Also, for a given roof area, a Cr-Si module would produce more electricity. Thus, due to the higher efficiency of Cr-Si modules, and the limited roof area available in each house, the Cr-Si type PV modules are modeled in this work. It is assumed that the entire roof area is covered by the PV module to maximize the available electricity generation.

PV Construction

PV modules are usually constructed from a layer of glass, encapsulated material, and a back sheet. The glass layer can be clear float glass or low-iron glass. The low-iron glass has high transmissivity and very low absorptivity. These characteristics make the low-iron an efficient cover for PV modules. So the cover glass is assumed to be of low-iron in this work.

There are two different encapsulation materials:

1- Ethylene vinyl acetate (EVA)
2- Silicone

Based on a study by McIntosh, et al. (2009) the silicone encapsulation has better optical properties, therefore it can improve the efficiency of the module by up to 1%. However, most of commercially available PV modules have EVA encapsulation. Therefore, the EVA encapsulation is assumed in this work.

For the back sheet of the PV module, a glass layer or a metal sheet can be used. The type of back sheet material used depends on the company and the model of module. For simplicity (and for future BIPV/T modeling work) the back sheet is assumed to be metal.

PV system Input

The input data used in the modeling of the mono-Si PV modules based on the NLI study data (Numerical logics Inc., 2010) and BP 380 (80-watt Multicrystalline PV module) (HSE, 2012) are presented in Table 3.10.

The input data used to model the DC-AC inverter are represented in Table 3.11.

Table 3.10 Input data required for PV model

Input Parameter	Unit	Description/comments	Values based on BP 380 and NLI study
Open circuit voltage at reference (Voc)*	V	User defined	22.1
Short circuit current at reference (Isc)*	A	User defined	4.8
Voltage at maximum power point at reference (Vmpp)*	V	User defined	17.6
Current at maximum power point at reference (Impp)*	A	User defined	4.55
Reference insolation (Href)	W/m^2	Constant	1000
Reference temperature	K	Constant	298
Temperature coefficient of Isc (α)	/K	User defined	0.00059
Temperature coefficient of Voc (γ)	/K	User defined	-0.00381
Empirical coefficient beta used in calc of Voc (β)	-	User defined	0.0578
Number of series connected cells (not panels)	-	User defined	36
Number of parallel connected branches	-	User defined	1
Number of panels in surface (N)**	-	User defined	10
Load type	-	0-maximum power, 1-fixed voltage	0
Load value	V	User defined	0
Shading treatment	-	0-default,1-propprtional power loss, 2-total power loss, 3-direct radiation power loss (diffuse component only)	0
Miscellaneous loss factor	-	User defined	0.1
Efficiency (η)	%	User defined	11.7

* The NLI study (Numerical logics Inc., 2010) reports the Voc/Vmpp and Isc/Impp ratios rather than the values of Voc, Vmpp, Isc and Impp. Therefore the values for these parameters are extracted from the BP 380 data (HES, 2012) and verified by the ratios given in the NLI study.

** The number of panels (N) for the given roof surface is calculated based on the NLI formulation (Numerical logics Inc., 2010):

$N < H_{ref}.\eta.A/P$

Where:
A = roof area
P = power of individual module which is suggested to be considered as 100 W/m^2
H_{ref} and η as per Table 3.10.

Table 3.11 Input data for DC-AC inverter

Input Parameter	Unit	Description/comments	Default Value (based on ESP-r)
Operating mode of PCU (power conditioning unit)	-	1- Connected to power source 2- Connected to power load	1
Nominal power	W	User defined	5000
Idling constant	-	Ratio of power loss when there is no voltage across the PCU and the nominal power	0.8975E-05
Set point voltage	V	User defined	3.65
Internal resistance constant	V^2	Product of internal resistance (ohms) and the nominal power (W)	2
Auxiliary power	W	User defined	0

3.3.2 Methodology to select houses eligible for PV system retrofit

The presence of a roof with significant surface area facing the correct direction with the correct tilt angle is the only criterion that needs to be satisfied to establish the suitability of a house for a PV storage retrofit.

Therefore, the following selection rule is used to identify houses for PV system retrofit.

1- Slope of the roof and its orientation: the same as solar collector rules in section 3.1.3.

CHAPTER 4 SIMULATION AND RESULTS

The methodology used to assess the techno-economic impact of the selected solar energy technologies on the end-use energy consumption and associated GHG emissions by the Canadian housing stock was described in the preceding chapters. This chapter presents the results of the parametric studies conducted to assess the end-use energy and GHG emission reduction potentials of selected solar technology upgrade scenarios for the CHS. It also presents the tolerable capital cost estimation for selected upgrade scenarios. In total 567 different scenarios were evaluated as follows: 2 SDHW upgrades, 14 window upgrades, 2 Venetian blind upgrades, 2 PCM upgrades, 1 PV upgrade for a total of 21 upgrades. For each upgrade scenario 27 different sensitivity analysis results were obtained by combination of 3 interest rates, 3 payback periods and 3 sets of fuel cost escalation rates. These result in 567 (21 x 27) sets of results. Since it is impractical to include 567 tables in this document, only selected results are presented here. The interested reader can obtain all results by contacting the author (s.nikoofard@dal.ca).

As it was discussed in Section 3.2.3, the TMC model was replaced by CFC model for all batch simulations conducted. Using the CFC model forces the higher resolution running time-steps. Therefore, the simulation's time-step was changed from one hour in the original CHREM simulations to 10 minutes in the simulations conducted for this work unless otherwise specified. Since the weather data is available in hourly time-step, the climatic parameters for sub-hourly time-steps are calculated in ESP-r by interpolation between two consecutive climatic parameters.

The batch simulations were done on one of the Atlantic Computational Excellence Network (ACEnet) clusters[1]. For simulations, about 200 cores were allocated with 8GB of RAM per core. The run-time for 5000 to 16000 houses was about 6-18 hours depending on the time-step of simulation and number of cores allocated.

The current energy consumption by the CHS and the associated GHG emissions as estimated by the CHREM are given in Table 4.1 (Swan, et al., 2010). The values presented in Table 4.1 constitute the "Base Case" energy consumption and GHG

[1] http://www.ace-net.ca/wiki/ACEnet

emissions for the CHS. In the subsequent sections, the energy savings and GHG emission reductions due to the various solar technologies evaluated here are calculated in reference to the base case values presented in Table 4.1.

Table 4.1 Estimate of annual energy consumption and GHG emissions

House type or province		Energy consumption (PJ)					GHG emissions (Mt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	218.9	519.4	113.0	38.0	889.3	6.6	26.4	8.0	40.9
	DR	49.2	104.9	18.0	0.2	172.3	0.9	5.3	1.3	7.5
Province	NB	11.8	0.0	10	10.8	32.5	1.5	0.0	0.7	2.2
	NF	9.3	0.0	9.7	3.4	22.4	0.1	0.0	0.7	0.8
	NS	7.8	0.0	23.1	6.1	37.0	1.7	0.0	1.6	3.3
	PE	0.3	0.0	4.1	1.6	5.9	0.0	0.0	0.3	0.3
	QC	154.9	0.4	36.5	14.2	206.0	0.3	0.0	2.6	2.9
	OT	50.0	345	47.6	0.0	442.7	2.9	17.5	3.4	23.8
	AB	0.5	120.9	0.0	0.0	121.4	0.1	6.1	0.0	6.3
	MB	12.0	32.9	0.0	0.0	44.9	0.1	1.7	0.0	1.7
	SK	2.9	40.6	0.0	0.0	43.6	0.7	2.1	0.0	2.7
	BC	18.6	84.5	0.0	2.1	105.2	0.1	4.3	0.0	4.4
Canada		268.1	624.3	131.0	38.2	1061.6	7.5	31.7	9.3	48.4

* Natural Gas

4.1 Techno-economic assessment of SDHW systems for the CHS

To assess the effect of replacing existing DHW systems with SDHW systems on energy requirement, the first two architectures shown in Figure 3.1were modeled and simulated for all eligible houses in the CHS. Since the input parameters for each component in a SDHW system are specific to the manufacturer of the product, a parametric study is not conducted here. The following assumptions were made in the models:

1- According to Thermodynamic Ltd. (2009), for houses with a DHW consumption of less than 200 liter/day installation of one collector and for houses with a consumption of more than 200 liter/day installation of two collectors are recommended. Therefore, in this study the area of collector is selected based on the daily hot water consumption of the house.
2- The existing DHW tanks use electricity, natural gas or oil as their fuel source. Since there is no model for oil fired water tank in ESP-r, oil fired DHW systems are assumed to use electrically heated domestic hot water tanks. Since in the entire CHS, only 3% of the houses – all in the Atlantic region – use oil fired DHW heaters (see Table 4.2), this assumption has a negligible effect on the overall

results with the exception of those for NS and PE. In these two provinces the energy savings and GHG emission reductions are likely underestimated.

Table 4.2 Percentage of DHW fuel source in the CHS for different provinces (%)

Province	Fuel type		
	Electricity	Natural gas	Oil
NB	98	0	2
NF	91	0	9
NS	64	0	36
PE	22	0	78
QC	100	0	0
OT	30	70	0
AB	1	99	0
MB	50	50	0
SK	15	87	0
BC	41	59	0
Canada	50	47	3

4.1.1 Batch simulation and results

4.1.1.1 Impact on energy consumption and GHG emissions due to SDHW upgrade in the CHS

This section presents the energy savings and GHG emission reduction results due to SDHW upgrades.

The breakdown of energy savings and GHG emission reductions due to upgrading all eligible houses by the addition of SDHW system are shown in Table 4.3 and Table 4.4 for each energy source, house type and province. The results show that addition of SDHW system reduces the energy consumption by 2.1% (representing 22.7 PJ/year) and GHG emissions by 2.2% (representing 1.0 Mt of CO2 equivalent) due to SDHW system number 1 (as per Figure 3.1) upgrade.

The distribution of energy savings and GHG emission reductions due to the addition of SDHW systems among the provinces of Canada are shown in Figure 4.1. The results show that SDHW system number 1 (as per Figure 3.1) has a larger impact on energy consumption and GHG emissions.

As seen in Figure 4.1, the energy savings potential with SDHW systems in all provinces are similar, while the GHG emission reductions vary significantly. This is due to the differences in the fuels used in different provinces as well as the source of electricity. In Quebec for example, there is practically no reduction in GHG emissions by switching to SDHW systems because of the fact that the electricity used to heat DHW is generated by hydro-electric power plants that have no GHG emissions. On the other extreme, the GHG emission reduction is the highest in NB because a large part of the electricity used in heating DHW is produced from fossil fuels.

Figure 4.2 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to SDHW upgrade.

Table 4.3 Annual energy savings due to SDHW upgrade

House type or province		Energy savings (TJ)									
		System 1					System 2				
		Electricity	NG*	Oil	Wood	Total	Electricity	NG*	Oil	Wood	Total
House type	SD	8,893	11,341	0	0	20,237	7,934	7,433	0	0	15,370
	DR	297	2,189	0	0	2,502	264	1,240	0	0	1,515
Province	NB	738	0	0	0	738	605	0	0	0	606
	NF	507	0	0	0	508	404	0	0	0	404
	NS	811	0	0	0	811	631	0	0	0	631
	PE	136	0	0	0	154	96	0	0	0	107
	QC	5,111	0	0	0	5,112	4,275	0	0	0	4,275
	OT	1,330	6,983	0	0	8,314	1,449	4,423	0	0	5,873
	AB	-381	3,114	0	0	2,732	-180	2,048	0	0	1,869
	MB	336	543	0	0	880	308	360	0	0	668
	SK	-39	1,134	0	0	1,094	28	759	0	0	786
	BC	640	1,756	0	0	2,397	583	1,083	0	0	1,665
Canada		9,190	13,530	0	0	22,739	8,198	8,673	0	0	16,885

* Natural Gas

Table 4.4 Annual GHG emission reductions due to SDHW upgrade

House type or province		GHG emission reductions (kt of CO_2 equivalent)							
		System 1				System 2			
		Electricity	NG*	Oil	Total	Electricity	NG	Oil	Total
House type	SD	376	575	0	952	376	377	0	753
	DR	-16	111	0	95	-4	63	0	59
Province	NB	175	0	0	175	143	0	0	143
	NF	3	0	0	3	3	0	0	3
	NS	84	0	0	84	66	0	0	66
	PE	0	0	0	0	0	0	0	0
	QC	1	0	0	1	1	0	0	1
	OT	183	354	0	537	196	224	0	420
	AB	-88	158	0	70	-41	104	0	63
	MB	0	28	0	28	0	18	0	18
	SK	-3	58	0	55	2	38	0	40
	BC	3	89	0	92	3	55	0	58
Canada		360	686	0	1046	372	440	0	812

* Natural Gas

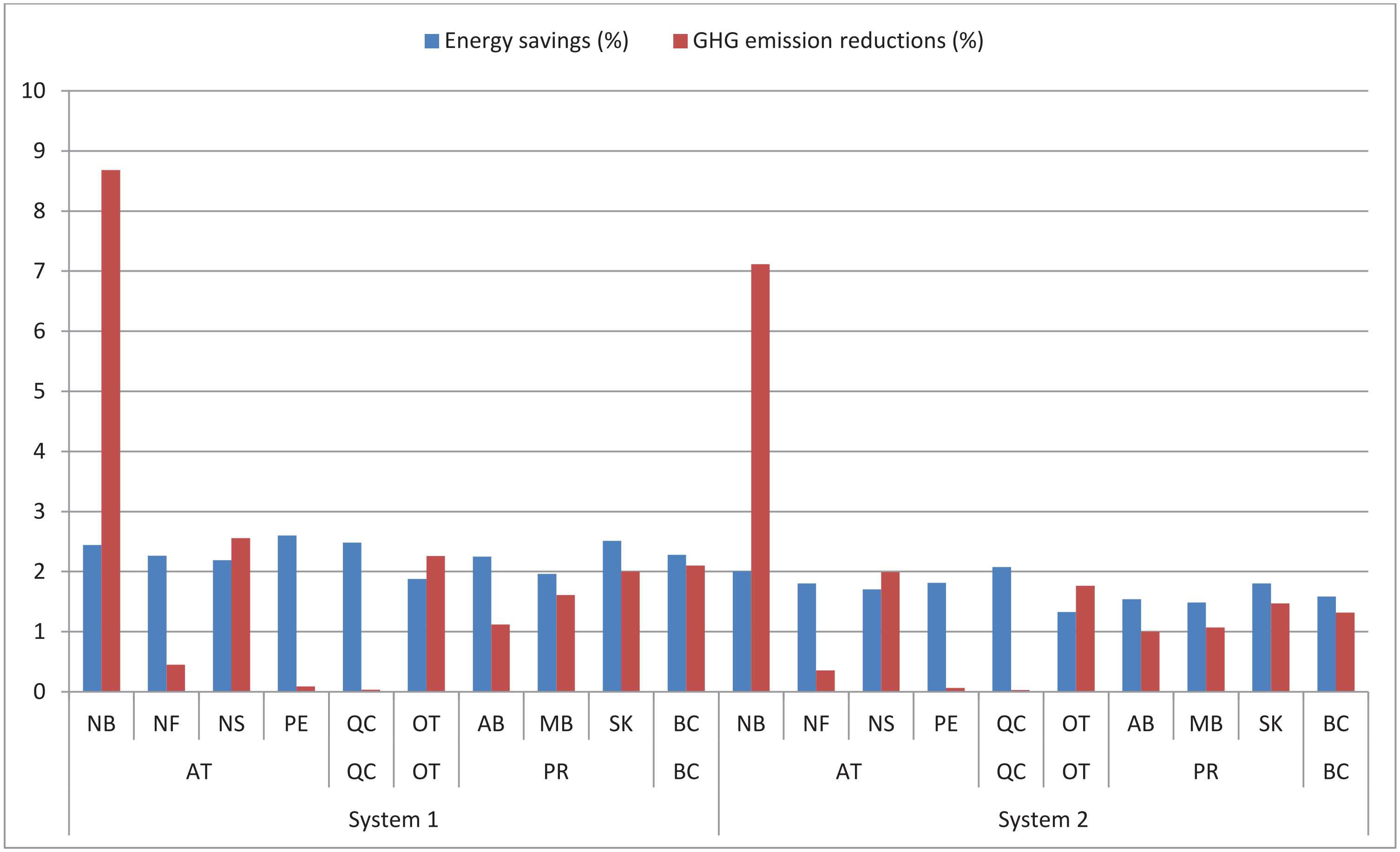


Figure 4.1 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to SDHW upgrade

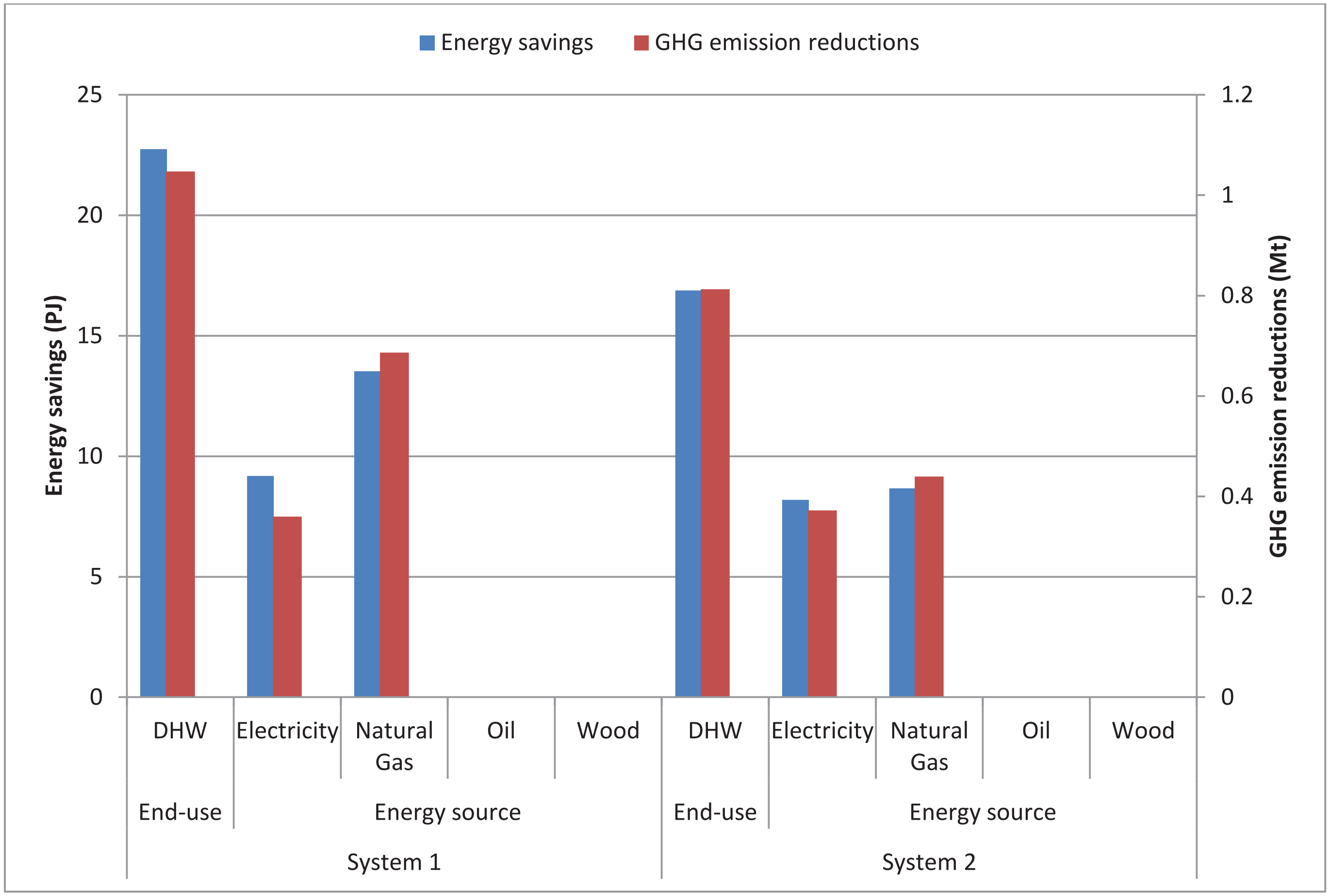


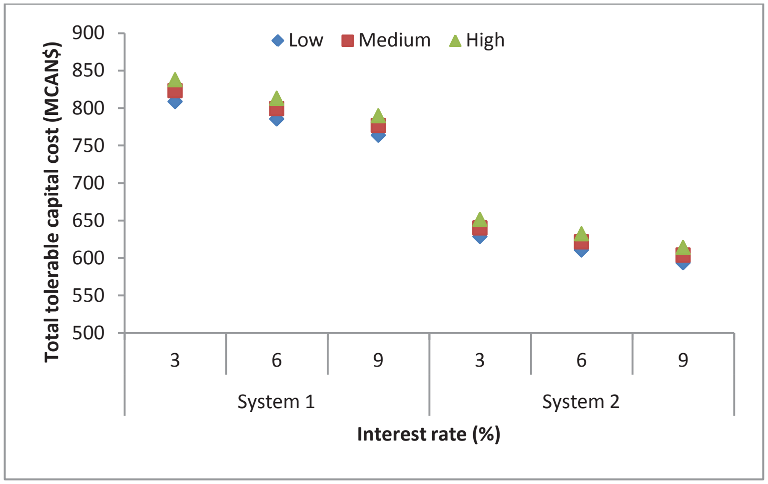
Figure 4.2 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to SDHW upgrade

4.1.1.2 Economic feasibility of SDHW upgrade for the CHS

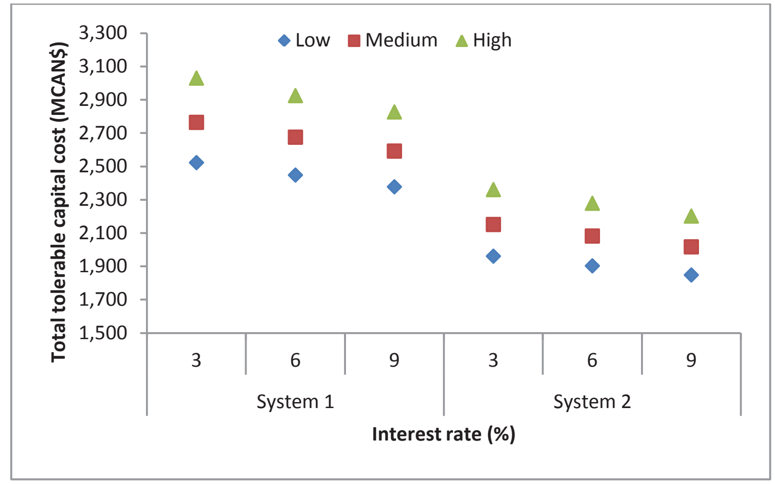
The CHREM estimates of the total tolerable capital cost for three different payback periods, interest rates and fuel cost escalation rates for the two SDHW upgrade options (as per Figure 3.1 (a) and (b)) are shown in Figure 4.3.

As it was concluded in section 4.1.1.1, both SDHW systems have a similar impact on energy consumption. Therefore, the total tolerable capital cost for both systems are comparable.

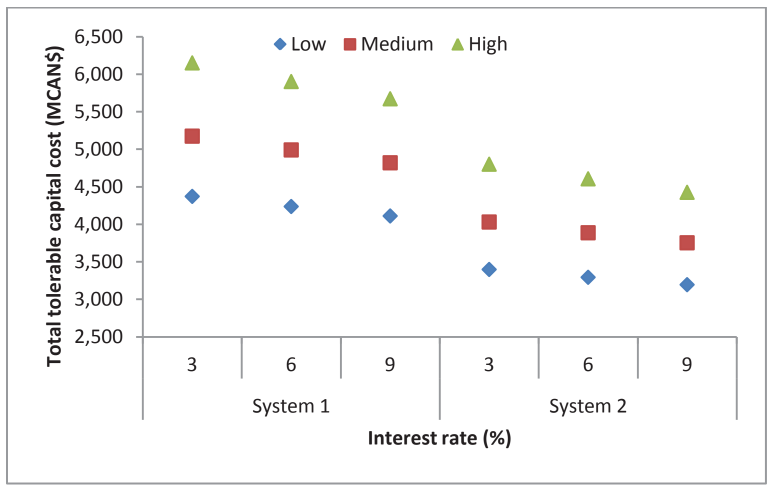
The provincial total tolerable capital cost and achievable savings per house for a 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to SDHW upgrade are shown in Table 4.5 and Table 4.6. The province of NB with tolerable capital cost of 1,723 CAN$ per house has the highest upgrading feasibility across Canada. The dominant DHW fuel source in this province is electricity while in all other provinces except QC it is natural gas or oil. Since the price of electricity per unit of energy is higher than natural gas it is more cost effective to apply the SDHW upgrade in the province of NB than in provinces using natural gas as the primary source of energy. Province of QC with tolerable capital cost of 973 CAN$ per house is the second best candidate for this upgrade.



(a) Payback period = 2 years



(b) Payback periods = 6 years



(c) Payback period = 10 years

Figure 4.3 Total national tolerable capital cost due to SDHW upgrades (systems 1 and 2 as per Figure 3.1 (a) and (b)) for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table 4.5 Total tolerable capital cost and achievable savings per house for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to SDHW system 1 upgrade

Province	No. of houses	TTCC* (MCAN$)	TCC** per house (CAN$)	Total energy saved (TJ)	Energy saved per house (GJ)	Total GHG reduced (kt)	GHG reduced per house (kg)
NB	103,732	179	1,723	738	7.1	174.5	1,682
NF	80,588	114	1,417	508	6.3	3.4	42
NS	127,574	210	1,647	811	6.4	84.4	662
PE	25,796	42	1,640	154	6.0	0.3	10
QC	733,080	713	973	5,112	7.0	1.0	1
OT	1,074,143	863	804	8,314	7.7	537.4	500
AB	341,507	118	345	2,732	8.0	70.3	206
MB	115,609	93	801	880	7.6	27.7	240
SK	131,470	82	625	1,094	8.3	54.9	418
BC	343,236	261	760	2,397	7.0	92.4	269

* Total tolerable capital cost
** Tolerable capital cost

Table 4.6 Total tolerable capital cost and achievable savings per house for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to SDHW system 2 upgrade

Province	No. of houses	TTCC* (MCAN$)	TCC** per house (CAN$)	Total energy saved (TJ)	Energy saved per house (GJ)	Total GHG reduced (kt)	GHG reduced per house (kg)
NB	103,732	147	1,413	606	5.8	143.0	1,379
NF	80,588	91	1,130	404	5.0	2.7	34
NS	127,574	164	1,282	631	4.9	65.8	515
PE	25,796	30	1,144	107	4.1	0.2	7
QC	733,080	597	814	4,275	5.8	0.9	1
OT	1,074,143	656	611	5,873	5.5	420.2	391
AB	341,507	79	232	1,869	5.5	62.7	184
MB	115,609	72	627	668	5.8	18.4	159
SK	131,470	62	475	786	6.0	40.3	306
BC	343,236	184	537	1,665	4.9	57.9	169

* Total tolerable capital cost
** Tolerable capital cost

4.1.2 Conclusion

The techno-economic assessment of applying SDHW to the CHS was presented in this section. Based on the literature review two common SDHW system architectures were selected for batch simulations. The input data for each component of SDHW systems were selected based on manufacturer specifications. The selected SDHW systems were applied to all eligible houses.

For this upgrade, it was assumed that one collector would be installed in houses with a DHW consumption of less than 200 liter/day, and two collectors would be installed in houses with a consumption of more than 200 liter/day. Also, due to modeling issues, all oil fired DHW systems were assumed to use electricity instead of oil.

CHREM estimates indicate that replacing all eligible existing DHW systems with SDHW systems would reduce the energy consumption by the CHS by 2.1% (representing 22.7 PJ/year) and GHG emissions by 2.2% (representing 1 Mt of CO_2 equivalent). From the economical point of view, upgrading houses to incorporate SDHW systems in the province of NB is more feasible than other provinces.

4.2 Techno-economic assessment of window modification for the CHS[1]

4.2.1 Parametric study

To assess the effect of window modifications on heating and cooling energy requirements, the "case study house" was first modeled and simulated without any windows to provide the "base case" energy requirement. Then, the effect of window type, orientation and size on heating and cooling energy requirement was assessed by conducting a series of building energy simulations, and comparing the results with those obtained from the simulation of the base case house. It should be noted that the CHREM assumes that if the zone temperature is greater than ambient temperature and less than

[1] Part of this section was previously published as: Nikoofard, S., Ugursal VI, Beausoleil-Morrison I (2012). Effect of window modifications on household energy requirement for heating and cooling in Canada. *In proceedings eSim 2012: The Canadian Conference on Building Simulation, Halifax, Canada, May 1-4, 325-337*

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cooling set-point the windows will be opened and if it rises above the cooling set-point, they will be closed.

4.2.1.1 Case studies conducted to select the suitable parameters for window modification upgrades for the CHS

To evaluate the effect of window upgrades on energy requirement, the following analyses were conducted:

- Effect of window glazing type: To study the effect of window glazing upgrades, different types of window glazings as per Table 3.7, were placed on all four sides of the test house. All windows are 8 m^2 per side and with wood frame.
- Effect of window frame type: To study the effect of window frame upgrades, different types of frames were placed on all four sides of the test house. The six types of frames that are represented in the CSDDRD are used in the simulations:
  - Aluminum window frame without thermal break
  - Aluminum window frame with thermal break
  - Wood window frame
  - Aluminum clad wood window frame
  - Vinyl window frame
  - Fiberglass window frame
- Effect of window orientation: To study the effect of window orientation, an 8 m^2, triple glazed, low-e (0.2), 13 mm argon filled window (type 3310) with wood frame was added to each side of the base case house (that has no windows).
- Effect of window size: To study the effect of window size, one window was added to the south side of the test case house. The size of the window was increased to cover 10% to 80% of the wall area in increments of 10%. This analysis was done for all window types given in Table 3.7.

The results for heating energy requirement are compared with those obtained from a house with no windows. Due to the big difference between the cooling energy requirement of a house with no windows and a house with any kind of window, the results for cooling energy requirement are compared to a house with single glazed windows unless otherwise specified.

4.2.1.2 Results and discussion

4.2.1.2.1 Effect of window glazing type

The purpose of this study is to assess the effect of window glazing type modification on annual heating and cooling energy requirements. The results are summarized in Figure

4.4 and Figure 4.5 where the changes are given as a percentage of the annual values of the base case house. Since the base case house energy requirement varies from location to location, the base case house energy requirement is included in each figure.

Effect on heating energy requirement

As seen in Figure 4.4, in comparison with a house that has no windows, the addition of single glazed windows on all four sides increases the annual heating energy requirement substantially. Addition of glazing layers, low emissivity (low-e) coating, less conductive fill gas and larger gap size increases the effective thermal resistance of the window. As the thermal resistance of the window increases with these features, the heat loss through the window approaches the heat loss through the same area of surrounding wall. The results shown in Figure 4.4 indicate that:

- Increasing the number of glazing reduces heating energy requirement,
- Increasing gap size from 6 mm to 9 mm and further to 13 mm reduces heating energy requirement,
- Replacing air with argon as the fill gas reduces heating energy requirement,
- Decreasing the emissivity of the coating applied to the outside of the inner glazing layer reduces heating energy requirement.

For example, upgrading a single glazed (type 1000) window to a double glazed window with low-e coating (0.04) and 13 mm argon filled air gap (type 2110) results in a reduction of 53% (from 37.6 GJ/year to 17.7 GJ/year) in the heating energy requirement of a house located in Vancouver, and 43% (from 76.2 GJ/year to 43.3 GJ/year) for a house located in Quebec, representing savings of 19.9 GJ/year and 32.9 GJ/year, respectively.

As the quality of the existing window increases, the benefit from an upgrade decreases. For example, upgrading from a well insulated double glazed window (low-e coated (0.04), 13 mm argon filled – type 2110) to a well insulated triple glazed window (low-e coated (0.2), 13 mm argon filled – type 3310) results in a small decrease in the heating energy requirement, which varies from 5.4% for a house located in Calgary (from 42.6 GJ/year to 40.3 GJ/year) to 4% for a house located in Vancouver (from 17.7 GJ/year to 17

GJ/year). The results also indicate that a high quality insulated window (type 3310) with low solar emissivity can offset the heat loss through the window.

Effect on cooling energy requirement

Solar heat gain is the dominant cause for the cooling load of a house. Thus, when a window is added to a house that has no windows, the cooling load, and consequently cooling energy requirement, may increase by as much as 10 times or more. Therefore, rather than using a windowless house as the base case house to compare changes in the cooling energy requirement due to window upgrades, a house with single glazed windows is used as the base case house.

As seen in Figure 4.5, in comparison to a house with single glazed windows, addition of glazing layers, low emissivity (low-e) coating, different gap fill gas and size may result in a decrease or increase in cooling energy requirement. Additions of these features to the window results in lower U-value for the window which may increase the cooling energy requirement by blocking long-wave radiation from inside to outside, or decrease it by transferring less heat from outside to inside. However, this also results in solar gain reduction, which decreases the cooling energy requirement. Therefore, a trade off between heat loss and solar heat gain may increase or decrease the cooling energy requirement. The results shown in Figure 4.5 indicate that:

- Increasing the number of glazing reduces cooling energy requirement,
- Decreasing gap size from 13 mm to 9 mm and further to 6 mm reduces cooling energy requirement,
- Replacing air with argon as the fill gas increases cooling energy requirement,
- Increasing the emissivity of the coating applied to the outside of the inner glazing layer increases cooling energy requirement.

For example, upgrading single glazed (type 1000) windows to double glazed, low-e coated (0.04), 13 mm air filled gap (type 2100) windows results in a reduction of cooling energy requirement, which varies from 24.4% (from 18.4 GJ/year to 13.9 GJ/year) for a house located in Calgary to 22.1% (from 13.1 GJ/year to 10.2 GJ/year) for a house located in Halifax, representing 4.5 GJ/year and 2.9 GJ/year, respectively.

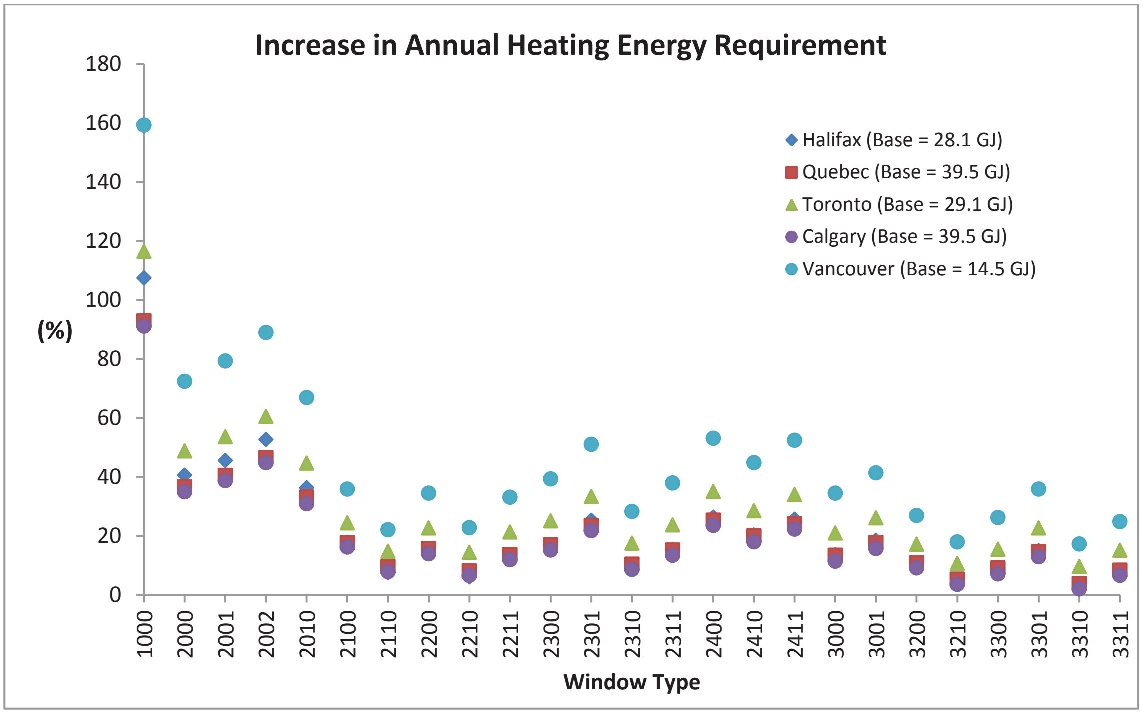


Figure 4.4 Increase in annual heating energy requirement (%) due to window glazing upgrades compared to the base case house with no window

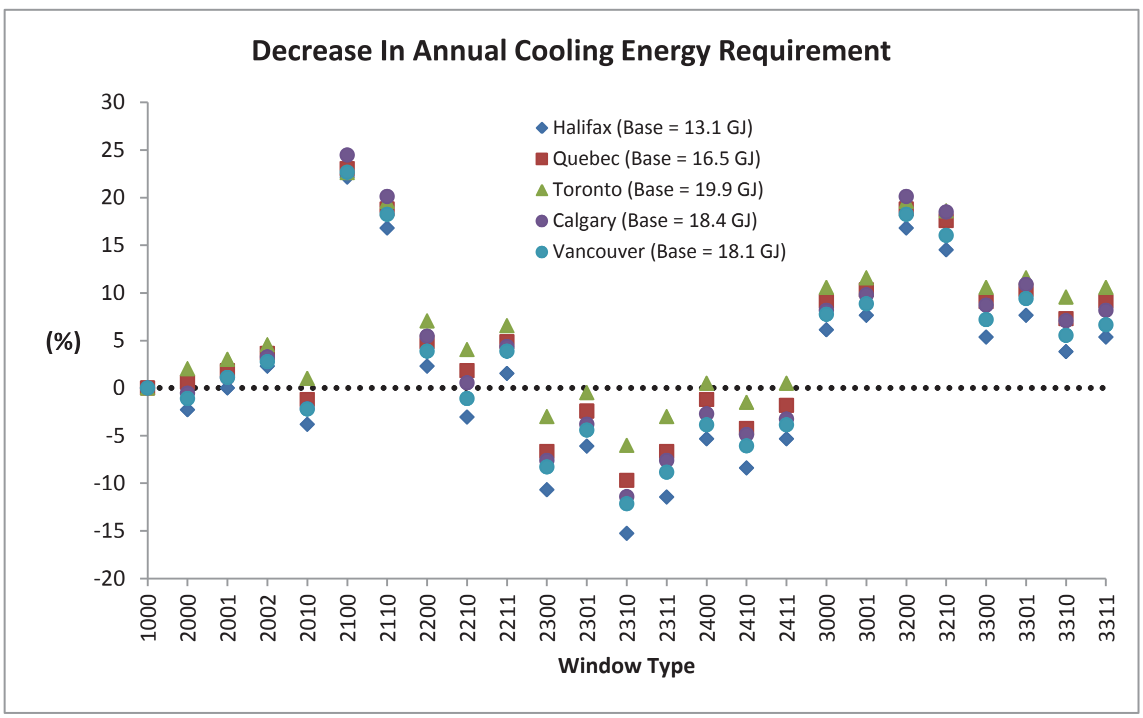


Figure 4.5 Decrease in annual cooling energy requirement (%) due to window glazing upgrade compared to the base case house with single glazed windows (negative numbers show increase)

As seen in Figure 4.5, double-glazed, low-e coated (0.04), 13 mm air filled gap (type 2100) results in the largest decrease in cooling energy requirement. Also all triple glazed windows decrease cooling energy requirement more than double glazed windows. To explain this trend, the annual solar gain through the windows is shown in Figure 4.6. Since the solar heat gain through the windows is the dominant heat gain during the cooling season, the cooling energy requirement is mainly due to the solar heat gain. Figure 4.6 indicates that:

- Double glazed, low-e (0.04), 13 mm air/argon filled window has the lowest solar gain,
- All triple glazed windows have lower solar gain compared to all double glazed windows except for double glazed windows with the low emissivity coating of 0.04 and 0.1.

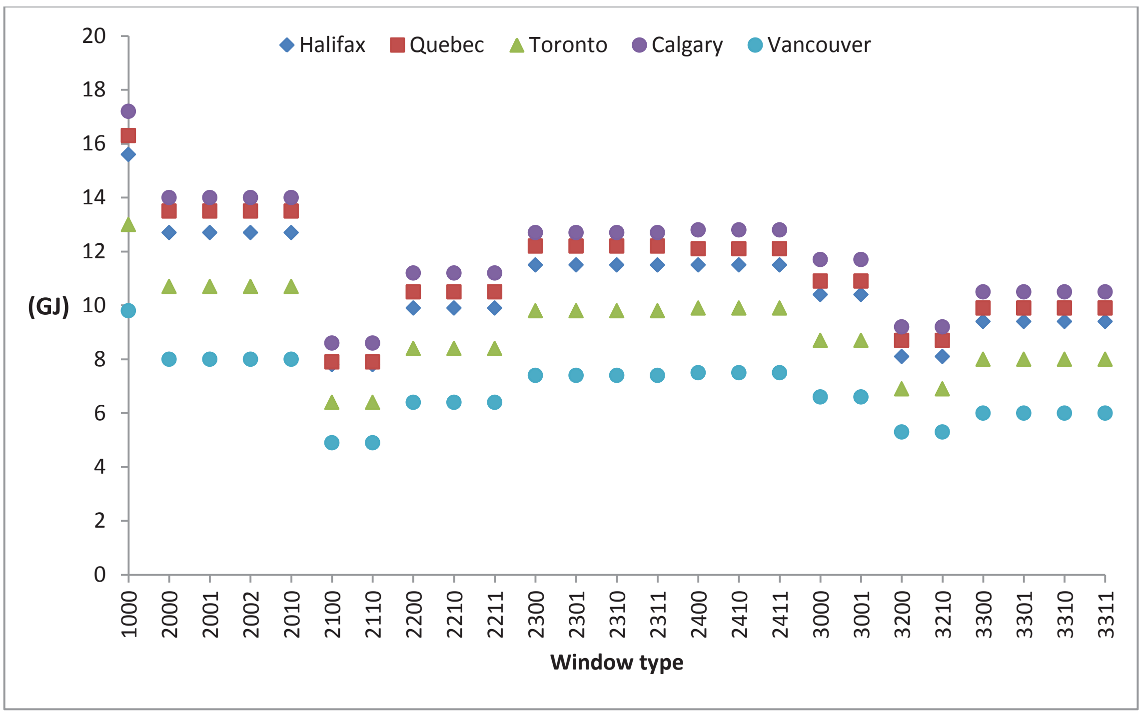


Figure 4.6 Annual solar heat gain through windows (GJ)

4.2.1.2.2 Effect of window frame type

The purpose of this study is to assess the effect of window frame type modifications on annual heating and cooling energy requirement. The results are summarized in Figure 4.7 and Figure 4.8 as a percentage of the annual values of the base case house that has triple glazed, low-e coated (0.2), 13 mm argon filled (type 3310) windows with aluminum frame. A window with high glazing insulation and low frame insulation is chosen as the base case to accentuate the effect of changing frame insulation. The base case house energy requirement is included in each figure.

Effect on heating energy requirement

As seen in Figure 4.7, in comparison with a house that has windows with aluminum frame, using a more insulated frame decreases annual heating energy requirement substantially. Since the frame covers 25% of the window area, improving the thermal resistance of the frame has a major impact on reducing the heat loss through the window.

Upgrading aluminum to wood frame results in the largest decrease in heating energy requirement, which varies from 19% for a house located in Vancouver (from 21.0 GJ/year to 17.0 GJ/year) to 14.7% for a house located in Quebec (from 48.1 GJ/year to 41.0 GJ/year).

Effect on cooling energy requirement

As seen in Figure 4.8, in comparison with a house that has windows with aluminum frame, using a more insulated frame increases annual cooling energy requirement due to reduced heat loss from the zone to the outdoors through the window frame since the indoor temperature is marginally higher than the outdoor temperature most of the time during the cooling season. However, compared to the reduction in heating energy requirement, the increase in cooling energy requirement is negligible.

4.2.1.2.3 Effect of window orientation

The objective of this sensitivity analysis is to assess the effect of window orientation on annual heating and cooling energy requirement. The results are summarized in Figure 4.9 and Figure 4.10. In these figures, the changes are given as a percentage of the annual values of the base case house that has no windows. The base case house energy requirement is included in each figure.

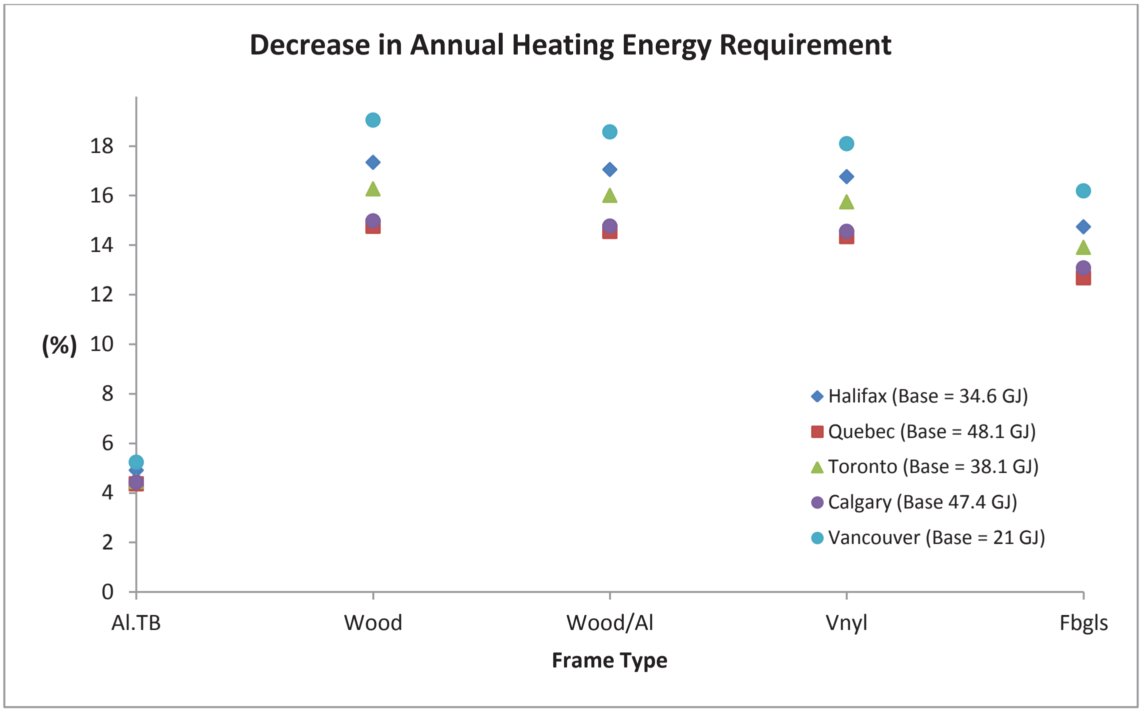


Figure 4.7 Decrease in annual heating energy requirement (%) due to window frame upgrades compared to base case house with Aluminum window frame type

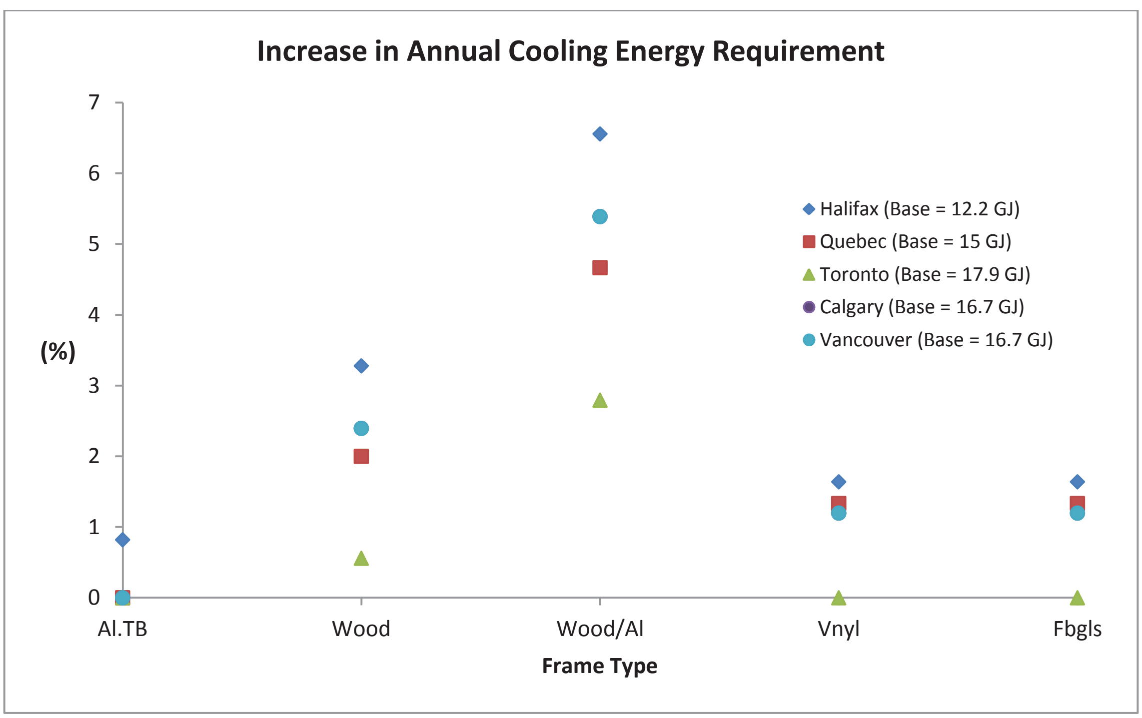


Figure 4.8 Increase in annual cooling energy requirement (%) due to window frame upgrades compared to base case house with Aluminum window frame type

Effect on heating energy requirement

As seen in Figure 4.9, in comparison with a house that has no windows, addition of an $8m^2$ triple glazed, low-e coated (0.2), 13 mm argon filled (type 3310) window with wood frame to the south side results in a decrease in annual heating energy requirement. Since the solar radiation is highest on the south exposure during the heating season, addition of a well insulated window to this side can increase the solar gain through the window while keeping the increase in heat loss to a minimum. In other words, there is a net heat gain since the benefit from the solar heat gain eclipses the increased heat loss.

Addition of window type 3310 with wood frame to the south side of a house decreases annual heating energy requirement which varies from 13.7% for a house located in Calgary (from 39.5 GJ/year to 34.1 GJ/year) to 8.6% for a house located in Toronto (from 29.1 GJ/year to 26.6 GJ/year).

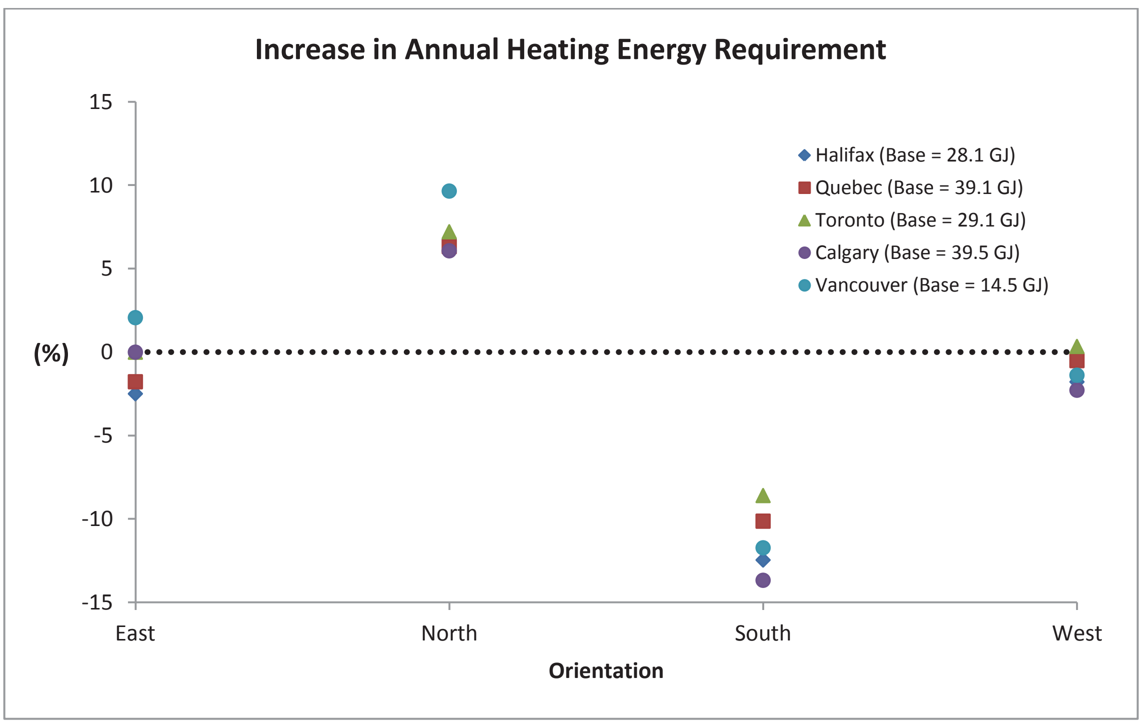


Figure 4.9 Increase in annual heating energy requirement (%) due to addition of a window to different orientations compared to the base case house (no window) (negative numbers show decrease)

Effect on cooling energy requirement

As seen in Figure 4.10, in comparison with a house that has no windows, addition of an $8m^2$ well insulated window to the west side results in the highest increase in annual cooling energy requirement. Since the solar azimuth arc is longer in the summer than in winter, the solar gain from west and east side is higher than the solar heat gain through the south side in summer. On the other hand, addition of a window to the north side results in the least increase in cooling energy requirement due to the fact that north side gains the least solar radiation through the year.

Addition of an $8m^2$ well insulated window (type 3310) to the west side results in the highest increase in cooling energy requirement which varies from 637% for a house located in Vancouver (from 0.8 GJ/year to 5.9 GJ/year) to 187% for a house located in Toronto (from 2.4 GJ/year to 6.9 GJ/year).

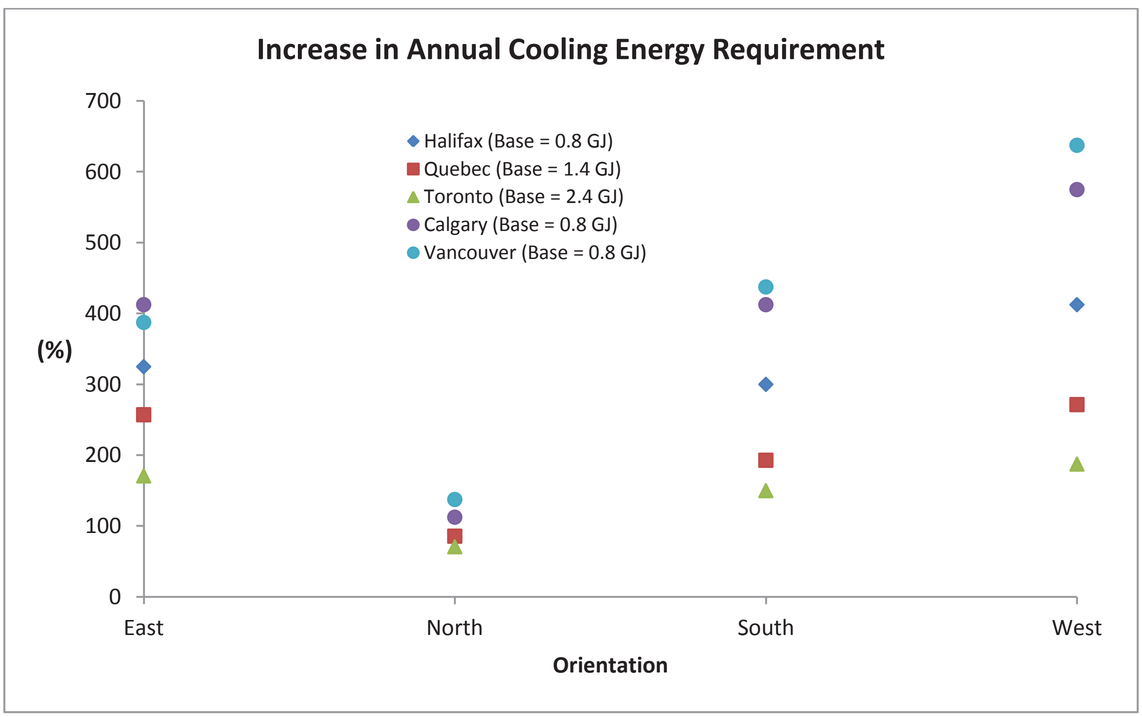


Figure 4.10 Increase in annual cooling energy requirement (%) due to addition of window to different orientation compared to the base case house (no window)

4.2.1.2.4 Effect of window size

The objective of this sensitivity analysis is to assess the effect of window size on annual heating and total energy requirement. The results are summarized in Figure 4.11 and Figure 4.12. In these figures, the changes are given as a percentage of the annual values of the base case house. Since the base case house energy requirement varies from location to location, the base case house energy requirement is included in each figure.

Effect on heating energy requirement

The effect of window area enlargement on annual heating energy requirement for four different window types is summarized in Figure 4.11.

As seen in Figure 4.11, upgrading single glazed (type 1000) windows to better insulated windows results in a decrease in annual heating energy requirement. The decrease is larger for larger windows. As it was concluded earlier, by improving the thermal resistance of the window and its emissivity, the heat loss through the window can be offset by the solar gain. Therefore, increasing the window area of a very well insulated window only increases the solar heat gain while the heat loss does not change significantly. In other words, by increasing the window area of a well insulated window, there is a net increase in heat gain as the increase in solar heat gain is larger than the increase in transmission heat loss. From Figure 4.11, the following can be concluded:

- Upgrading a window to a better insulated one allows to have a larger window,
- For climates with higher HDD, benefit from solar gain for a well insulated window becomes almost constant for window area/wall area ratios higher than 50%,
- Enlarging well-insulated windows has more benefit for climates with higher sunshine hours during the heating season. (The average monthly sunshine hours for different cities are shown in Figure 4.13).

For example, compared to a house with no windows, addition of a triple glazed window with low-e coating (0.1) and 13 mm argon filled gap (type 3210) to achieve a window area/wall area ratio of 50% results in a reduction of 20% (from 39.5 GJ/year to 31.6 GJ/year) in the annual heating energy requirement in Calgary, and 10.3% (from 14.5

GJ/year to 13 GJ/year) for a house located in Vancouver, representing savings of 7.9 GJ/year and 1.5 GJ/year, respectively.

As the area of a window increases, the benefit from an upgrade decreases or may reverse. For example, upgrading from 50% to 80% of wall area for a well insulated triple glazed window (low-e coated (0.1), 13 mm argon filled – type 3210) results in a small reduction of 1.9% (from 31.6 GJ/year to 31 GJ/year) for a house located in Calgary and an increase of 7.7% (from 13 GJ/year to 14 GJ/year) for a house located in Vancouver.

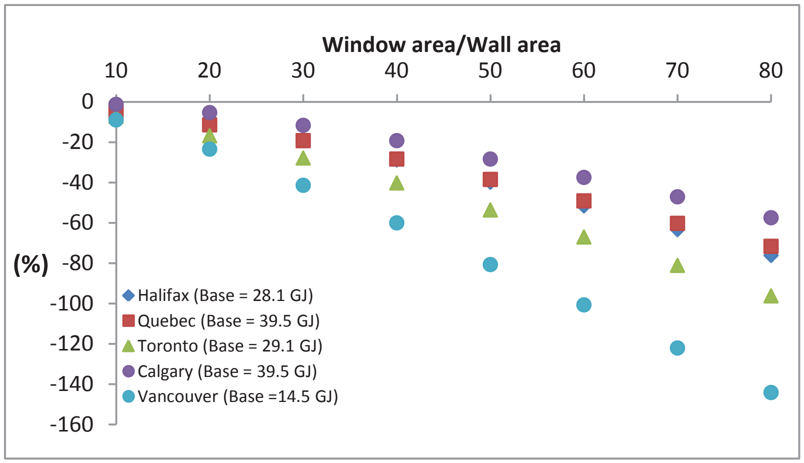
Effect on cooling energy requirement

As discussed earlier, in comparison to a house with no windows, addition of a window increases the cooling energy requirement dramatically. However, if the appropriate window type and area is used, the benefit of reducing the heating energy requirement can overcome the disadvantage of increasing the cooling energy requirement. It should be noted that in this sensitivity analysis all cases are compared to a house with no windows. Therefore, the benefit of reducing the heating energy requirement only overcomes the disadvantage of increasing the cooling energy requirement in limited cases. Since the trade off between cooling and heating energy requirement is a matter of interest in this part, the difference between the reduction in heating and the increase in cooling energy requirement due to window enlargement is shown in Figure 4.12.

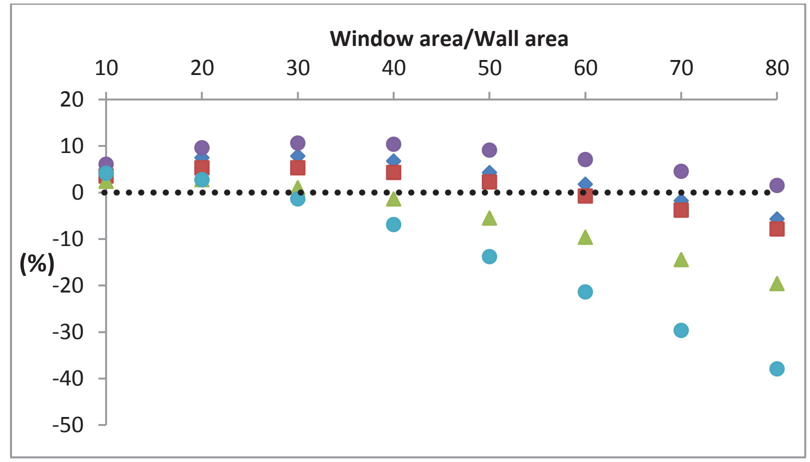
Figure 4.12(a)-(d) show that:

- Enlarging window area increases the annual space energy requirement. In other words, the increase in cooling energy requirement minus the decrease in heating energy requirement is greater than zero.
- Using a more insulated window type mitigates the increase in annual space energy requirement.

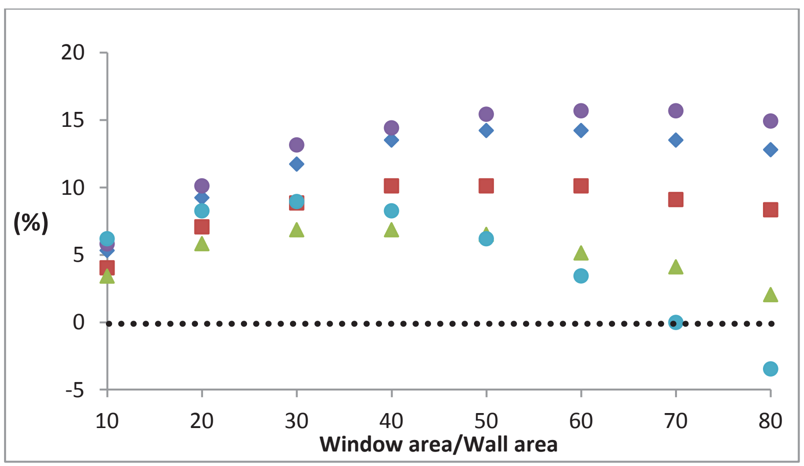
For example, addition of a triple glazed window, low-e coating (0.1), 13 mm argon filled (type 3210) and window area/wall area ratio of 30% results in 1.2 GJ/year saving in space energy requirement for a house located in Calgary while it increases space energy requirement by 3.7 GJ/year for a house located in Vancouver.



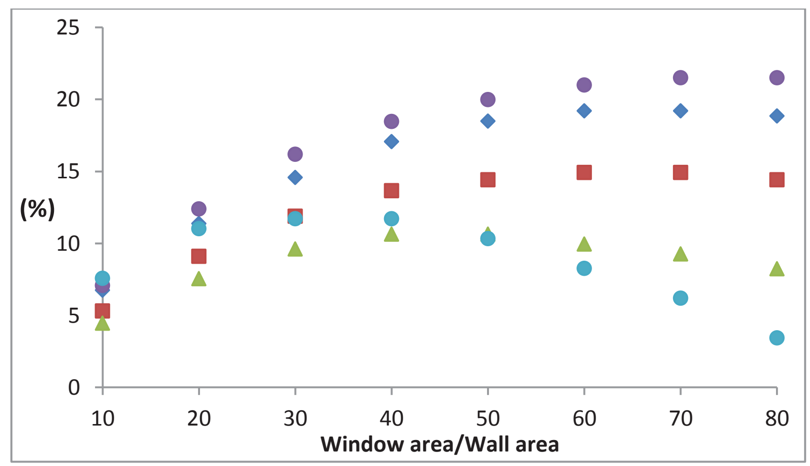
(a) Window type 1000



(b) Window type 2000

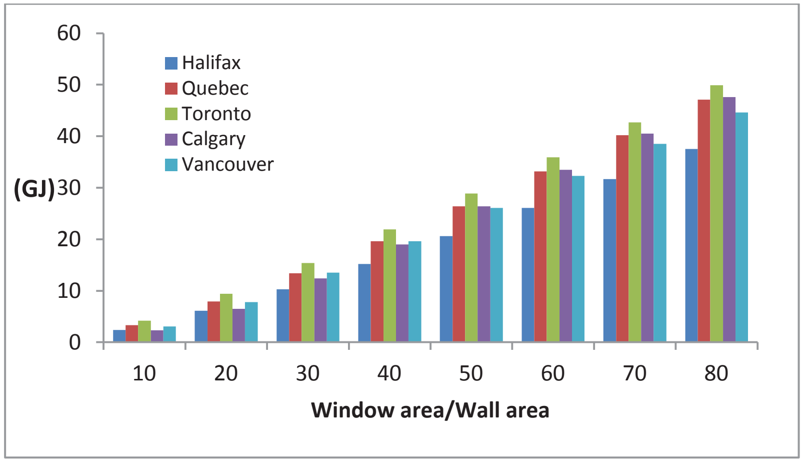


(c) Window type 2110

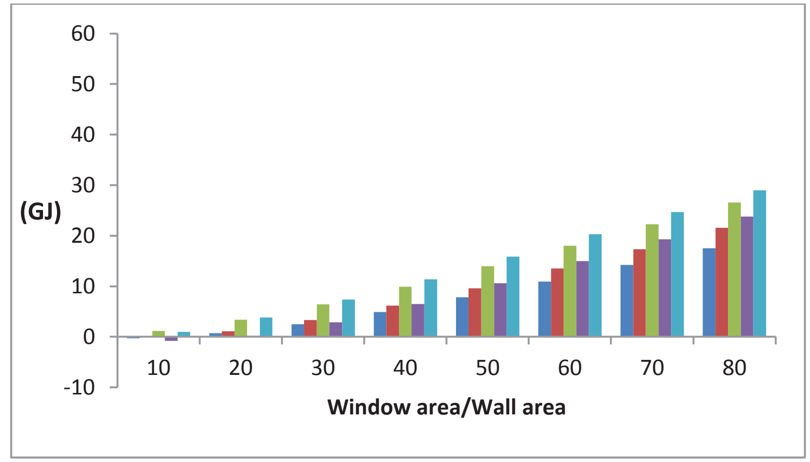


(d) Window type 3210

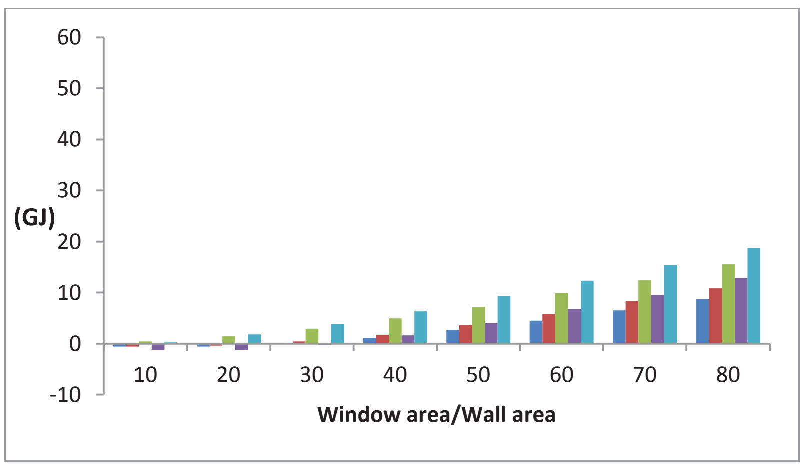
Figure 4.11 Decrease in annual heating energy requirement (%) due to window enlargement compared to the base case house that has no windows



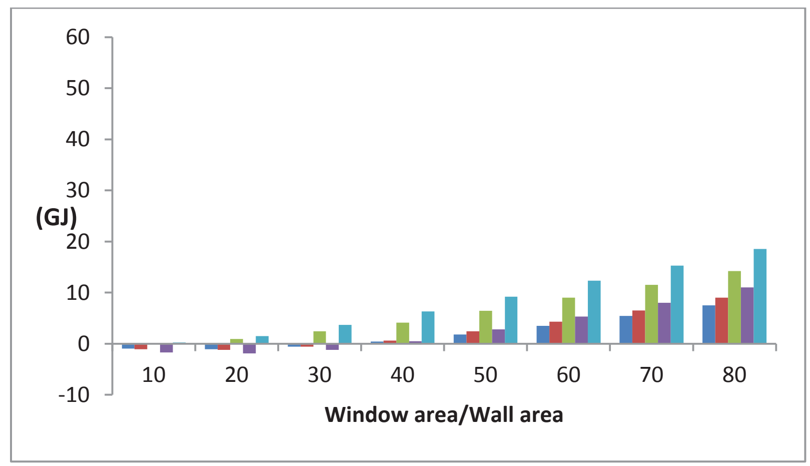
a) Window type 1000



(b) Window type 2000



(c) Window type 2110



(d) Window type 3210

Figure 4.12 Effect of window enlargement: annual increase in space energy requirement (GJ) (i.e. difference between the increase in cooling energy requirement and the decrease in heating energy requirement) due to window enlargement

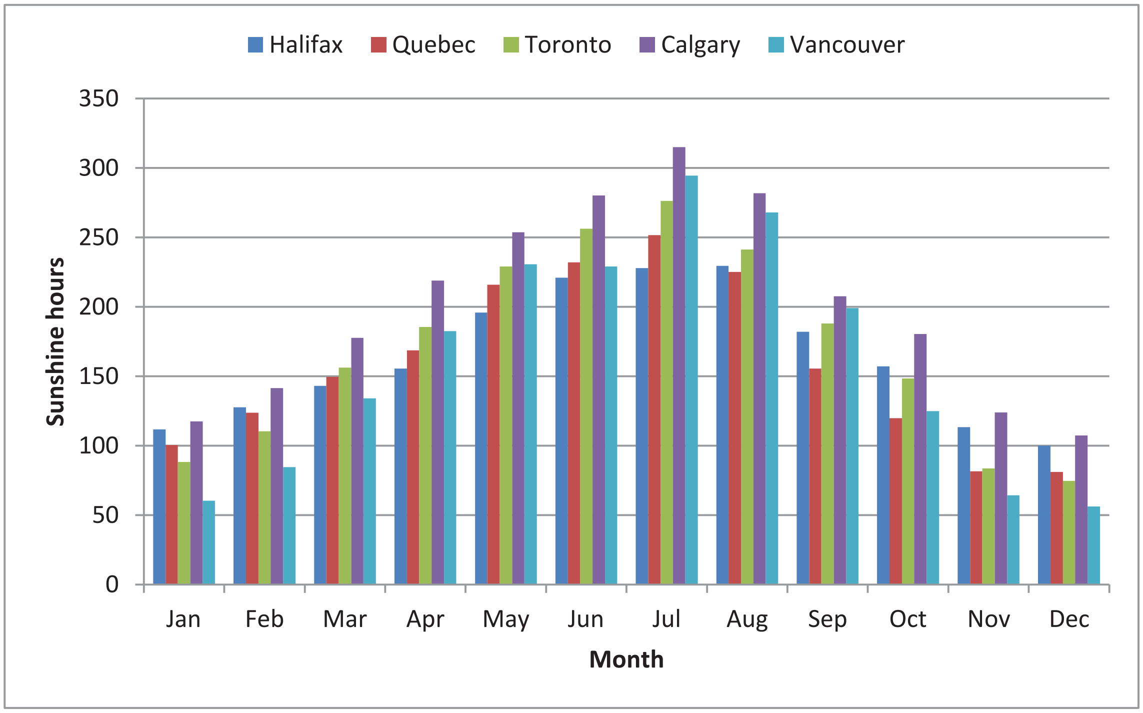


Figure 4.13 Average monthly sunshine hours for five cities of Canada (Environment Canada, 2012)

4.2.1.3 Conclusion

According to the frequency distribution analysis of the window type by Swan, et al. (2009c), the double-glazed window, with clear glass and 13 mm air filled gap (type 2000) is the dominant window type for all cardinal directions and both single and double/row house types in CSDDRD. Therefore to conduct a techno-economic assessment of window upgrades on the CHS, the selected houses should be upgraded to a better insulated window type than type 2000.

Based on the results of the analyses presented above, the following glazing upgrades are selected to conduct a techno-economic assessment of window upgrades of all windows in a given house in the CHS:

1- Upgrading to double-glazed window, with clear glass and 13 mm Argon filled gap (type 2010),
2- Upgrading to double-glazed window, with low-e coating (0.04) and 13 mm Air filled gap (type 2100),
3- Upgrading to double-glazed window, with low-e coating (0.04) and 13 mm Argon filled gap (type 2110),

4- Upgrading to triple-glazed window, with clear glass and 13 mm Air filled gap (type 3000),
5- Upgrading to triple-glazed window, with low-e coating (0.1) and 13 mm Air filled gap (type 3200),
6- Upgrading to triple-glazed window, with low-e coating (0.1) and 13 mm Argon filled gap (type 3210).

Based on criteria for finding eligible houses for window area enlargement, it was found that 85% of the houses in the CHS have a window area/wall area ratio of less than 30%.

Based on the results of analyses above, increasing window area/wall area ratio from 30% to 60% decreases annual heating energy requirement. Whereas, increasing window area/wall area ratio more than 60% for a good insulated window does not have significant effect on annual heating energy requirement but increases space heating energy requirement. Thus, for this study, south side window area/wall area ratios of 30 to 60% are selected to conduct a techno-economic assessment of window enlargement upgrades in the CHS.

4.2.2 Batch simulation and results

Based on the results of the parametric study, the selected upgrade scenarios were applied to all eligible houses. Since each house can have more than one type of window, the eligible houses were selected based on their most prevalent window type. Then all windows were uniformly replaced by the better performance window compared to the most prevalent window type. The distribution of window types based on the most prevalent window of each house is shown in Table 4.7 for each province. The distribution of eligible houses which can receive each window type upgrade is presented in Table 4.8.

4.2.2.1 Impact on energy consumption and GHG emissions due to window modification upgrades in the CHS

The annual energy savings and GHG emission reductions for window type and area modifications are presented in this section.

Table 4.7 Distribution of window types for provinces of Canada (%)

Province	Window type							
	1000	2000	2002	2301	2311	3001	3301	3311
NB	12.8	78.9	3.1	0.2	4.8	0.0	0.0	0.0
NF	1.5	86.6	6.9	2.0	3.0	0.0	0.0	0.0
NS	3.2	85.4	1.8	2.4	6.3	0.1	0.0	0.0
PE	1.3	77.2	8.9	1.3	5.1	1.3	0.0	0.0
QC	2.4	78.0	4.4	5.0	7.9	1.1	0.2	0.5
OT	3.7	78.6	5.5	3.1	8.2	0.3	0.0	0.2
AB	0.7	78.9	3.2	7.4	6.9	1.1	0.4	1.2
MB	2.6	53.8	1.7	1.9	2.1	26.9	2.8	8.2
SK	2.0	69.3	2.5	4.0	4.5	10.9	1.0	2.0
BC	25.2	61.3	10.9	1.4	0.9	0.1	0.0	0.0
Canada	5.8	75.3	5.3	3.6	6.4	2.1	0.3	0.8

Table 4.8 Distribution of houses eligible to get each window type upgrade (%)

Province	Window type					
	2010	2100	2110	3000	3200	3210
NB	94.9	94.9	94.9	100.0	100.0	100.0
NF	95.0	95.0	95.0	100.0	100.0	100.0
NS	90.5	90.5	90.5	99.9	100.0	100.0
PE	87.3	87.3	87.3	98.7	100.0	100.0
QB	84.8	84.9	84.9	97.9	99.2	100.0
OT	87.9	87.9	88.0	99.5	99.8	100.0
AB	82.9	82.9	82.9	97.2	98.3	100.0
MB	58.1	58.1	58.1	62.1	89.0	100.0
SK	73.8	73.8	73.8	82.2	95.5	99.0
BC	97.4	97.4	97.4	99.8	100.0	100.0
Canada	86.4	86.4	86.4	96.7	98.9	100.0

4.2.2.1.1 Window type modification

This section presents the national energy savings and GHG emission reduction results due to window type upgrade. Since the complete analysis of energy savings and GHG emission reductions for all window type upgrades shows similar trends, detailed results of window type 3210 upgrade are presented here while the rest of the results are provided in Appendix C.

The CHREM estimates of national energy savings and GHG emission reductions due to window type upgrade is shown in Figure 4.14. The results show that changing all window characteristics (i.e. increasing glazing layers, addition of low-e coating, using less conductive fill gas and larger gap size) can reduce energy consumption by 7% (representing 75.8 PJ/year) and GHG emissions by 8% (representing 3.7 Mt of CO_2 equivalent) due to window type 3210 upgrade.

According to Table 4.7 and Table 4.8, 86% of houses are eligible to get the lowest quality of window type upgrade (i.e. window type 2010) and from those eligible houses 80% has already double glazed windows. From the results it can be seen that changing fill gas to a less conductive one (window type 2010) or addition of only a layer of low-e coating (window type 2100) or a combination of both (window type 2110) without increasing glazing layers can still reduce energy consumption and GHG emissions significantly.

Although increasing glazing layer (window type 3000) is more effective than changing properties of either glazing layer or filling gas, it is still less effective than changing both properties without addition of any layer to the window (window type 2110).

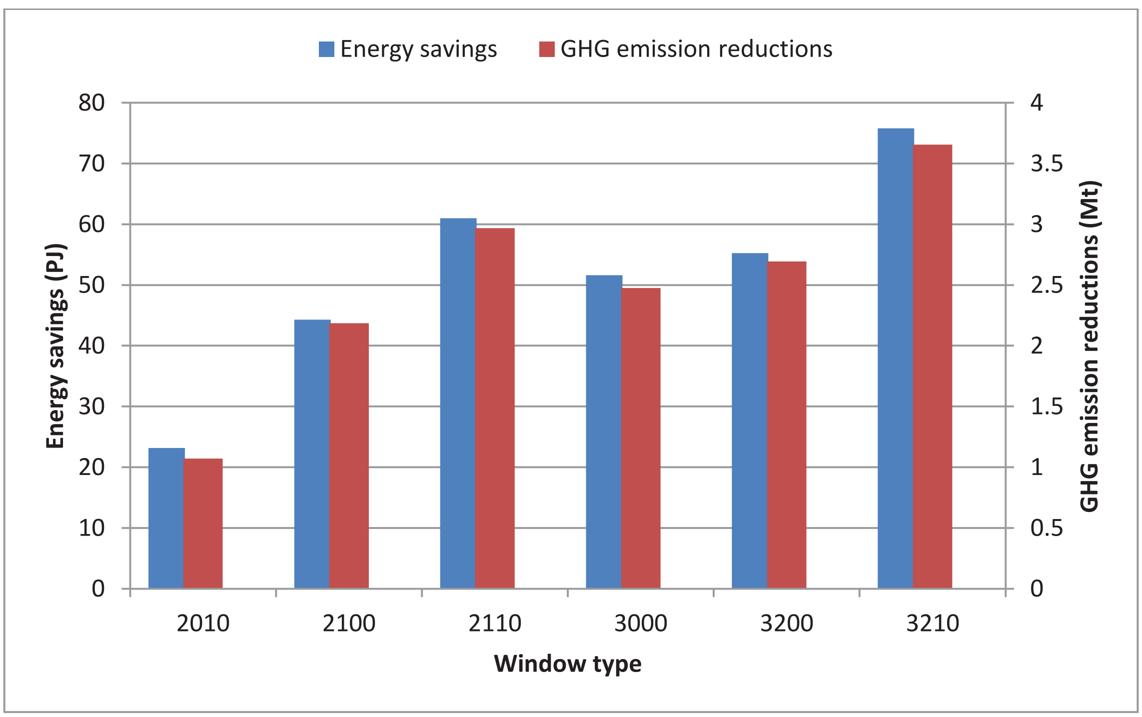


Figure 4.14 Energy consumption savings and GHG emission reductions due to window type upgrade for the CHS

The breakdown of energy savings and GHG emission reductions due to upgrading windows to triple-glazed window, with low-e coating (0.10) and 13 mm Argon filled gap (type 3210) by energy source for the house types and provinces is shown in Table 4.9.

The distribution of energy savings and GHG emission reductions due to window type 3210 upgrade among provinces of Canada are shown in Figure 4.15. By 12% of the savings, BC dominates the annual energy and GHG savings across Canada. This is because BC has a high proportion of SG windows as shown in Table 4.7.

The GHG emission reductions show a different distribution than energy savings due to the variation in marginal GHG EIFs among the provinces. It should be noted that GHG emission reductions are due to upgrades are calculated using marginal GHG EIFs while the base case GHG emissions are calculated using average GHG EIF.

Table 4.9 Estimates of annual energy consumption and GHG emission reduction due to window type 3210 upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	13,990	39,440	8,202	2,471	64,103	552	2,000	580	3,133
	DR	3,307	7,198	1,178	16	11,699	76	365	83	524
Province	NB	471	0	771	914	2,156	111	0	55	166
	NF	440	0	661	183	1,283	3	0	47	50
	NS	343	1	1,546	353	2,243	36	0	109	145
	PE	5	0	258	100	363	0	0	18	18
	QC	10,113	93	2,552	684	13,443	14	5	181	200
	OT	3,538	23,073	3,592	0	30,204	440	1,170	254	1,865
	AB	18	8,603	0	0	8,621	4	436	0	440
	MB	480	1,750	0	0	2,229	0	89	0	89
	SK	136	2,354	0	0	2,490	9	119	0	128
	BC	1,753	10,765	0	254	12,771	9	546	0	555
Canada		17,297	46,638	9,380	2,487	75,803	627	2365	664	3657

* Natural Gas

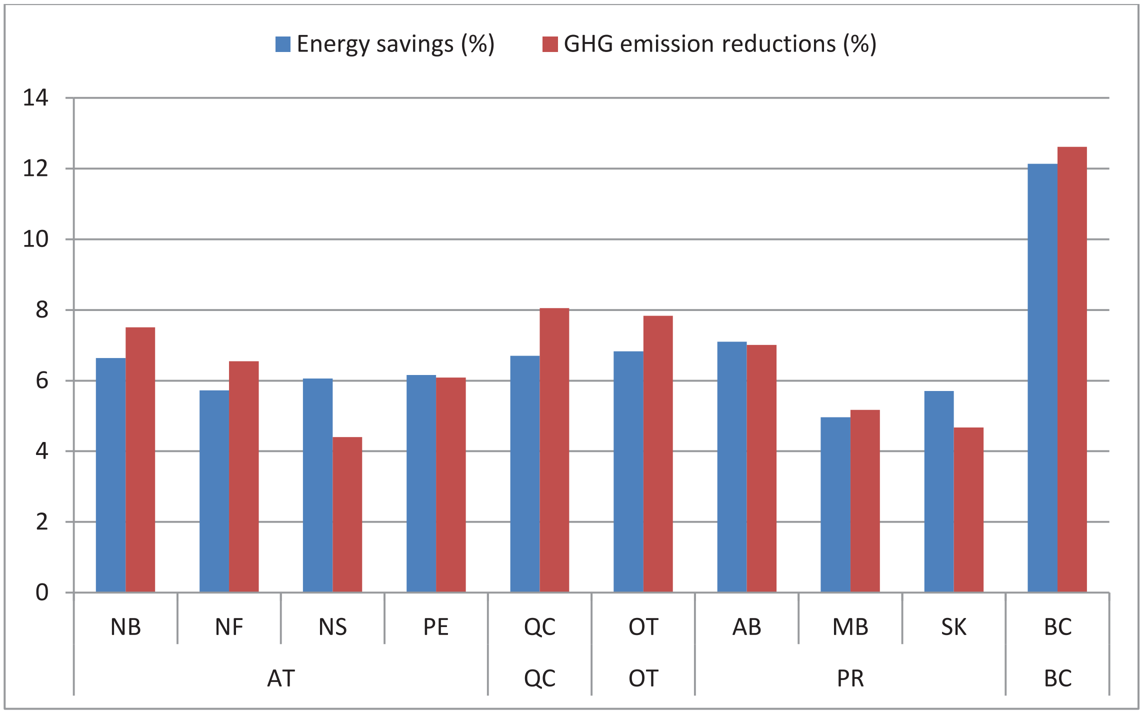


Figure 4.15 Energy consumption and GHG emission reduction specific to individual provinces of Canada due to window type 3210 upgrade

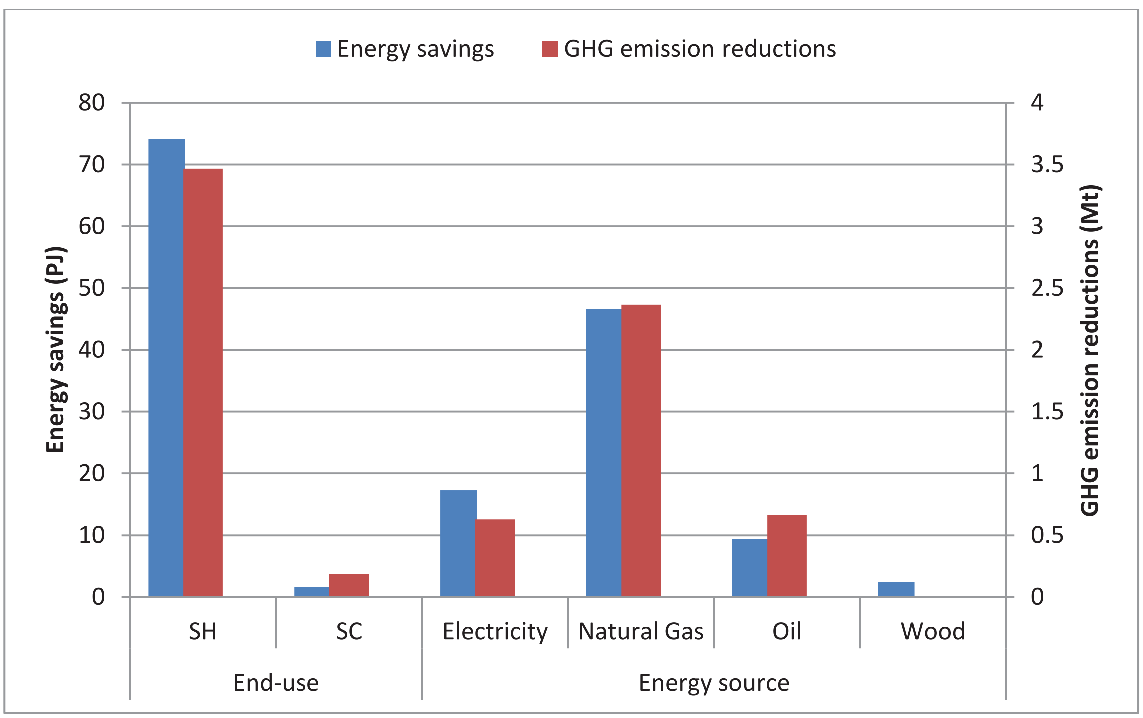


Figure 4.16 National annual energy consumption and GHG emission reduction specific to end-uses and energy sources due to window type 3210 upgrade

Figure 4.16 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 upgrade. 98% of savings are attributed to space heating (SH). It is also shown that the energy and GHG emissions saving of natural gas is higher than other sources of energy. It is because most Canadian households use natural gas as the primary source of energy for SH.

4.2.2.1.2 Window area modification

This section presents the national energy savings and GHG emission reductions results due to window area enlargement along with window type upgrade. The window/wall area ratio of the south window of eligible houses is increased from 30% to 60% by 10% increments. Since upgrading widow area without window type is not very effective, the window type was changed as well.

As it was concluded in previous section, window types 2110 and 3210 have the highest impact on energy consumption and GHG emissions. Therefore, the eligible houses are upgraded to receive both window type and area modifications.

Since the complete analysis of energy savings and GHG emission reductions for all window modifications shows similar trends, detailed results of upgrading windows to window type 3210 and enlargement of 60% are presented here while the rest of the results are provided in Appendix C.

The CHREM estimates of national energy savings and GHG emission reductions due to window type and area modification are shown in Figure 4.17.

The results show that by using a high thermal resistance window on the south side of a house and window/wall area ratio in the range of 30 to 50%, energy consumption and GHG emissions can be reduced by 2%. This amount represents 20 PJ (from 1061 PJ/year to 1041 PJ/year) of energy consumption and 1.05 Mt/year (from 48.4 to 47.4 Mt of CO_2 equivalent) of GHG emissions.

The results show that using a high thermal resistance window would allow us to increase window area without sacrificing energy savings. Although the GHG emissions increase by window area enlargement due to increase in space cooling requirement, the increase is negligible.

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to triple-glazed windows, with low-e coating (0.1) and 13 mm Argon filled gap (type 3210) and increasing the window/wall area ratio to 60% is shown in Table 4.10 for each energy source, house type and province.

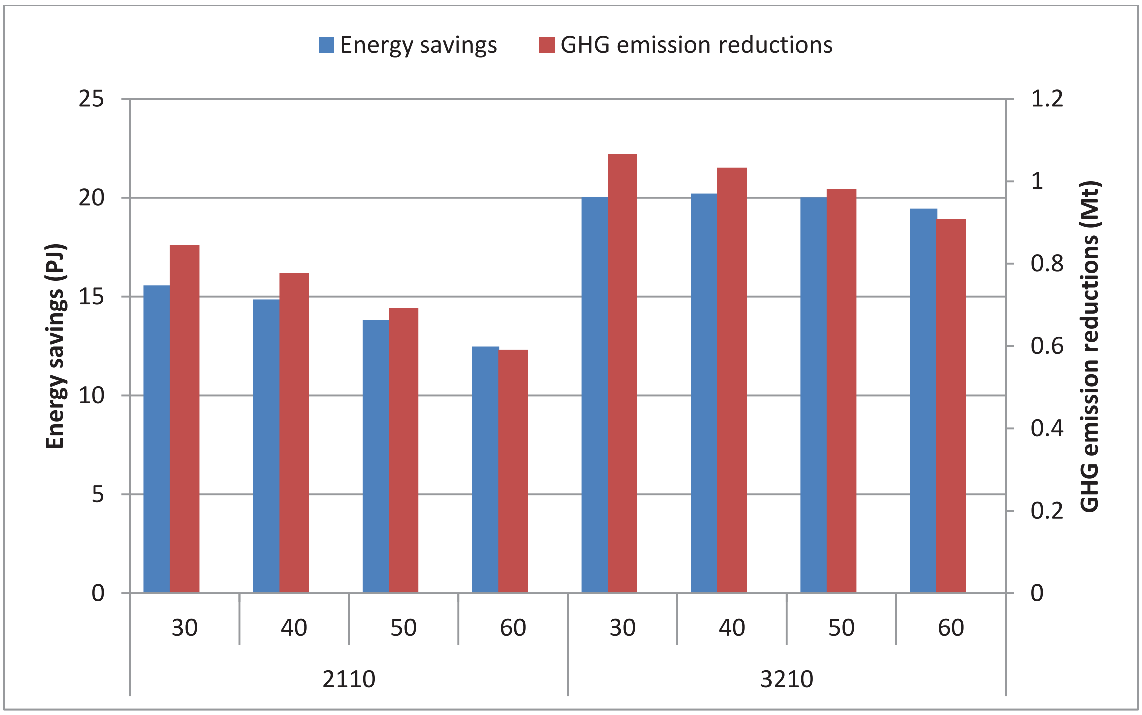


Figure 4.17 Energy consumption savings and GHG emission reductions due to window type and area upgrade

The distribution of energy savings and GHG emission reductions due to window type 3210 and window/wall area ratio of 60% upgrade among provinces of Canada are shown in Figure 4.18. By 3.5% of the savings, NB dominates the annual energy and GHG savings across Canada. This is because NB has the second highest proportion of SG windows as shown in Table 4.7 and according to Environment Canada (2012) it has more sunshine hours during heating season than cooling season.

Figure 4.19 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ratio of 60% upgrade. Since window enlargement increases solar radiation through windows during cooling season as well as heating season, SC energy requirement increases by this upgrade. Therefore, the savings due to window enlargements are in SH.

Table 4.10 Estimates of annual energy consumption and GHG emission reductions due to window type 3210 and window/wall area ratio of 60% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	-286	12,396	2,792	923	15,822	-59	629	198	767
	DR	675	2,404	548	0	3,628	-19	122	39	141
Province	NB	208	0	459	449	1,114	49	0	32	82
	NF	183	0	325	84	592	1	0	23	24
	NS	144	0	739	178	1,061	15	0	52	67
	PE	2	0	114	48	163	0	0	8	8
	QC	557	1	451	122	1,132	-1	0	32	31
	OT	-794	8,762	1,251	0	9,218	-133	444	88	400
	AB	-24	3,126	0	0	3,102	-5	159	0	153
	MB	157	771	0	0	928	0	39	0	39
	SK	-78	922	0	0	843	-5	47	0	42
	BC	36	1,218	0	42	1,296	0	62	0	62
Canada		390	14,799	3,340	923	19,450	-79	751	236	908

* Natural Gas

4.2.2.2 Economic feasibility of window modification upgrade for the CHS

The total tolerable capital costs for window type and area upgrade as well as per unit of upgrade are presented as follows.

4.2.2.2.1 Window type modification

This section presents the total tolerable capital costs for window type upgrades. Since the complete analysis of total tolerable capital cost for all window type upgrades shows similar trends, detailed results of window type 3210 upgrade are presented here while the rest of the results are provided in Appendix D.

The CHREM estimates of total tolerable capital costs for three different payback periods, interest rates and fuel cost escalation rates for each window type upgrade are shown in Figure 4.20.

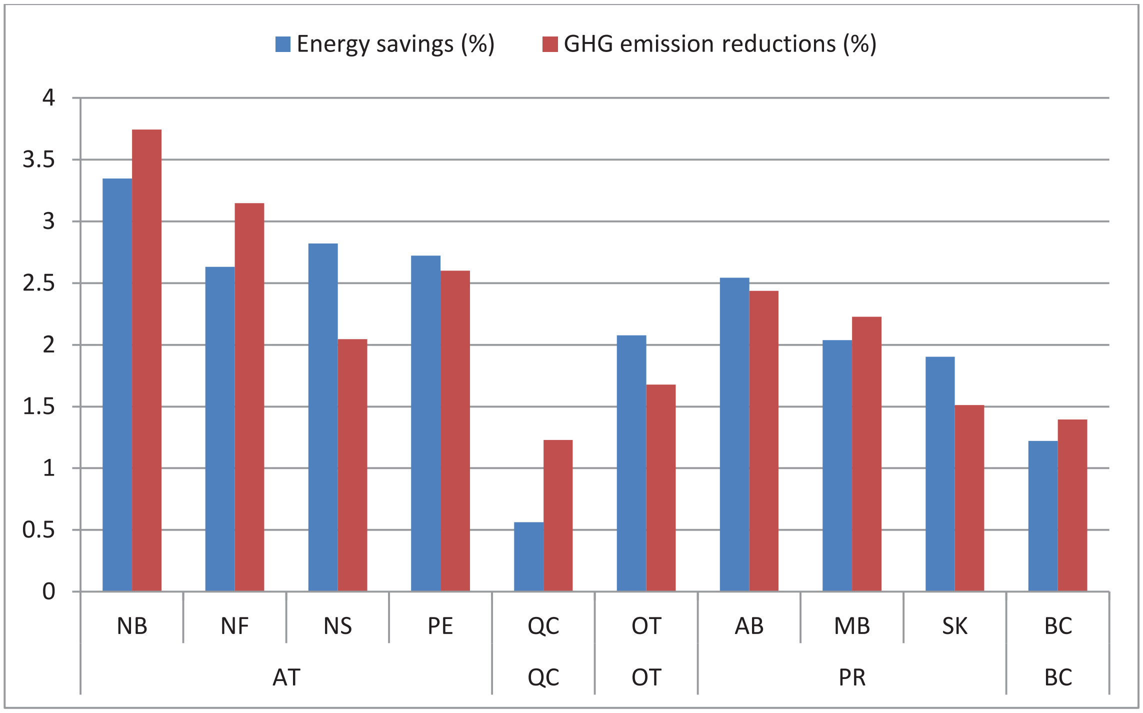


Figure 4.18 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 3210 and window/wall area ratio of 60% upgrade

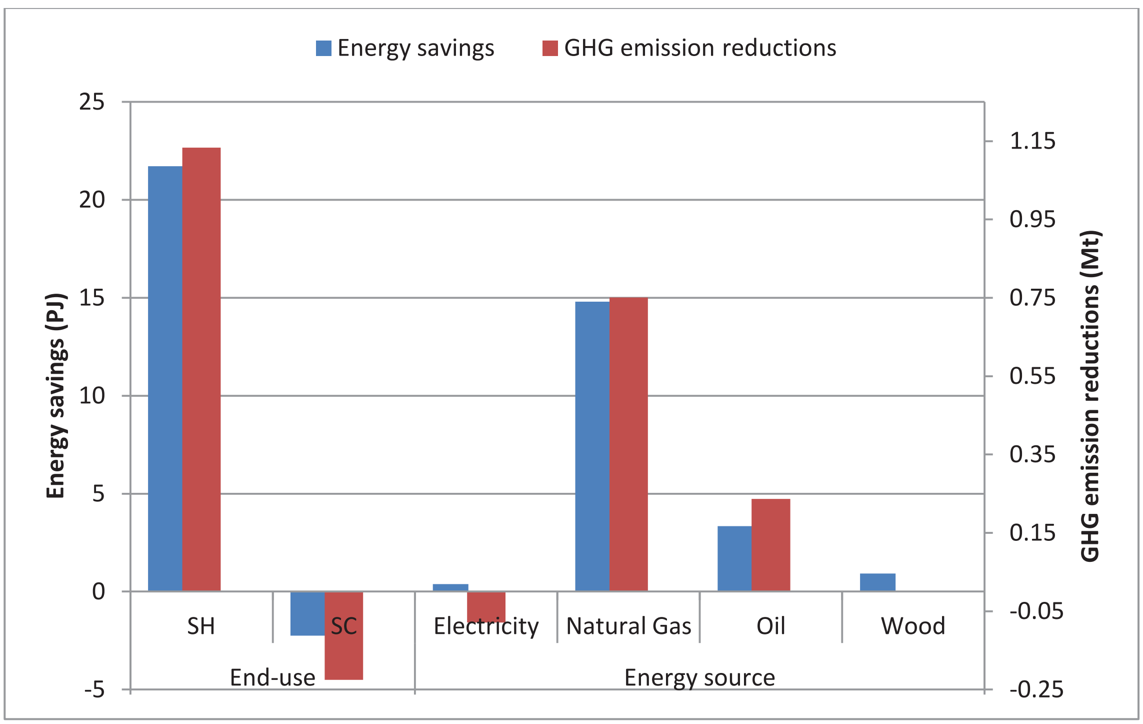


Figure 4.19 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ratio of 60% upgrade

As it was concluded in section 4.2.2.1.1, window types 2110 and 3210 have the highest impact on energy consumption and GHG emissions. Therefore, they have the highest total tolerable capital cost compared to other window types.

Since higher thermal resistance windows save more energy, their total tolerable capital cost in the lower range of fuel cost escalation rates is comparable with the lower thermal resistance windows and higher range of fuel cost escalation rates. For example, total tolerable capital cost of window type 2110 with medium fuel cost escalation rate is almost the same as total tolerable capital cost of window type 2100 with high fuel cost escalation rate.

The provincial total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 upgrade are shown in Table 4.11. The province of NB with tolerable capital cost of 87 CAN$ per m^2 of window has the highest upgrading feasibility across Canada. The dominant fuel in this province is oil while in other provinces except Quebec and other Atlantic provinces it is natural gas. Since the price of oil per unit of energy is higher than natural gas it is more cost effective to apply the window type upgrade in NB rather than in provinces using natural gas as the primary source of energy.

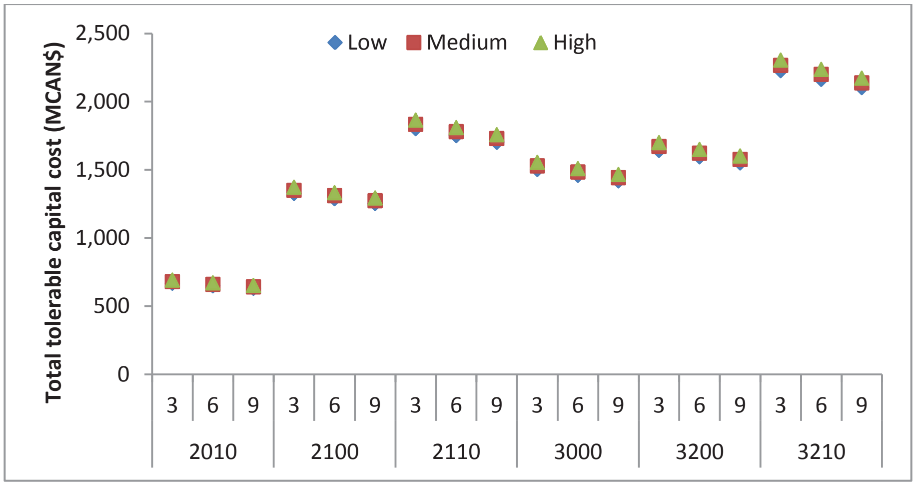
Although electricity price per unit of energy is higher than oil, the energy saved per unit area of window in QC is much less than NB. Therefore, it is still not cost effective to apply the window type upgrade in Quebec as the primary choice.

4.2.2.2.2 Window area modification

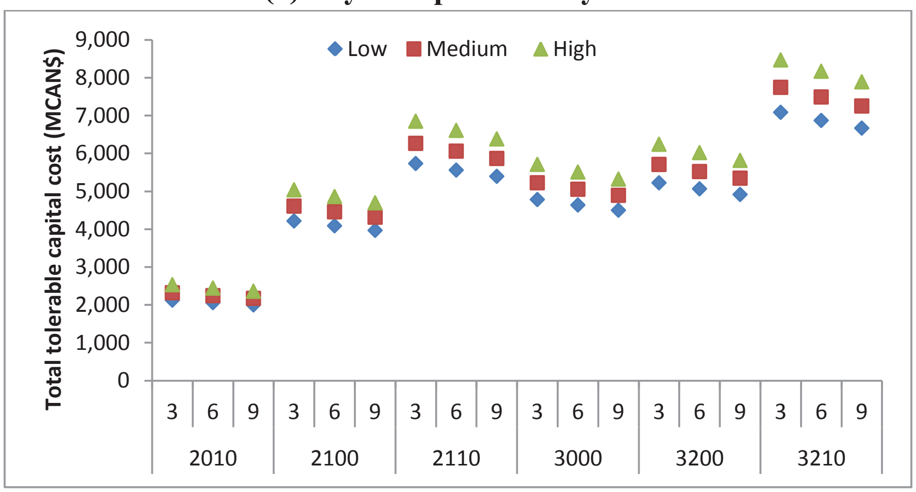
This section presents the total tolerable capital costs for window area enlargement along with window type upgrade. Since the complete analysis of total tolerable capital cost for all window modifications shows similar trends, detailed results of window type 3210 upgrade and window/wall area ratio of 60% are presented here while the rest of the results are provided in Appendix D.

The CHREM estimates of total tolerable capital costs for three different payback periods, interest rates and fuel cost escalation rates for all window enlargement and selected window types are shown in Figure 4.22. The results show that for each payback period, interest rate and fuel cost escalation rate, increasing the window/wall area ratio for each window type the total tolerable capital cost remains constant.

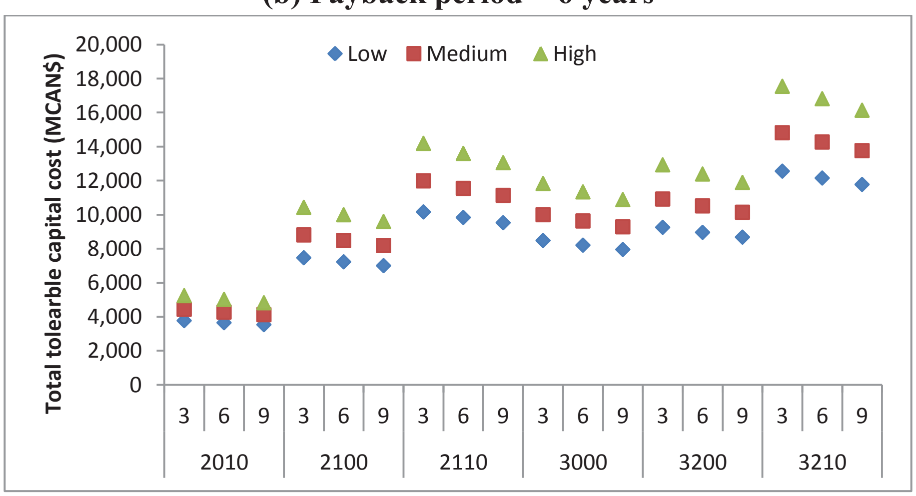
The provincial total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 upgrade is shown in Table 4.12. The province of NB with an average tolerable capital cost of 54 CAN$ per m^2 of window has the highest upgrading feasibility across Canada. Since the sunshine hours during heating season is higher than cooling season in NB, the energy savings per unit area of window increases by increasing window area/wall area ratio. Therefore, it is more cost effective to apply the window enlargement along with window type upgrade in this province.



(a) Payback period = 2 years

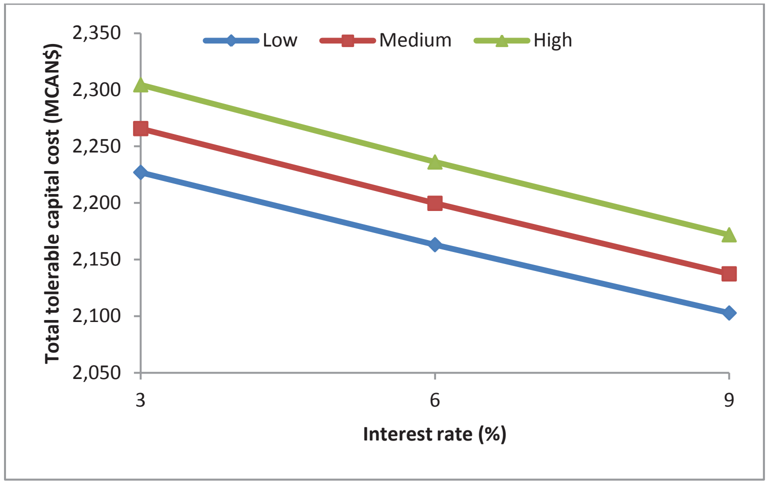


(b) Payback period = 6 years

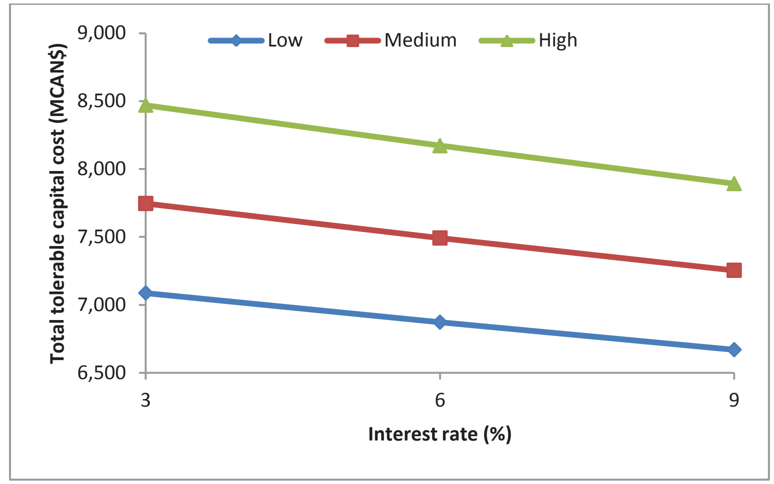


(c) Payback period = 10 years

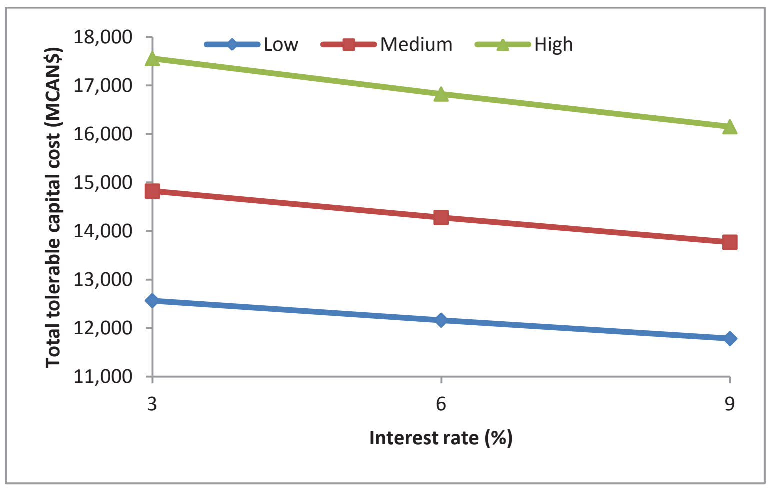
Figure 4.20 Total national tolerable capital cost due to window type upgrade for different interest rates (3, 6, 9%) and fuel cost escalation rates (Low, Medium, High as per Table 2.6)



(a) Payback period = 2 years



(b) Payback period = 6 years



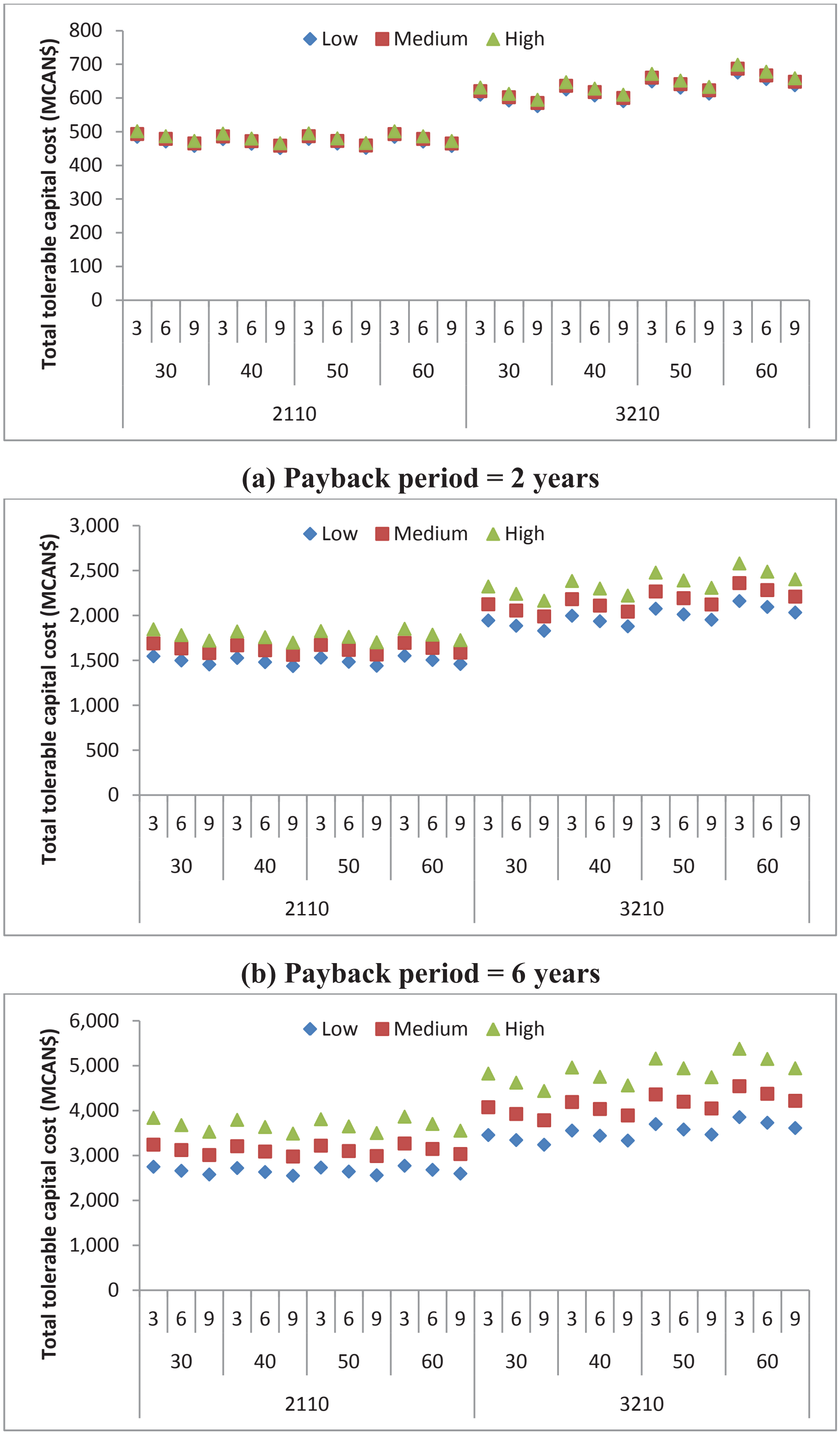
(c) Payback period = 10 years

Figure 4.21 Total national tolerable capital cost due to window type 3210 upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table 4.11 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	238,327	4,165,997	363	1,522	87	2,156	9.0	518	166	696	39.8
NF	174,977	3,010,928	240	1,373	80	1,283	7.3	426	50	284	16.5
NS	298,174	5,848,122	405	1,359	69	2,243	7.5	383	145	487	24.8
PE	44,995	744,030	55	1,233	75	363	8.1	488	18	406	24.5
QC	1,992,258	38,212,810	1,992	1,000	52	13,443	6.7	352	200	100	5.2
OT	3,436,650	73,448,632	2,740	797	37	30,204	8.8	411	1,865	543	25.4
AB	973,158	18,411,855	305	314	17	8,621	8.9	468	440	453	23.9
MB	339,713	5,023,820	173	509	34	2,229	6.6	444	89	262	17.7
SK	312,066	4,659,917	148	475	32	2,490	8.0	534	128	412	27.6
BC	1,113,593	26,714,487	1,070	961	40	12,771	11.5	478	555	498	20.8

* Total tolerable capital cost
** Tolerable capital cost

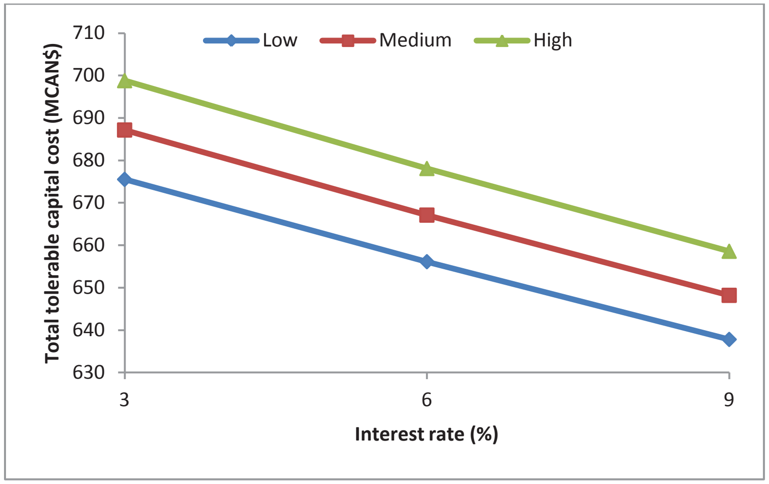


(a) Payback period = 2 years

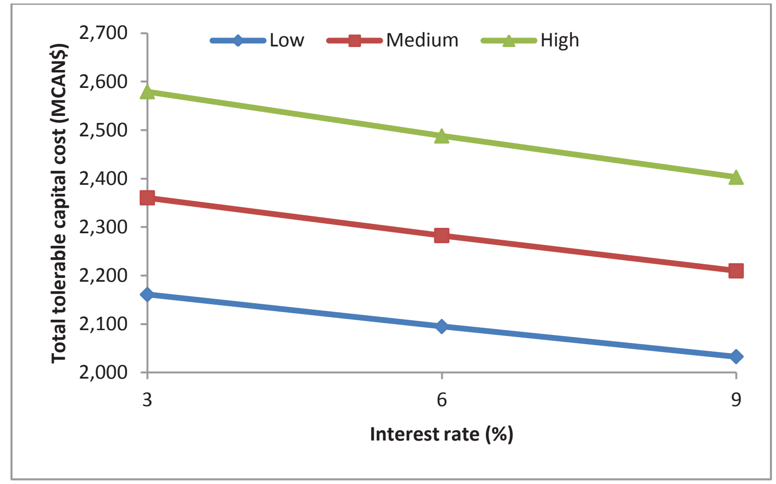
(b) Payback period = 6 years

(c) Payback period = 10 years

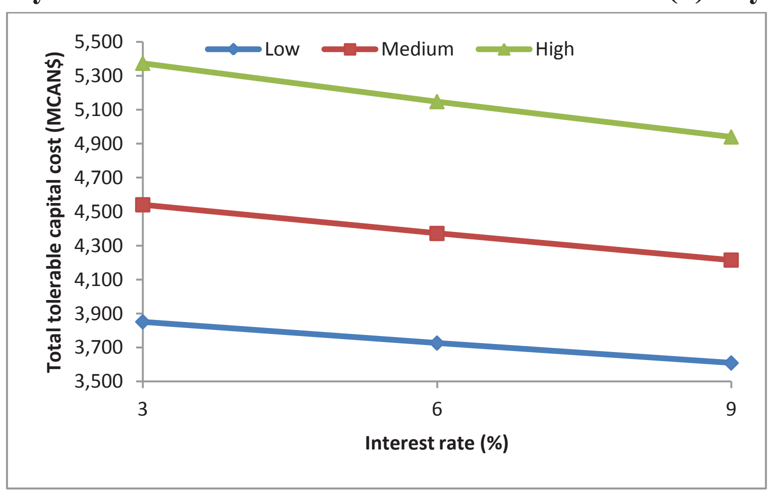
Figure 4.22 Total national tolerable capital cost due to window type (2110 and 3210) and area (30, 40, 50, 60% increase) upgrade for different interest rates (3, 6, 9%) and fuel cost escalation rates (Low, Medium, High as per Table 2.6)



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure 4.23 Total national tolerable capital cost due to window type 3210 and window/wall area ratio of 60% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table 4.12 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 and window/wall area ratio of 60% upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	209,261	3,524,726	191	914	54	1,114	5.3	316	82	390	23.2
NF	162,679	2,792,109	111	683	40	592	3.6	212	24	149	8.7
NS	260,108	4,954,555	192	738	39	1,061	4.1	214	67	259	13.6
PE	40,538	670,798	26	629	38	163	4.0	244	8	199	12.0
QC	1,688,792	31,784,527	435	258	14	1,132	0.7	36	31	18	1.0
OT	2,949,530	62,477,176	911	309	15	9,218	3.1	148	400	136	6.4
AB	851,528	15,926,256	116	136	7	3,102	3.6	195	153	180	9.6
MB	311,439	4,630,931	81	261	18	928	3.0	200	39	126	8.5
SK	275,829	4,159,569	60	218	14	843	3.1	203	42	151	10.0
BC	806,356	18,327,200	159	198	9	1,296	1.6	71	62	77	3.4

* Total tolerable capital cost

** Tolerable capital cost

4.2.2.3 Conclusion

The techno-economic assessment of window modifications was presented in this section. Based on the results of the parametric study, six different types of window and four different window/wall area ratios were selected. The selected upgrade scenarios were applied to all eligible houses.

In the case of window type upgrade, all windows were uniformly replaced by the better performance window compared to the most prevalent window type of each house. CHREM estimates that by upgrading all windows to window type 3210 the energy consumption reduces by 7% (from 1061.6 to 986 PJ/year) and GHG emissions reduces by 8% (from 48.4 to 44.7 Mt of CO_2 equivalent). From the economical point of view, upgrading windows in the province of NB is more feasible than other provinces.

In case of window area enlargement, the window/wall area ratio of the south window of eligible houses was increased from 30% to 60% by 10% increments and it was upgraded to window types 2110 and 3210. The results showed that using a high thermal resistance window would allow us to increase window area without sacrificing energy savings and therefore any total tolerable capital cost. Similar to window type upgrade, window enlargement is more cost effective in the province of NB.

4.3 Techno-economic assessment of Venetian blinds for the CHS

4.3.1 Parametric study

To assess the effect of external and internal shading on heating and cooling energy requirement, the "case study house" was first modeled and simulated without any external or internal shading to provide the "base case" energy requirement. Then, the effect of slat angle, type, curvature, and position (horizontal or vertical), and orientation (e.g. south) of Venetian blinds as well as different control strategies for Venetian blinds on heating and cooling energy requirement was assessed by conducting a series of building energy simulations, and comparing the results with those obtained from the simulation of the base case house.

4.3.1.1 *Case studies conducted to select the suitable parameters for Venetian blind upgrades for the CHS*

To evaluate the effect of Venetian blinds on energy requirement, the following analyses were conducted:

- Effect of slat angle: To study the effect of slat angle, a flat, horizontal, 1 inch Dark Aluminum slat type Venetian blind was added on the outside of the windows on all four sides of the case study house and simulations were conducted assuming that the blinds are not controlled (i.e. stay at the same position at all times). The slat angle was increased from 0 (fully open) to 90 (fully closed) degrees in increments of 15 degrees. In these simulations, the weather data set of Toronto was used.
- Effect of slat type and Venetian blind placement: To study the effect of slat type upgrade, a 45 degree, flat, horizontal slat type Venetian blind with different type of slats was added on the outside and inside of the windows as well as between the layers of glazing on all four sides of the case study house and simulations were conducted assuming that the blinds are not controlled (i.e. stay at the same position at all times). In these simulations, the weather data set of Toronto was used. The types of slat that are used in the simulations are the eight types of slats that are represented in GSLedit (ESRU 2010) which are:

    a. ½ inch light aluminum
    b. ½ inch medium aluminum
    c. ½ inch dark aluminum
    d. ½ inch light vinyl
    e. 1 inch light aluminum
    f. 1 inch medium aluminum
    g. 1 inch dark aluminum
    h. 1 inch light-dark aluminum

- Effect of slat curvature: To study the effect of slat curvature, a 45 degree, horizontal, 1 inch Dark Aluminum slat type Venetian blind with two slat curvatures, flat and curved, was added on the outside of the windows on all four sides of the case study house and simulations were conducted assuming that the blinds are not controlled (i.e. stay at the same position at all times). In these simulations, the weather data set of Toronto was used.
- Effect of slat orientation: To study the effect of slat orientation, a 45 degree, flat, 1 inch Dark Aluminum slat type Venetian blind with two slat orientations, horizontal and vertical (louver-drape), was added on the outside of the windows on all four sides of the case study house and simulations were conducted assuming that the blinds are not controlled (i.e. stay at the same position at all times). In these simulations, the weather data set of Toronto was used.
- Effect of shading orientation: To study the effect of shading orientation, a 45 degree, flat, 1 inch Dark Aluminum slat type Venetian blind was added on the outside of the windows on each side of the case study house and the simulations

were conducted once with horizontal slat orientation and then vertical assuming that the blinds are not controlled (i.e. stay at the same position at all times). In these simulations, the weather data set of Toronto was used.

- Effect of climate: To study the effect of climate, a 45 degree, flat, horizontal, 1 inch Dark Aluminum slat type Venetian blind was added on the outside of the windows on all four sides of the case study house and simulations were conducted assuming that the blinds are not controlled (i.e. stay at the same position at all times). Simulations were conducted for five cities, Halifax, Quebec, Toronto, Calgary and Vancouver, which represent the five major climatic regions in Canada, namely Atlantic, Quebec, Ontario, Prairies and Pacific.
- Effect of control strategy: to study the effect of Venetian blind control, a flat, horizontal, 1 inch Dark Aluminum slat type Venetian blind was added once on the inside and once on the outside of the windows on all four sides of the case study house and simulations were conducted with different control strategies as explained below. In these simulations, the weather data set of Toronto was used.

<u>Control strategies:</u>

In ESP-r the following parameters can be used to specify the desired control strategy for a window type.

1. Sensor:
   a. Sensor not used (schedule only)
   b. Senses mix of zone dry bulb temperature and mean radiant temperature (MRT) (senses an ambient condition)
   c. Senses dry bulb temperature
   d. Senses sol-air temperature
   e. Senses wind speed
   f. Senses wind direction
   g. Senses diffuse horizontal solar radiation
   h. Senses direct normal radiation
   i. Senses direct solar radiation incident on a surface
   j. Senses temperature in a specific zone
2. Actuator:
   a. Shading layer On/Off state
   b. Slat angle of slat type shade
   c. Shade On/Off state and slat angle (schedule)
3. Controller type: There are seven control types in ESP-r which are shown in Table 4.13. The controller type is determined by the combination of sensor and actuator. For example, controller type (1) is a control that senses the temperature in a specific zone and actuates shading layer on/off. However, because the solar radiation and the temperature of the room is more important in the heating and cooling energy requirement of the house, controller types (5) and (6) are not used in this study.

Table 4.13 Controller types defined in ESP-r

Controller type	Sensor	Actuator
1	Senses temperature in a specific zone	Shading layer On/Off
2	Senses temperature in a specific zone	Slat angle of slat type shade
3	Senses direct solar radiation incident on a surface	Shading layer On/Off
4	Senses direct solar radiation incident on a surface	Slat angle of slat type shade
5	Senses wind speed	Shading layer On/Off
6	Senses wind direction	Shading layer On/Off
7	Sensor not used (schedule only)	Shade On/Off state and slat angle (schedule)

4. Control law
    a. Basic control: is an ideal controller which actuates shading device for specific set points based on the defined sensor.
    b. Schedule: is an ideal controller which actuates shading device based on the schedule provided by the user.

Besides all these parameters which define the control strategy, the control period in year and day can be defined.

To use the advantage of shading in cooling season and using the solar gain in winter, a combination of strategies through the year has been considered in this work. To account for thermostat use by an occupant, and the varied climates found throughout Canada, a five period control strategy similar to building control periods defined by Swan (2010) is employed. Meanwhile, the time-of-day control strategy was used to divide a whole day into night time and the day time. The resulting periods and HVAC status in each period are given in Table 4.14.

Table 4.14 Periods of control strategy

Seasonal periods		HVAC status		Time-of-day periods		
Periods	Dates	Space heating available	Space cooling available	Period 1 (hr)	Period 2 (hr)	Period 3 (hr)
1	Jan1 – Apr 1	Yes	No	0 – 7	7 – 18	18 – 24
2	Apr 2 – Jun 3	Yes	Yes	0 – 7	7 – 19	19 – 24
3	Jun 4 – Sep 16	No	Yes	0 – 6	6 – 20	20 – 24
4	Sep 17 – Oct 7	Yes	Yes	0 – 7	7 – 19	19 – 24
5	Oct 8 – Dec 31	Yes	No	0 – 7	7 – 18	18 – 24

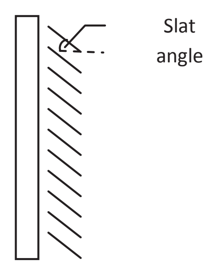
The control law used during the five periods of the year is summarized in Table 4.15. It was assumed that the blinds are closed during the night time in all seasons. In heating only season it was assumed the blinds are open during the day to take advantage of the solar gain through windows (controller type 7). During cooling season the basic control with one of the controller types (1-4) was used during the day to change the status of blind when the sensor sends the signal. Table 4.16 shows the input data that is assumed for each controller type.

Table 4.15 Control law used during each period

Dates	Day period 1		Day period 2		Day period 3	
	Duration (hr)	Control law	Duration (hr)	Control law	Duration (hr)	Control law
Jan1 – Apr 1	0 – 7	Schedule	7 – 18	Schedule	18 – 24	Schedule
Apr 2 – Jun 3	0 – 7	Schedule	7 – 19	Basic control	19 – 24	Schedule
Jun 4 – Sep 16	0 – 6	Schedule	6 – 20	Basic control	20 – 24	Schedule
Sep 17 – Oct 7	0 – 7	Schedule	7 – 19	Basic control	19 – 24	Schedule
Oct 8 – Dec 31	0 – 7	Schedule	7 – 18	Schedule	18 – 24	Schedule

Table 4.16 Input data for different controller types

	Control law					
	Basic Control				Schedule	
Input Data / Controller type	1	2	3	4	7	
Temperature shade-on (˚C)	24	24				
Temperature shade-off (˚C)	21	21				
Solar radiation shade-on (W/m^2)			233*	233*		
Solar radiation shade-off (W/m^2)			200	200		
Slat angle-on (degree)		89		89		
Slat angle-off (degree)		0		0		
Shade on/off **					On	Off
Slat angle (degree)					89	0



* The solar radiation that leads to thermal discomfort is determined based on a study by Newsham (1994)
** "Shade on" means there is a shading layer and "shade off" means there is no shading layer.

4.3.1.2 Results and discussion

4.3.1.2.1 Effect of slat angle

The purpose of this study is to assess the effect of changing slat angle on annual heating and cooling energy requirements. The results are summarized in Figure 4.24 and Figure

4.25 where the changes are given as a percentage of the annual values of the base case house that has no blinds and is located in Toronto.

<u>Effect on heating energy requirement</u>

As seen in Figure 4.24, in comparison with a house that has no shading, addition of fully closed blinds increases the annual heating energy requirement substantially. Decreasing the slat angle of the Venetian blind allows a larger portion of the solar radiation to be absorbed by the zone. As the slat angle decreases, the solar radiation that passes through the windows increases. Therefore, the solar heat gain can compensate part of the heat loss through the building envelope, reducing the heating energy requirement.

The results shown in Figure 4.24 indicate the following:

- Increasing slat angle increases heating energy requirement by up to 13% which represents 16 GJ/year,
- Presence of Venetian blinds even in fully open mode (slat angle = 0˚) increases the heating energy requirement substantially due to the scattering of the solar beam energy.

<u>Effect on cooling energy requirement</u>

As seen in Figure 4.25, in comparison with a house that has no shadings, addition of fully closed blind decreases the annual cooling energy requirement substantially. Since the solar heat gain is the main cause of the cooling load, addition of a blind to the window blocks the solar radiation to be absorbed to the zone. Therefore, the cooling load is reduced.

The results shown in Figure 4.25 indicate the following:

- Increasing slat angle decreases the cooling energy requirement by up to 64% which represents 4.2 GJ/year,
- Presence of Venetian blinds, even in fully open mode (slat angle = 0˚) decreases the cooling energy requirement substantially due to the scattering of the solar beam energy.

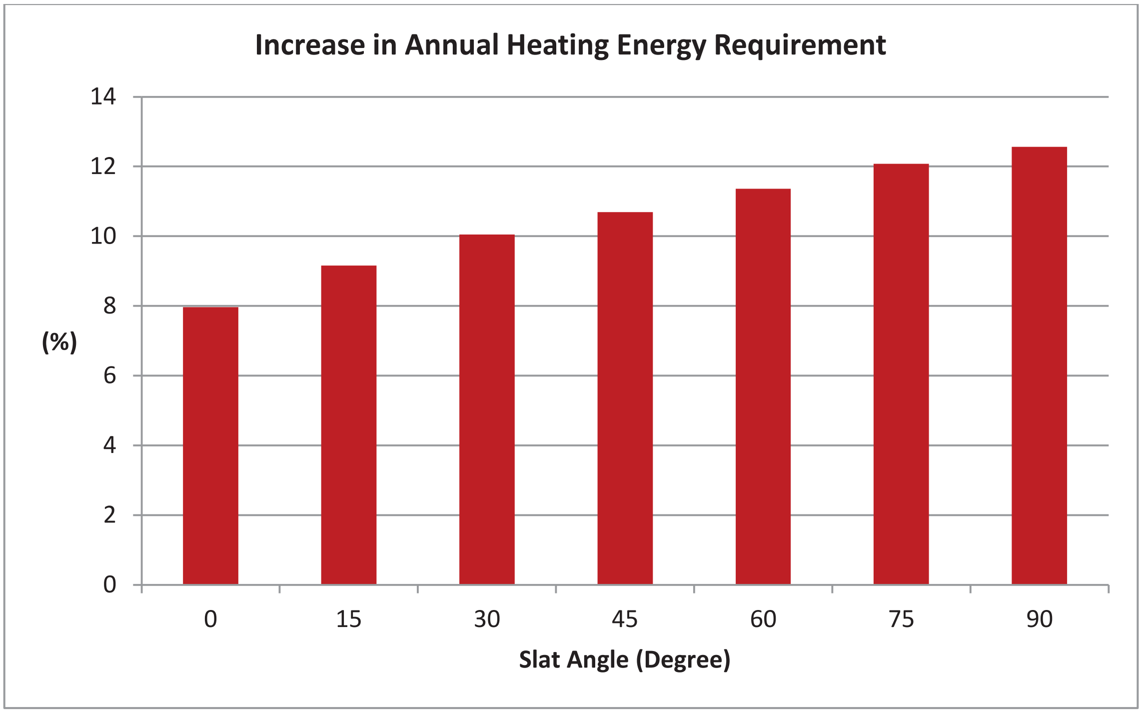


Figure 4.24 Increase in annual heating energy requirement due to increasing slat angle compared to the base case house (heating = 126 GJ; weather data set used: Toronto)

4.3.1.2.2 Effect of slat type and shading position

The purpose of this analysis is to assess the effect of slat type modifications and shading position on annual heating and cooling energy requirements. The results are summarized in Figure 4.26 and Figure 4.27 where the changes are given as a percentage of the annual values of the base case house that has no blinds and is located in Toronto.

<u>Effect on heating energy requirement</u>

As seen in Figure 4.26, in comparison with a house that has no shading, addition of indoor blind reduces annual heating energy requirement while the outdoor blind increases annual heating energy requirement. Addition of a blind in the outdoor side of the glazing system prevents the solar radiation to be absorbed by the zone. Therefore, the zone loses the benefit of solar heat gain through sunshine hours during the heating season.

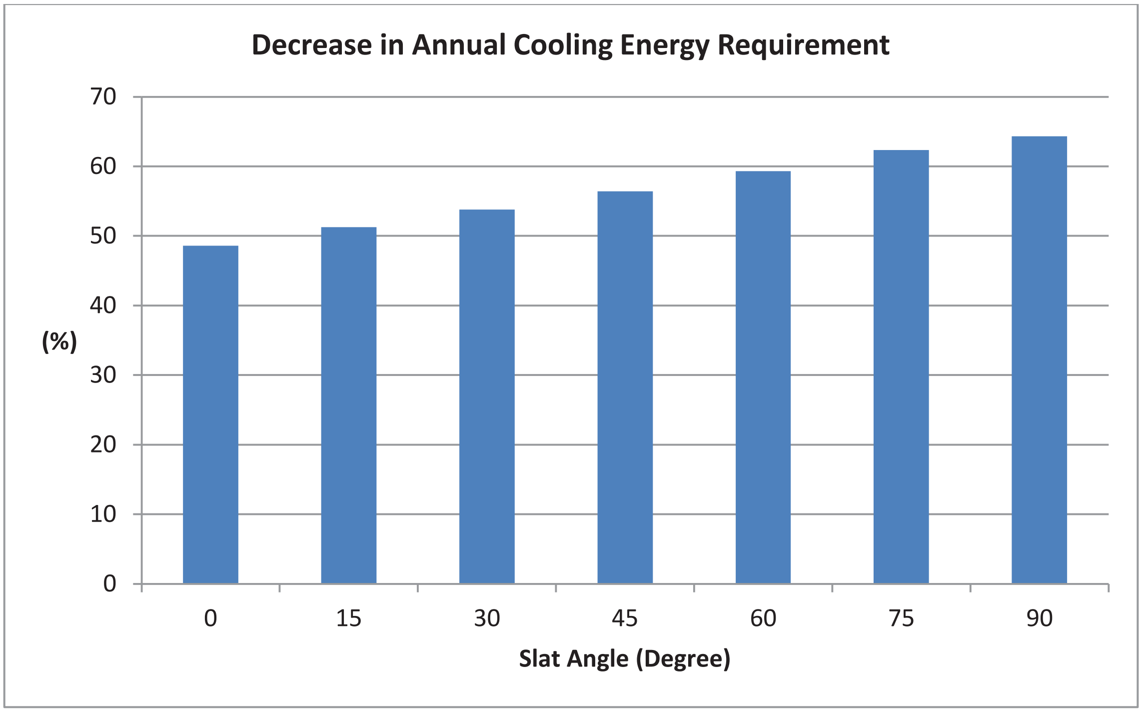


Figure 4.25 Decrease in annual cooling energy requirement due to increasing slat angle compared to the base case house (cooling = 6.5 GJ; weather data set used: Toronto)

On other hand, addition of the blind to the indoor side allows a large portion of solar radiation to be absorbed by the blind and later transferred to the zone by convection heat transfer. It also traps the heat on the interior of the glass which acts as an extra insulation. Therefore, the solar heat gain along with the extra insulation compensates part of the heat loss through the building envelope and reduces the heating energy requirement. These results are in agreement with Lomanowski, et al. (2009) study.

The results shown in Figure 4.26 indicate the following:

- Presence of indoor blind decreases heating energy requirement while outdoor blind and between glazing blind increases heating energy requirement,
- Using darker color blind has higher impact on heating energy requirement due to its lower solar reflectance,
- Using wider slat type has no significant impact on heating energy requirement.

For example addition of ½ inch dark aluminum on the indoor side of window decreases heating energy requirement by 10% which represents 12 GJ/year while addition of it on the outdoor side of window increases heating energy requirement by 11% which represents 13 GJ/year.

Effect on cooling energy requirement

As seen in Figure 4.27, in comparison with a house that has no shading, addition of a blind reduces annual cooling energy requirement independent of its position except the dark color blinds. Since the solar heat gain is the main cause of the cooling load, addition of a blind to the window blocks the solar radiation to be absorbed to the zone. Therefore, the cooling load is reduced.

The results shown in Figure 4.27 indicate the following:

- Outdoor blind has the highest impact on decreasing the cooling energy requirement which is in agreement with previous studies (Lomanowski, et al. 2009),
- Indoor blinds can increase cooling energy requirement;
- The slat width has no significant impact on cooling energy requirement.

For example addition of ½ inch dark aluminum on the outdoor side of window decreases cooling energy requirement by 57% which represents 3.7 GJ/year while addition of it on the indoor side of window increases cooling energy requirement by 19% which represents 1.2 GJ/year.

As seen in Figure 4.27 a dark colored outdoor blind results in a larger decrease in annual cooling energy requirement than does a light colored one. This result is counter-intuitive and it may have something to do with the modeling assumptions made in ESP-r that effect thermal behaviour of windows with exterior blinds during calm sunny conditions when the solar radiation absorbed in the outdoor blind is not readily rejected back to the ambient due to low convective heat transfer rates, thus creating a hot zone adjacent to the window (Lomanowski, 2008) as explained in section 3.2.1.1.2. However, since the difference between the reduction in cooling energy requirement with light and dark colored Venetian blinds is small, further investigation into this potential problem was not carried out.

4.3.1.2.3 Effect of slat curvature

The effect of slat curvature on annual heating and cooling energy requirement was assessed. The results show that changing the slat curvature has no effect on annual heating and cooling energy requirements. Since there is no effect, for the sake of brevity these results are not shown.

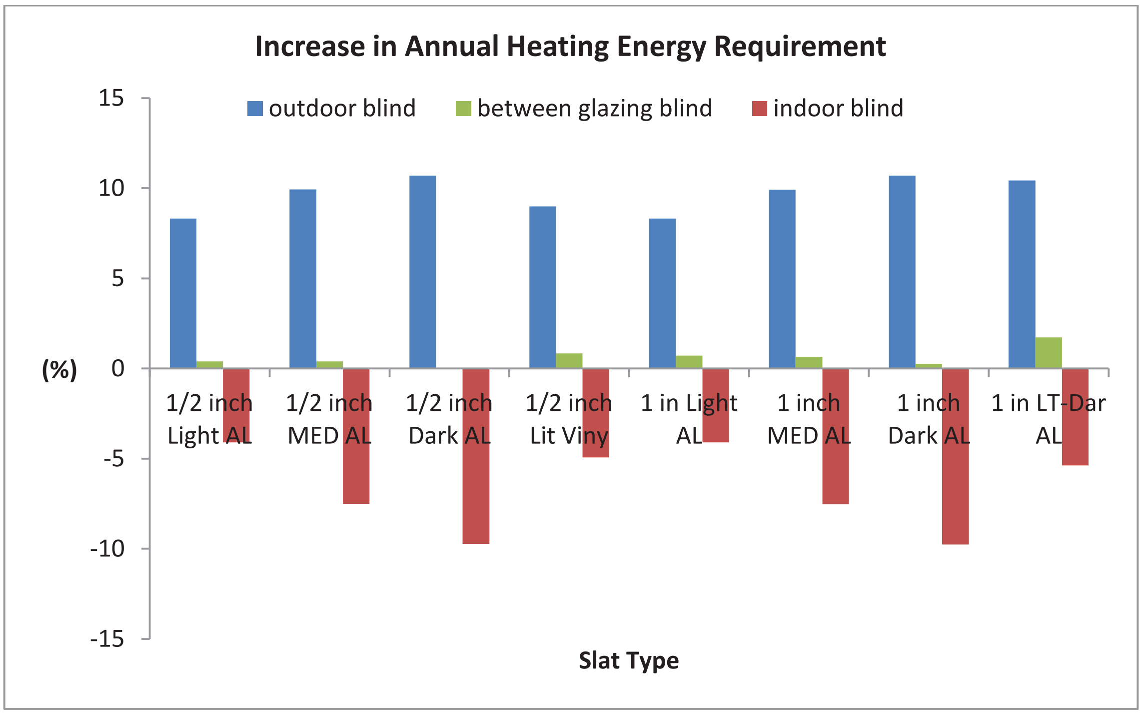


Figure 4.26 Increase in annual heating energy requirement due to slat type upgrade compared to the base case (heating = 126 GJ; weather data set used: Toronto)

4.3.1.2.4 Effect of slat orientation

The object of this study is to assess the effect of slat orientation on annual heating and cooling energy requirement. The results are summarized in Figure 4.28. The results show that addition of Horizontal slat type increases heating energy requirement and decreases cooling energy requirement more than Vertical one. That happens because the angle of incidence of the solar radiation is closer to normal for Horizontal slat type than Vertical slat type.

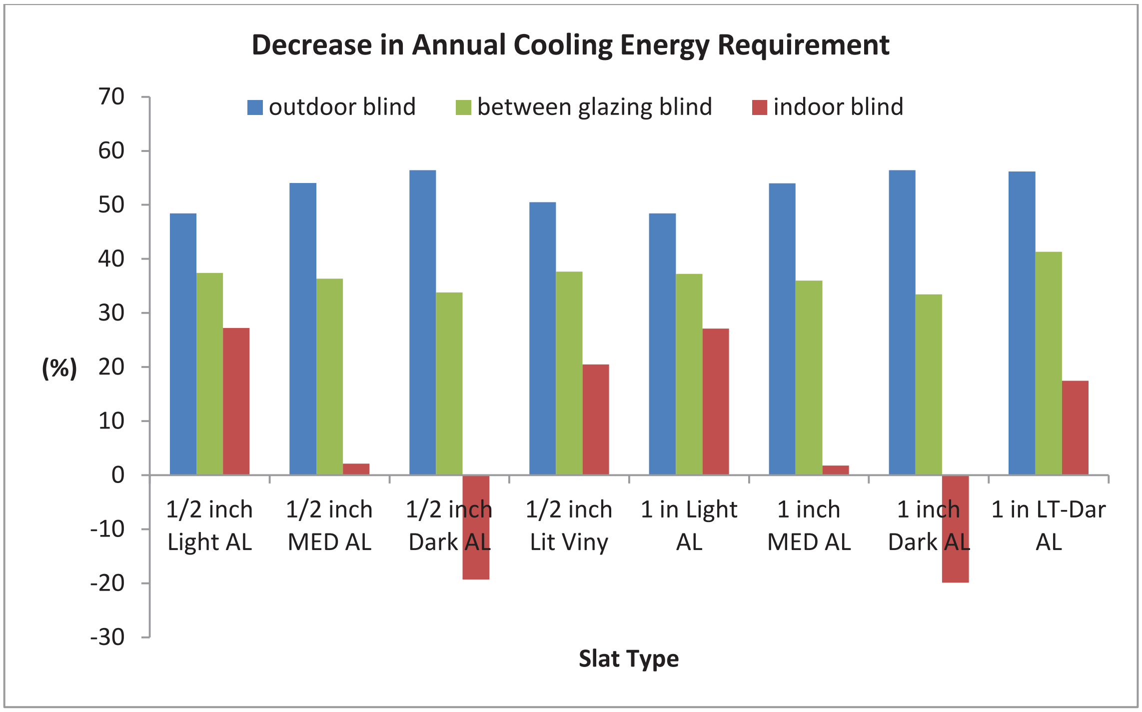


Figure 4.27 Decrease in annual cooling energy requirement due to slat type upgrade compared to the base case (cooling = 6.5 GJ; weather data set used: Toronto)

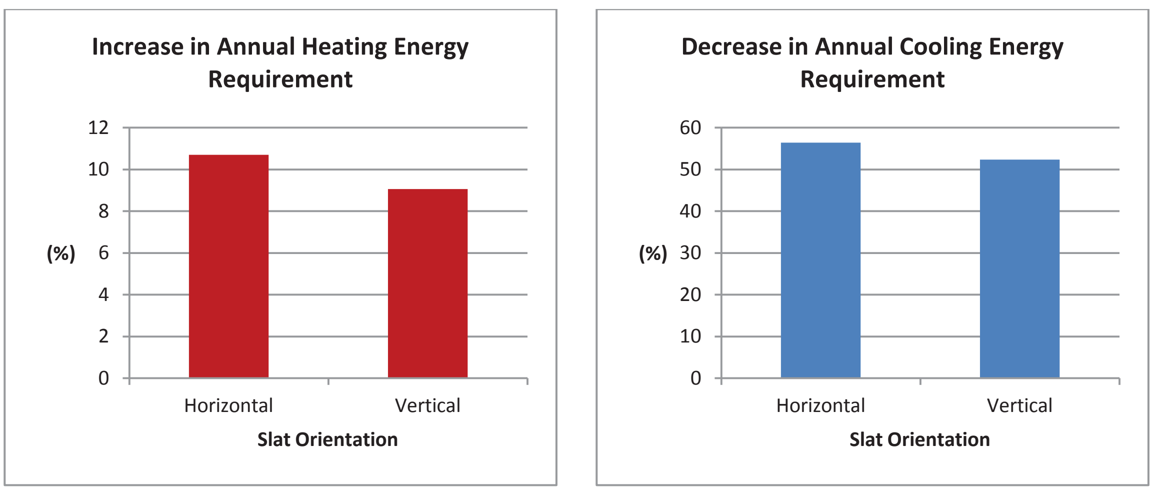


Figure 4.28 a)Increase in annual heating energy requirement, b)Decrease in annual cooling energy requirement due to slat orientation compared to the base case (heating = 126 GJ, cooling = 6.5 GJ; weather data set used: Toronto)

4.3.1.2.5 Effect of shading orientation

The purpose of this analysis is to assess the effect of shading orientation on annual heating and cooling energy requirements. The results are summarized in Figure 4.29 and

Figure 4.30 where the changes are given as a percentage of the annual values of the base case house that has no blinds and is located in Toronto.

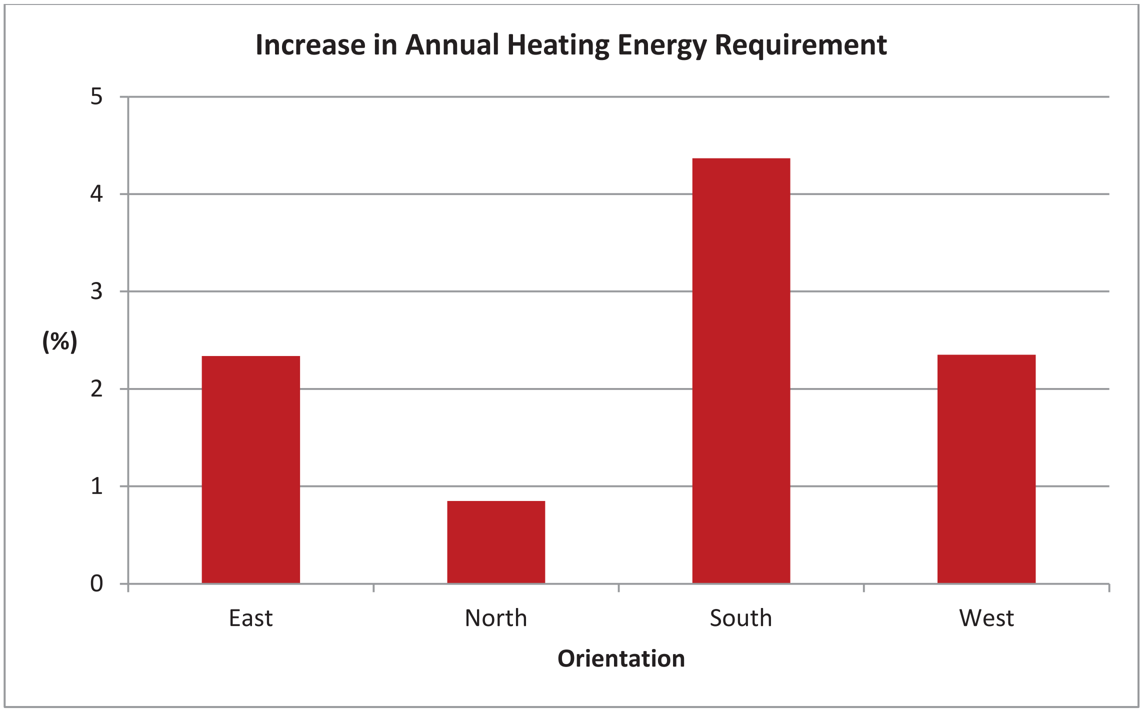


Figure 4.29 Increase in annual heating energy requirement due to shading orientation compared to the base case (heating = 126 GJ; weather data set used: Toronto)

Effect on heating energy requirement

As seen in Figure 4.29, in comparison with a house that has no shading, addition of a blind on the south side of the test case house results in the largest increase in heating energy requirement which is about 4% for a house located in Toronto, representing 5.5 GJ/year. Since the solar radiation is highest on the south exposure during the heating season, addition of a blind on the south side prevents the solar gain during the day which increases the heating energy requirement.

Effect on cooling energy requirement

As seen in Figure 4.30, in comparison with a house that has no shading, addition of a blind on the west side of the test case house results in the largest decrease in cooling energy requirement which is about 20% for a house located in Toronto, representing 1.4 GJ/year.

Since the solar azimuth arc is longer in the summer than in winter, addition of blinds on the west and east causes blocking more solar radiation than other sides. Therefore, the cooling energy requirement decreases more if the blinds are on the east or west side.

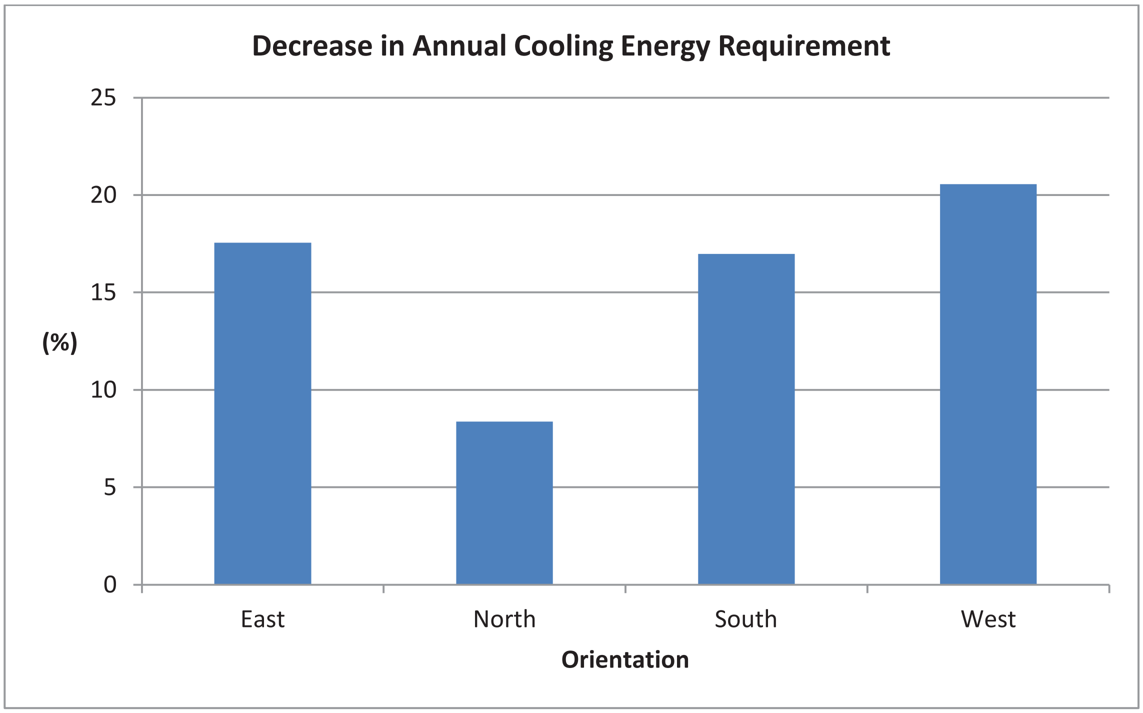


Figure 4.30 Decrease in annual cooling energy requirement due to shading orientation compared to the base case (cooling = 6.5 GJ; weather data set used: Toronto)

4.3.1.2.6 Effect of outside blinds in different climates

The purpose of this analysis is to assess the effect of outside blinds in different climates on the annual heating and cooling energy requirements. The results are summarized in Figure 4.31 and Figure 4.32 where the changes are given as a percentage of the annual values of the base case house that has no blinds.

<u>Effect on heating energy requirement</u>

As seen in Figure 4.31, in comparison with a house that has no shading, addition of blinds on the outside of the windows on all four sides of the test case house results in the largest increase in heating energy requirement in Halifax and Vancouver. It is interesting that although Halifax has higher HDD (Table 2.1) and sunshine hours during heating season (Figure 4.13) compared to Vancouver, the trade-off between the need for heating system and the availability of solar gain resulted in the same percentage of heating energy requirement increase in both cities.

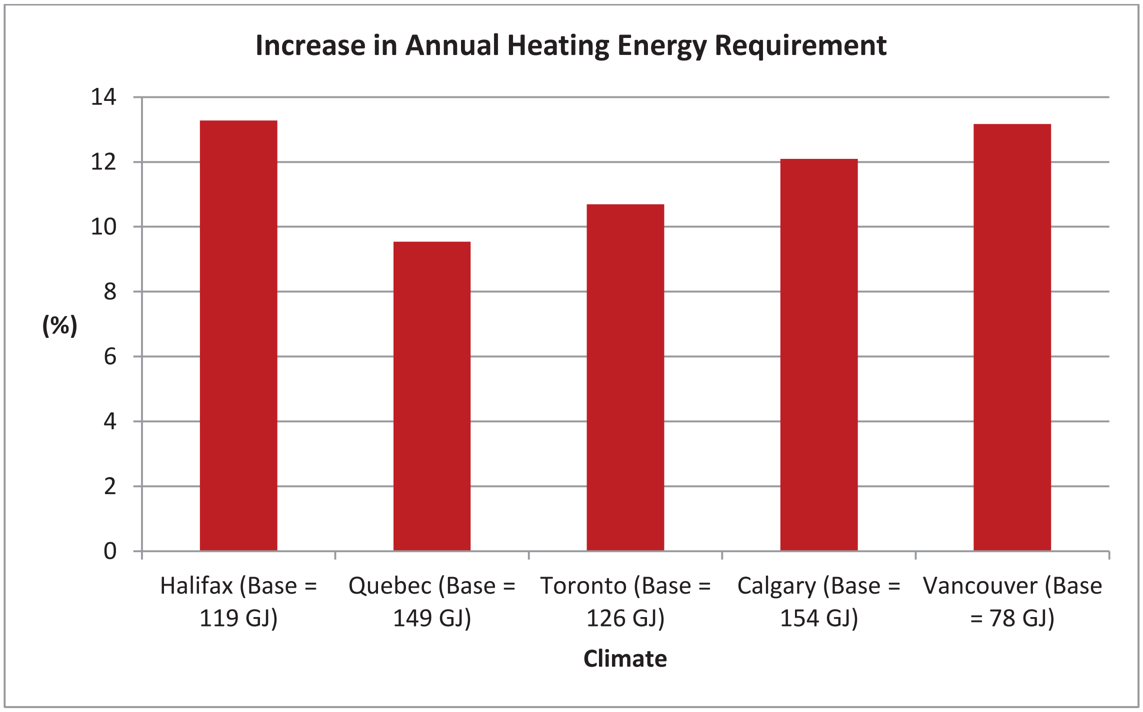


Figure 4.31 Increase in annual heating energy requirement with outside blinds in different climates

Effect on cooling energy requirement

As seen in Figure 4.32, in comparison with a house that has no shading, addition of blinds on the outside of the windows on all four sides of the test case house results in the largest decrease in cooling energy requirement in Vancouver. Although Vancouver does not have a high CDD (Table 2.1), according to Figure 4.13 it has a high sun shine hours during the cooling season. Therefore, preventing solar radiation to be absorbed by the zone has a higher effect in Vancouver than other cities.

4.3.1.2.7 Effect of control strategy

The purpose of this analysis is to assess the effect of control strategy on annual heating and cooling energy requirements. The results are summarized in Figure 4.33 and Figure 4.34 where the changes are given as a percentage of the annual values of the base case house that has no blinds.

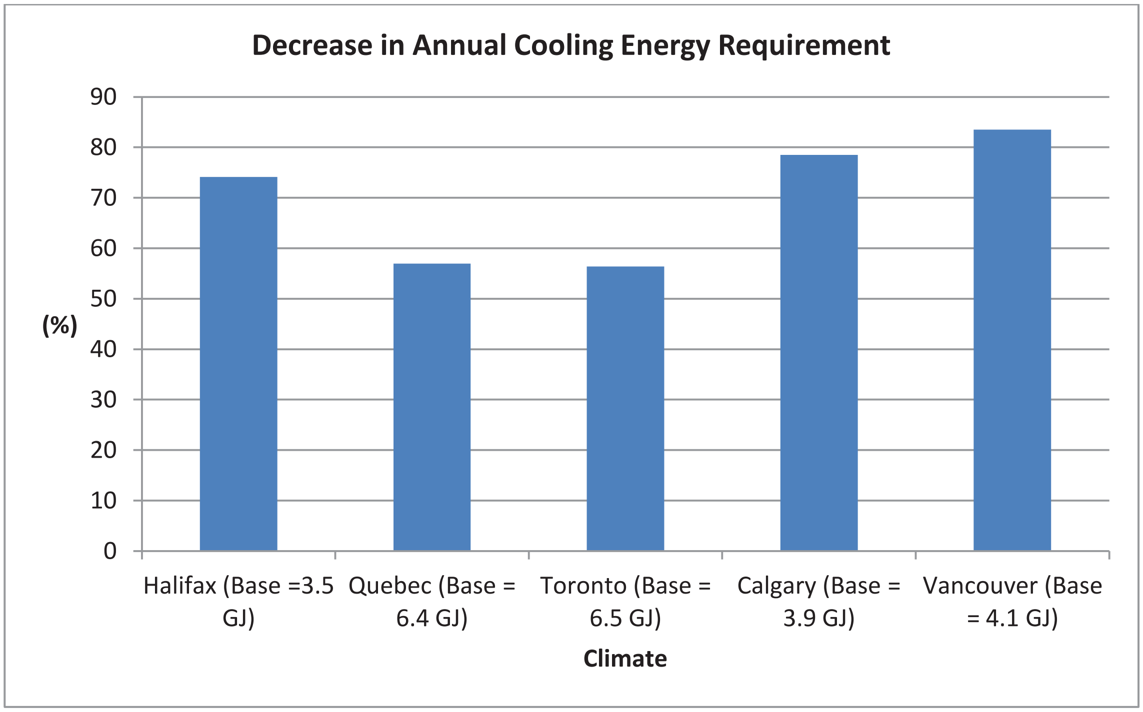


Figure 4.32 Decrease in annual cooling energy requirement with outside blinds in different climates

Effect on heating energy requirement

As seen in Figure 4.33, in comparison with a house that has no shading, addition of controlled indoor blinds decreases annual heating energy requirement substantially. Controlling the blind through the heating season allows the solar radiation to be absorbed by the zone during the sunshine hours while trapping the heat during night time. Therefore, solar heat gain along with an extra layer of insulation caused by trapped air decreases the heat loss from the zone.

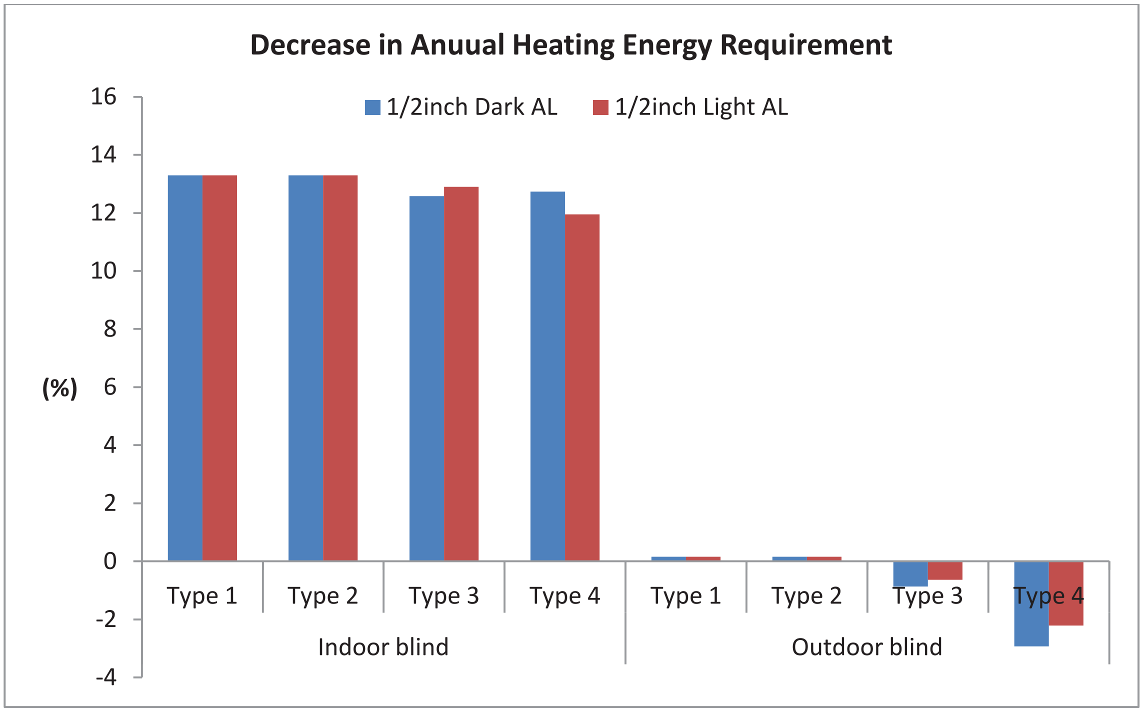


Figure 4.33 Decrease in annual heating energy requirement due to different control strategies defined in Table 4.16 compared to the base case (heating = 126 GJ; weather data set used: Toronto)

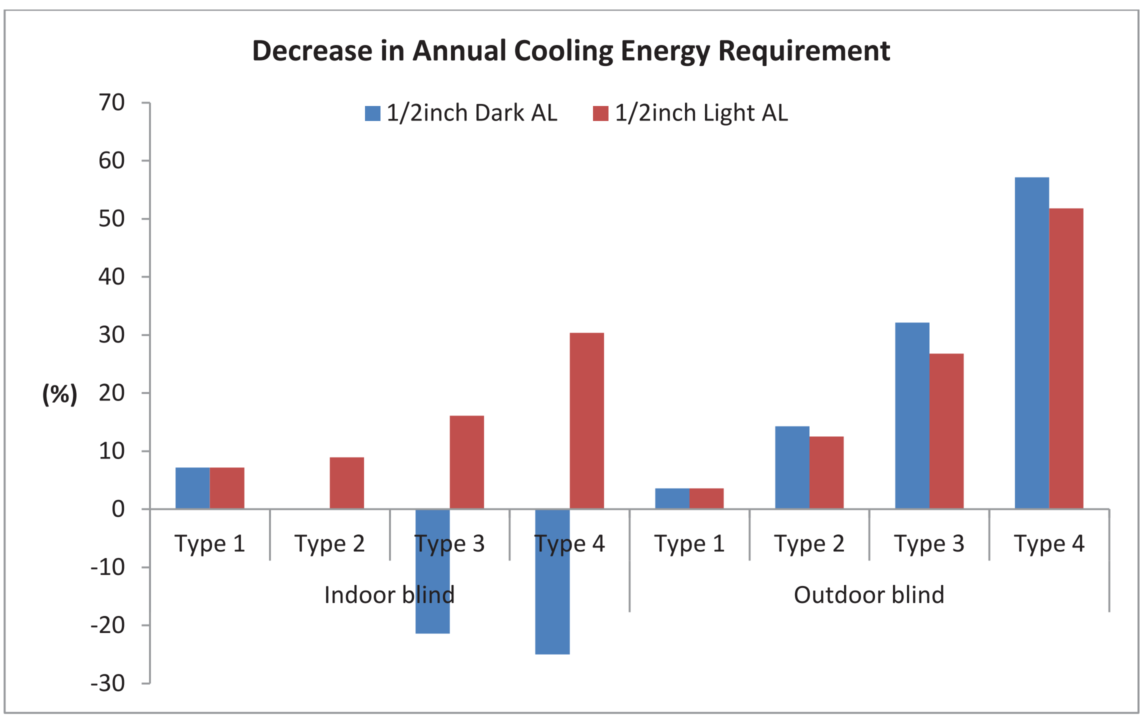


Figure 4.34 Decrease in annual cooling energy requirement due to different control strategies defined in Table 4.16 compared to the base case (cooling = 6.5 GJ; weather data set used: Toronto)

The results shown in Figure 4.33 indicate the following:

- Presence of any type of indoor blind with any control type reduces heating energy requirement while the outdoor blind increases or does not change the heating energy requirement,
- Controllers which sense temperature are more effective than the one that senses solar-radiation.
- Control types 3 and 4 which senses solar radiation incidence to actuate the blind are sensitive to blind.

For example using dark color indoor blind with control type 1 reduces heating energy requirement by 13%, representing 16.4 GJ/year decrease.

Effect on cooling energy requirement

As seen in Figure 4.34, in comparison with a house that has no shading, addition of controlled outdoor blind decreases annual cooling energy requirement by up to 57%. Addition of the blind on the outdoor side and controlling it prevents the solar radiation to pass through the window and be absorbed by the zone during the sunshine hours.

The results shown in Figure 4.34 indicate the following:

- Presence of any type of outdoor blind with any control type reduces cooling energy requirement,
- Presence of solar-radiation sensor is more effective than temperature sensor,
- Actuation of slat angle is more effective than switching shading layer on and off,
- Addition of a dark color blind on the outside of the window decreases cooling energy requirement more than light color blind while addition of a light color blind on the inside of the window decreases cooling energy requirement more than dark color one.

For example using dark color outdoor blind with control type 4 reduces cooling energy requirement by 57%, representing 3.7 GJ/year decrease while using the same blind on the indoor side with the same control type increases cooling energy requirement by 21%, representing 1.4 GJ/year.

It should be noted here that the comment made in section 4.3.1.2.2 'Effect on cooling energy requirement' applies to the results presented in Figure 4.34.

4.3.1.3 Conclusion

Based on the results of the parametric study presented above, the following Venetian blind upgrades are selected to be added to all windows of eligible houses in the CHS:

> Case 1: Addition of ½ inch light aluminum Venetian blinds, indoor side and control type 1
>
> Case 2: Addition of ½ inch dark aluminum Venetian blinds, outdoor side and control type 4

4.3.2 Batch simulation and results

Based on the results of the parametric study, the selected upgrade scenarios were applied to all eligible houses. Addition of controls to the Venetian blinds forces a higher resolution of running time-steps. Therefore, the simulation's time-step was changed from 10 minutes in the other sections to 2 minutes in the simulations conducted for the controlled Venetian blinds modeling.

4.3.2.1 Impact on energy consumption and GHG emissions due to Venetian blind upgrades in the CHS

This section presents the energy savings and GHG emission reduction results due to Venetian blind upgrades.

The breakdown of energy savings and GHG emission reductions due to Venetian blind upgrades are shown in Table 4.17 and Table 4.18 for each energy source, house type and province. The results show that addition of ½ inch light aluminum Venetian blinds on the indoor side with control type 1 (case 1) reduces the energy consumption by 2.3% (representing 24.2 PJ/year) and GHG emissions by 2.7% (representing 1.3 Mt of CO_2 equivalent).

The distributions of energy savings and GHG emission reductions due to Venetian blind upgrades among the provinces of Canada are shown in Figure 4.35. The results show that while addition of ½ inch light aluminum Venetian blinds on the indoor side with control type 1 (case 1) reduces energy consumption and GHG emissions, addition of ½ inch dark aluminum Venetian blinds on the outdoor side with control type 4 (case 2) may increase energy consumption and GHG emissions. By 4% of the savings, OT dominates the annual energy and GHG savings across Canada. This happens due to the fact that the province of OT has the highest percentage of eligible houses for this upgrade across Canada (see Table 4.19).

Figure 4.2 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to Venetian blind upgrades. The results indicate that addition of a controllable light color blind inside the windows reduces SH energy consumption substantially. Also, it shows that addition of a controllable dark color blind outside of the windows reduces SC energy consumption. However, the increase in SH energy consumption is almost the same as SC which results in an increase in total energy consumption in case 2.

4.3.2.2 Economic feasibility of Venetian blind upgrades for the CHS

The CHREM estimates of the total tolerable capital costs for three different payback periods, interest rates and fuel cost escalation rates for the two Venetian blinds upgrades options (as indicated in section 4.3.1.3) are shown in Figure 4.37.

As it was concluded in section 4.3.2.1, addition of ½ inch light aluminum Venetian blinds on the indoor side with control type 1 (case 1) decreases energy consumption while addition of ½ inch dark aluminum Venetian blinds on the outdoor side with control type 4 (case 2) increases energy consumption in most provinces. Therefore, this type of Venetian blinds (case 2) provides no economic benefit.

The provincial total tolerable capital cost and achievable savings per house and per square meter of window for a 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to Venetian blind upgrades are shown in Table 4.20 and Table 4.21. The province of NB with a tolerable capital cost of 113 CAN$ per square meter of window has the highest upgrading feasibility across Canada due to case 1 upgrade.

Table 4.17 Annual energy savings due to Venetian blinds upgrade

House type or province		Energy savings (TJ)									
		Case 1					Case 2				
		Electricity	NG*	Oil	Wood	Total	Electricity	NG*	Oil	Wood	Total
House type	SD	3,538	16,619	1,262	24	21,442	4,819	-5,294	1	-12	-894
	DR	603	2,113	117	0	2,834	832	-683	1	0	97
Province	NB	1	0	0	7	8	1	0	0	-3	-2
	NS	2	0	13	0	15	1	0	-2	0	0
	QC	2,062	4	407	16	2,489	334	-4	2	-7	225
	OT	1,794	16,731	959	0	19,484	4,627	-5,130	1	0	-863
	AB	19	321	0	0	339	78	-112	0	0	-35
	MB	87	296	0	0	383	92	-161	0	0	-69
	SK	52	864	0	0	917	208	-372	0	0	-163
	BC	125	517	0	0	642	310	-199	0	-2	109
Canada		4,141	18,732	1,380	24	24,276	5,651	-5,977	20	-12	-798

* Natural Gas

Table 4.18 Annual GHG emission reductions due to Venetian blinds upgrade

House type or province		GHG emission reductions (kt of CO_2 equivalent)							
		Case 1				Case 2			
		Electricity	NG*	Oil	Total	Electricity	NG	Oil	Total
House type	SD	223	843	89	1,156	605	-268	-29	308
	DR	33	107	8	148	100	-35	-4	61
Province	NB	0			0	0			0
	NS	0		1	1	0		0	0
	QC	2	0	29	32	0	0	-7	-7
	OT	245	849	68	1161	671	-260	-25	386
	AB	4	16		20	18	-6		12
	MB	0	15		15	0	-8		-8
	SK	4	44		47	14	-19		-5
	BC	1	26		27	2	-10		-8
Canada		256	950	98	1,304	705	-303	-32	369

* Natural Gas

Table 4.19 The percentage of houses eligible for Venetian blinds upgrade (%)

Province	NB	NS	QC	OT	AB	MB	SK	BC
Eligible Houses	0.02	0.09	12.06	78.01	1.37	3.32	1.42	3.70

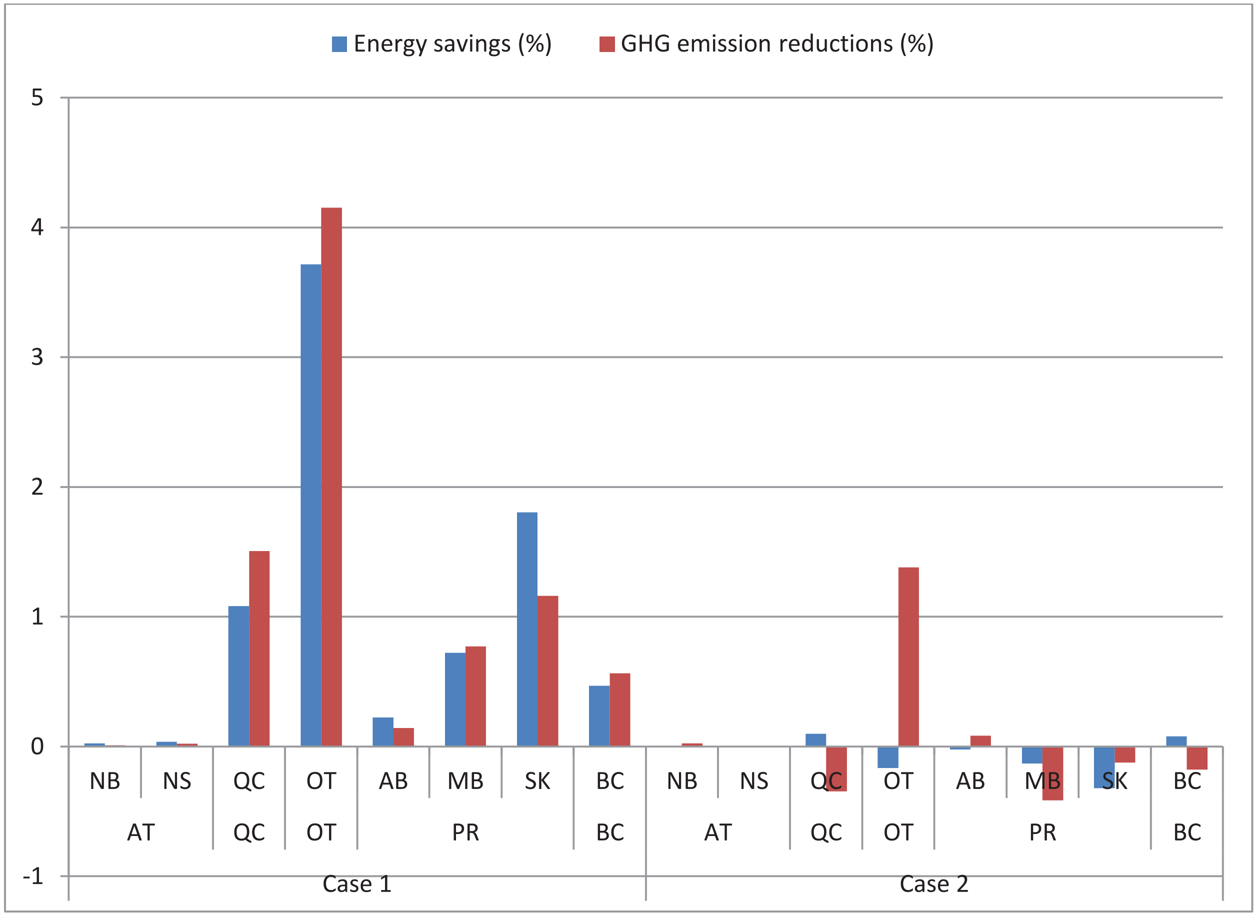


Figure 4.35 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to Venetian blinds upgrades

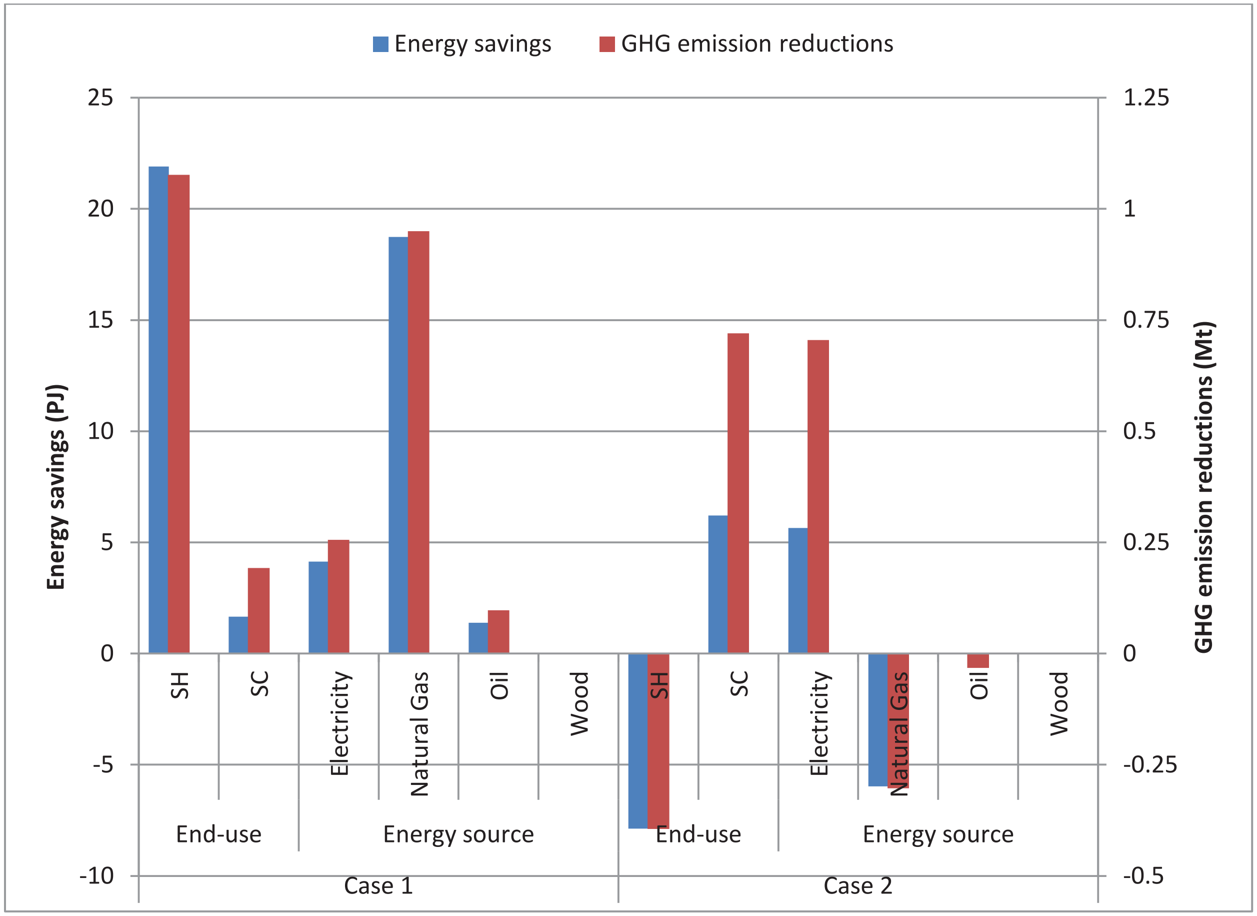


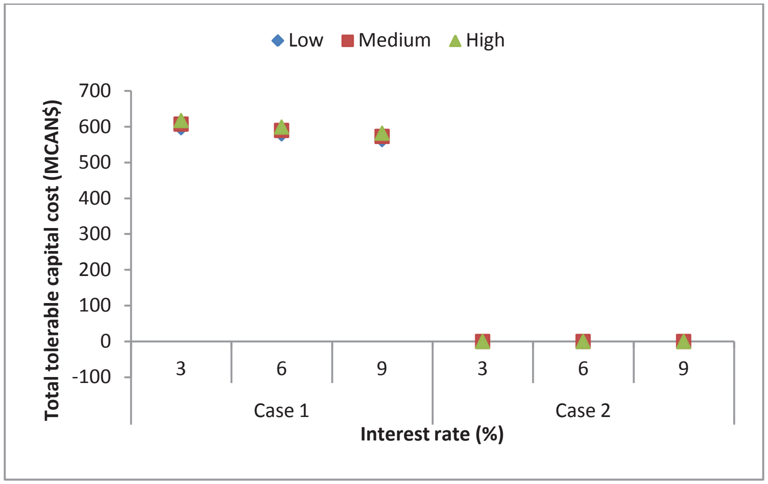
Figure 4.36 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to Venetian blinds upgrades

4.3.2.3 Conclusion

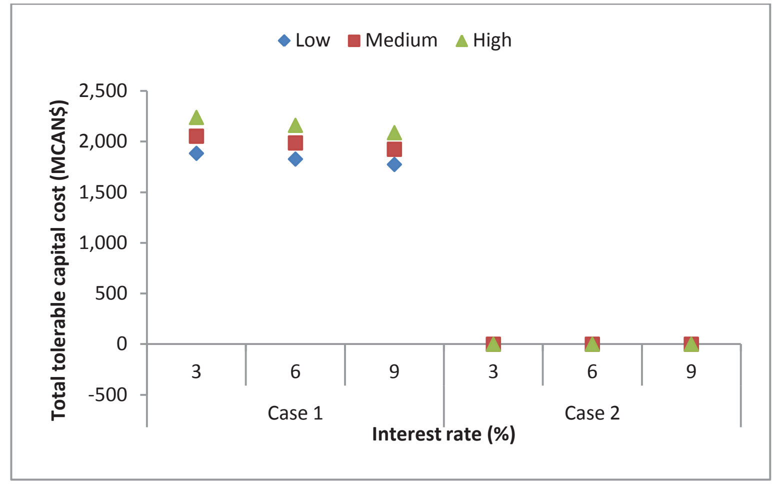
The techno-economic assessment of Venetian blind upgrades was presented in this section. Based on the results of the parametric study, two different types of Venetian blinds and control types were selected. The selected upgrade scenarios were applied to all eligible houses.

For this upgrade, all windows were covered with Venetian blinds. CHREM estimates that by addition of ½ inch light aluminum Venetian blinds on the indoor side with control type 1 (case 1) reduces the energy consumption by 2.3% (representing 24.2 PJ/year) and GHG emissions by 2.7% (representing 1.3 Mt of CO_2 equivalent). From the economical point of view, addition of Venetian blind case 1 in the province of NB is more feasible than other provinces.

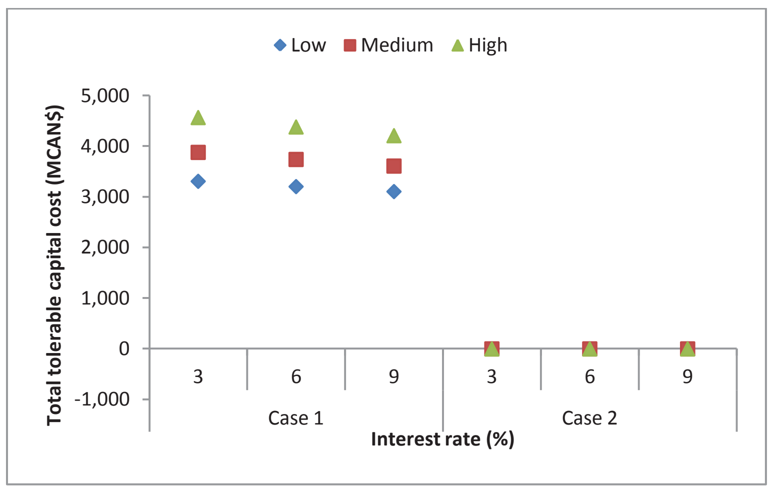
As it was discussed in Section 3.2.1.2, the existence of a cooling system in a house is one of the criteria used to select an eligible house. Since most houses in Canada do not have a cooling system, this criterion results in the elimination of most houses that match the other criterion (i.e. presence of a window in the proper orientation). Therefore, the results for each province are highly affected by the number of houses eligible. For example, OT has the highest percentage of eligible houses across Canada due to the fact that OT has the highest percentage of houses with cooling systems. Therefore, OT shows the highest reduction in energy consumption. However, if the requirement of a cooling system is removed as a criterion in the selection of eligible houses, the results will change dramatically for each province.



(a) Payback period = 2 years



(b) Payback periods = 6 years



(c) Payback period = 10 years

Figure 4.37 Total national tolerable capital cost due to Venetian blinds upgrades (cases 1 and 2 as indicated in section 4.3.1.3) for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table 4.20 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to Venetian blinds Case 1 upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	543	7,176	1	1,494	113	8	14.4	1,087	0	239	18.1
NS	2,314	45,778	3	1,173	59	15	6.6	332	1	493	24.9
QC	278,255	5,508,591	339	1,218	62	2,489	8.9	452	32	113	5.7
OT	1,703,319	39,196,519	1,338	785	34	19,484	11.4	497	1,161	682	29.6
AB	28,146	611,559	16	568	26	339	12.0	554	20	728	33.5
MB	50,964	795,983	28	544	35	383	7.5	481	15	295	18.9
SK	94,478	1,483,528	51	539	34	917	9.7	618	47	501	31.9
BC	84,166	2,027,512	52	622	26	642	7.6	317	27	319	13.2

* Total tolerable capital cost
** Tolerable capital cost

Table 4.21 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to Venetian blinds Case 2 upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	543	7,176	-0.3	-596.6	-45.2	-2	-3.5	-265	0	552	41.8
NS	2,314	45,778	0.0	0.0	0.0	0	-0.1	-7	0	4	0.2
QC	278,255	5,508,591	-0.5	-1.7	-0.1	225	0.8	41	-7	-26	-1.3
OT	1,703,319	39,196,519	0.0	0.0	0.0	-863	-0.5	-22	386	226	9.8
AB	28,146	611,559	0.0	0.0	0.0	-35	-1.2	-56	12	424	19.5
MB	50,964	795,983	0.0	0.0	0.0	-69	-1.4	-87	-8	-159	-10.2
SK	94,478	1,483,528	0.0	0.0	0.0	-163	-1.7	-110	-5	-53	-3.4
BC	84,166	2,027,512	-0.2	-1.9	-0.1	109	1.3	54	-8	-101	-4.2

* Total tolerable capital cost
** Tolerable capital cost

4.4 Techno-economic assessment of PCMs for the CHS

To assess the effect of addition of PCM on annual heating and cooling energy requirement of CHS the following parameters are selected based on the literature (Table 4.22).

Table 4.22 Input data selected for PCM model

Input Parameter		Unit	Values
Melting temperature	Case 1	˚C	23
	Case 2		25
Solidification temperature	Case 1	˚C	24
	Case 2		26
Conductivity in solid phase		W/m.K	0.4
Conductivity in liquid phase		W/m.K	0.2
Specific heat		KJ/kg.K	1.4
Latent heat member a		$KJ/kg.K^2$	0
Latent heat member b		KJ/kg.K	160

4.4.1 Batch simulation and results

Two different scenarios are selected for batch simulations. In the first scenario it is assumed that the melting temperature of the PCM is 23˚C which is one degree higher than the dead band of the heating set-point temperature. For the second scenario the melting temperature of the PCM is assumed to be 25˚C. It was assumed that for each eligible house one PCM stand-alone unit will be provided. Therefore, in each case the PCM is incorporated only to the main_1 zone floor of all eligible houses.

4.4.1.1 Impact on energy consumption and GHG emission due to PCM upgrade in CHS

This section presents the national energy savings and GHG emission reduction results due to PCM upgrades.

The breakdown of energy savings and GHG emission reductions due to upgrading all eligible houses by applying PCM to their floors are shown in Table 4.23 and Table 4.24 for each energy source, house type and province. The results show that addition of PCMs to the floor can reduce energy consumption by 2.4% (representing 25.8 PJ/year) and GHG emissions by 2.6% (representing 1.2 Mt of CO_2 equivalent) due to PCM upgrade (Tmelt = 23 ˚C).

The distribution of energy savings and GHG emission reductions due to PCM upgrade among provinces of Canada are shown in Figure 4.38. The results show that PCM with lower melting temperature has higher impact on energy consumption and GHG emissions. By 4% of the savings due to PCM with lower melting temperature (Tmelt = 23 ˚C) upgrade, BC dominates the annual energy and GHG savings across Canada. This happens because of the following reasons:

- According to Environment Canada (2012), BC has the highest maximum daily temperature during the heating season,
- According to Table 4.7, BC has a high proportion of SG windows which has the highest solar radiation transmittance among other window types. Therefore, this window type allows more solar radiation to be stored by the PCM.

The GHG emission reductions show a different distribution than energy savings due to the variation in marginal GHG EIFs among the provinces.

Figure 4.39 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to PCM upgrade. The savings due to PCM upgrades are in SH. It is also shown that the energy and GHG emissions saving of natural gas is higher than other sources of energy. It is because most Canadian households use natural gas as the primary source of energy for SH. Using PCM with melting temperature that is lower than cooling set-point shows less increase in the annual cooling energy use.

Table 4.23 Annual energy savings due to PCM upgrade

House type or province		Energy savings (TJ)									
		Tmelt = 23 ˚C					Tmelt = 25 ˚C				
		Electricity	NG*	Oil	Wood	Total	Electricity	NG*	Oil	Wood	Total
House type	SD	3,400	15,544	2,928	771	22,640	1,178	7,107	1,204	300	9,790
	DR	531	2,330	297	2	3,160	166	1,032	112	0	1,310
Province	NB	159	0	250	268	676	76	0	88	102	266
	NF	72	0	115	35	222	28	0	34	9	72
	NS	100	0	553	110	762	45	0	210	40	295
	PE	2	0	86	26	113	1	0	26	10	36
	QC	2,502	4	849	258	3,613	1,121	0	374	102	1,598
	OT	505	8,057	1,373	0	9,932	-175	3,181	584	0	3,589
	AB	7	4,126	0	0	4,133	-1	2,027	0	0	2,026
	MB	134	693	0	0	828	37	293	0	0	329
	SK	24	1,150	0	0	1,174	-4	540	0	0	535
	BC	426	3,845	0	78	4,348	217	2,099	0	37	2,353
Canada		3,930	17,874	3,225	773	25,800	1,344	8,140	1,316	300	11,100

* Natural Gas

Table 4.24 Annual GHG emission reductions due to PCM upgrade

House type or province		GHG emission reductions (kt of CO_2 equivalent)							
		Tmelt = 23 ˚C				Tmelt = 25 ˚C			
		Electricity	NG*	Oil	Total	Electricity	NG	Oil	Total
House type	SD	104	788	207	1,099	-5	360	85	441
	DR	12	118	21	151	-1	52	8	59
Province	NB	38	0	18	55	18	0	6	24
	NF	0	0	8	9	0	0	2	3
	NS	10	0	39	50	5	0	15	20
	PE	0	0	6	6	0	0	2	2
	QC	1	0	60	61	0	0	27	27
	OT	61	409	97	567	-29	161	41	173
	AB	1	209	0	211	0	103	0	103
	MB	0	35	0	35	0	15	0	15
	SK	2	58	0	60	0	27	0	27
	BC	2	195	0	197	1	106	0	108
Canada		116	907	228	1,251	-6	413	93	500

* Natural Gas

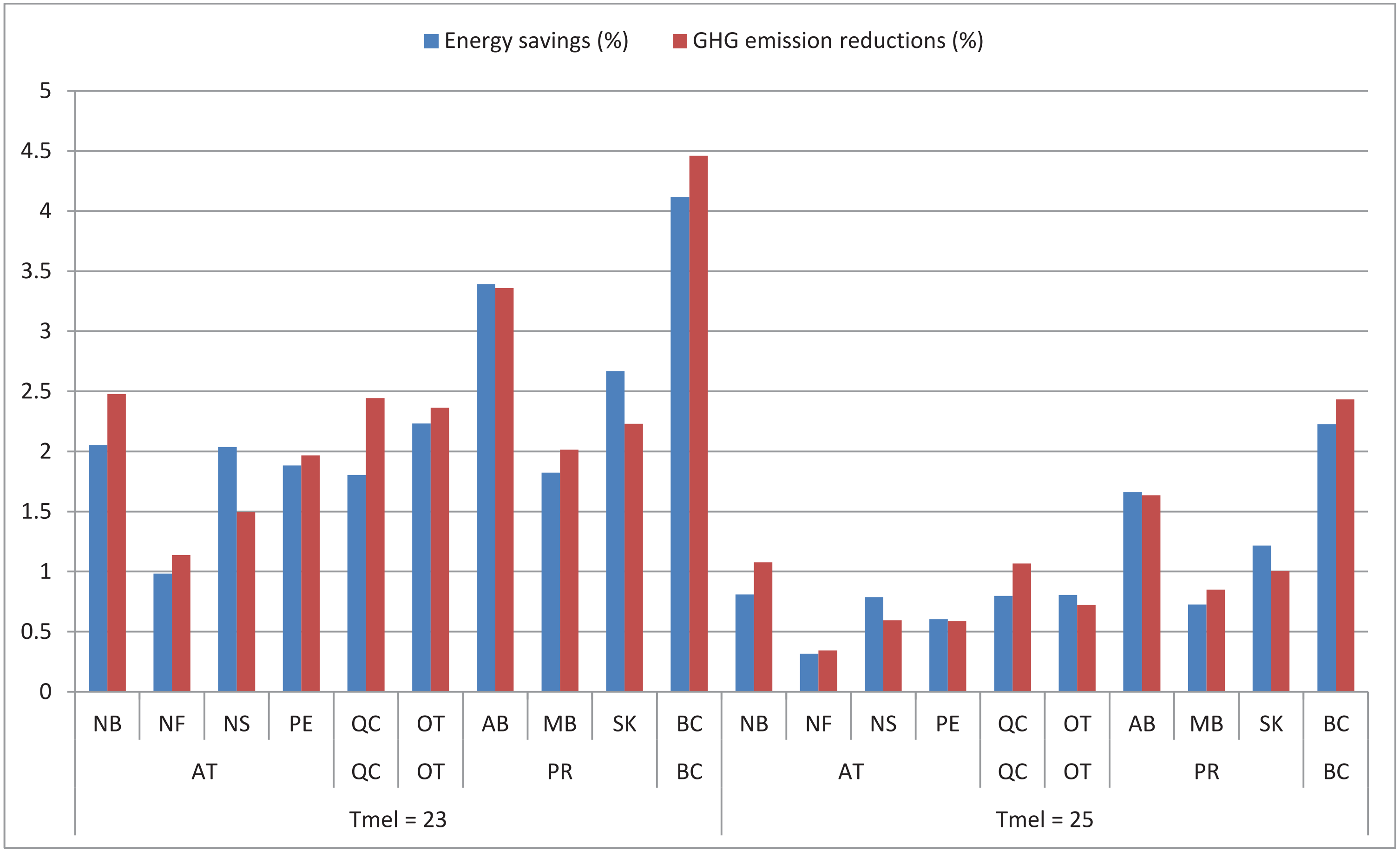


Figure 4.38 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to PCM upgrade

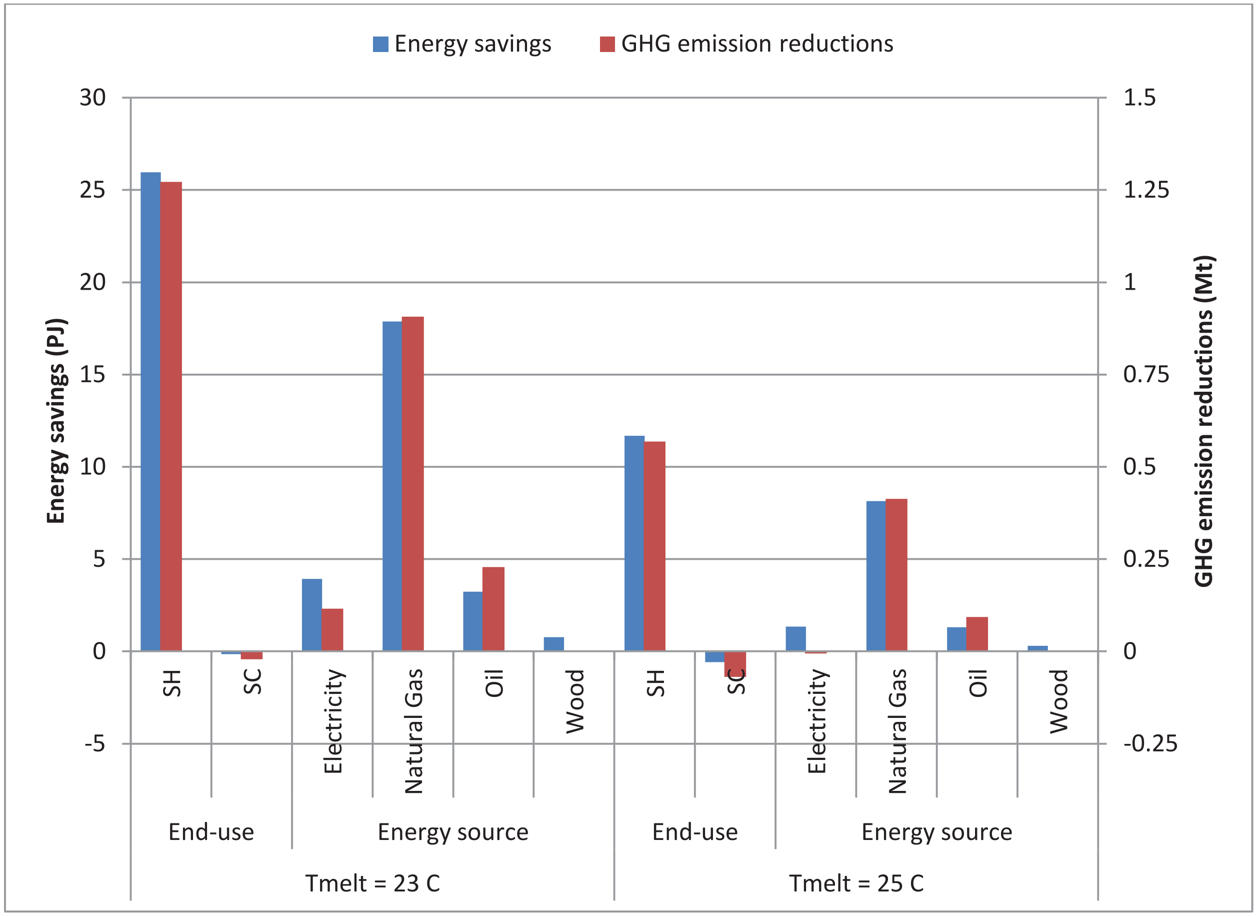


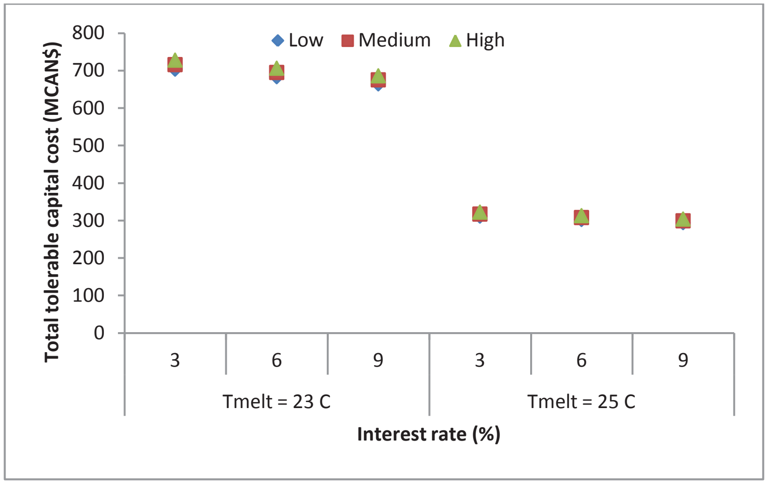
Figure 4.39 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to PCM upgrade

4.4.1.2 Economic feasibility of PCM upgrade for the CHS

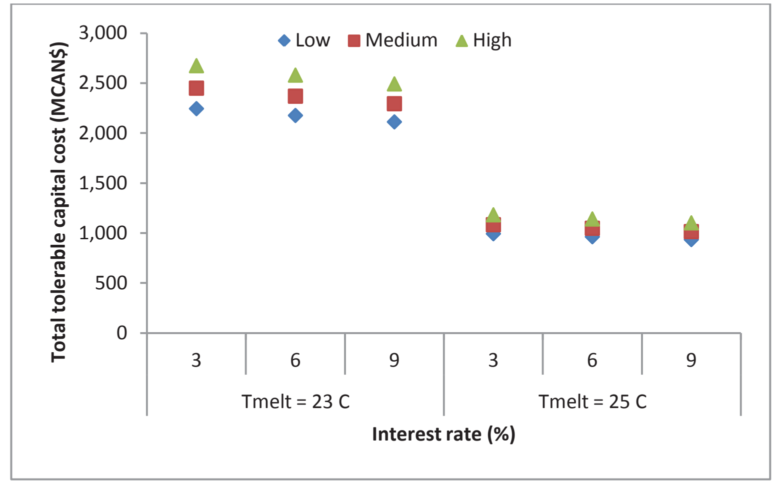
The CHREM estimates of total tolerable capital costs for three different payback periods, interest rates and fuel cost escalation rates for each PCMs upgrade scenario are shown in Figure 4.40.

As it was concluded in section 4.2.2.1.1, PCM with lower melting temperature (Tmelt = 23 ˚C) has a higher impact on energy consumption and GHG emissions. Therefore, it has a higher total tolerable capital cost compared PCM upgrade scenario with higher melting temperature (Tmelt = 25 ˚C).

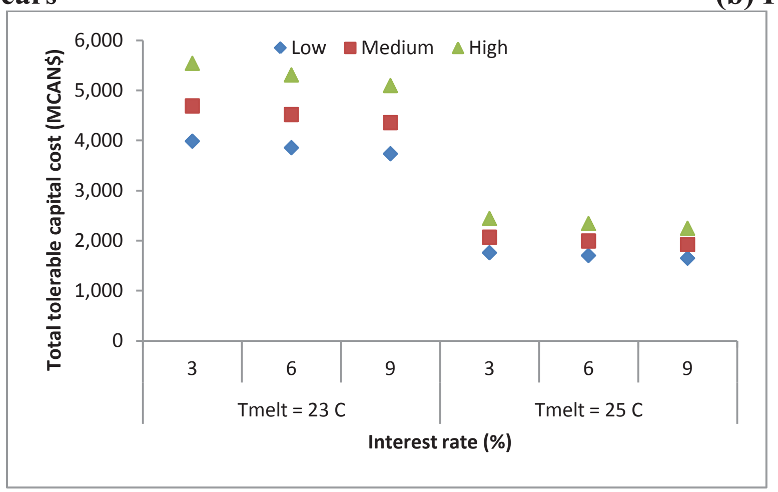
The provincial total tolerable capital cost and achievable savings per house for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to PCM upgrades are shown in Table 4.25 and Table 4.26. The province of NB with tolerable capital cost of 527 CAN$ per house has the highest upgrading feasibility across Canada. The dominant fuel in this province is oil while in all other provinces except Quebec it is natural gas. Since the price of oil per unit of energy is higher than natural gas it is more cost effective to apply the PCM upgrade in the province of NB than provinces using natural gas as the primary source of energy. Province of NS with tolerable capital cost of 482 CAN$ per house is the second best candidate for this upgrade.



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure 4.40 Total national tolerable capital cost due to PCM upgrade for different interest rates and escalation rate (Low, Medium, High as per Table 2.6)

Table 4.25 Total tolerable capital cost and achievable savings per house for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to PCM upgrade (Tmelt = 23 ˚C)

Province	No. of houses	TTCC* (MCAN$)	TCC** per house (CAN$)	Total energy saved (TJ)	Energy saved per house (GJ)	Total GHG reduced (kt)	GHG reduced per house (kg)
NB	220,102	116	527	676	3.1	55	251
NF	162,793	41	251	222	1.4	9	53
NS	285,760	138	482	762	2.7	50	173
PE	43,714	18	410	113	2.6	6	140
QC	1,784,501	543	304	3,613	2.0	61	34
OT	3,127,029	889	284	9,932	3.2	567	181
AB	899,606	146	163	4,133	4.6	211	234
MB	317,503	61	191	828	2.6	35	111
SK	286,384	64	222	1,174	4.1	60	209
BC	990,871	354	357	4,348	4.4	197	199

* Total tolerable capital cost
** Tolerable capital cost

Table 4.26 Total tolerable capital cost and achievable savings per house for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to PCM upgrade (Tmelt = 25 ˚C)

Province	No. of houses	TTCC* (MCAN$)	TCC** per house (CAN$)	Total energy saved (TJ)	Energy saved per house (GJ)	Total GHG reduced (kt)	GHG reduced per house (kg)
NB	220,102	46	211	266	1.2	24	109
NF	162,793	14	83	72	0.4	3	16
NS	285,760	54	190	295	1.0	20	69
PE	43,714	6	127	36	0.8	2	42
QC	1,784,501	245	137	1,598	0.9	27	15
OT	3,127,029	364	117	3,589	1.1	173	55
AB	899,606	72	80	2,026	2.3	103	114
MB	317,503	24	75	329	1.0	15	47
SK	286,384	30	104	535	1.9	27	95
BC	990,871	192	194	2,353	2.4	108	109

* Total tolerable capital cost

** Tolerable capital cost

4.4.2 Conclusion

The techno-economic assessment of applying PCMs to the CHS was presented in this section. Based on the literature review, thermo-physical properties of PCM were selected. Among these properties, melting temperature has been the subject of many studies. Therefore, two scenarios which have different melting temperatures, and consequently different solidification temperatures, were determined for batch simulations. The selected upgrade scenarios were applied to all eligible houses.

For this upgrade, it was assumed all eligible houses will be provided by one stand-alone unit; therefore only the main_1 zone floor was modified to incorporate the PCMs. CHREM estimates that by applying PCMs with melting temperature of 23 ˚C to the eligible houses energy consumption reduces by 2.4% (from 1061 to 1035 PJ/year) and GHG emissions by 2.6% (from 48.4 to 47 Mt of CO_2 equivalent). From the economical point of view, upgrading houses to incorporate PCM storage in the province of NB is more feasible than other provinces.

4.5 Techno-economic assessment of PV system for the CHS

As it was discussed in section 3.3.1.1 the specific parameters were selected to incorporate the PV system to a house. Therefore, only one scenario is selected for batch simulations.

4.5.1 Batch simulation and results

4.5.1.1 Impact on energy consumption and GHG emission due to PV upgrade in the CHS

This section presents the energy savings and GHG emission reduction results due to PV upgrade.

The breakdown of energy savings and GHG emission reductions due to upgrading all eligible houses by the addition of PV system are shown in Table 4.27 for each energy source, house type and province. The results show that addition of PV system reduces the energy consumption by 3.4% (representing 35.7 PJ/year) and GHG emissions by 6.4% (representing 3.1 Mt of CO_2 equivalent).

Table 4.27 Estimates of annual energy consumption and GHG emission reductions due to PV upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	32,856	-53	-10	-3	32,788	2,835	-3	-1	2,832
	DR	2,896	-12	-1	0	2,884	283	-1	0	282
Province	NB	1,521	0	-1	-1	1,518	360	0	0	359
	NF	921	0	0	0	920	6	0	0	6
	NS	1,401	0	-2	0	1,399	146	0	0	146
	PE	312	0	0	0	311	1	0	0	1
	QC	8,451	0	-3	-1	8,445	2	0	0	2
	OT	12,207	-30	-5	0	12,173	1,644	-2	0	1,642
	AB	3,641	-15	0	0	3,628	835	-1	0	834
	MB	1,306	-3	0	0	1,303	0	0	0	0
	SK	1,518	-5	0	0	1,513	101	0	0	101
	BC	4,475	-12	0	0	4,461	23	-1	0	22
Canada		35,752	-65	-11	-3	35,671	3,118	-4	-1	3,114

* Natural Gas

The distribution of energy savings and GHG emission reductions due to the addition of PV system among the provinces of Canada is shown in Figure 4.41.

As seen in Figure 4.1, the energy savings potential with PV system in all provinces are similar, while the GHG emission reductions vary significantly. This is due to the differences in the source of electricity. In Quebec for example, there is practically no reduction in GHG emissions by switching to PV systems because of the fact that the electricity used for AL is generated by hydro-electric power plants that have no GHG emissions. On the other extreme, the GHG emission reduction is the highest in NB because a large part of the electricity used for AL electricity generation is produced from fossil fuels.

Figure 4.42 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to PV upgrade. Since the PV upgrade is only used to generate the electricity for AL, the savings are in electricity source.

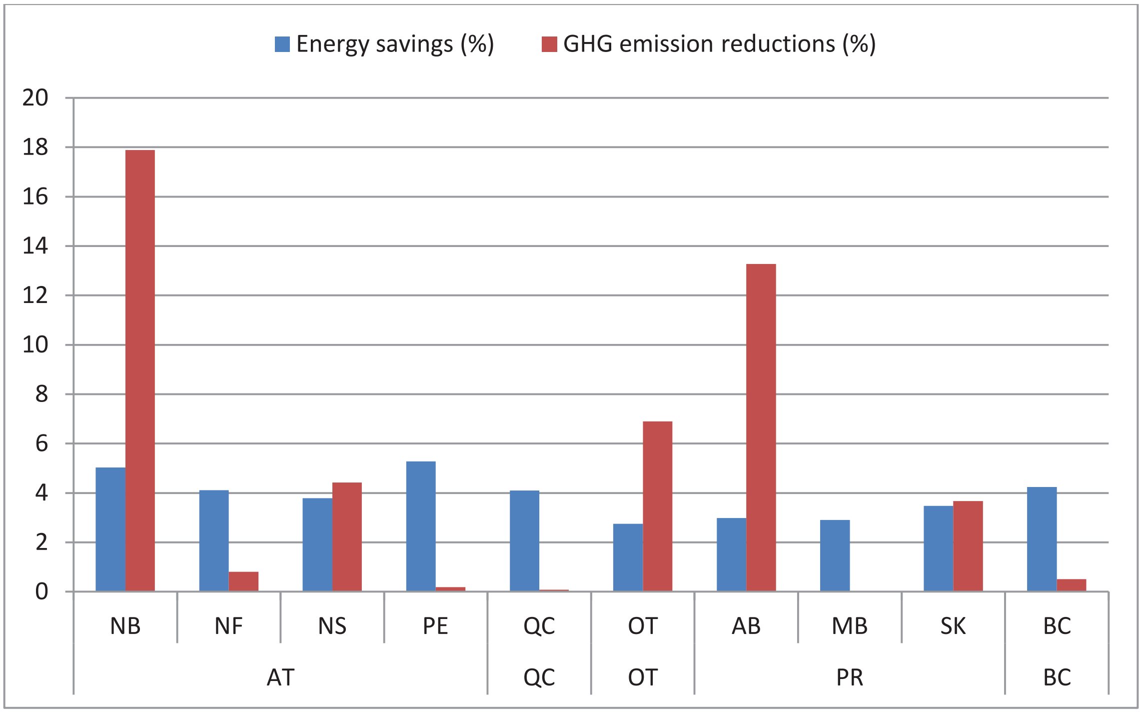


Figure 4.41 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to PV upgrade

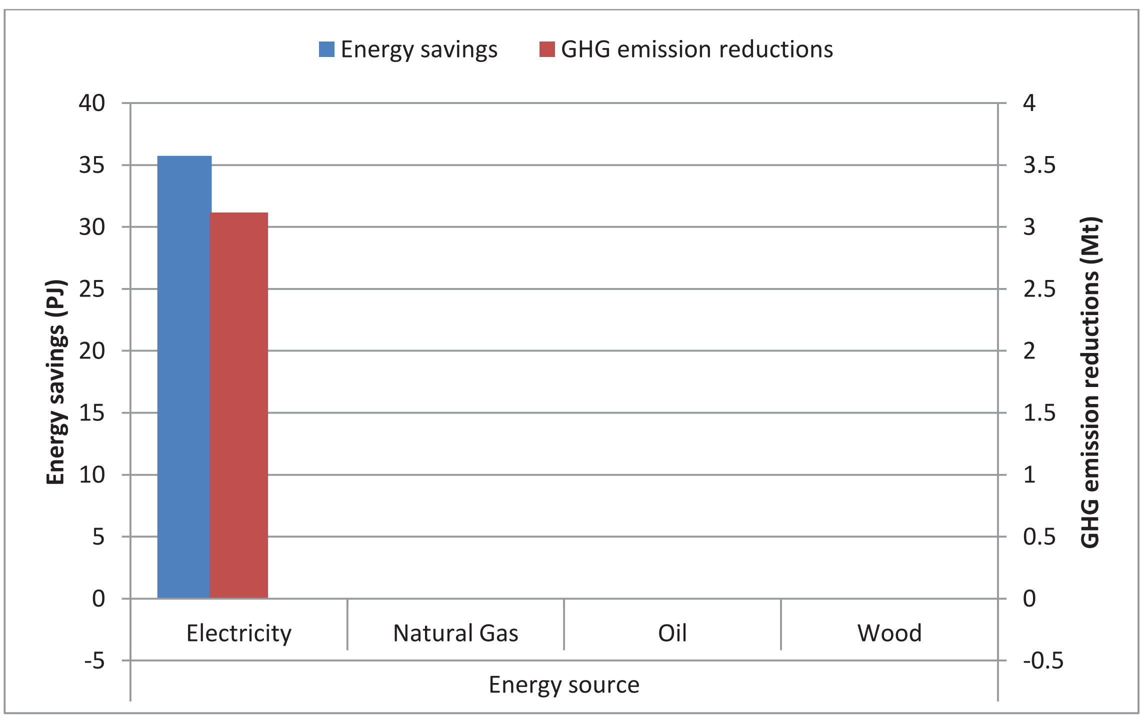


Figure 4.42 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to PV upgrade

4.5.1.2 Economic feasibility of PV upgrade for the CHS

The CHREM estimates of the total tolerable capital costs for three different payback periods, interest rates and fuel cost escalation rates for the PV upgrade is shown in Figure 4.43.

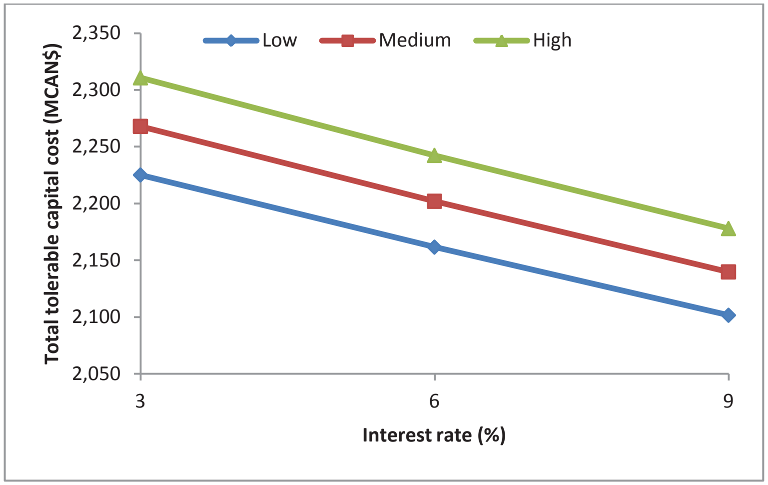
The provincial total tolerable capital cost and achievable savings per house for a 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to PV upgrade is shown in Table 4.28. The province of NB with an average tolerable capital cost of 3,551 CAN$ per house has the highest upgrading feasibility across Canada. This can be due to a number of reasons such as amount of sunshine hours, electricity price, as well as available roof area compare to other provinces.

4.5.2 Conclusion

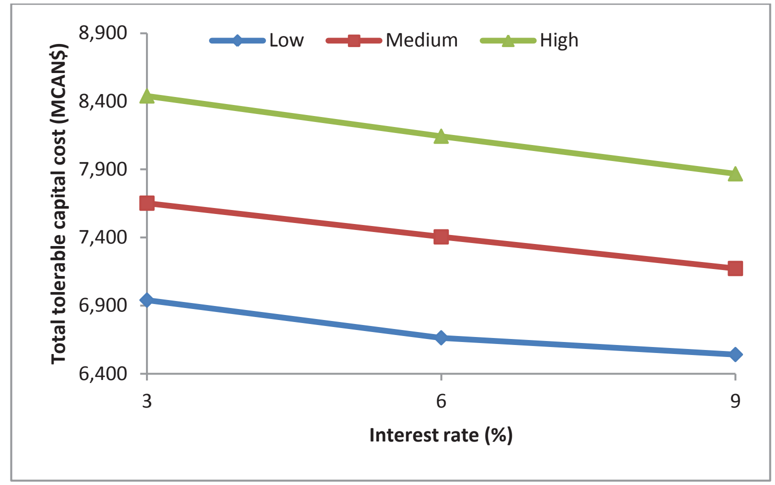
The techno-economic assessment of PV integration to the CHS was presented in this section. Based on the literature review the PV system was selected for batch simulations. The input data for each component of PV system were selected based on manufacturer specifications. The selected PV system was applied to all eligible houses.

CHREM estimates indicate that integration of PV system to the CHS would reduce the energy consumption by 3.4% (representing 35.7 PJ/year) and GHG emissions by 6.4% (representing 3.1 Mt of CO_2 equivalent). From the economical point of view, upgrading houses to incorporate PV systems in the province of NB is more feasible than other provinces.

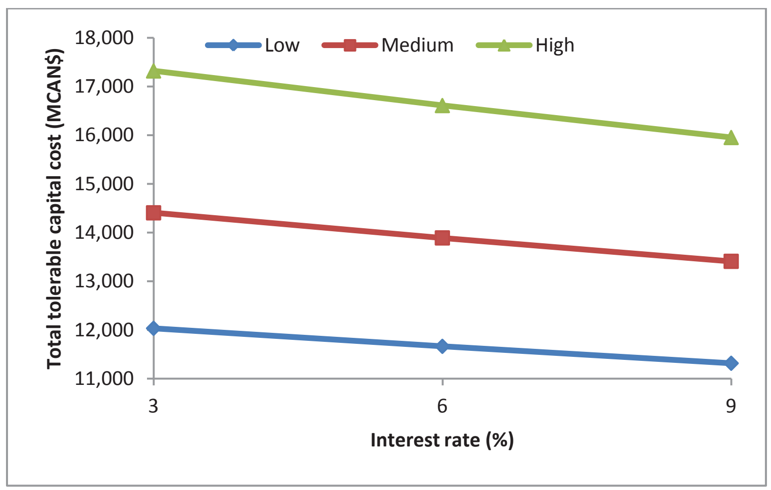
It should be noted here that the price of PV modules has decreased by a factor of 50% over the past 12 years, and further and substantial reductions are expected (Enerdata, 2012). Thus, the economic feasibility of PV systems is expected to improve over the next decade.



(a) Payback period = 2 years



(b) Payback periods = 6 years



(c) Payback period = 10 years

Figure 4.43 Total national tolerable capital cost due to PV upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table 4.28 Total tolerable capital cost and achievable savings per house for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to PV upgrade

Province	No. of houses	TTCC* (MCAN$)	TCC** per house (CAN$)	Total energy saved (TJ)	Energy saved per house (GJ)	Total GHG reduced (kt)	GHG reduced per house (kg)
NB	103,732	368	3,551	1,518	14.6	359	3,465
NF	80,588	207	2,569	920	11.4	6	76
NS	127,574	363	2,848	1,399	11.0	146	1,143
PE	25,796	86	3,336	311	12.1	1	21
QC	733,080	1,179	1,609	8,445	11.5	2	3
OT	1,074,143	2,799	2,606	12,173	11.3	1,642	1,529
AB	341,507	1,136	3,328	3,628	10.6	834	2,442
MB	115,609	198	1,712	1,303	11.3	0.3	2
SK	131,470	397	3,018	1,513	11.5	101	766
BC	343,236	671	1,954	4,461	13.0	22	65

* Total tolerable capital cost
** Tolerable capital cost

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

5.1.1 Overview of the work and accomplishments

The main objective of this thesis was to conduct a realistic assessment of the cost effectiveness, energy savings and GHG emission reductions of selected solar technologies on the CHS. This assessment was conducted using the Canadian Hybrid Residential Energy End-use and Emissions Model (CHREM) (Swan, et al. 2011) which uses ESP-r (ESRU, 2009) as its building energy simulation engine.

For each selected solar technology, the following major steps were accomplished to achieve the objectives of the work:

1- A comprehensive literature review was conducted to identify solar technologies suitable for the Canadian climatic conditions (Chapter 1).
2- Detailed parametric studies were conducted for each identified solar technology to determine the critical parameters that impact performance as well as the values of the critical parameters (Chapter 4). Suitable "test case" house descriptions were extracted from the Canadian Single-Detached and Double/Row Housing Database (CSDDRD) (Swan et al., 2009b) to conduct the parametric studies (Chapter 2). The parameters identified were later used in conducting techno-economic assessment of the selected solar technologies for the entire CHS (Chapter 4).
3- There is more than one approach to model the selected solar technologies within the ESP-r environment. Therefore, for each technology, the most suitable approach was selected to use with the CHREM to achieve the level of accuracy needed for this work.
4- Not all houses in the CSDDRD are suitable to receive all selected solar technologies. Therefore, for each solar technology, suitability criteria were developed and incorporated into the CHREM to select eligible houses.
5- The CHREM was modified to incorporate the models for selected solar technologies. This involved the modification of data input files as well as post processing of results.
6- Since many solar technologies (e.g. Photovoltaics, phase change material thermal storage) are still in a state of development, it is not possible to estimate realistic capital costs for these technologies. In other cases, the capital costs are highly variable based on location and manufacturer (e.g. windows, blinds, solar domestic

hot water systems). Therefore, a new approach (Tolerable Capital Cost - TCC) was developed in this work to conduct economic feasibility analysis (Section 2.4).

7- Batch simulations using the CHREM were conducted for each selected solar technology to determine the impact of the selected solar technology on the end-use energy consumption and GHG emissions of the CHS.
8- Sensitivity analyses were conducted to determine the impact of interest rate, fuel cost escalation rate and payback period on the TCC of each technology for each province of Canada.

The following solar technologies were selected for techno-economic assessment in this work (Section 1.3):

1- Solar water heating (using flat plate solar collector)
    a. Active (forced circulation)
2- Solar space heating
    a. Passive
        i. Direct gain systems
            1. Changing windows area
            2. Changing windows type
            3. Shading devices
                a. Fixed internal or external shading (Venetian blind)
        ii. Phase change materials (PCMs)
    b. Active
        i. Controlled internal and external shading devices (Venetian blind)
2. Photovoltaics
    b. PV electricity generation

5.1.2 Summary of Findings

Due to the large magnitude of the quantitative results available from the analyses conducted, one of the most difficult challenges associated with a study of this nature is the distillation of the results into an easily comprehensible and useful fashion. To complicate the matters further, each reader generally has a different interest and expectation in terms of the results presented. On the other hand, one of the most useful aspects of a model such as the CHREM is the latitude of flexibility it provides in the type of technologies it can evaluate as well as the type of results that can be extracted from it and presented to the reader.

Another big challenge is in the interpretation and analysis of the results presented. In most cases, the results presented in table and figure form are self explanatory in terms of the message that they give. However, the reasons behind the results can be complicated to identify and often require in-depth analysis of the intermediate results.

In this work, a large body of results were presented in Chapter 4 as well as in the appendices. Considering the size of the work, detailed commentary on the results were spared. It is the hope and the humble opinion of the author that the reader will study the results and see the picture presented. Nevertheless, in the sections below, an attempt is made to distill the results into what the author hopes to be useful for most of the readers. Thus, the results are re-organized into two formats: (1) Results for each solar technology, (2) Results for each province.

5.1.2.1 The impact of assumptions on the results of economic analysis

In this work the concept of TCC was used as a measure of economic performance. Since the economic analysis is based on reductions in energy consumption, assumptions were made on the fuel costs, escalation rate of fuel costs, interest rates and payback periods to be used in the analyses. Furthermore, sensitivity analyses were done by varying the parameter values upwards and downwards from the basic assumptions (Section 2.5). It should therefore be noted that all economic results presented in this work are based on the assumptions made and as it was shown in the sensitivity analyses, the results can change substantially based on these assumptions. Consequently, the results presented in this work apply only under the economic conditions reflected by the assumptions made. If economic conditions change such as higher fuel cost or lower interest rates, the economic feasibility of solar technology upgrades may change dramatically. It is therefore, important to recognize that generalized conclusions cannot be reached from the results presented here, and new economic analyses need to be done for each set of economic parameters deemed to be applicable under current circumstances.

5.1.2.2 A summary of techno-economic assessment of each solar technology

The tolerable capital cost, the amount of energy savings and the associated GHG emission reductions are given for each selected solar technology in Table 5.1. The results presented are for a six year payback period, 6% interest rate and medium fuel cost escalation rate (as per Table 2.6). It is possible to develop these tables for other economic parameters from the data presented earlier; however, this is not done here for the sake of brevity. The parameters selected for Table 5.1 represent the middle point values used in the sensitivity analyses conducted. The results given in Table 5.1 are sorted in descending order based on the TCC.

Some of the interesting conclusions that can be drawn from Table 5.1 are presented as follows for SDHW system upgrade. Similar conclusions can be extracted for the other solar technologies by inspecting the respective tables.

If the objective is to introduce SDHW systems into Canada with the least amount of government incentive or subsidy, the province to start such a program would be NB. As seen in Table 5.1 (a), the tolerable capital cost for each household is the highest in NB at $1,723. Therefore, the government subsidy will only have to cover the balance between the actual cost and $1,723. With such a program, the GHG emission reduction would also be substantial at 175 kt/yr (8.0% reduction relative to the GHG emissions of the NB housing sector), the second highest amongst all provinces.

If however, the objective is to reduce energy consumption as much as possible by introducing SDHW systems into Canada, then one has to focus on OT because the potential for savings is the highest at 8,314 TJ/yr (2.0% savings relative to the energy consumption of the OT housing sector). This high level of savings is primarily due to the scale of OT housing stock compared to all other provinces (more than 1 million households). If OT were selected for SDHW program introduction, the GHG emission reduction potential would also be the highest among all provinces at 537 kt/yr (2.2% reduction relative to the GHG emission of the OT housing sector).

Another interesting finding is the large range of TCC amongst the provinces: from a minimum of $345 for AB to $1,723 for NB, a five-fold difference. This is due to a number of factors, most important of which is the price of fuel used to heat the DHW. The energy savings and GHG emission reduction potentials follow more or less the size of the housing stock.

Table 5.1 The total tolerable capital per house, energy savings and GHG emission reductions for 6 year payback period, 6% interest rate and medium fuel cost escalation rate (as per Table 2.6) for the selected solar technologies

(a) SDHW system upgrade

Province	No. Of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
NB	103,732	1,723	738	174.5
NS	127,574	1,647	811	84.4
PE	25,796	1,640	154	0.3
NF	80,588	1,417	508	3.4
QC	733,080	973	5,112	1.0
OT	1,074,143	804	8,314	537.4
MB	115,609	801	880	27.7
BC	343,236	760	2,397	92.4
SK	131,470	625	1,094	54.9
AB	341,507	345	2,732	70.3

* Tolerable capital cost

(b) Window type 3210 upgrade

Province	No. Of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
NB	238,327	1,522	2,156	166
NF	174,977	1,373	1,283	50
NS	298,174	1,359	2,243	145
PE	44,995	1,233	363	18
QC	1,992,258	1,000	13,443	200
BC	1,113,593	961	12,771	555
OT	3,436,650	797	30,204	1,865
MB	339,713	509	2,229	89
SK	312,066	475	2,490	128
AB	973,158	314	8,621	440

* Tolerable capital cost

(c) Window type 3210 and window/wall area ratio 60% upgrade

Province	No. Of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
NB	209,261	914	1,114	82
NS	260,108	738	1,061	67
NF	162,679	683	592	24
PE	40,538	629	163	8
OT	2,949,530	309	9,218	400
MB	311,439	261	928	39
QC	1,688,792	258	1,132	31
SK	275,829	218	843	42
BC	806,356	198	1,296	62
AB	851,528	136	3,102	153

* Tolerable capital cost

(d) Venetian blind (case 1) upgrade

Province	No. Of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
NB	543	1,494	8	0
QB	278,255	1,218	2,489	32
NS	2,314	1,173	15	1
OT	1,703,319	785	19,484	1,161
BC	84,166	622	642	27
AB	28,146	568	339	20
MB	50,964	544	383	15
SK	94,478	539	917	47
NF	0	0	0	0
PE	0	0	0	0

* Tolerable capital cost

(e) PCM (Tmelt = 23 ˚C)

Province	No. Of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
NB	220,102	527	676	55
NS	285,760	482	762	50
PE	43,714	410	113	6
BC	990,871	357	4,348	197
QC	1,784,501	304	3,613	61
OT	3,127,029	284	9,932	567
NF	162,793	251	222	9
SK	286,384	222	1,174	60
MB	317,503	191	828	35
AB	899,606	163	4,133	211

* Tolerable capital cost

(f) PV

Province	No. Of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
NB	103,732	3,551	1,518	359
PE	25,796	3,336	311	1
AB	341,507	3,328	3,628	834
SK	131,470	3,018	1,513	101
NS	127,574	2,848	1,399	146
OT	1,074,143	2,606	12,173	1,642
NF	80,588	2,569	920	6
BC	343,236	1,954	4,461	22
MB	115,609	1,712	1,303	0.3
QC	733,080	1,609	8,445	2

* Tolerable capital cost

5.1.2.3 A summary of techno-economic assessment of solar technologies for each province

The tolerable capital cost, the amount of energy savings and the associated GHG emission reductions are given for each province in Table 5.2. The results presented are for a six year payback period, 6% interest rate and medium fuel cost escalation rate (as per Table 2.6). It is possible to develop these tables for other economic parameters from the data presented earlier; however, this is not done here for the sake of brevity. The parameters selected for Table 5.2 represent the middle point values used in the sensitivity analyses conducted. The results given in Table 5.2 are sorted in descending order based on the TCC.

Some of the interesting conclusions that can be drawn from Table 5.2 are presented as follows for NF. Similar conclusions can be extracted for the other provinces by inspecting the respective tables.

If the primary objective of introducing solar technologies into the housing sector of NF is to reduce the energy consumption, the technology to focus on would be replacing all eligible windows in the province with triple-glazed, with low-e coating (0.1) and 13 mm Argon filled gap windows (window type 3210). This will result in a reduction of energy consumption by 1,283 TJ/yr (5.7% savings relative to the energy consumption of the NF housing sector) and will also result in the largest GHG reduction at 50kt/yr (6.3% reduction relative to the GHG emissions of the NF housing sector). The tolerable capital cost for this upgrade is $1,373 per household. This means that to ensure a large scale uptake of this upgrade, a government incentive/subsidy equivalent to the difference between the actual cost and $1,400 needs to be offered to the households.

The second largest potential to save energy is by introducing PV systems into the province. The TCC for PV systems in NF is close to $2,600; i.e. if the government would like to promote PV systems, it has to introduce incentives/subsidies equivalent to the difference between the actual cost and TCC.

Table 5.2 The tolerable capital cost per house and provincial energy savings and GHG reduction for 6 year payback period, 6% interest rate and medium fuel cost escalation rate (as per Table 2.6) for the selected solar technologies

(a) Newfoundland and Labrador

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	80,588	2,569	920	6
SDHW (case 1)	80,588	1,417	508	3
Window type 3210	174,977	1,373	1,283	50
Window type 3210-window/wall ratio 60%	162,679	683	592	24
PCM (Tmelt = 23 ˚C)	162,793	251	222	9
Venetian blind (case 1)	0	0	0	0

* Tolerable capital cost

(b) Prince Edward Island

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	25,796	3,336	311	1
SDHW (case 1)	25,796	1,640	154	0
Window type 3210	44,995	1,233	363	18
Window type 3210-window/wall ratio 60%	40,538	629	163	8
PCM (Tmelt = 23 ˚C)	43,714	410	113	6
Venetian blind (case 1)	0	0	0	0

* Tolerable capital cost

(c) Nova Scotia

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	127,574	2,848	1,399	146
SDHW (case 1)	127,574	1,647	811	84
Window type 3210	298,174	1,359	2,243	145
Venetian blind (case 1)	2,314	1,173	15	1
Window type 3210-window/wall ratio 60%	260,108	738	1,061	67
PCM (Tmelt = 23 ˚C)	285,760	482	762	50

* Tolerable capital cost

(d) New Brunswick

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	103,732	3,551	1,518	359
SDHW (case 1)	103,732	1,723	738	175
Window type 3210	238,327	1,522	2,156	166
Venetian blind (case 1)	543	1,494	8	0
Window type 3210-window/wall ratio 60%	209,261	914	1,114	82
PCM (Tmelt = 23 ˚C)	220,102	527	676	55

* Tolerable capital cost

(e) Quebec

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	733,080	1,609	8,445	2
Venetian blind (case 1)	278,255	1,218	2,489	32
Window type 3210	1,992,258	1,000	13,443	200
SDHW (case 1)	733,080	973	5,112	1
PCM (Tmelt = 23 ˚C)	1,784,501	304	3,613	61
Window type 3210-window/wall ratio 60%	1,688,792	258	1,132	31

* Tolerable capital cost

(f) Ontario

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	1,074,143	2,606	12,173	1,642
SDHW (case 1)	1,074,143	804	8,314	537
Window type 3210	3,436,650	797	30,204	1,865
Venetian blind (case 1)	1,703,319	785	19,484	1,161
Window type 3210-window/wall ratio 60%	2,949,530	309	9,218	400
PCM (Tmelt = 23 ˚C)	3,127,029	284	9,932	567

* Tolerable capital cost

(g) Manitoba

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	115,609	1,712	1,303	0
SDHW (case 1)	115,609	801	880	28
Venetian blind (case 1)	50,964	544	383	15
Window type 3210	339,713	509	2,229	89
Window type 3210-window/wall ratio 60%	311,439	261	928	39
PCM (Tmelt = 23 ˚C)	317,503	191	828	35

* Tolerable capital cost

(h) Saskatchewan

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	131,470	3,018	1,513	101
SDHW (case 1)	131,470	625	1,094	55
Venetian blind (case 1)	94,478	539	917	47
Window type 3210	312,066	475	2,490	128
PCM (Tmelt = 23 ˚C)	286,384	222	1,174	60
Window type 3210-window/wall ratio 60%	275,829	218	843	42

* Tolerable capital cost

(i) Alberta

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	341,507	3,328	3,628	834
Venetian blind (case 1)	28,146	568	339	20
SDHW (case 1)	341,507	345	2,732	70
Window type 3210	973,158	314	8,621	440
PCM (Tmelt = 23 ˚C)	899,606	163	4,133	211
Window type 3210-window/wall ratio 60%	851,528	136	3,102	153

* Tolerable capital cost

(j) British Columbia

Technology	No. of houses	TCC* per house (CAN$)	Total energy saved (TJ)	Total GHG reduced (kt)
PV	343,236	1,954	4,461	22
Window type 3210	1,113,593	961	12,771	555
SDHW (case 1)	343,236	760	2,397	92
Venetian blind (case 1)	84,166	622	642	27
PCM (Tmelt = 23 ˚C)	990,871	357	4,348	197
Window type 3210-window/wall ratio 60%	806,356	198	1,296	62

* Tolerable capital cost

5.2 Recommendations for future work

This work was carried out using the CHREM which uses ESP-r as its simulation engine. As they stand, ESP-r is one of the most sophisticated and capable building energy simulation tools, and CHREM is the most comprehensive national housing stock model available anywhere. Consequently, the flexibility and capability offered by the CHREM/ESP-r combination in conducting techno-economic analyses for the residential sector is unequalled. However, ESP-r is extremely complicated to deal with due to insufficient (and often unclear and scattered) instructions and no useful user interface for inputting data and outputting results. Furthermore, it is an open-source software, which allows and promotes its modification and improvement, and ensures that it remains to be the state-of-the-art; but this also often results in further complication. Consequently, conducting a study similar to the one conducted here requires a huge amount of effort (measured in person-years) and expertise (gained with a steep learning curve). In order to make CHREM (and other similar models) more usable, some development work needs to be put into the ESP-r to make it more user friendly.

The techno-economic analysis work presented here on solar technologies for the CHS is the first of its kind considering the range of technologies evaluated as well as the level of detail. Consequently, a large amount of findings have been created, most of which are presented here. Due to the magnitude of results generated, the reader has to use judgement and filtering to extract the type of conclusions needed. If similar studies are conducted in the future, the author of the work needs to ensure that she receives from the organization that commissions the work the type of results sought as well as the level of detail, i.e. the questions to be answered should be clarified at the outset.

There are a plethora of solar technologies available now. In this work, a limited number of these technologies were evaluated. Due to lack of time and energy, some promising technologies (such as building integrated Photovoltaics/thermal – BIPV/T) were not included. Also, it was not possible to assess the implications of using more than one solar technology in a house to study combination/integration issues and effects of the technologies. It is expected that by carefully selecting combinations of solar technologies applied to houses, it would be possible to reduce energy consumption and GHG emissions while improving economic feasibility of solar technologies due to favorable thermal interactions amongst technologies. Therefore, it is recommended that combination/integration of solar technologies (such as PCM and passive solar, and BIPV/T-SDHW) be assessed in future studies.

The economic analysis method (TCC) developed in this work does not explicitly deal with the additional maintenance cost due to the upgrade. As explained in Section 2.4, the TCC implicitly includes the capitalized maintenance costs. It may be desirable to modify the TCC method to explicitly address the additional maintenance cost.

No effort was expanded in this work to estimate possible penetration levels of the solar technologies studied. In itself, this is not a shortcoming since the results presented can be directly scaled to any level of penetration level by a simple multiplication. If for example, a 10% penetration level is expected, the energy savings will be 10% of the results presented here. Likewise, the GHG emissions will be 10% of the reported values. Furthermore, this approach was suitable for the purposes of this work since the objective is to compare different technologies. Nevertheless, it is acknowledged that a 100% penetration level is unrealistic for any technology. Thus, it is recommended that in future studies effort should be expanded to estimate realistic or potential penetration levels.

No monetary value has been assigned to reductions in GHG emissions in the economic analysis conducted in this work. This reflects the current state of affairs in Canada as there is no carbon credit trading and no monetary value assessed for carbon credits. Depending on the way Canada chooses to deal with this issue, it may be worthwhile to include carbon credits in the economic evaluation method.

In Appendix B of this work, a study conducted by the author is presented, which shows that external shading due to neighboring structures (such as buildings and trees) can have substantial influence on the energy requirement and solar potentials of buildings. So far, there is no systematic approach to include external shading effects into the energy modeling of the existing residential stock. As indicated in the paper given in Appendix B, this will require a substantial amount of work. However, considering the potential magnitude of the impact of external shading, it is recommended that methodologies be developed and included into the CHREM.

In section 4.3.2.3, the impact of the selection criteria for shading devices was discussed. As explained in that section, the existence of a cooling system in a house results in the elimination of most houses that only match the other criterion (i.e. presence of a window in the proper orientation). Therefore, it is recommended to remove the cooling system criterion and simulate the new group of eligible houses and compare the results with those given in this study.

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APPENDIX A DETAILED LITERATURE REVIEW

1. Trombe wall

   The concept of Trombe wall was introduced by Trombe et al. (1977) who studied the performance of the heavy masonry wall for a house in Odeillo, France. They reported that the heating energy savings is 60-70% annually. This work was continued by researchers around the world. Studies conducted include parametric studies of the performance of a Trombe wall (Balcomb, et al. 1977, Arumi, et al. 1977, Ohanessian, et al. 1978, Akbarzadeh, et al. 1982, Tasdemiroglu, 1983, Tasdemiroglu, 1985), control strategies for a Trombe wall (Sebald, et al. 1979), numerical and experimental analysis of the flow regime and convection in the air gap of a Trombe wall (Trombe, et al. 1977, Akbari, et al. 1979, Utzinger, et al. 1980, Borgers, et al. 1984, Orminston, et al. 1986, Bansal, et al. 1987, Abd Rabbo, et al. 1988, Hesieh, et al. 1988, Yedder, et al. 1991, Smolec, et al. 1991), analytical and numerical modeling of a Trombe wall (Robbins, et al. 1980, Gordon, et al. 1981(a, b, c), Monsen, et al. 1982, Duffin, et al. 1985, Hassid, 1986), and Trombe wall modifications such as solar chimney, modifying the geometry and using composite materials (Fuchs, et al. 1979, Bilgen, et al. 1982, Faiman, 1982, Knowles, 1983, Zrikem, et al. 1987, Zrikem, et al. 1989, Kaushik, et al. 1989, Du, et al. 1990, Khedari, et al. 1991).

   From the literature, it was found that the optimum thickness of the Trombe wall is around 25-35 cm, depending on the latitude of the site the building is located. However, this thickness can be reduced to 15 cm by adding controlled fan to the vents. Since the flow regime in the air gap is not completely laminar and not transient, it was modeled as a one-dimensional and two-dimensional laminar flow and transient flow by different studies. The analytical models have been developed for parametric study and it was found that these simplified models have less than 10% error comparing to complicated numerical models. Trombe wall modification by means of changing its geometry, using composite materials and solar chimney can increase its efficiency by 20%.

2. Isolated gain systems

There are extensive studies on the sunspace energy analysis and its design and modeling. In an experimental study conducted at the Building Technology Institute of the National Research Council in Milan, Italy in January, the performance of a window with an attached sunspace and a window where the heat collecting area is the living area was compared with that of an insulated opaque wall, positioned facing the same way as the first two systems (Espoti, et al., 1990). It was found that the energy performance of the sunspace is the same as the insulated wall. However, sunspace offers a living space with attractive environmental characteristics.

In a simulation based sensitivity study conducted using 1996 weather data for the cold and warm periods in Milano, Dublin, Athens and Florence, Mihalakakou, et al. (2000) studied the energy saving potential of a sunspace and the impact of orientation, glazing materials and boundary conditions for a single zone building with a sunspace on the south side. It was found that adding sunspace to the building, especially on the south side, increases indoor temperatures significantly during both the cold and the hot periods, resulting in potential overheating over the warm period, while low-emissivity double glazing provides a slight improvement over single glazing in terms of energy performance.

A modeling study conducted in Greece to investigate the impact of using buried pipes, night ventilation techniques and shading to improve the thermal behaviour of sunspaces in the summer found that all techniques can improve the thermal behaviour of the building with the sunspace while the combined use of the three methods was found to be the most efficient way to provide space cooling and prevent overheating during the warm period of the year (Mihalakaou, 2002).

These and other similar studies indicate that adding sunspace to a building has the potential to improve the energy performance of the building.

APPENDIX B SHADING EFFECT

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Sara Nikoofard is the principal researcher and author of the article. She conducted the research as part of her PhD. Thus, while she received supervision and guidance from her supervisors Drs. Ugursal and Beausoleil-Morrison, she carried out the work, wrote the published article, communicated with the editor of the journal, and carried out the necessary revisions before publication. Minor grammatical changes have been made to integrate the article within this dissertation.

B.1 Abstract

Shading by neighbouring buildings and trees impacts the energy requirement of a building by reducing the amount of radiant energy absorbed and stored by its thermal mass. This study intends to quantify the magnitude of the effect of site shading on the energy requirement of residential buildings in Canada using a representative two-story detached house. Site shading effects of neighbouring buildings and trees on annual heating and cooling energy requirements are evaluated using a building energy simulation program. The effects of the orientation, distance and size of the neighbouring object on heating and cooling energy requirement are investigated for four major cities (Halifax, Toronto, Calgary, Vancouver) representing the major climatic regions in Canada (Atlantic, Central, Prairies, Pacific). It is found that the annual heating and cooling energy requirement of a house in Canada may be affected by as much as 10% and 90%, respectively, by the existence as well as the orientation, size and distance of a neighbouring obstruction. Therefore, it is recommended that in building energy simulation studies, external shading should be given due consideration.

B.2 Introduction

Shading may decrease or increase the energy requirement of a building depending on building characteristics and environmental conditions. A potential benefit of shading for adjacent structures is decreasing the cooling energy requirement. Negative consequences of shading include the loss of natural light for passive or active solar energy applications and the loss of warming influences, which increase the heating energy requirement during the cold season. Factors influencing the impact of shading are site-specific such as the latitude and climate, as well as the direction, number, size and distance of neighbouring structures. Although potentially significant, the impact of neighbouring structures on the heating and cooling energy requirement of houses is often neglected in building energy analysis.

Due to the potentially substantial effect of shading due to neighbouring structures on the energy requirement of buildings, numerous studies have been conducted to assess the effect of shading by neighbouring buildings and trees. Frank, et al. (1981) developed a program that calculates the view factors of a building and the alignment of obstructions to simulate the shading effect by trees and buildings in urban environments. A decade later, Ok (1992) developed a model to calculate the effect of shading due to adjacent or nearby buildings on the cooling load taking into consideration settlement density, as well as the shape, distance and orientation of the obstruction. A multi-story residential building located in Istanbul was simulated for July 21st as a case study. The results showed that the effect of shading is more significant for the west and east oriented surfaces primarily due to the lower angle of solar radiation in the afternoon that results in a significant heating effect. In a similar study, Lam (2000) investigated the shading effects due to neighbouring buildings on commercial buildings in seven main business districts in Hong Kong using the building energy simulation software DOE-2.1E (LBNL 2009). The results of this study showed that the reduction in cooling load due to shading is about two percent, which is not significant for commercial buildings.

Farrar-Nagy, et al. (2000) studied a residential building in Tucson, Arizona to evaluate the opportunities for reducing cooling energy requirement in a hot dry climate through the use of spectrally selective windows, architectural shading, and site shading from adjacent buildings. Building performance was modeled using the building energy simulation software DOE-2 (LBNL 2009) and was measured while the building was unoccupied for a period of 12 days. It was found that ignoring the shading effect due to neighbouring buildings could result in overestimating the annual cooling energy requirement by up to 24%, depending on the orientation of the building, existence of overhangs and the type of windows.

In a paper that studied the impact of a number of parameters on the heating energy requirement of Canadian houses, Purdy and Beausoleil-Morrison (2001) assessed the shading effect of surrounding objects. The study was conducted using a developmental version of the HOT3000 building simulation software (CanmetENERGY 2009), which uses the comprehensive building energy simulation software ESP-r (ESRU 2009) as its simulation engine. A two-storey research house at the Canadian Center for Housing Technology in Ottawa was selected as the base case house for this study. It was found that the shading caused by the neighbouring houses increases the annual heating load requirement by up to 5%. It was also found that the results are sensitive to the location of the neighbouring house. Furthermore, the results demonstrated that the solar shading caused by surrounding buildings, and by extension other large objects such as trees, have more impact than the shading caused by a typical roof overhang.

Li and Wong (2007) studied the daylighting performance and energy use of a commercial building shaded by nearby buildings in Hong Kong. A procedure involving computer simulation techniques was employed to evaluate the energy performance of office buildings with day-lighting controls shaded by neighbouring buildings. A detailed study of the shading effects showed that day-lighting is always an energy saver in the Hong Kong climate. Results from a regression analysis were used to establish a number of correlation equations, which could predict the energy savings due to shading by external obstructions.

Akbari, et al. (1992) studied, among other parameters, the effect of shading by trees and the impact of painting the house white (high albedo) on residential heating and cooling energy use in four Canadian cities. For this purpose, three different building prototypes were simulated for Vancouver, Edmonton, Toronto and Montreal using the building energy simulation program DOE-2.1D (LBNL 2009). The building prototypes included a detached one-story and a detached two-story single-family house, and a row house. It was found that a 30% increase in the vegetative cover of an urban neighbourhood in Toronto (corresponding to about three trees per house), increases the annual heating energy consumption by up to 1%, while decreasing the cooling energy consumption by up to 30%. In urban neighbourhoods of Edmonton, Montreal and Vancouver, the predicted savings in heating energy use due to addition of trees and high albedo was about 10%. It was also found that the effect of shading and high albedo could totally offset the cooling energy in Edmonton and Vancouver, and average savings of 35% can be achieved in Montreal.

Simpson, et al. (1996) studied the shading effect of trees on the energy use of energy efficient, attic insulated and uninsulated houses in eleven California climate zones. Trees shading a west, southwest and east exposure were found to produce the largest annual energy savings for all climate zones and insulation levels considered. Depending on the climate zone, three mature trees (two on the west, one on the east side) reduced annual energy use for cooling up to 50%. Trees planted on the south and southeast exposures were found to be advantageous for cooling. It was however noted that increased heating loads due to reduced solar thermal gains in winter may substantially reduce or eliminate any savings from cooling energy reduction.

Akbari, et al. (1997) studied the impact of trees on cooling energy use. For this study, two houses in Sacramento, CA were instrumented for extensive data collection. The houses were shaded directly from the south and west with sixteen trees, eight tall (about 6 m high) and eight short (about 2.4 m high), and were simulated by DOE-2.1E building energy simulation program to compare the results of measurements and simulations. It was found that cooling energy savings for the house with a central air-conditioning system was 47% while the savings for the house with a heat pump system was 26%. In another study conducted for the Sacramento, California environment based on simulations of 254 residential properties, by Simpson, et al. (1998) found that planting an average of three trees per property reduces the annual and peak cooling energy use by 7.1% and 2.3%, respectively.

Higuchi, et al. (2007) studied the shading effect of broad leaved evergreen and deciduous trees. A two storey house was simulated using the simulation program EESLISM (Udagawa, et al. 1999, EESLISM 2009). Simulations were carried out for five cases, which consist of a base case with no trees, and two types of trees and two kinds of tree planting arrangements. It was found that the annual cooling load reduced by up to 20% and the heating load increased by 5% when two evergreen trees exist on the south and one on the west side.

This review of the literature shows that shading caused by neighbouring structures can have a significant impact on the energy consumption of a building. The objective of this work is therefore to quantify the effect of shading from neighbouring structures on the heating and cooling energy requirements of Canadian houses.

B.3 Methodology

A two-storey detached house commonly found in Canada is used as the “test case house”, which was first modeled and simulated without any external shading to provide the “base case” energy requirement. Then, external shading, in the form of neighbouring houses and trees, was added to the model and simulated to assess the effect of external shading in a variety of forms. The test case house was selected from the Canadian Single-Detached and Double/Row Database (CSDDRD) (Swan, et al. 2009b) and modeled using the building energy simulation program, ESP-r, a comprehensive building modeling tool based on the finite volume technique (ESRU, 2009). The parameters examined in this work include the orientation, size and distance of the shading objects.

B.3.1 Test Case House

The two-storey test case house is composed of two above-grade storeys, a conditioned basement and a non-conditioned attic. It is occupied by two adults and two children, and has a set of appliances including a refrigerator, washer and dryer, dishwasher and TV. The thermal characteristics of the house are given in Table B.1, while Figure B.1 shows the geometry.

Three thermal zones representing the basement, the attic and the two-storey living space were used to model the house in the ESP-r energy simulations. In the thermal model, the living space and basement are conditioned by the HVAC system while the attic is “free floating” in response to the thermal contact with the other zones and the outdoors. The contact between the basement zone and the ground is modeled with the BASESIMP model (Beausoleil-Morrison and Mitalas, 1997) and the air infiltration is modeled with the AIM-2 model (Walker and Wilson, 1990). To simplify the model, windows are placed at the geometric center of the walls. This is a reasonable assumption based on the findings of Purdy and Beausoleil-Morrison (2001). It is also assumed that windows are always closed and they have no blinds to isolate the effect of external shading.

Neighbouring structures are modeled in ESP-r by adding one or more obstructions to the test case house. In this work trees are assumed to be fully opaque. The shading and insolation module of ESP-r was used to calculate the temporal distribution of shading patterns on exterior surfaces and the distribution of insolation within zones (Li and Wong, 2007)

B.3.2 Case Studies Conducted

The effect of shading due to neighbouring obstructions is assessed by conducting simulations with different orientations, sizes and distances of shading. The space heating and cooling energy requirements predicted for each case are compared to those for the base case house. Since the effect of shading on heating and cooling energy requirement varies substantially based on the climate and the geographical location of a house, four cities, Halifax, Toronto, Calgary and Vancouver, were selected to represent the four major climatic regions in Canada, namely Atlantic, Central, Prairies and Pacific. The climatic characteristics of selected cities are summarized in Table B.2.

The type, size, orientation and distance of shading obstructions considered are summarized in Table B.3. The neighbouring house is assumed to be the same size as the base case house to reflect the pattern of houses in suburban neighbourhoods. In all cases, the obstructions are assumed to be located at the centerline of the house. The effect of shading by trees is examined for evergreen and deciduous trees. It is assumed that deciduous trees provide shading only during the April 1 - October 1 period, while evergreen trees provide shading throughout the year. Due to the vast landmass of Canada, a tree that is common in one area may be completely absent or unable to grow in another area. Therefore, an average size for both type of trees is assumed.

The orientation and number of shading obstructions, as well as the obstruction combinations considered are given in Table B.4. To assess the effect of the size of the shading obstructions, the width and height of the obstructions located on the south and west side of the base case house were doubled as shown in Table B.5. To assess the distance of neighbouring obstructions, their distance from the base case house were changed as shown in Table B.6.

B.4 Results and discussion

The results are summarized in Figures B.2-B.6. In every figure, the changes in the heating and cooling energy requirement are given as a percentage of the heating and cooling energy requirement of the base case house with no external shading. Since the base case house energy requirement varies from location to location, the base case house energy requirement values are included in each figure.

As seen in Figure B.2.a, shading from a neighbouring house located on the south side of the test case house results in the largest increase in heating energy requirement, which varies from 2.7% for the house located in Calgary to 1.5% in Toronto, representing 3.2 GJ/year and 1.5 GJ/year, respectively. On the other hand, shading caused by a house located on the west side decreases cooling energy requirement the most, by more than 25% in Vancouver (representing 2.5 GJ/year), as shown in Figure B.2.b. The results are sensitive to the orientation of the neighbouring structure, which confirms Purdy's results on shading by surrounding objects (Purdy and Beausoleil-Morrison, 2001). The effect of shading caused by a tree is smaller than that of a house, as shown in Figures B.2.a and B.2.b, due to the smaller size of the shade produced. However, while a deciduous or an evergreen tree has the same effect on the cooling energy requirement, the increase in the heating energy requirement due to the shade of a deciduous tree was found to be negligible (less than 0.5%) because deciduous trees shed their leaves in the winter.

Since the solar azimuth arc is longer in the summer than in winter, neighbouring structures on the east and west exposures cause more shade. Therefore, the cooling energy requirement decreases more if the neighbouring structure is on the east or west side as opposed to the south side as shown in Figure B.2. On the other hand, the heating energy requirement increases more if the neighbouring structure is on the south side, since the solar radiation is highest on the south exposure during the heating season.

The effect of having obstructions on more than one side was studied by adding obstructions to two and three sides of the base case house as shown in Table B.4. It was found that the shading caused by two obstructions to the east and west sides decreases the cooling energy requirement more than the shading caused by two obstructions located on any other combination of directions. The decrease in cooling energy requirement is as high as 36% for the house located in Vancouver (3.4 GJ/year), and as low as 7% for the house in Toronto (0.9 GJ/year). On the other hand, adding two obstructions to the west and south sides results in the largest increase in the heating energy requirement, up to 4% increase for the house located in Calgary (4.6 GJ/year).

Three obstructions added to the south, east and west sides reduce the cooling energy requirement more than any other combination of directions, resulting in a reduction of 40% for the house located in Vancouver (3.8 GJ/year). The same combination also results in the highest increase in the heating energy requirement, up to 4.6% (5.3 GJ/year) for a house in Calgary.

The results obtained for shading from multiple directions also revealed that the changes in hHeating and cooling energy requirements due to obstructions located on two or three sides of the base case house can be estimated using results of single obstruction simulations with less than 5% error. For example, if two obstructions are added to the west and east sides of the house, the increase in heating energy requirement or reduction in cooling energy requirement can be estimated, with less than 5% error, as follows:

Change in the energy requirement with one easterly and one westerly obstruction =

Change in the energy requirement with one easterly obstruction +

Change in the energy requirement with one westerly obstruction

Using the same approach, the effect of obstructions on three sides can also be estimated with less than 5% error.

As shown in Figures B.3 and B.4, increasing sizes of the neighbouring structure has a substantial impact on the heating and cooling energy requirements. As to be expected, due to the shorter azimuth arc of the sun during the winter months, an increase in the width of the obstruction creates a larger shadow and has a larger impact on the heating energy requirement than an increase in the height of the obstruction. Similarly, an increase in the height of the obstruction has a larger impact on the cooling energy requirement than an increase in the width due to the longer azimuth arc of the sun during the summer months.

The effect of the distance of the obstruction on the heating and cooling energy requirements are shown in Figures B.5 and B.6. The results indicate that as the distance decreases, the effect of shading increases at an increasing rate. Thus, while there would be substantial reductions in the energy requirement for cooling in densely zoned neighbourhoods due to shading, the increase in heating energy requirements would likely be higher. For example, if the distance of a neighbouring house located on the south side is decreased from 14.2 m to 2.3 m in Calgary, the heating energy requirement would increase by about 5 GJ/year while the cooling energy requirement would decrease by 1.6 GJ/yr.

To explore the largest magnitude of the potential effect of shading by neighbouring buildings, an extreme case of shading was modeled where obstructions were added to the south, west and east side of the house, with each obstruction being 2.4 m away from and twice as big as the base case house. As can be seen in Figure B.7, in this extreme situation, the cooling energy requirement is reduced by 90% (8.6 GJ/year) for the house in Vancouver and heating energy requirement is increased by 10% (12 GJ/year) for the house in Calgary.

B.5 Conclusion

The findings of this study, which are in general agreement with the findings of other studies, indicate that the annual heating and cooling energy requirements of a house in Canada may be significantly affected due to the shading provided by neighbouring objects such as houses and trees. The orientation, size and distance of the neighbouring object determine the magnitude of the shading effect on the heating and cooling energy requirement. Shading caused by a neighbouring object reduces the solar heat gain, resulting in an increase in the energy requirement for heating while reducing the energy requirement for cooling. Due to the lower altitude of the sun and its shorter azimuth arc during the winter months, a neighbouring object located on the south side of a house was found to have a larger impact on the heating energy requirement than that of objects located on the other sides. Similarly, a neighbouring object on the west side has a larger impact on the cooling energy requirement compared to those on other sides due to the higher altitude and the longer azimuth arc of the sun during the summer months. In high density neighbourhoods with closely situated and larger houses on all three sides, the heating energy requirement may increase due to shading by as much as 10 percent, while the cooling energy requirement may decrease by as much as 90 percent compared to an unshaded house.

Planting deciduous trees around a house can give the advantage of reducing cooling energy requirement in summer and eliminate the disadvantage of increasing heating energy requirement in the winter.

Considering the potentially substantial impact of external shading by neighbouring objects on the annual energy requirement for heating and cooling in Canadian houses, it is recommended that external shading effects need to be accounted for in modeling residential energy consumption. For the same reason, shading effects need also be taken into consideration in planning new neighbourhood developments.

Table B.1 Characteristics of the test case house

Built year	1955
Floor-Area (m2)	66
Width (m)	9.6
Depth (m)	6.9
Height (including attic) (m)	6.3
U-value Above-grade walls (W/m2 K)	0.55
U-value Above-grade ceiling (W/m2 K)	0.47
U-value Basement walls (W/m2 K)	2.89
U-value Basement floor (W/m2K)	1.39
U-value windows (W/m2 K)	2.00
Number of windows	4 (one each side)
Dimensions of windows (m)	3 x 2
Front side	South

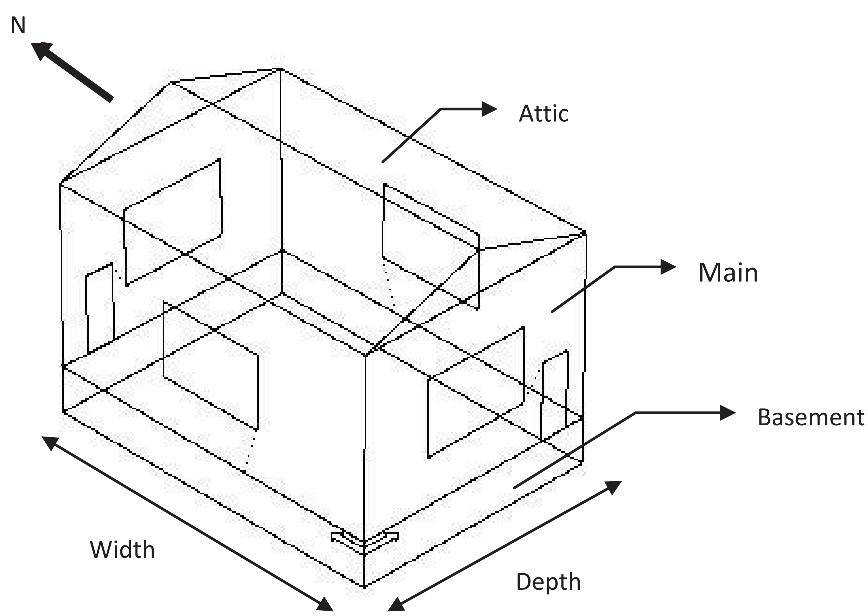


Figure B.1 Test case house

Table B.2 Climatic characteristics of selected cities

City	Latitude	Longitude	HDD (Based on 18˚C)	CDD (Based on 18˚C)
Halifax	44˚ 54’ N	63˚ 34’ W	4031	105
Toronto	43˚ 41’ N	79˚ 24’ W	3570	359
Calgary	51˚ 6’ N	114˚ W	5108	40
Vancouver	49˚ 11’ N	123˚ 10’ W	2926	44

Table B.3 Size and orientation of neighbouring structures

Obstruction Type	Dimensions (m)	Orientation	Distance from the shaded house (m)	Shading period
House	Height = 6.3 Width = 9.6 Depth = 6.9	East or West	4.7	Whole year
House	Height = 6.3 Width = 6.9 Depth = 9.6	North or South	3.3	Whole year
Tree	Trunk Height = 2 Crown Height = 6 Crown Width = 4 Crown Depth = 4	All sides	4.7	Evergreen: Whole year Deciduous: April 1st – October 1st

Table B.4 Orientation and number of neighbouring structures

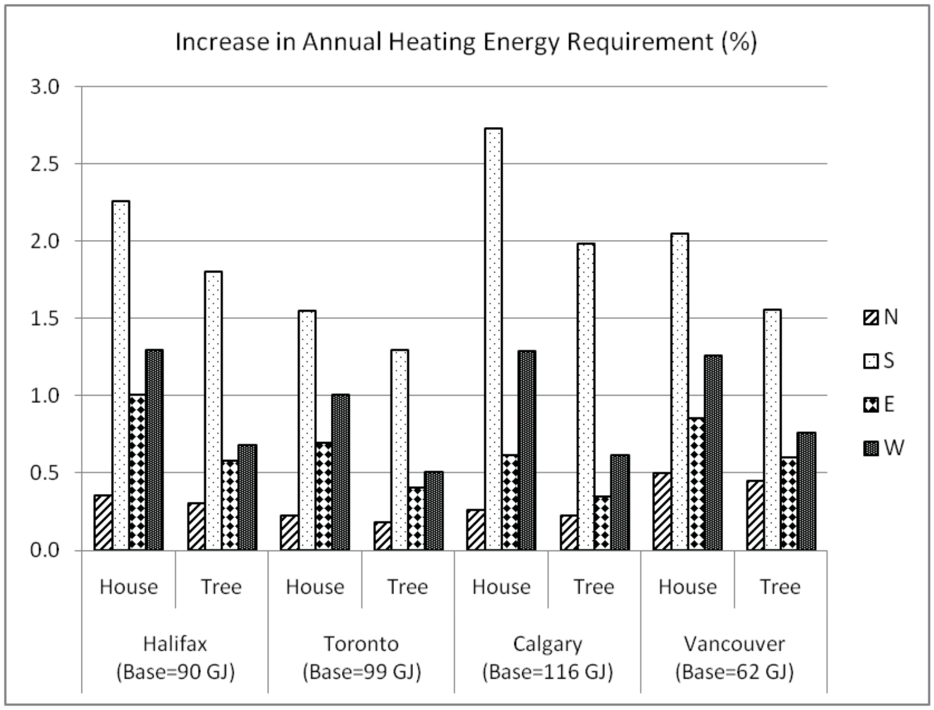
Number of Neighbouring Structures	2	3
Orientation	W/S E/S W/N S/N E/W E/N	S/N/E S/N/W S/E/W N/E/W - -

Table B.5 Size of neighbouring structures

Orientation	Neighbouring house (H(m) x W(m))	Neighbouring tree (H(m) x W(m))
West	6.3 x 9.6	6 x 4
	6.3 x 19.2	6 x 8
	12.6 x 9.6	12 x 4
	12.6 x 19.2	12 x 8
South	6.3 x 6.9	6 x 4
	6.3 x 13.8	6 x 8
	12.6 x 6.9	12 x 4
	12.5 x 13.8	12 x 8

Table B.6 Distance of neighbouring structures

Orientation	Distance of neighbouring structures from the shaded house (m)
West or South	2.3
	4.7
	9.5
	14.2



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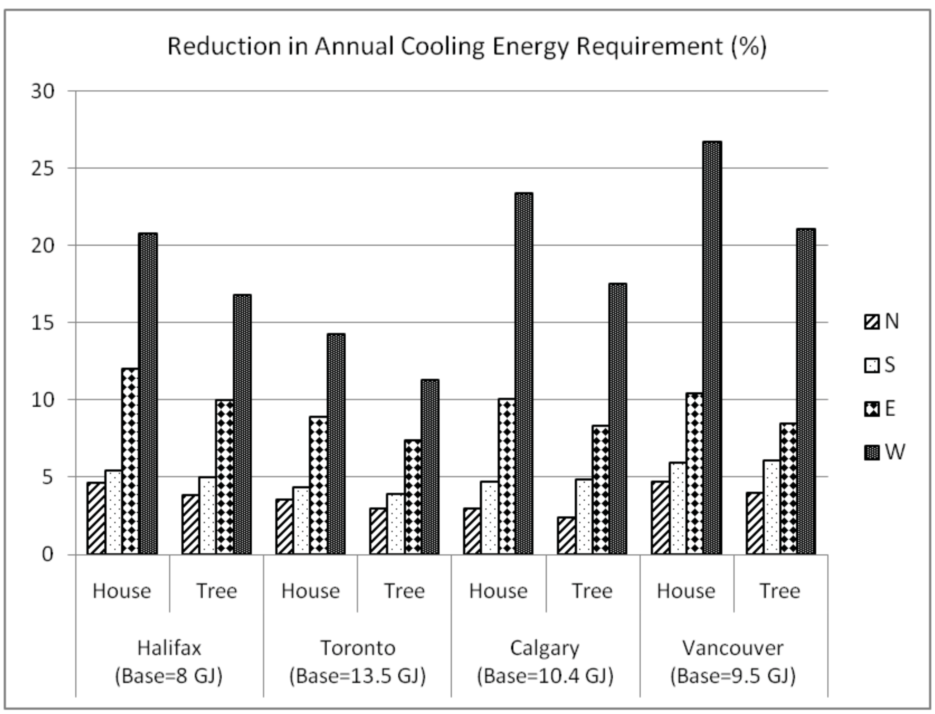
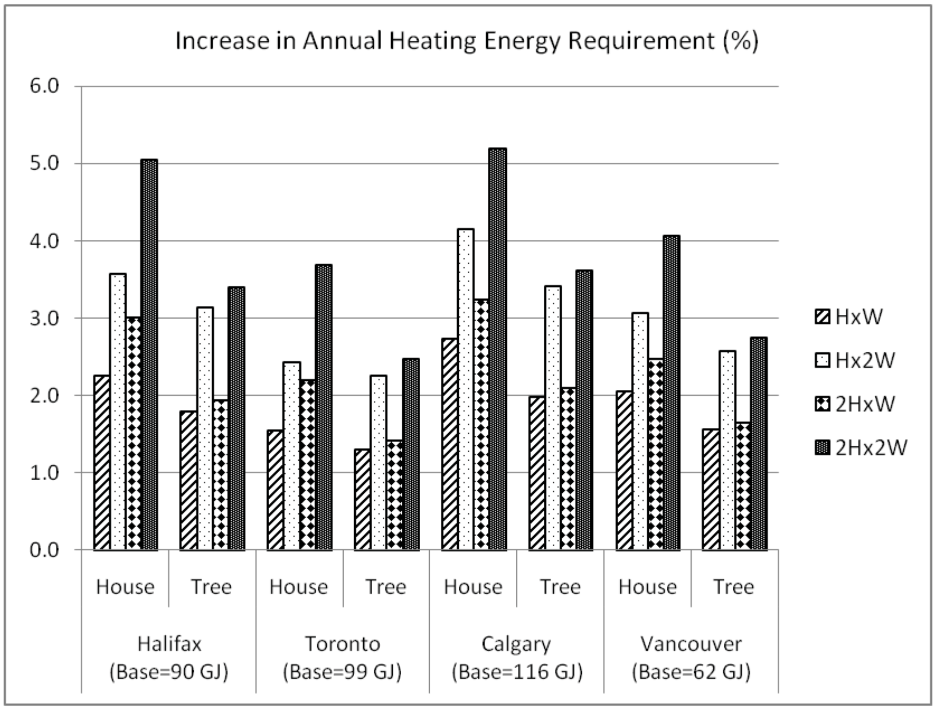


(b)

Figure B.2 Effect of orientation of neighbouring structures on the heating and cooling energy requirements



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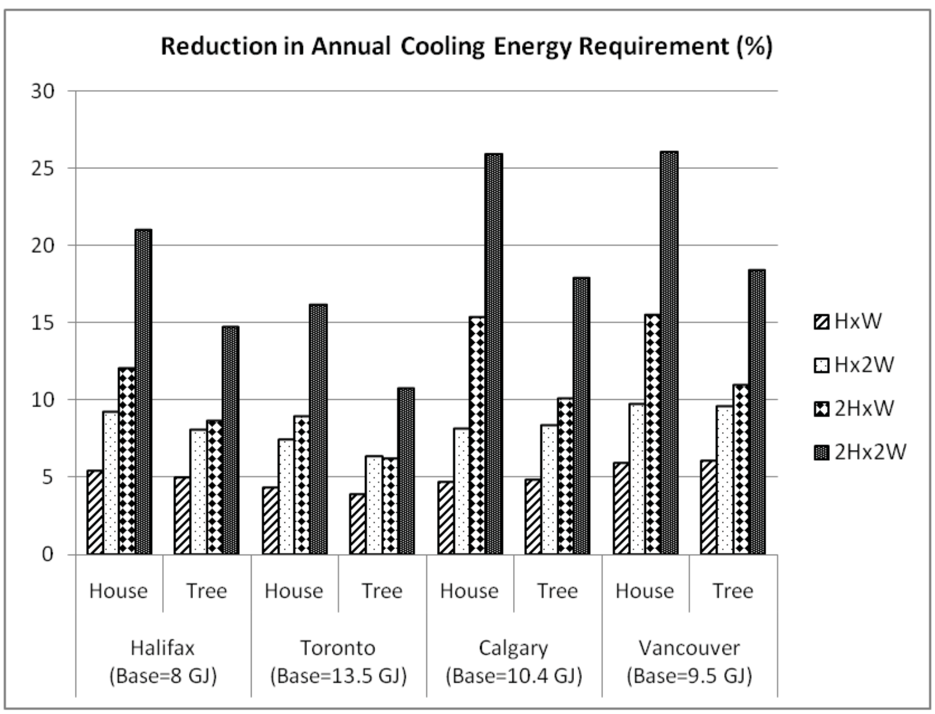
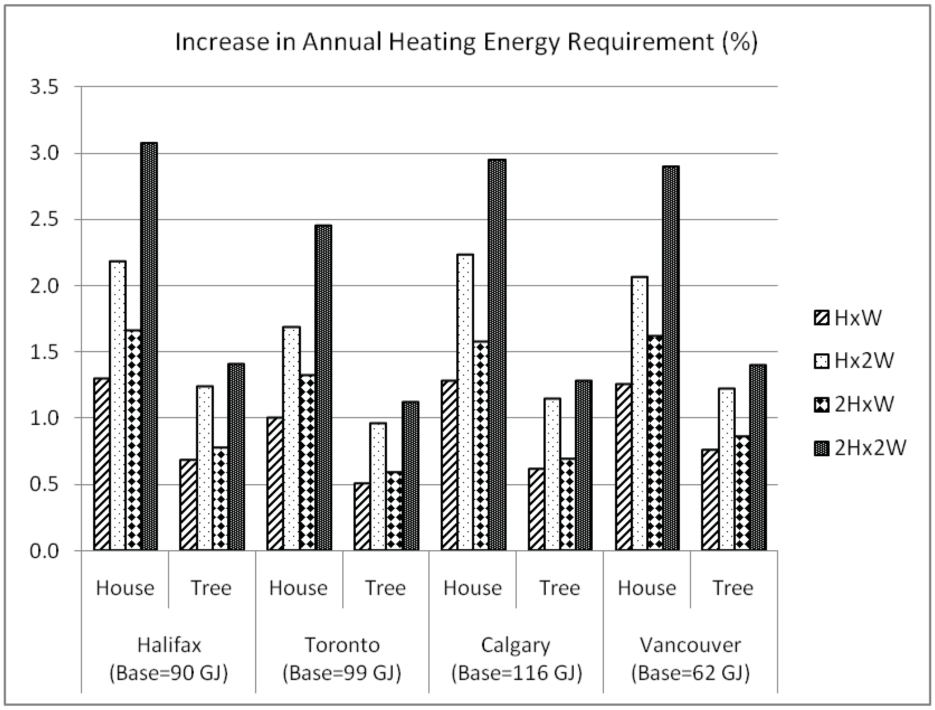


(b)

Figure B.3 Effect of the size of southerly neighbouring structures on the heating and cooling energy requirements



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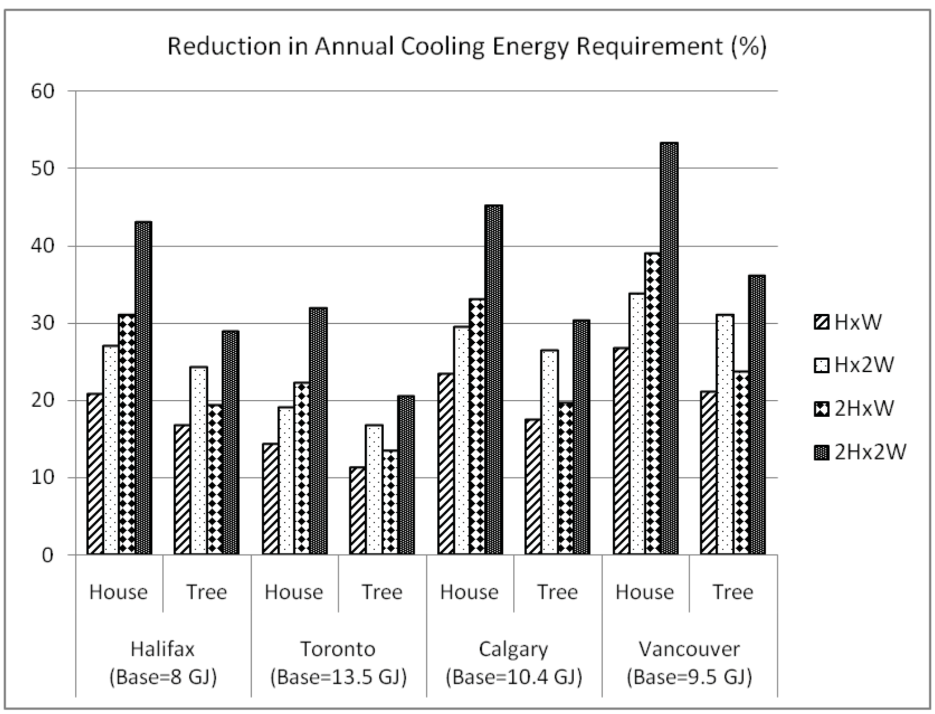
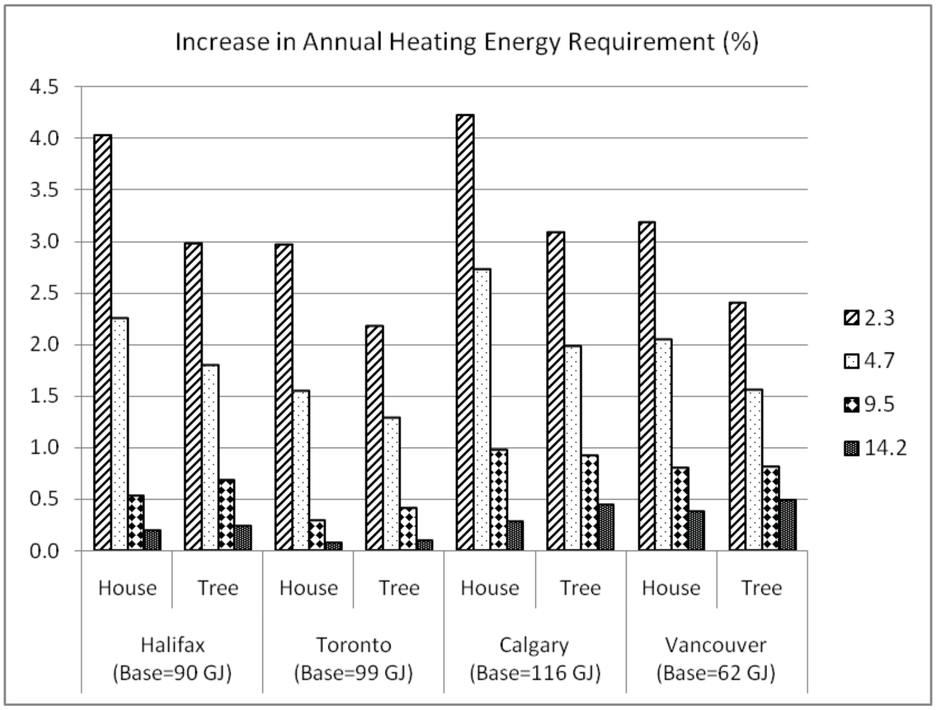


(b)

Figure B.4 Effect of the size of westerly neighbouring structures on the heating and cooling energy requirements



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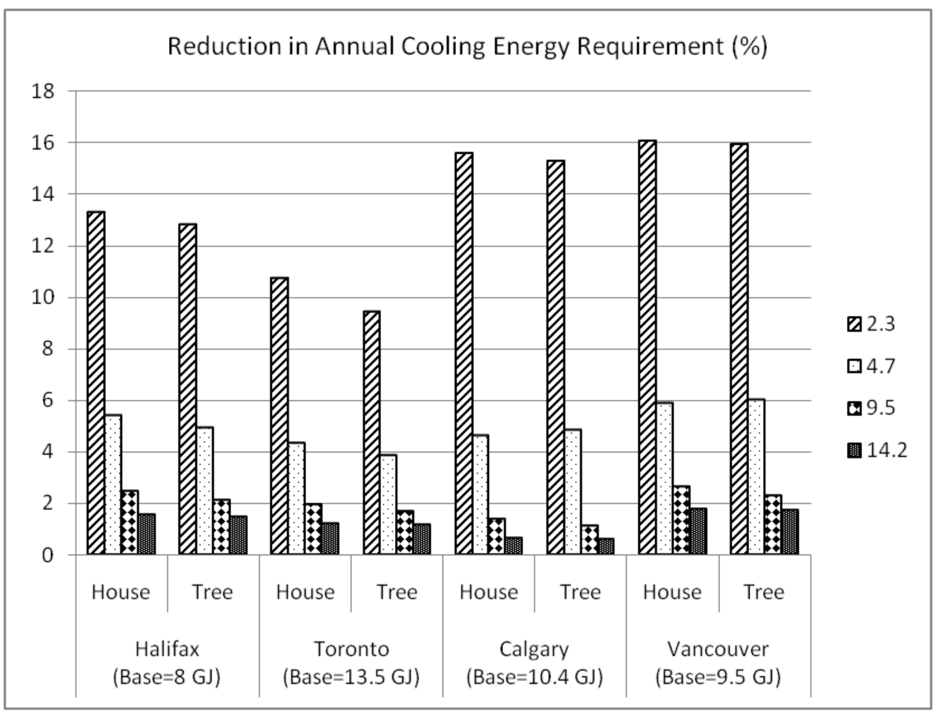
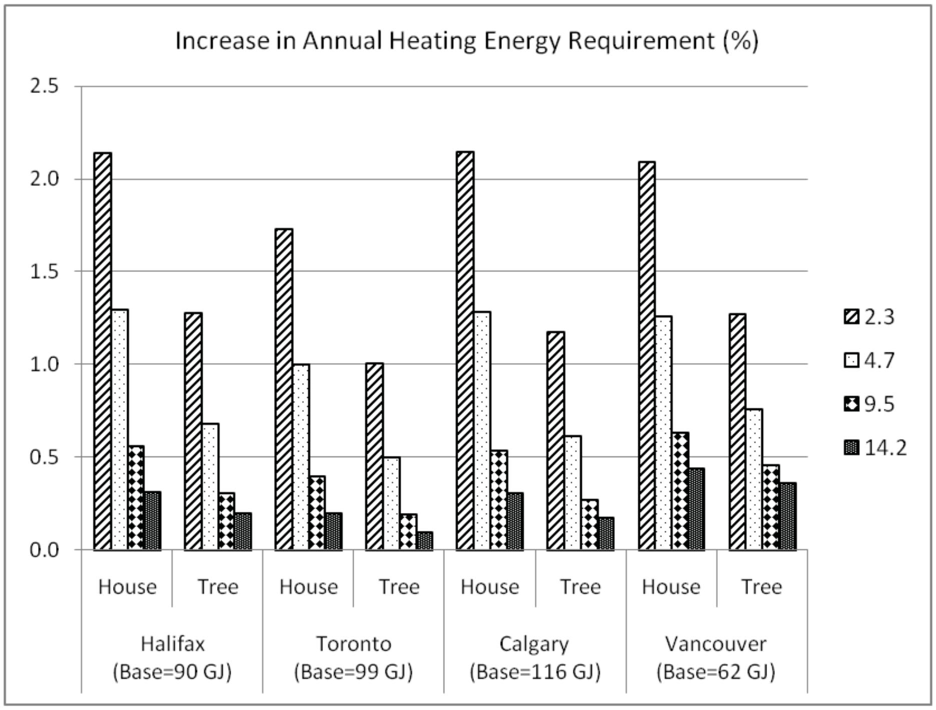


(b)

Figure B.5 Effect of the distance of southerly neighbouring structures on the heating and cooling energy requirements



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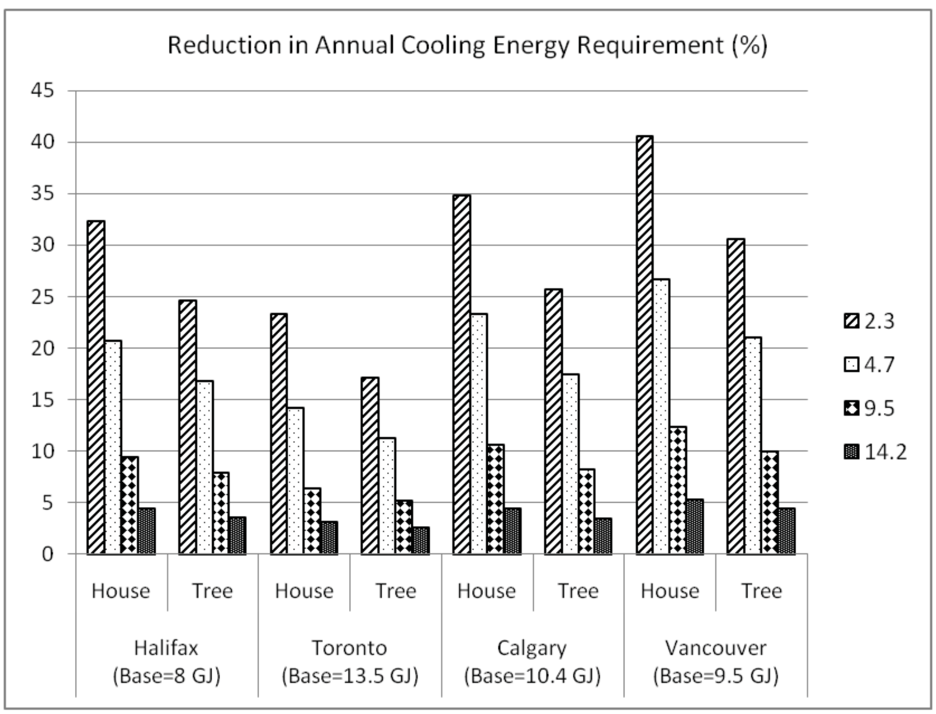
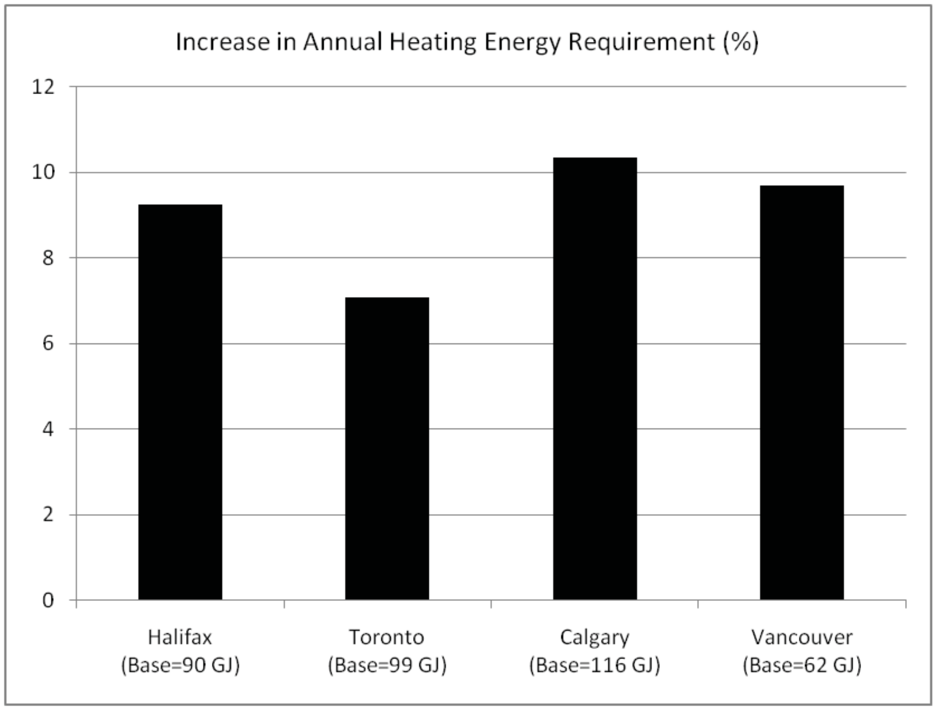


(b)

Figure B.6 Effect of the distance of westerly neighbouring structures on the heating and cooling energy requirements



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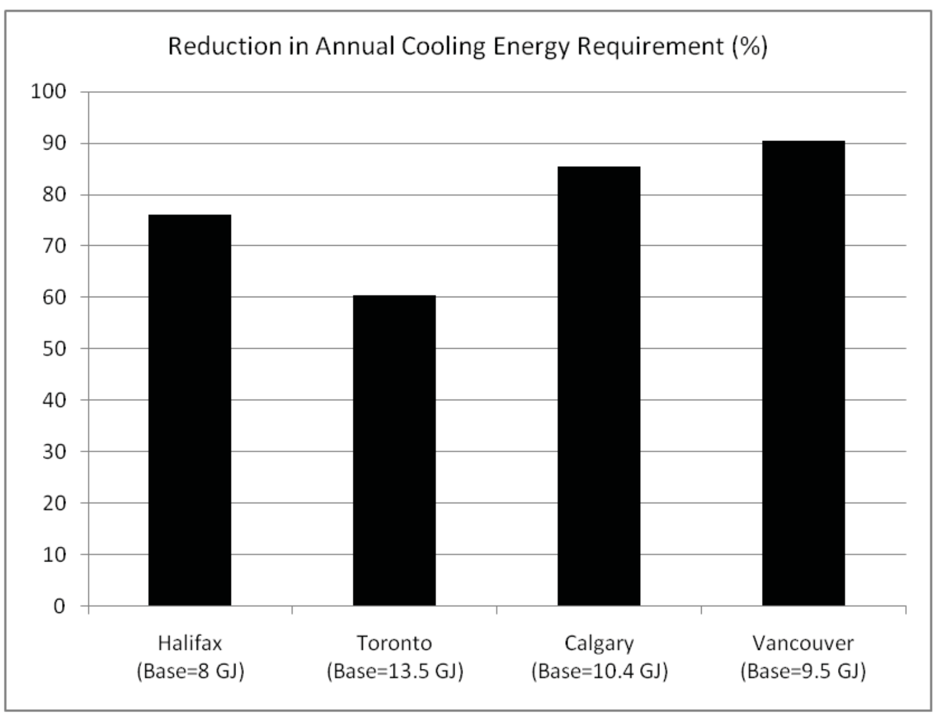


(b)

Figure B.7 Worst case results

APPENDIX C DETAILED ANALYSIS OF ANNUAL ENERGY SAVINGS AND GHG EMISSION REDUCTIONS DUE TO WINDOW UPGRADES

C.1 Upgrade to window type 2010

The breakdown of energy savings and GHG emission reductions due to upgrading all eligible windows to double-glazed clear glass windows with 13 mm Argon filled gap (type 2010) is shown in Table C.1 for each energy source, house type and province.

Table C.1 Estimates of annual energy consumption and GHG emission reductions due to window type 2010 upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	3,393	12,602	2,460	890	19,342	93	639	174	906
	DR	956	2,450	391	8	3,805	13	124	28	165
Province	NB	122	0	280	451	853	29	0	20	49
	NF	77	0	201	50	327	1	0	14	15
	NS	71	0	435	95	601	7	0	31	38
	PE	0	0	67	25	92	0	0	5	5
	QC	2,594	21	740	147	3,502	3	1	52	57
	OT	539	6,200	1,128	0	7,868	60	315	80	454
	AB	-3	2,218	0	0	2,215	-1	112	0	112
	MB	71	419	0	0	490	0	21	0	21
	SK	26	567	0	0	591	2	29	0	30
	BC	851	5,627	0	130	6,608	4	285	0	290
Canada		4,348	15,052	2,851	899	23,147	106	763	202	1,071

* Natural Gas

The distribution of energy and GHG emission reductions due to window type 2010 upgrade among provinces is shown in Figure C.1.

Figure C.2 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2010 upgrade.

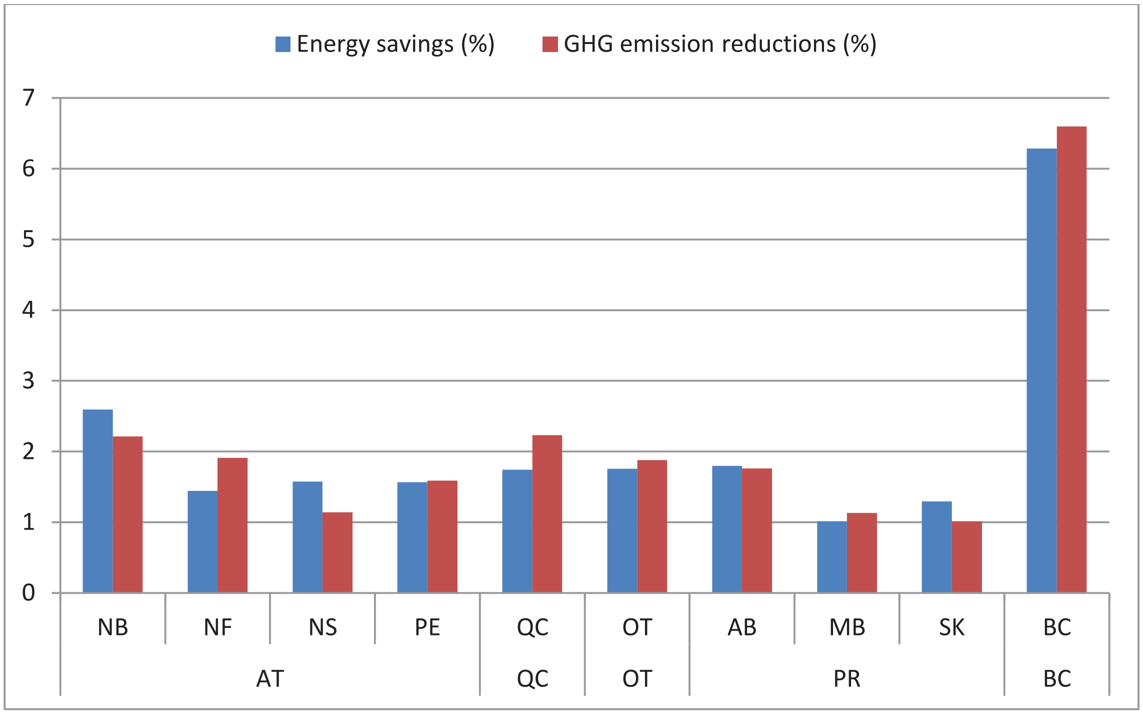


Figure C.1 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2010 upgrade

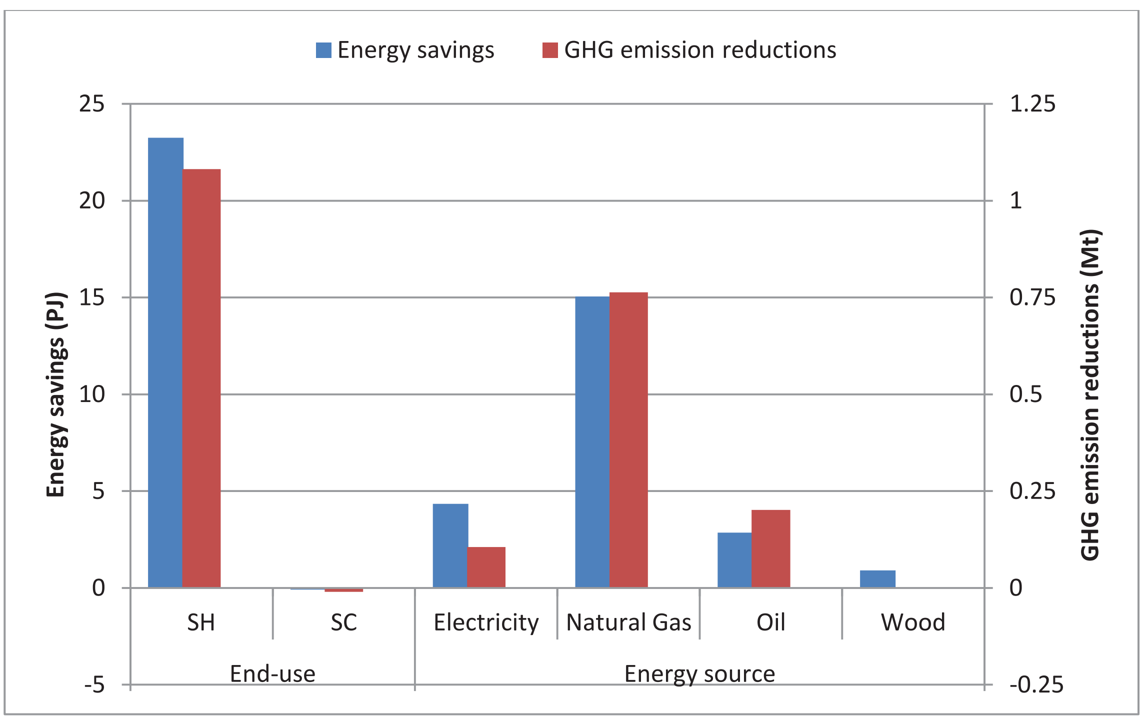


Figure C.2 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2010 upgrade

C.2 Upgrade to window type 2100

The breakdown of energy savings and GHG emission reductions due to upgrading all eligible windows to double-glazed windows, with low-e coating (0.04) and 13 mm air filled gap (type 2100) is shown in Table C.2 for each energy source, house type and province.

Table C.2 Estimates of annual energy consumption and GHG emissions reduction due to window type 2100 upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	8,063	22,892	4,726	1,506	37,186	366	1,161	335	1,862
	DR	2,074	4,317	685	12	7,087	57	219	48	325
Province	NB	230	0	472	635	1,336	54	0	33	88
	NF	231	0	420	118	769	2	0	30	31
	NS	157	1	866	196	1,218	16	0	61	78
	PE	1	0	142	51	193	0	0	10	10
	QC	5,366	52	1,460	333	7,211	8	3	103	114
	OT	2,526	12,827	2,053	0	17,405	327	651	145	1,123
	AB	15	4,420	0	0	4,435	3	224	0	228
	MB	182	788	0	0	970	0	40	0	40
	SK	82	1,088	0	0	1,169	5	55	0	61
	BC	1,347	8,035	0	187	9,569	7	407	0	414
Canada		10,137	27,209	5,411	1,518	44,273	423	1,380	383	2,186

* Natural Gas

The distribution of energy and GHG emission reductions due to window type 2100 upgrade among the provinces are shown in Figure C.3.

Figure C.4 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2100 upgrade.

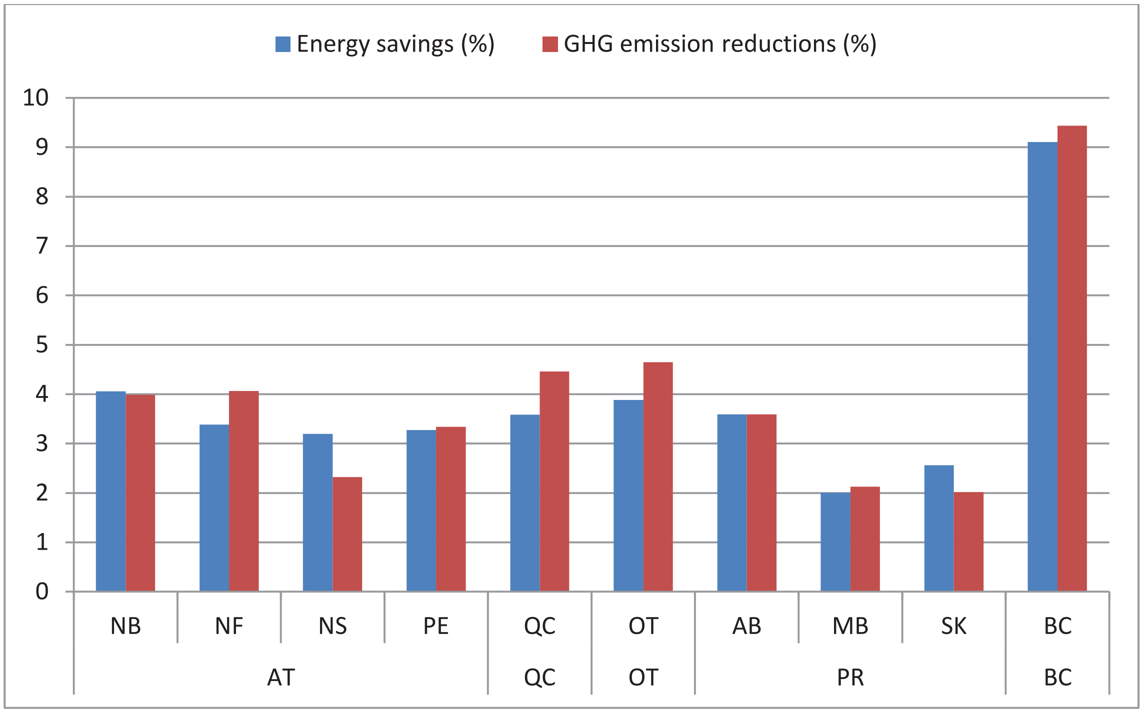


Figure C.3 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2100 upgrade

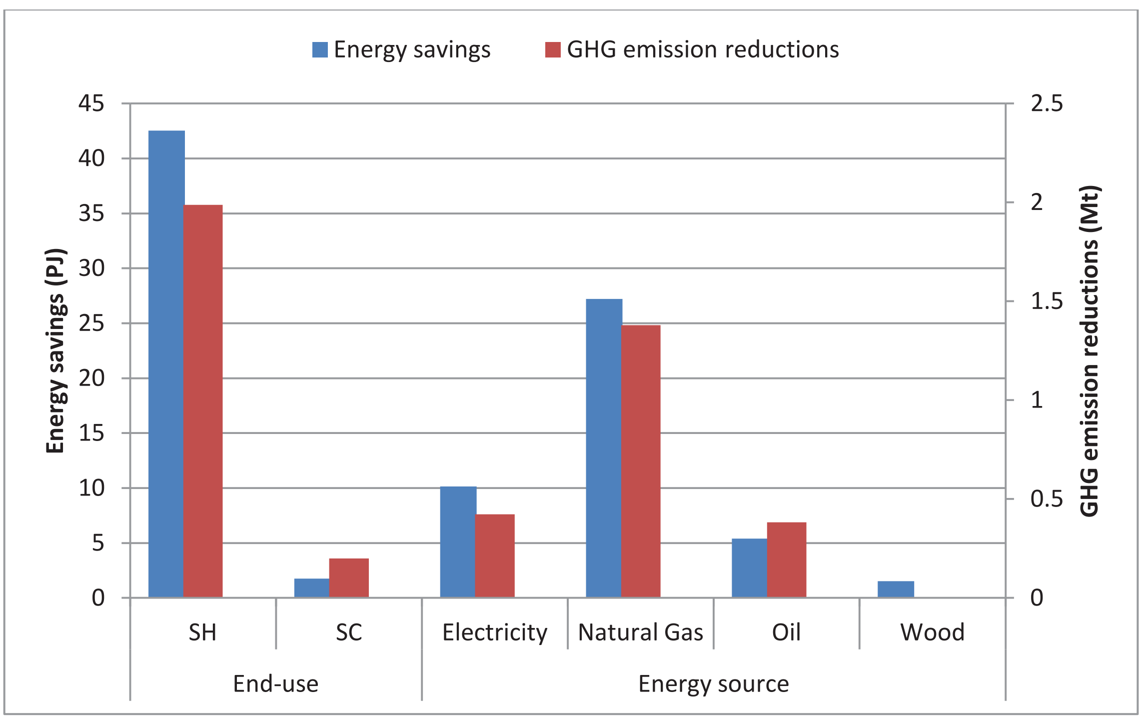


Figure C.4 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2100 upgrade

C.3 Upgrade to window type 2110

The breakdown of energy savings and GHG emission reductions due to upgrading all eligible windows to double-glazed windows, with low-e coating (0.04) and 13 mm Argon filled gap (type 2110) is shown in Table C.3 for each energy source, house type and province.

Table C.3 Estimates of annual energy consumption and GHG emission reductions due to window type 2110 upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	10,968	31,781	6,659	2,055	51,456	455	1,612	471	2,538
	DR	2,719	5,879	947	15	9,561	66	298	67	431
Province	NB	377	0	644	814	1,834	89	0	46	135
	NF	357	0	576	163	1,095	2	0	41	43
	NS	264	1	1,264	281	1,810	27	0	89	117
	PE	2	0	205	74	280	0	0	14	15
	QC	7,719	69	2,036	507	10,331	11	4	144	158
	OT	2,967	18,546	2,881	0	24,391	373	941	204	1,518
	AB	13	6,500	0	0	6,513	3	330	0	333
	MB	268	1,101	0	0	1,369	0	56	0	56
	SK	101	1,613	0	0	1,714	7	82	0	89
	BC	1,621	9,829	0	231	11,680	8	498	0	507
Canada		13,687	37,660	7,606	2,070	61,016	521	1,910	538	2,969

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 2110 upgrade among provinces are shown in Figure C.5.

Figure C.6 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 upgrade.

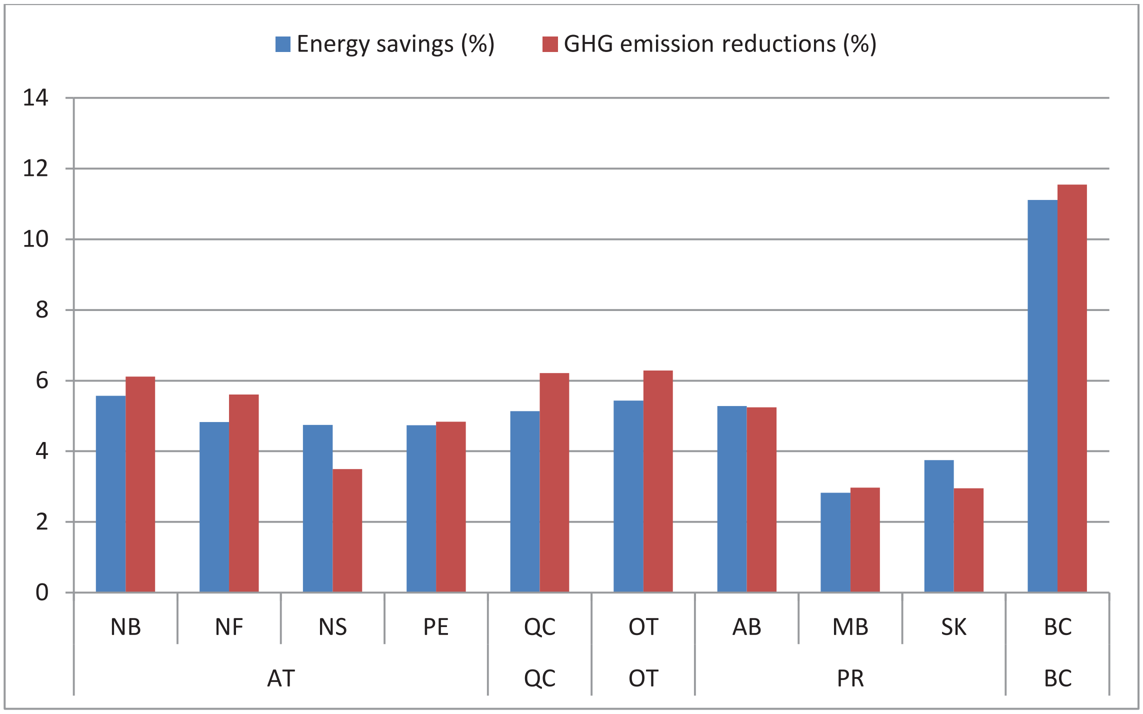


Figure C.5 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2110 upgrade

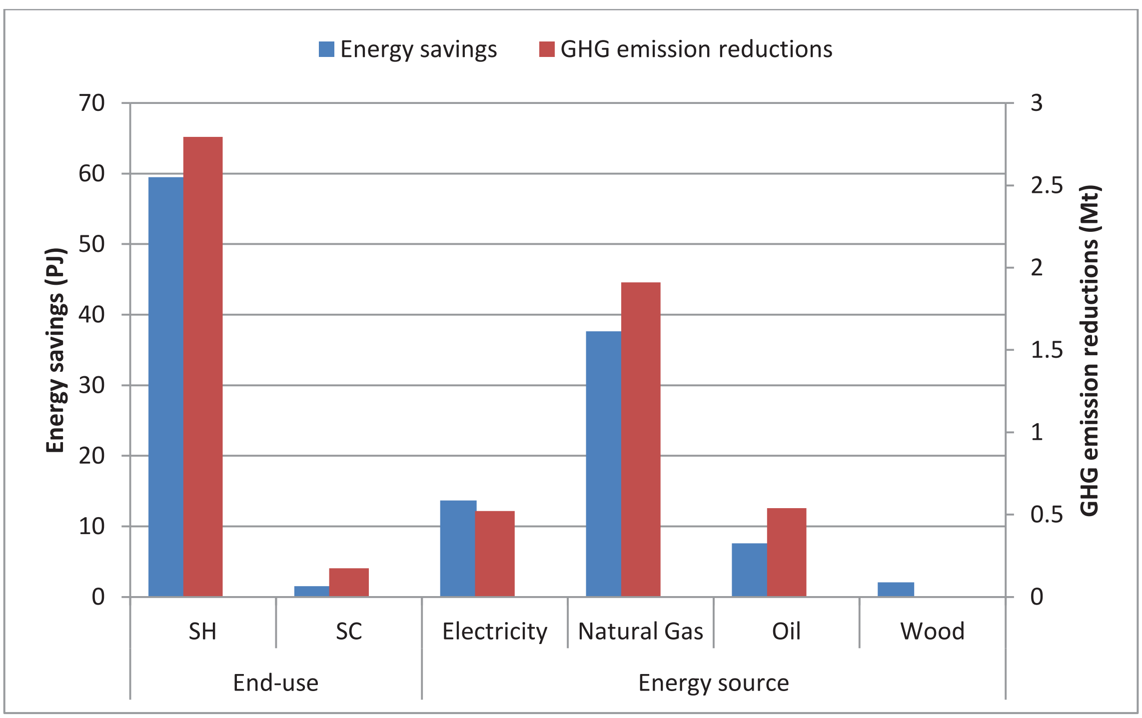


Figure C.6 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 upgrade

C.4 Upgrade to window type 3000

The breakdown of energy savings and GHG emission reductions due to upgrading windows to triple-glazed window, with clear glass and 13 mm Air filled gap (type 3000) energy source for the house types and provinces is shown in Table C.4.

Table C.4 Estimates of annual energy consumption and GHG emission reductions due to window type 3000 upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	8,669	27,041	5,628	1,826	43,163	329	1,372	398	2,099
	DR	2,304	5,259	856	13	8,432	48	267	61	375
Province	NB	325	0	593	733	1,651	77	0	593	119
	NF	289	0	473	135	898	2	0	473	35
	NS	218	0	1,069	250	1,537	23	0	1,069	98
	PE	4	0	172	73	249	0	0	172	12
	QC	6,426	62	1,682	441	8,612	9	3	1,682	131
	OT	2,077	15,789	2,496	0	20,362	254	801	2,496	1,231
	AB	7	5,581	0	0	5,587	1	283	0	285
	MB	206	839	0	0	1,046	0	43	0	43
	SK	63	1,380	0	0	1,442	4	70	0	74
	BC	1,359	8,648	0	207	10,214	7	439	0	446
Canada		10,973	32,300	6,484	1,838	51,596	377	1,638	459	2,474

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 3000 upgrade among provinces of Canada are shown in Figure C.7.

Figure C.8 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3000 upgrade.

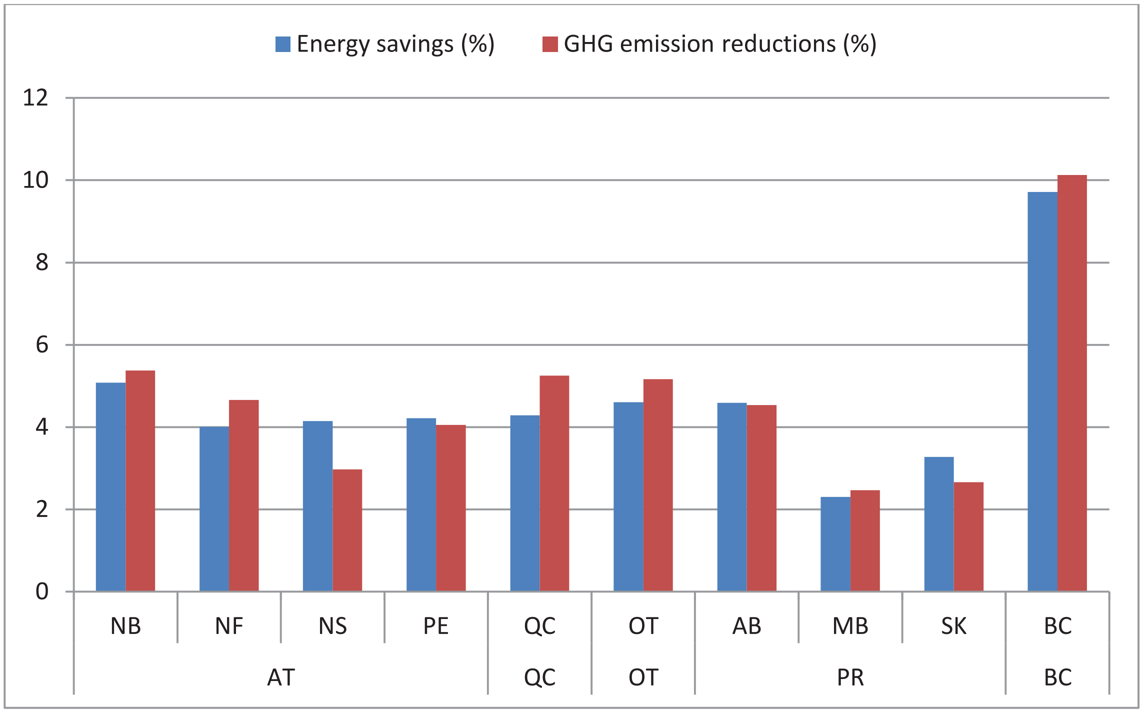


Figure C.7 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 3000 upgrade

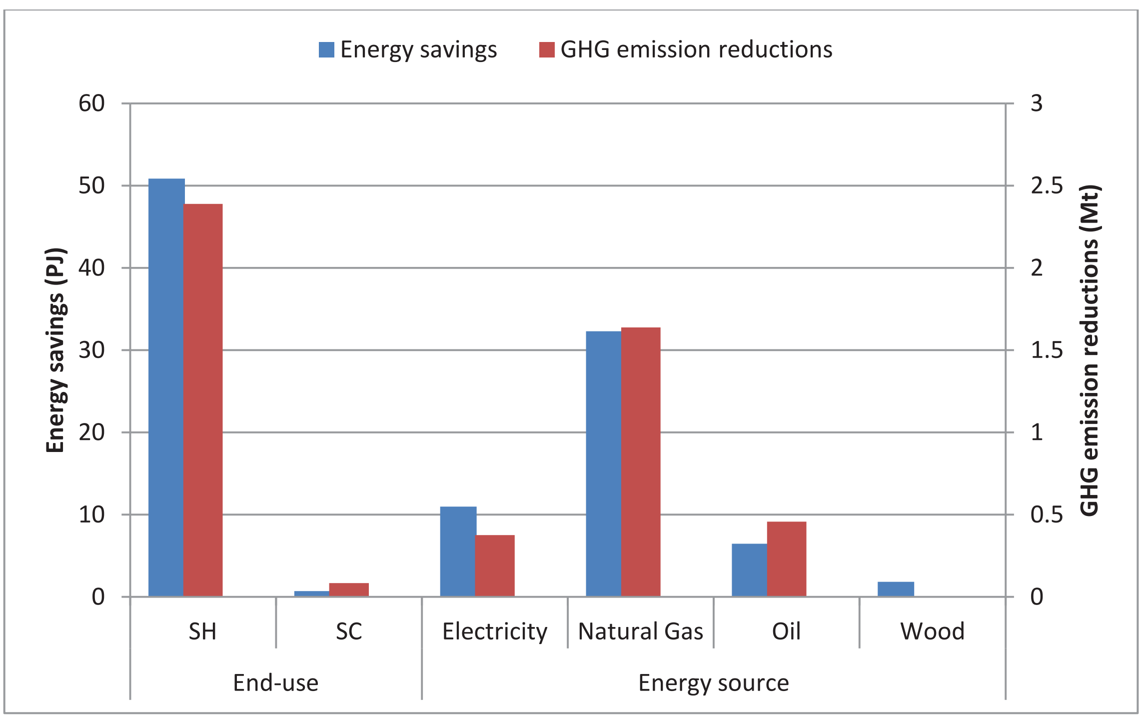


Figure C.8 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3000 upgrade

C.5 Upgrade to window type 3200

The breakdown of energy savings and GHG emission reductions due to upgrading windows to triple-glazed window, with low-e coating (0.10) and 13 mm Air filled gap (type 3200) energy source for the house types and provinces is shown in Table C.5.

Table C.5 Estimates of annual energy consumption and GHG emission reductions due to window type 3200 upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	10,067	28,498	5,973	1,896	46,438	425	1,445	423	2,294
	DR	2,497	5,438	878	13	8,826	61	276	62	399
Province	NB	350	0	614	754	1,718	83	0	43	126
	NF	332	0	522	145	1,000	2	0	37	39
	NS	239	1	1,136	261	1,636	25	0	80	105
	PE	4	0	180	72	256	0	0	13	13
	QC	7,017	75	1,802	460	9,354	10	4	128	142
	OT	2,765	16,505	2,597	0	21,869	349	837	184	1,370
	AB	16	5,776	0	0	5,792	4	293	0	297
	MB	227	873	0	0	1,099	0	44	0	44
	SK	92	1,427	0	0	1,519	6	72	0	79
	BC	1,524	9,281	0	218	11,022	8	471	0	479
Canada		12,564	33,937	6,851	1,909	55,264	487	1,721	485	2,693

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 3200 upgrade among provinces of Canada are shown in Figure C.9.

Figure C.10 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3200 upgrade.

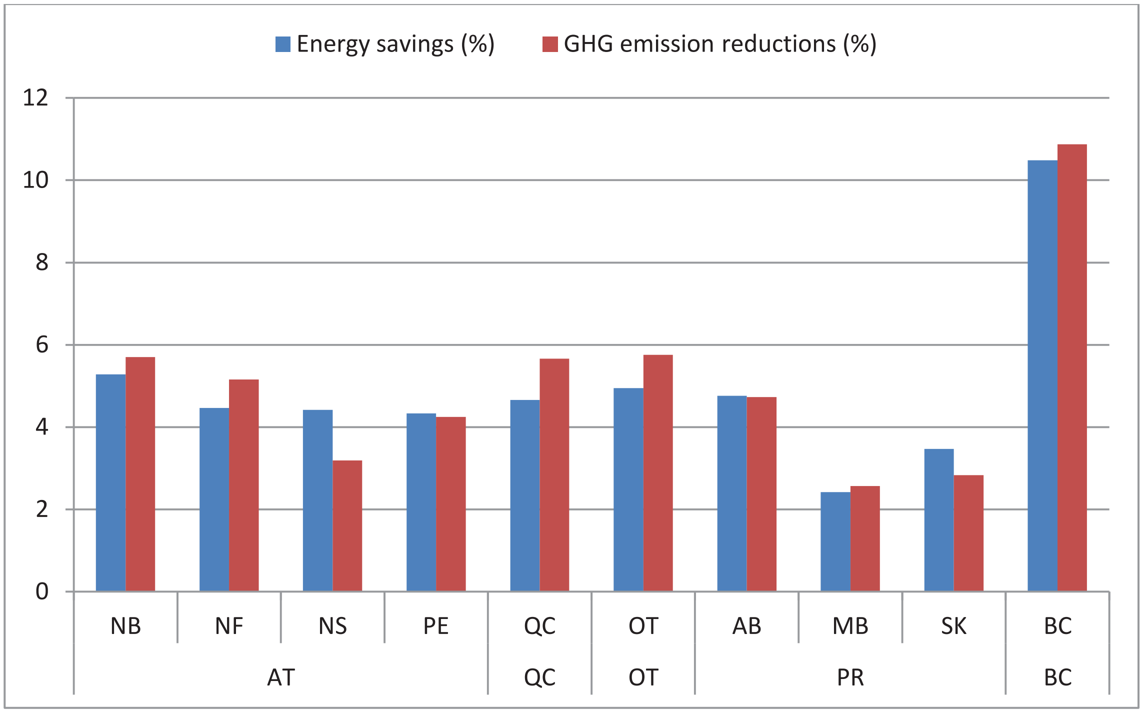


Figure C.9 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 3200 upgrade

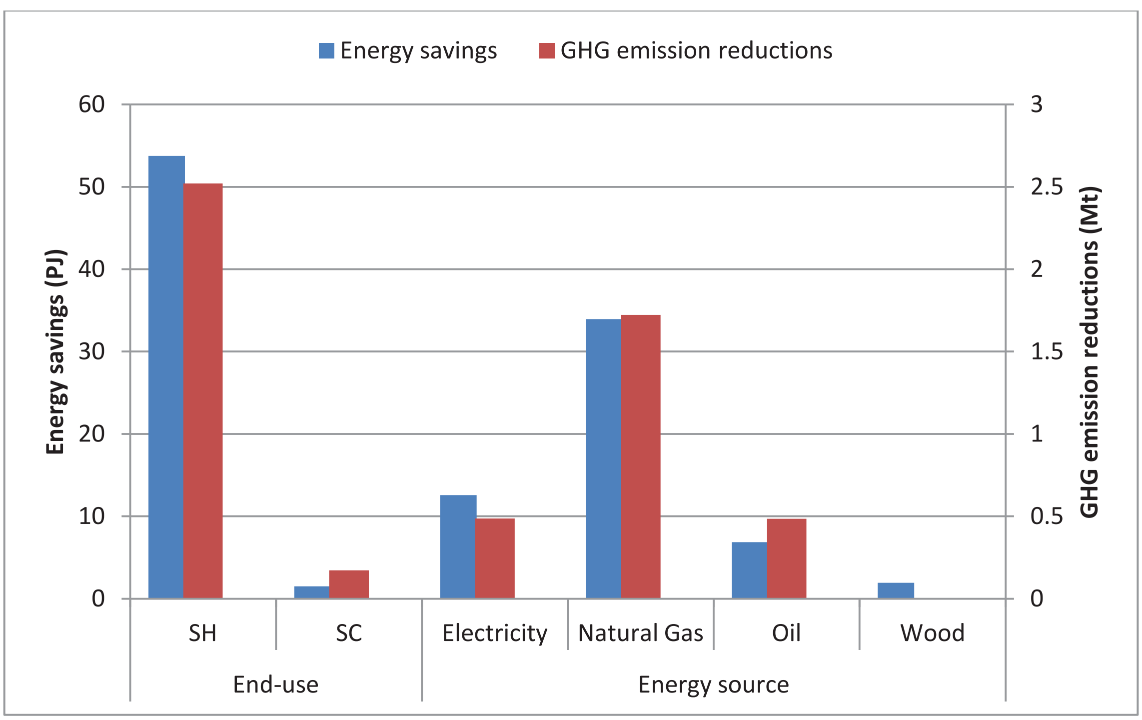


Figure C.10 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3200 upgrade

C.6 Upgrade to window type 2110 and window/wall area ratio of 30%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to double-glazed windows, with low-e coating (0.04) and 13 mm Argon filled gap (type 2110) and increasing the window/wall area ration to 30% is shown in Table C.6 for each energy source, house type and province.

Table C.6 Estimates of annual energy consumption and GHG emission reductions due to window type 2110 and window/wall area ratio of 30% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	1,265	8,870	1,808	581	12,523	136	450	128	714
	DR	876	1,830	346	2	3,054	15	93	24	132
Province	NB	133	0	258	283	673	31	0	18	50
	NF	173	0	238	60	471	1	0	17	18
	NS	91	0	455	106	651	9	0	32	42
	PE	1	0	71	28	99	0	0	5	5
	QC	663	5	283	67	1,018	0	0	20	21
	OT	845	6,439	849	0	8,132	106	327	60	493
	AB	1	2,091	0	0	2,093	0	106	0	106
	MB	88	402	0	0	490	0	20	0	20
	SK	24	613	0	0	638	2	31	0	33
	BC	124	1,150	0	39	1,312	1	58	0	59
Canada		2,141	10,700	2,154	583	15,577	151	543	152	846

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 2110 and window/wall area ration of 30% upgrade among provinces of Canada are shown in Figure C.11.

Figure C.12 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ration of 30% upgrade.

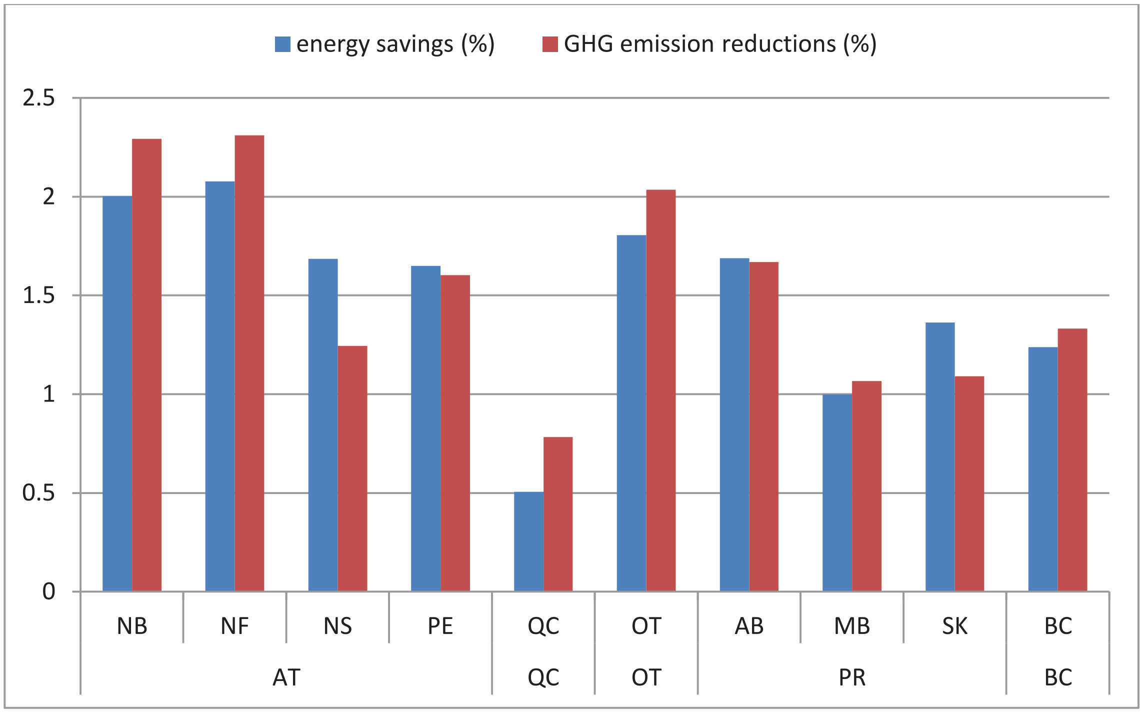


Figure C.11 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2110 and window/wall area ratio of 30% upgrade

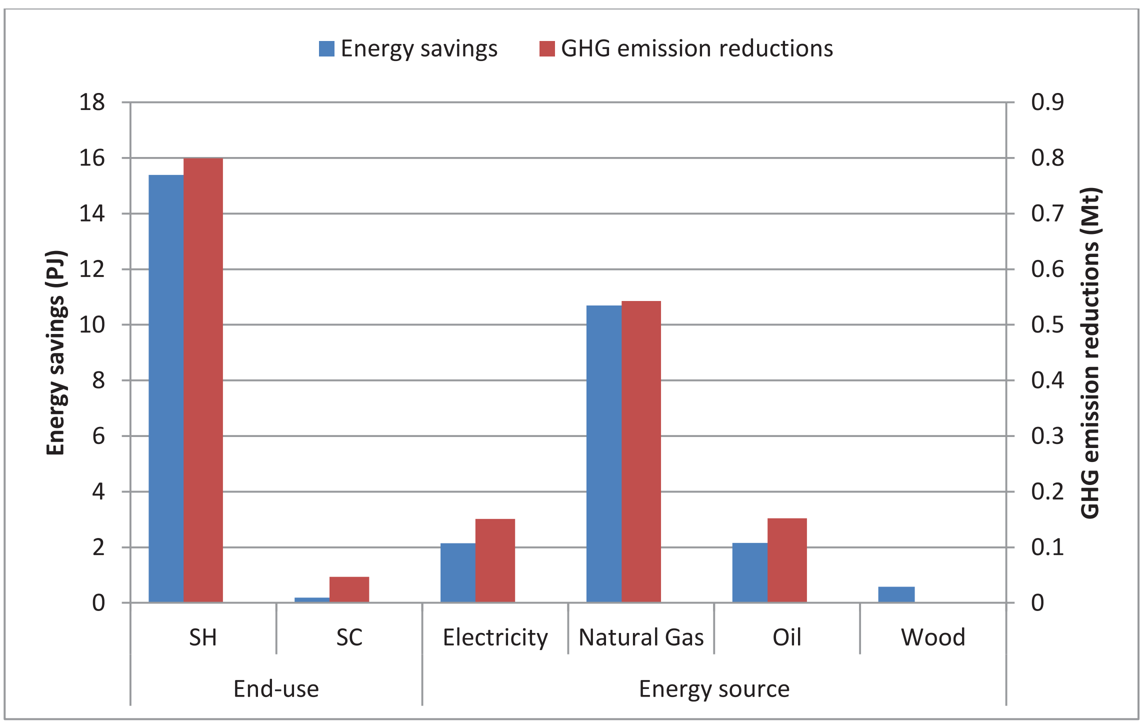


Figure C.12 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ratio of 30% upgrade

C.7 Upgrade to window type 2110 and window/wall area ratio of 40%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to double-glazed windows, with low-e coating (0.04) and 13 mm Argon filled gap (type 2110) and increasing the window/wall area ration to 40% is shown in Table C.7 for each energy source, house type and province.

Table C.7 Estimates of annual energy consumption and GHG emission reductions due to window type 2110 and window/wall area ratio of 40% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	545	8,892	1,896	623	11,958	71	451	134	656
	DR	722	1,812	366	1	2,901	3	92	26	121
Province	NB	142	0	296	318	756	34	0	21	54
	NF	164	0	249	60	473	1	0	18	19
	NS	95	-1	506	119	719	10	0	36	46
	PE	1	0	75	31	106	0	0	5	5
	QC	388	9	271	59	727	0	0	19	19
	OT	309	6,479	865	0	7,656	31	329	61	421
	AB	-5	2,116	0	0	2,111	-1	107	0	106
	MB	83	414	0	0	496	0	21	0	21
	SK	7	616	0	0	623	1	31	0	32
	BC	83	1,071	0	38	1,192	0	54	0	55
Canada		1,267	10,704	2,262	624	14,859	75	543	160	778

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 2110 and window/wall area ration of 40% upgrade among provinces of Canada are shown in Figure C.13.

Figure C.14 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ration of 40% upgrade.

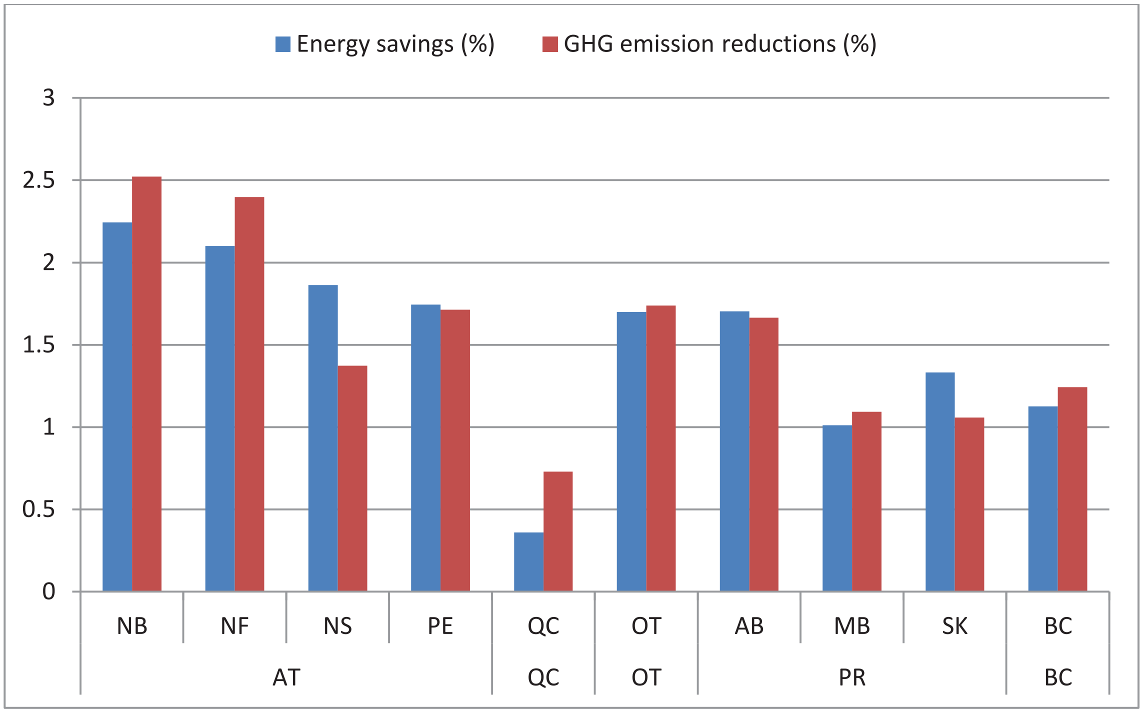


Figure C.13 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2110 and window/wall area ratio of 40% upgrade

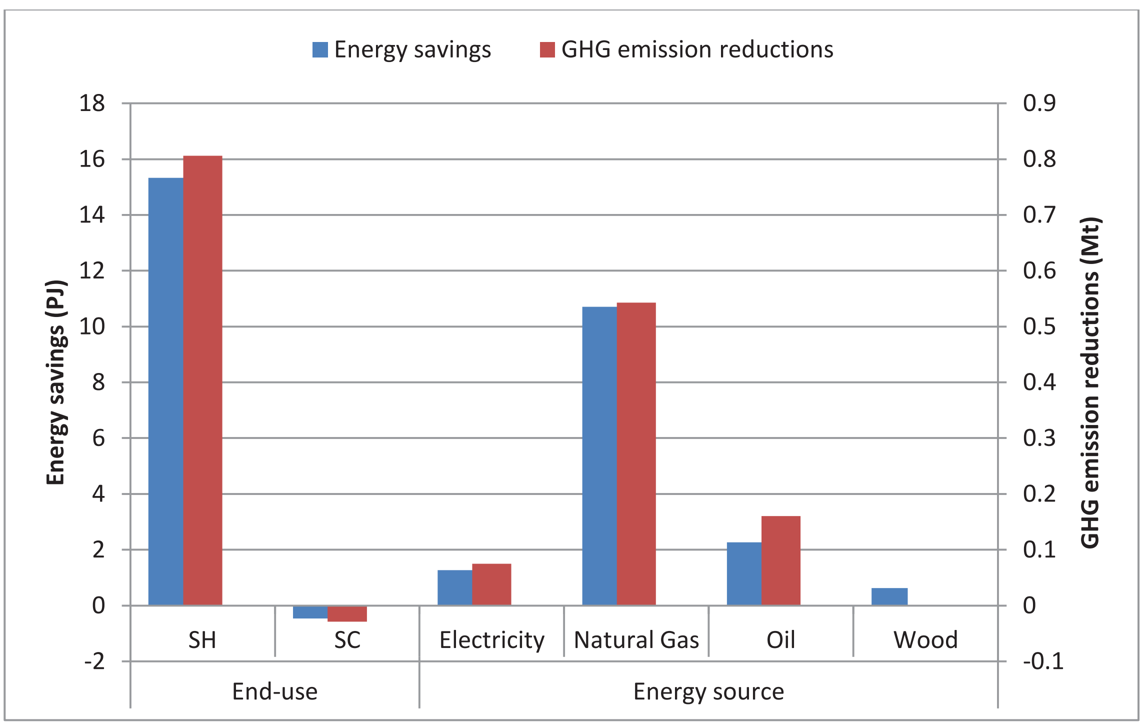


Figure C.14 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ratio of 40% upgrade

C.8 Upgrade to window type 2110 and window/wall area ratio of 50%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to double-glazed windows, with low-e coating (0.04) and 13 mm Argon filled gap (type 2110) and increasing the window/wall area ration to 50% is shown in Table C.8 for each energy source, house type and province.

Table C.8 Estimates of annual energy consumption and GHG emission reductions due to window type 2110 and window/wall area ratio of 50% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	-232	8,747	1,956	656	11,126	2	444	138	585
	DR	555	1,758	381	0	2,692	-9	89	27	107
Province	NB	146	0	335	346	826	34	0	24	58
	NF	152	0	255	65	471	1	0	18	19
	NS	97	-1	546	130	772	10	0	39	49
	PE	1	0	79	32	111	0	0	6	6
	QC	81	1	251	48	381	-1	0	18	17
	OT	-244	6,411	871	0	7,038	-48	325	62	339
	AB	-12	2,101	0	0	2,089	-3	107	0	104
	MB	76	418	0	0	495	0	21	0	21
	SK	-10	607	0	0	596	-1	31	0	30
	BC	36	969	0	35	1,039	0	49	0	49
Canada		323	10,505	2,337	656	13,818	-6	533	165	692

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 2110 and window/wall area ration of 50% upgrade among provinces of Canada are shown in Figure C.15.

Figure C.16 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ration of 50% upgrade.

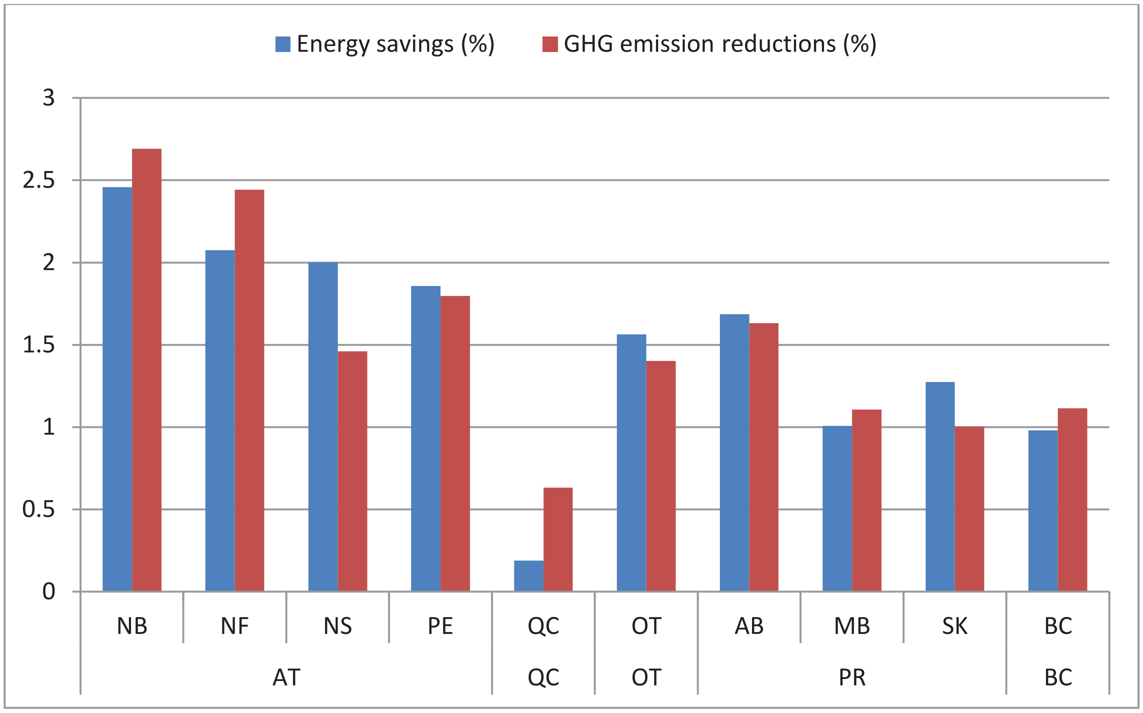


Figure C.15 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2110 and window/wall area ratio of 50% upgrade

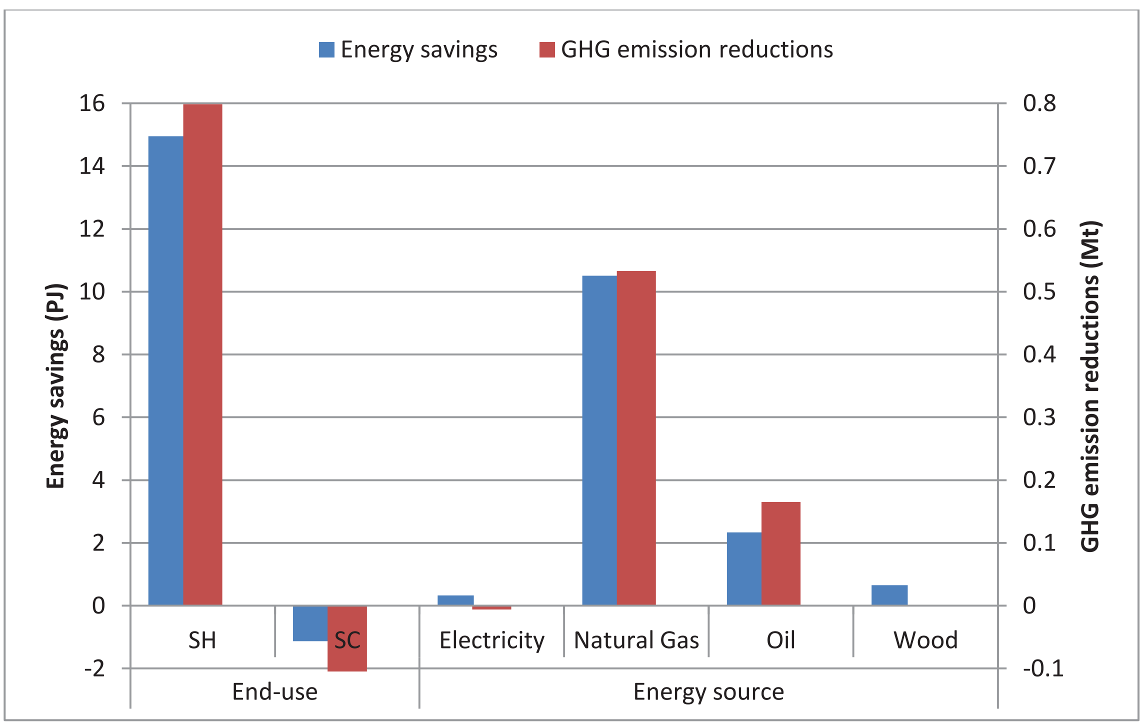


Figure C.16 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ratio of 50% upgrade

C.9 Upgrade to window type 2110 and window/wall area ratio of 60%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to double-glazed windows, with low-e coating (0.04) and 13 mm Argon filled gap (type 2110) and increasing the window/wall area ration to 60% is shown in Table C.9 for each energy source, house type and province.

Table C.9 Estimates of annual energy consumption and GHG emission reductions due to window type 2110 and window/wall area ratio of 60% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	1,064	8,444	1,993	682	10,055	-69	428	141	500
	DR	369	1,674	392	-1	2,433	-21	85	28	91
Province	NB	151	0	368	373	891	36	0	26	62
	NF	138	0	260	67	465	1	0	18	19
	NS	99	-1	583	141	821	10	0	41	52
	PE	1	0	82	34	116	0	0	6	6
	QC	-265	-4	223	35	-10	-2	0	16	14
	OT	-824	6,244	869	0	6,290	-129	317	62	249
	AB	-18	2,043	0	0	2,024	-4	104	0	99
	MB	68	418	0	0	486	0	21	0	21
	SK	-29	587	0	0	557	-2	30	0	28
	BC	-14	831	0	32	849	0	42	0	42
Canada		-695	10,118	2,385	681	12,488	-90	513	169	591

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 2110 and window/wall area ration of 60% upgrade among provinces of Canada are shown in Figure C.17.

Figure C.18 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ration of 60% upgrade.

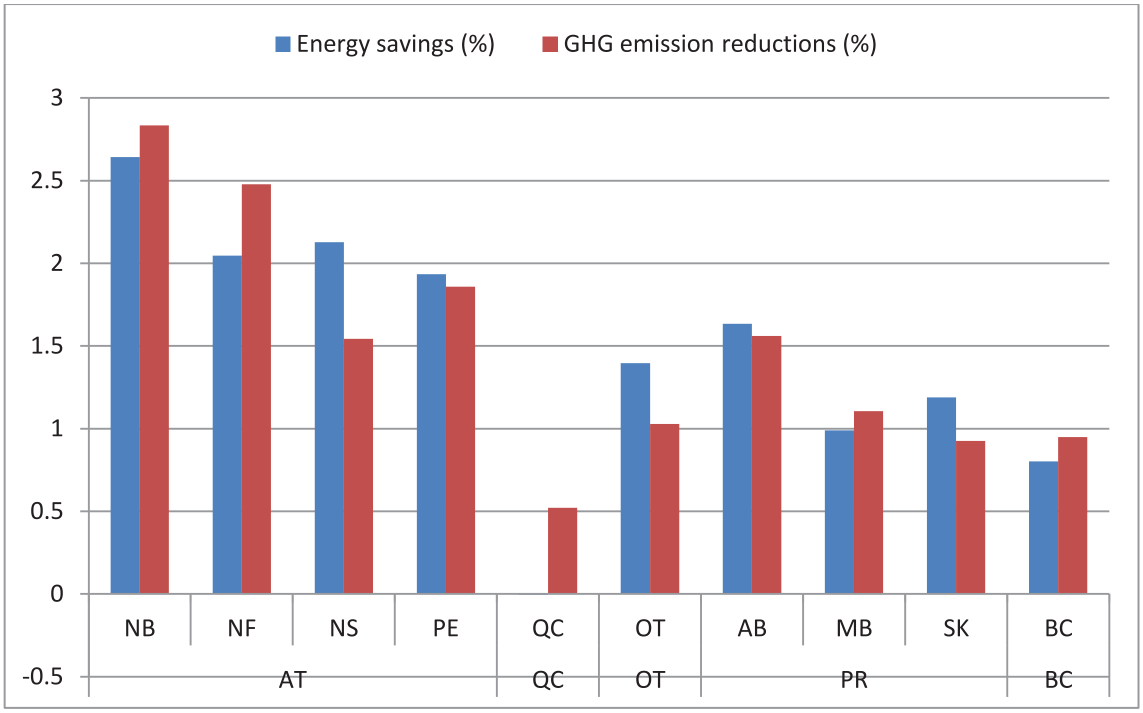


Figure C.17 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 2110 and window/wall area ratio of 60% upgrade

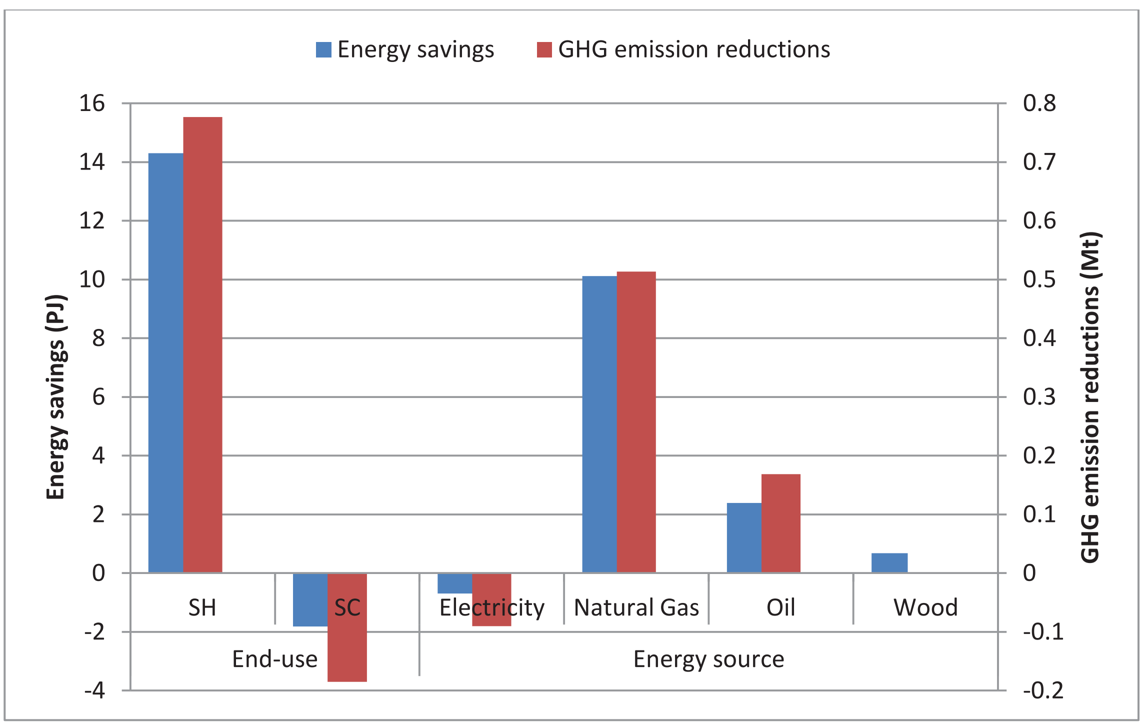


Figure C.18 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 2110 and window/wall area ratio of 60% upgrade

C.10 Upgrade to window type 3210 and window/wall area ratio of 30%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to triple-glazed windows, with low-e coating (0.1) and 13 mm Argon filled gap (type 3210) and increasing the window/wall area ration to 30% is shown in Table C.10 for each energy source, house type and province.

Table C.10 Estimates of annual energy consumption and GHG emission reductions due to window type 3210 and window/wall area ratio of 30% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	1,955	11,320	2,267	710	16,253	169	574	160	903
	DR	1,094	2,267	426	3	3,790	19	115	30	164
Province	NB	163	0	300	321	784	39	0	21	60
	NF	205	0	265	69	539	1	0	19	20
	NS	114	0	543	127	784	12	0	38	50
	PE	2	0	93	35	130	0	0	7	7
	QC	1,170	9	419	116	1,713	1	0	30	31
	OT	1,057	7,962	1,074	0	10,094	132	404	76	612
	AB	2	2,758	0	0	2,760	0	140	0	140
	MB	162	630	0	0	791	0	32	0	32
	SK	22	865	0	0	886	1	44	0	45
	BC	154	1,364	0	45	1,562	1	69	0	70
Canada		3,049	13,586	2,693	713	20,042	187	689	191	1,067

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 3210 and window/wall area ration of 30% upgrade among provinces of Canada are shown in Figure C.19.

Figure C.20 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ration of 30% upgrade.

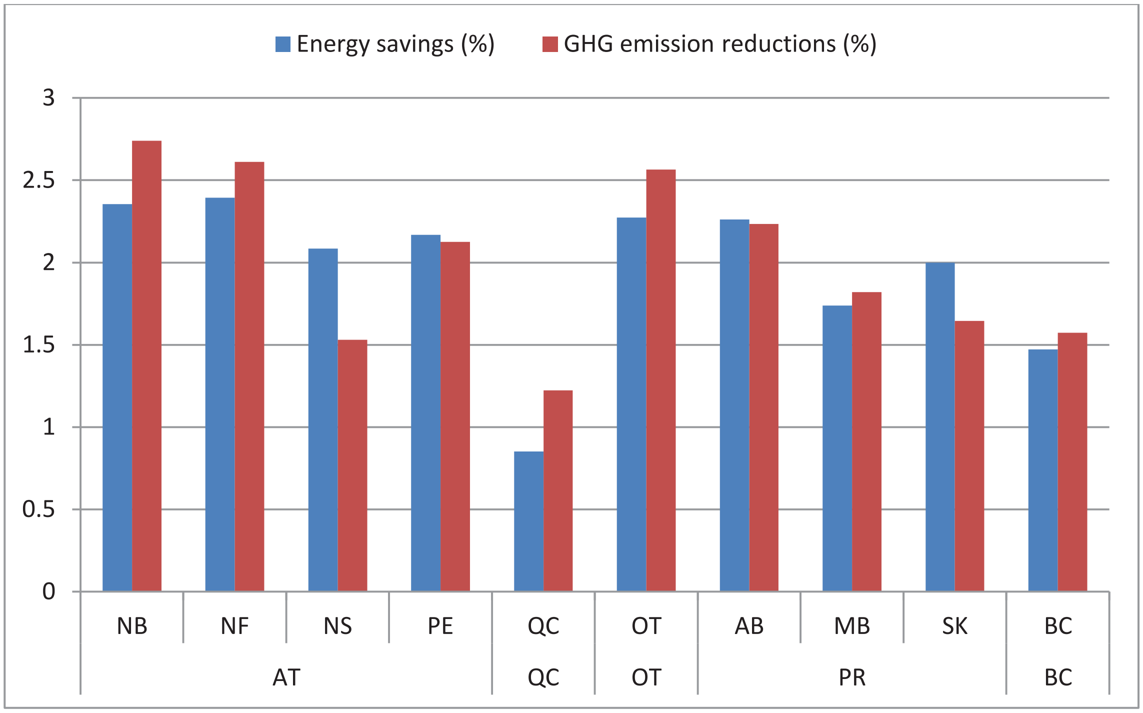


Figure C.19 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 3210 and window/wall area ratio of 30% upgrade

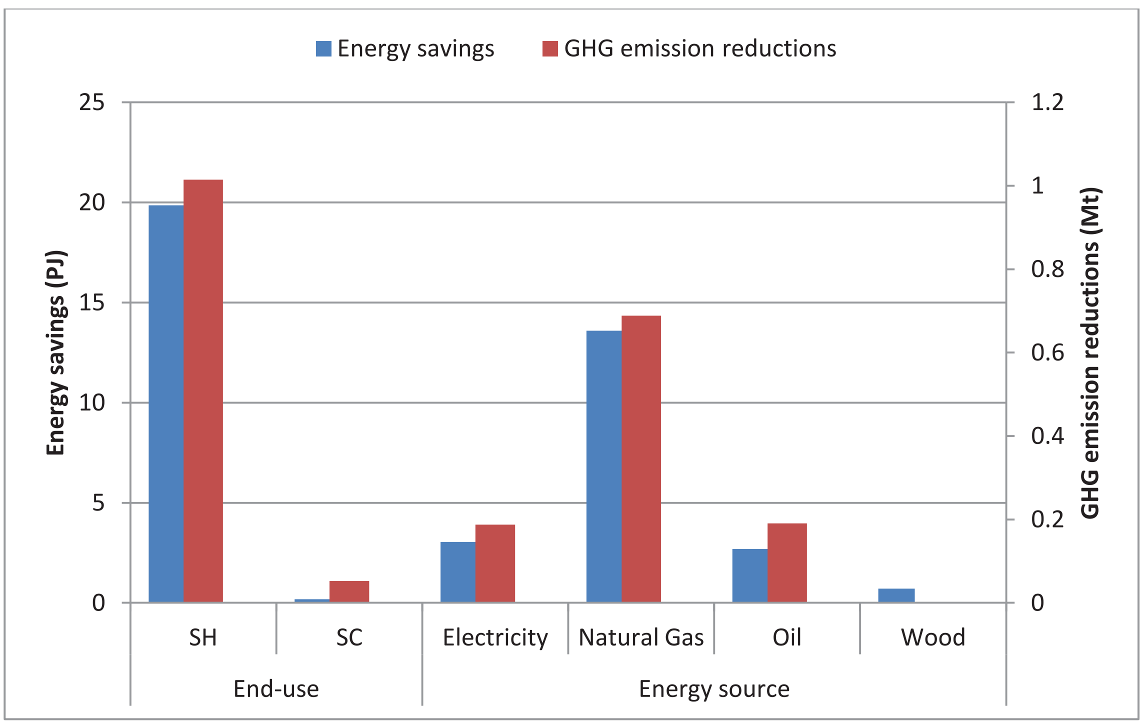


Figure C.20 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ratio of 30% upgrade

C.11 Upgrade to window type 3210 and window/wall area ratio of 40%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to triple-glazed windows, with low-e coating (0.1) and 13 mm Argon filled gap (type 3210) and increasing the window/wall area ration to 40% is shown in Table C.11 for each energy source, house type and province.

Table C.11 Estimates of annual energy consumption and GHG emission reductions due to window type 3210 and window/wall area ratio of 40% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	1,274	11,876	2,473	791	16,414	96	602	175	874
	DR	970	2,355	473	2	3,800	7	119	33	160
Province	NB	181	0	358	367	906	43	0	25	68
	NF	200	0	289	75	563	1	0	20	22
	NS	127	0	617	145	888	13	0	44	57
	PE	2	0	102	40	143	0	0	7	7
	QC	1,004	13	440	121	1,579	0	0	31	32
	OT	462	8,350	1,142	0	9,955	47	424	81	551
	AB	-7	2,933	0	0	2,926	-2	149	0	147
	MB	165	685	0	0	851	0	35	0	35
	SK	-9	908	0	0	899	-1	46	0	46
	BC	119	1,343	0	44	1,505	1	68	0	69
Canada		2,243	14,231	2,946	793	20,214	103	722	209	1,033

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 3210 and window/wall area ration of 40% upgrade among provinces of Canada are shown in Figure C.21.

Figure C.22 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ration of 40% upgrade.

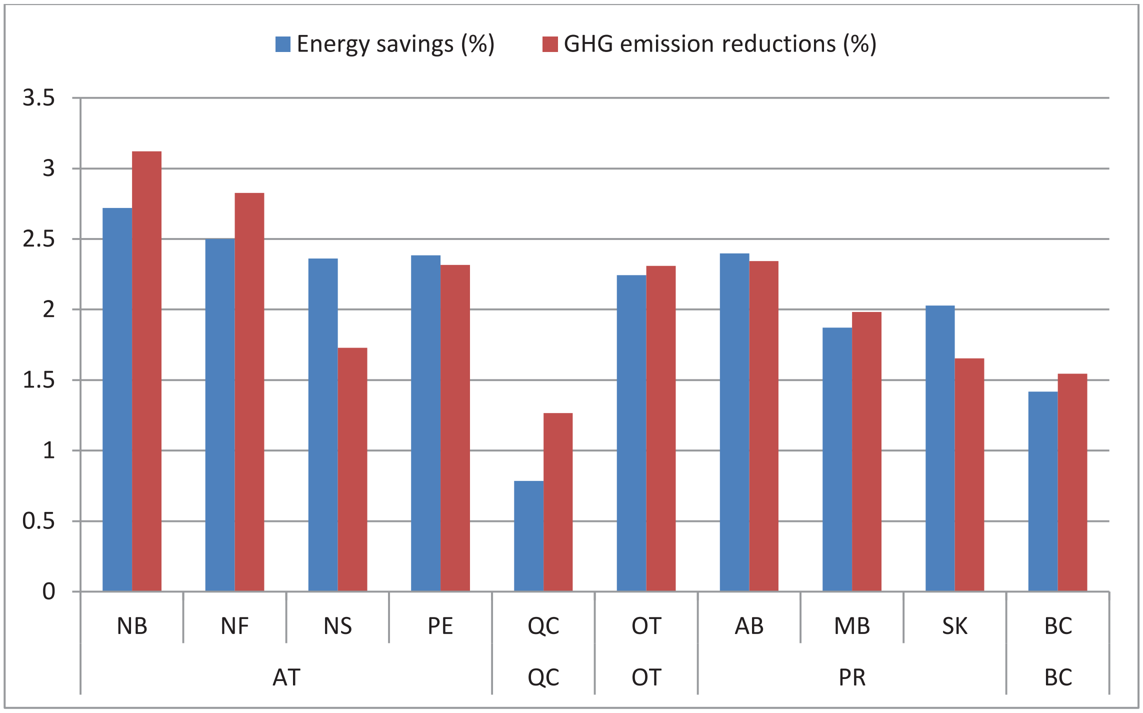


Figure C.21 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 3210 and window/wall area ratio of 40% upgrade

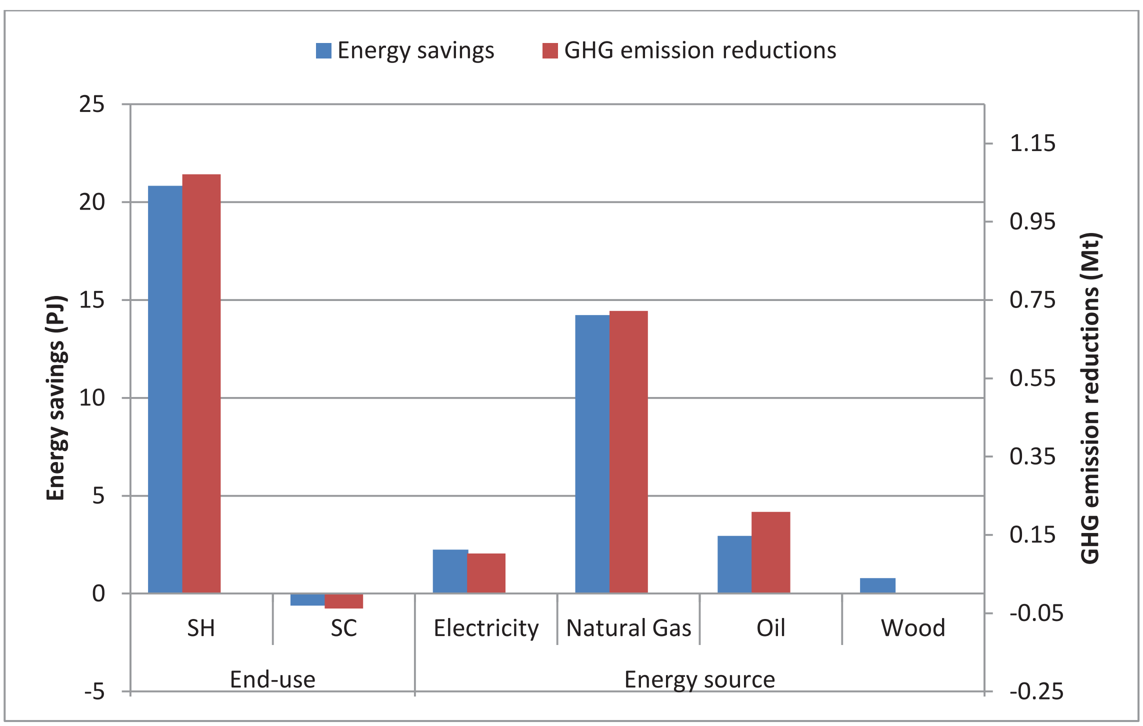


Figure C.22 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ratio of 40% upgrade

C.12 Upgrade to window type 3210 and window/wall area ratio of 50%

The breakdown of energy savings and GHG emission reductions due to upgrading south side window of all eligible houses to triple-glazed windows, with low-e coating (0.1) and 13 mm Argon filled gap (type 3210) and increasing the window/wall area ration to 50% is shown in Table C.12 for each energy source, house type and province.

Table C.12 Estimates of annual energy consumption and GHG emission reductions due to window type 3210 and window/wall area ratio of 50% upgrade

House type or province		Energy savings (TJ)					GHG emission reductions (kt of CO_2 equivalent)			
		Electricity	NG*	Oil	Wood	Total	Electricity	NG	Oil	Total
House type	SD	524	12,253	2,655	851	16,281	20	621	188	829
	DR	831	2,400	513	1	3,744	-6	122	36	152
Province	NB	195	0	410	409	1,015	46	0	29	75
	NF	194	0	308	80	582	1	0	22	23
	NS	138	-1	684	152	974	14	0	48	63
	PE	2	0	108	44	154	0	0	8	8
	QC	799	11	453	122	1,384	0	0	32	32
	OT	-157	8,626	1,206	0	9,675	-42	438	85	481
	AB	-15	3,051	0	0	3,036	-3	155	0	151
	MB	165	731	0	0	896	0	37	0	37
	SK	-42	937	0	0	894	-3	48	0	45
	BC	75	1,297	0	44	1,416	0	66	0	66
Canada		1,354	14,653	3,168	851	20,025	14	743	224	981

* Natural Gas

The distribution of energy savings and GHG emission reductions due to window type 3210 and window/wall area ration of 50% upgrade among provinces of Canada are shown in Figure C.23.

Figure C.24 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ration of 50% upgrade.

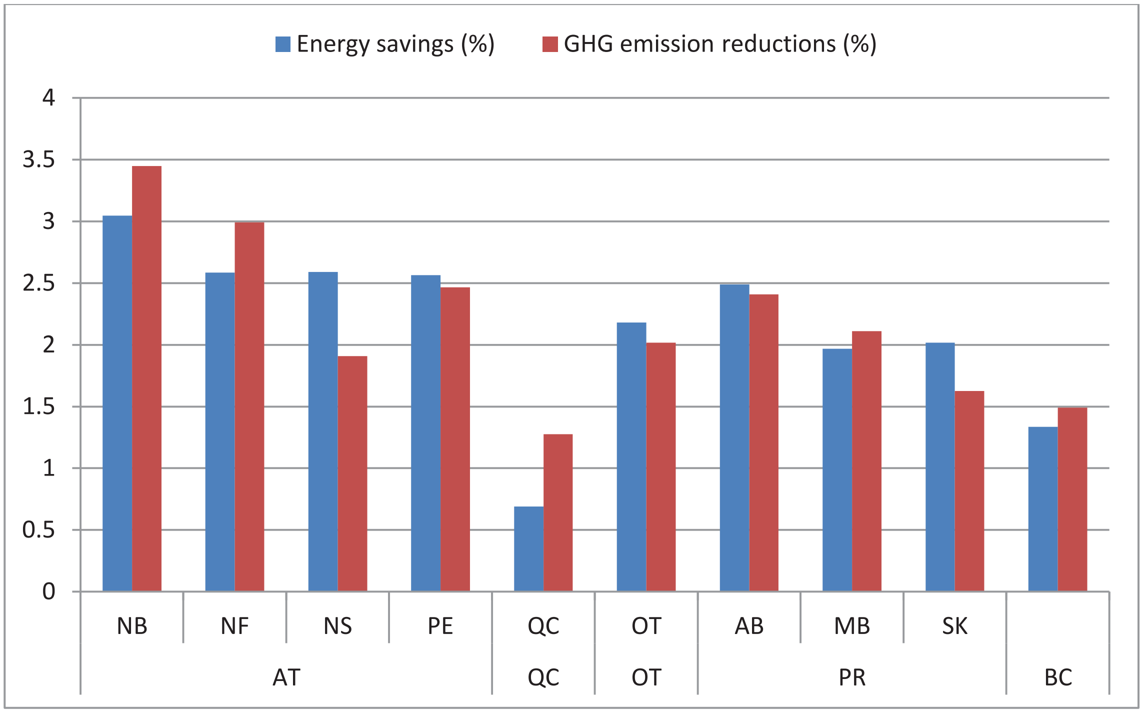


Figure C.23 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to window type 3210 and window/wall area ratio of 50% upgrade

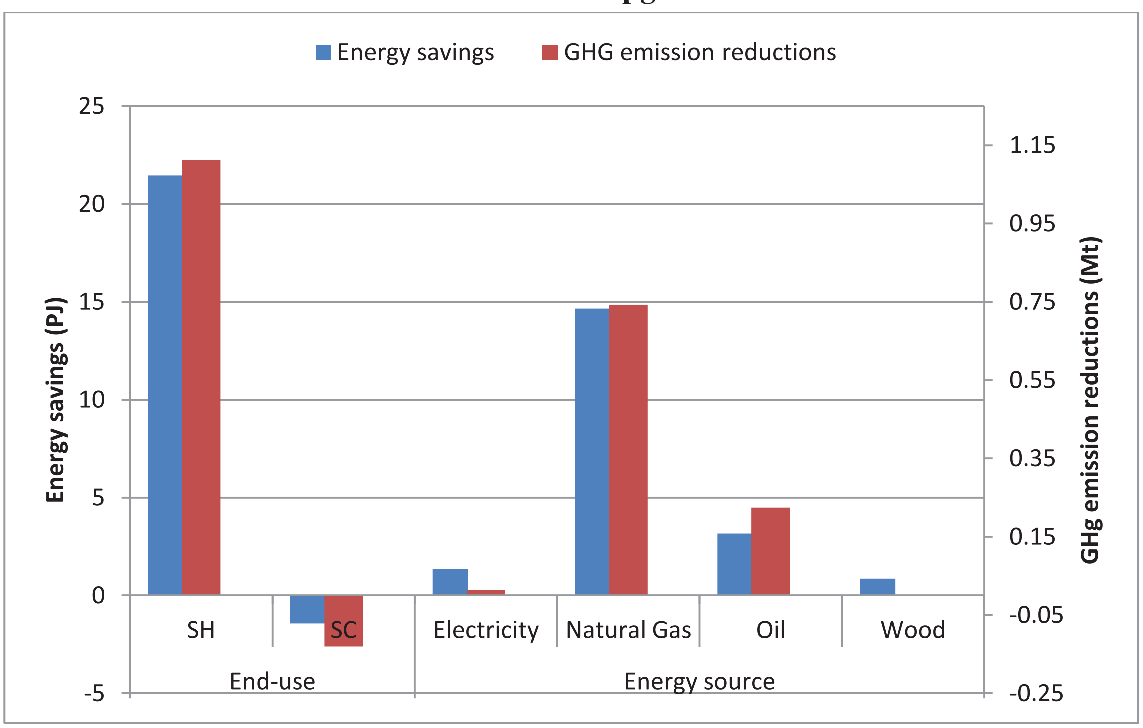
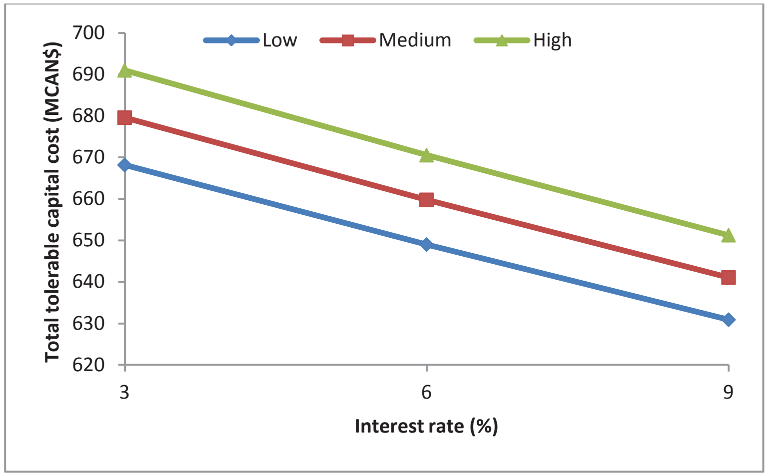


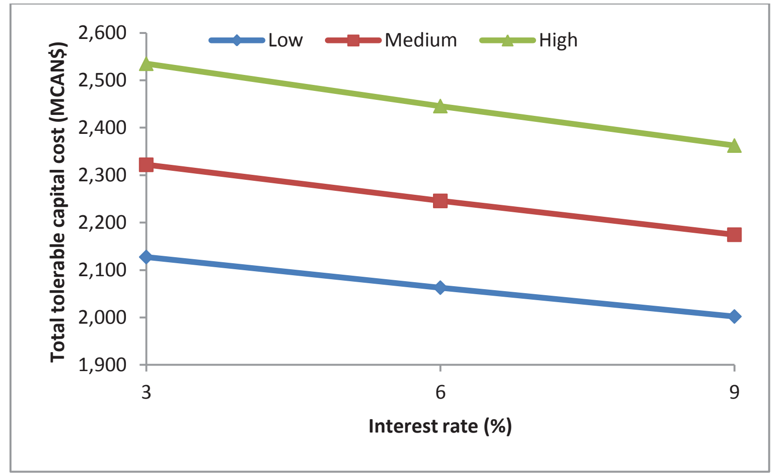
Figure C.24 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to window type 3210 and window/wall area ratio of 50% upgrade

APPENDIX D DETAILED ANALYSIS OF ECONOMIC FEASIBILITY OF WINDOW UPGRADES

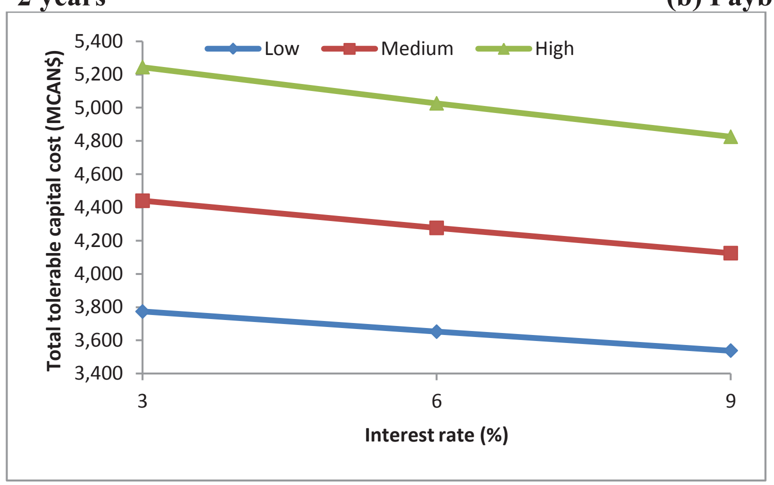
D.1 Upgrade to window type 2010



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure D.1 Total national tolerable capital cost due to window type 2010 upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

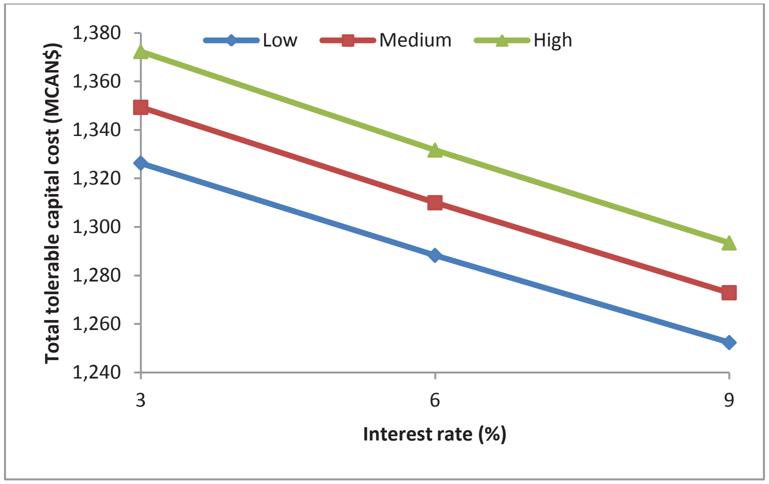
Table D.1 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2010 upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	226,097	3,935,677	132	585	34	853	3.8	217	49	215	12.4
NF	165,987	2,801,293	60	360	21	327	2.0	117	15	89	5.3
NS	269,991	5,239,619	108	398	21	601	2.2	115	38	141	7.3
PE	39,168	622,406	14	359	23	92	2.4	148	5	122	7.6
QC	1,689,762	32,147,220	531	314	17	3,502	2.1	109	57	34	1.8
OT	3,022,683	64,247,255	701	232	11	7,868	2.6	122	454	150	7.1
AB	807,308	14,936,587	78	97	5	2,215	2.7	148	112	139	7.5
MB	198,716	2,859,563	37	185	13	490	2.5	171	21	107	7.4
SK	233,489	3,404,050	35	151	10	591	2.5	174	30	130	8.9
BC	1,085,421	25,944,541	550	507	21	6,608	6.1	255	290	267	11.2

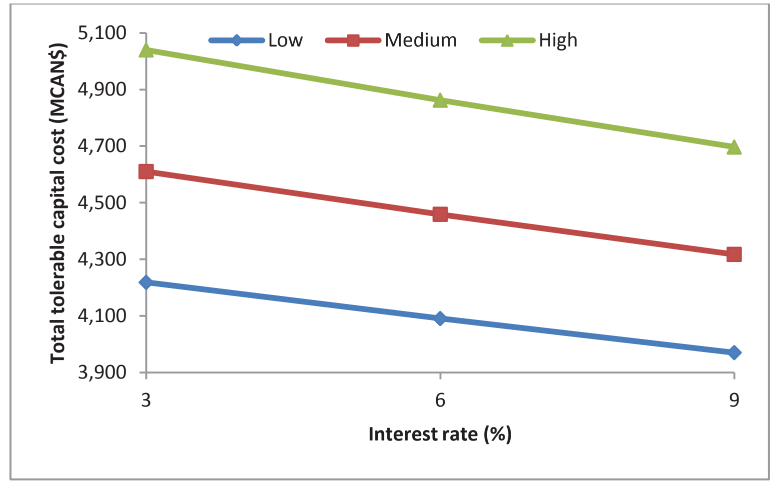
* Total tolerable capital cost

** Tolerable capital cost

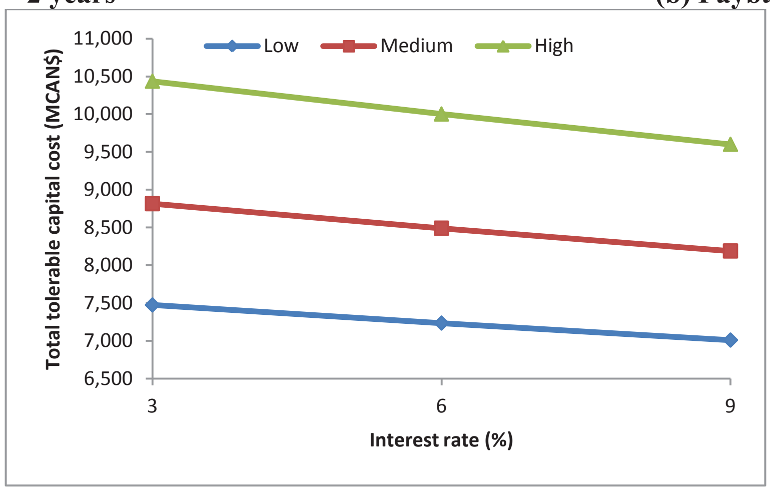
D.2 Upgrade to window type 2100



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

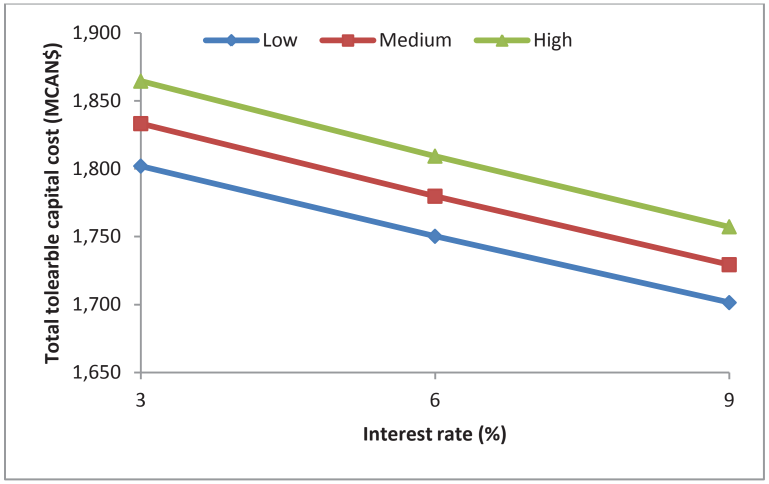
Figure D.2 Total national tolerable capital cost due to window type 2100 upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.2 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2100 upgrade

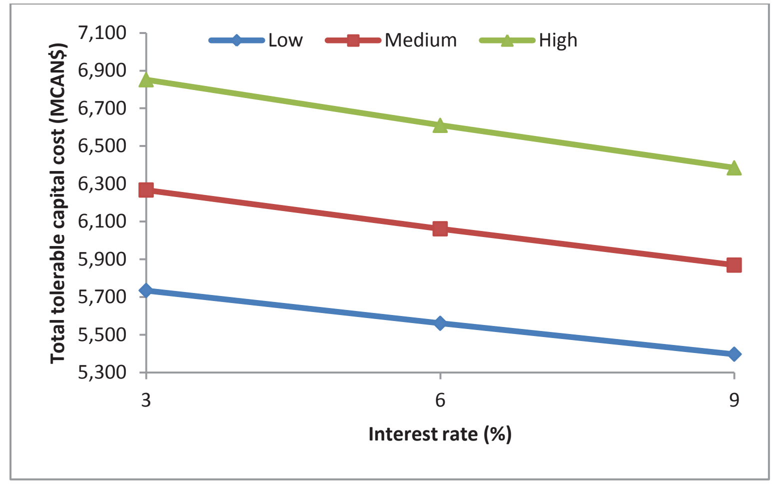
Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	226,097	3,935,677	216	954	55	1,336	5.9	339	88	388	22.3
NF	165,987	2,801,293	142	855	51	769	4.6	274	31	189	11.2
NS	269,991	5,239,619	218	807	42	1,218	4.5	232	78	288	14.8
PE	39,168	622,406	30	756	48	193	4.9	310	10	256	16.1
QC	1,690,291	32,143,266	1,077	637	34	7,211	4.3	224	114	67	3.5
OT	3,023,189	64,258,356	1,666	551	26	17,405	5.8	271	1,123	371	17.5
AB	806,760	14,925,898	159	197	11	4,435	5.5	297	228	282	15.2
MB	198,716	2,859,563	73	367	25	970	4.9	339	40	201	14.0
SK	233,489	3,404,050	74	318	22	1,169	5.0	343	61	259	17.8
BC	1,084,904	25,931,381	804	741	31	9,569	8.8	369	414	382	16.0

* Total tolerable capital cost
** Tolerable capital cost

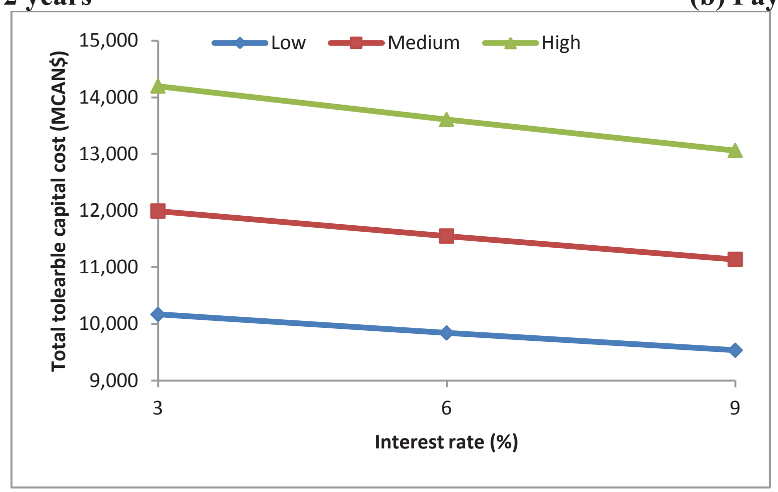
D.3 Upgrade to window type 2110



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

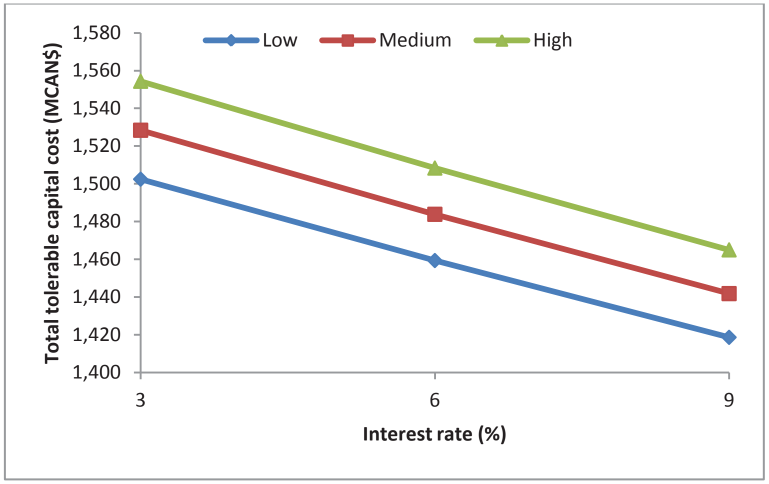
Figure D.3 Total national tolerable capital cost due to window type 2110 upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.3 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2110 upgrade

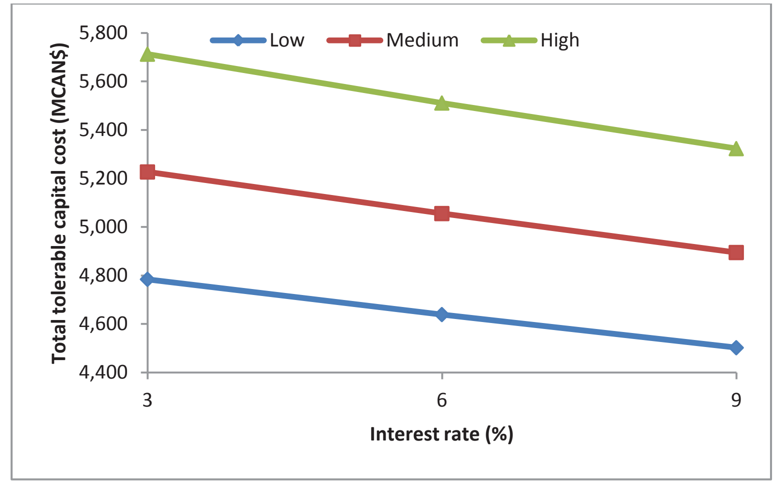
Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	226,097	3,935,677	304	1,344	77	1,834	8.1	466	135	595	34.2
NF	165,987	2,801,293	204	1,227	73	1,095	6.6	391	43	260	15.4
NS	269,991	5,239,619	326	1,209	62	1,810	6.7	345	117	433	22.3
PE	39,168	622,406	43	1,094	69	280	7.1	449	15	370	23.3
QC	1,689,762	32,140,620	1,537	910	48	10,331	6.1	321	158	94	4.9
OT	3,024,339	64,271,920	2,230	737	35	24,391	8.1	380	1,518	502	23.6
AB	806,760	14,925,898	231	286	15	6,513	8.1	436	333	412	22.3
MB	198,716	2,859,563	104	522	36	1,369	6.9	479	56	281	19.5
SK	233,489	3,404,050	104	445	31	1,714	7.3	504	89	379	26.0
BC	1,084,904	25,931,381	980	903	38	11,680	10.8	450	507	467	19.5

* Total tolerable capital cost
** Tolerable capital cost

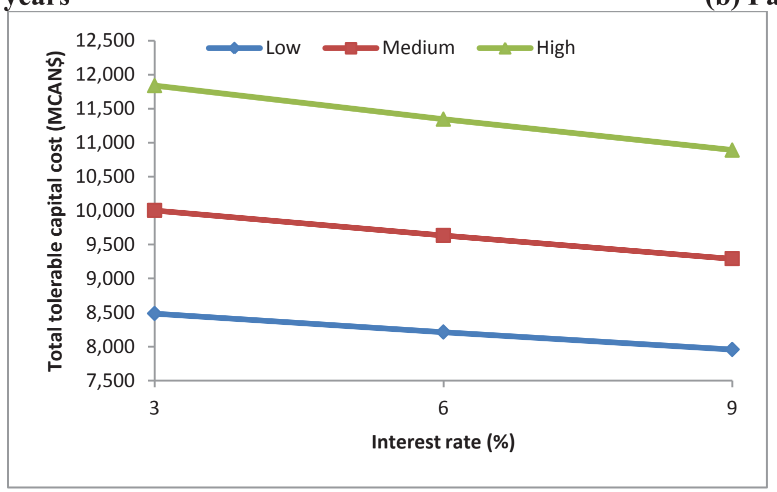
D.4 Upgrade to window type 3000



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure D.4 Total national tolerable capital cost due to window type 3000 upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

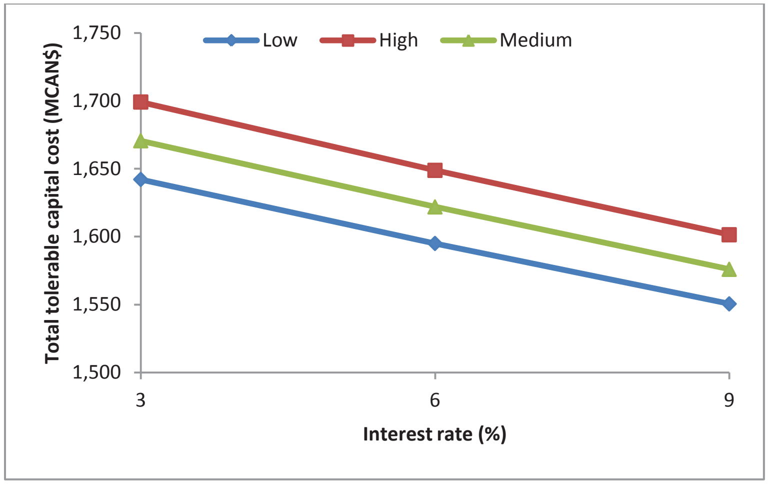
Table D.4 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3000 upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	226,110	3,952,951	273	1,209	69	1,651	7.3	418	119	525	30.0
NF	165,979	2,859,000	167	1,004	58	898	5.4	314	35	213	12.4
NS	269,995	5,288,359	276	1,023	52	1,537	5.7	291	98	365	18.6
PE	39,170	635,823	37	956	59	249	6.3	391	12	311	19.1
QC	1,691,355	32,377,699	1,282	758	40	8,612	5.1	266	131	78	4.1
OT	3,023,723	64,525,602	1,808	598	28	20,362	6.7	316	1,231	407	19.1
AB	806,791	15,268,647	197	244	13	5,587	6.9	366	285	353	18.6
MB	198,697	2,890,153	79	400	27	1,046	5.3	362	43	215	14.8
SK	233,499	3,468,168	83	354	24	1,442	6.2	416	74	318	21.4
BC	1,084,838	26,023,610	852	786	33	10,214	9.4	392	446	411	17.1

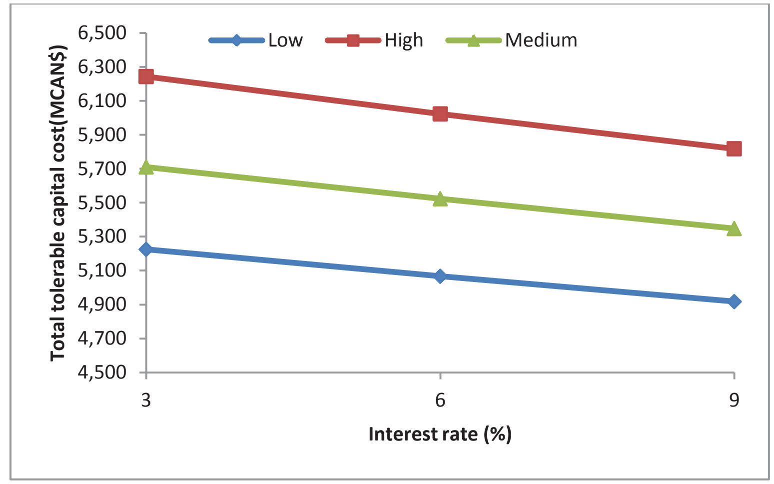
* Total tolerable capital cost

** Tolerable capital cost

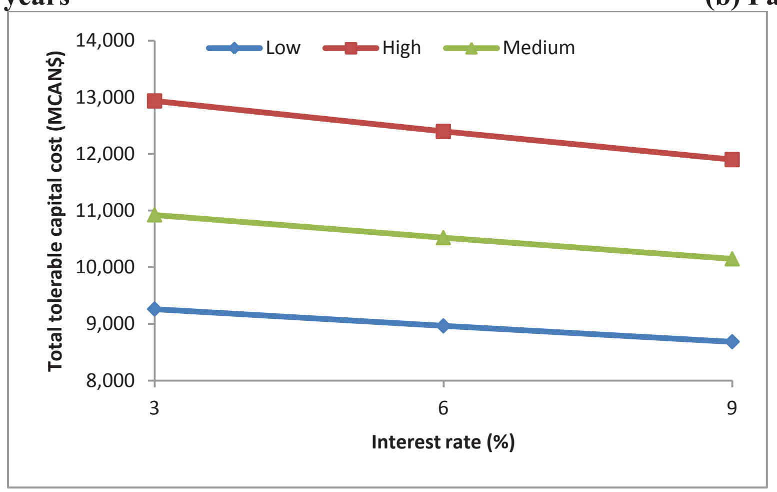
D.5 Upgrade to window type 3200



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

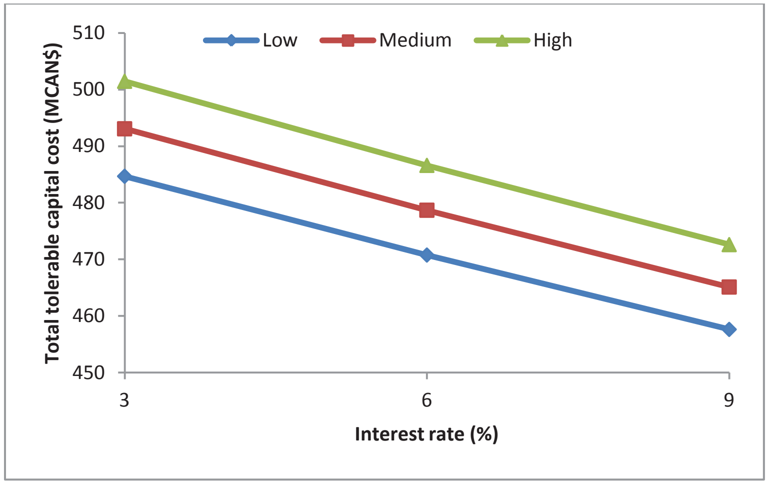
Figure D.5 Total national tolerable capital cost due to window type 3200 upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.5 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3200 upgrade

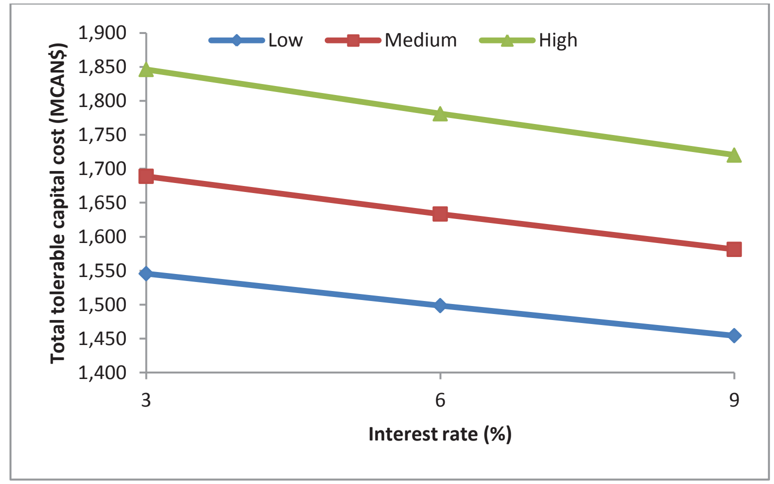
Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	226,110	3,952,951	286	1,263	72	1,718	7.6	435	126	558	31.9
NF	165,979	2,859,000	186	1,123	65	1,000	6.0	350	39	236	13.7
NS	269,979	5,285,212	295	1,092	56	1,636	6.1	310	105	390	19.9
PE	39,170	644,434	39	995	60	256	6.5	397	13	325	19.8
QC	1,691,363	32,383,511	1,389	821	43	9,354	5.5	289	142	84	4.4
OT	3,023,788	64,518,100	2,021	668	31	21,869	7.2	339	1,370	453	21.2
AB	806,791	15,268,647	206	256	14	5,792	7.2	379	297	368	19.4
MB	198,697	2,890,153	84	424	29	1,099	5.5	380	44	223	15.3
SK	233,486	3,464,800	92	395	27	1,519	6.5	438	79	336	22.7
BC	1,084,838	26,023,610	924	852	36	11,022	10.2	424	479	441	18.4

* Total tolerable capital cost
** Tolerable capital cost

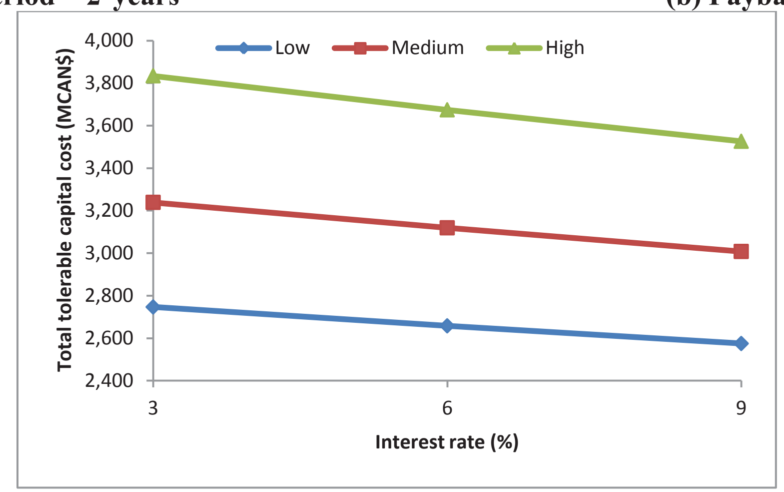
D.6 Upgrade to window type 2110 and window/wall area ratio of 30%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure D.6 Total national tolerable capital cost due to window type 2110 and window/wall area ratio of 30% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

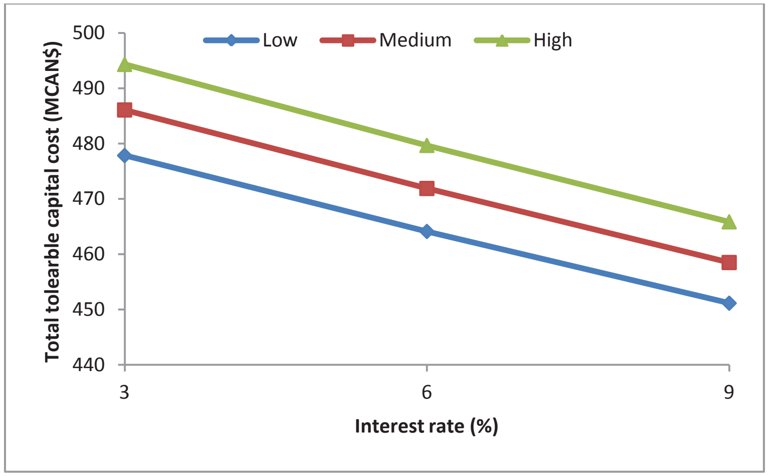
Table D.6 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2110 and window/wall area ratio of 30% upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	198,117	3,318,911	114	576	34	673	3.4	203	50	250	14.9
NF	153,689	2,582,474	89	582	35	471	3.1	183	18	117	7.0
NS	236,421	4,483,936	118	497	26	651	2.8	145	42	176	9.3
PE	35,310	562,181	15	424	27	99	2.8	176	5	141	8.8
QC	1,435,321	26,882,023	275	191	10	1,018	0.7	38	21	14	0.8
OT	2,579,160	54,293,219	741	287	14	8,132	3.2	150	493	191	9.1
AB	708,996	12,976,819	76	108	6	2,093	3.0	161	106	150	8.2
MB	179,453	2,627,552	37	209	14	490	2.7	186	20	114	7.8
SK	200,236	2,920,159	39	196	13	638	3.2	218	33	163	11.2
BC	784,101	17,742,234	129	164	7	1,312	1.7	74	59	75	3.3

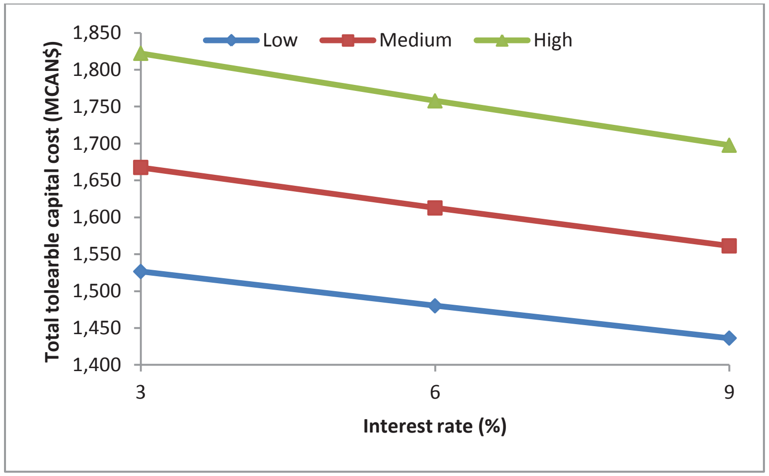
* Total tolerable capital cost

** Tolerable capital cost

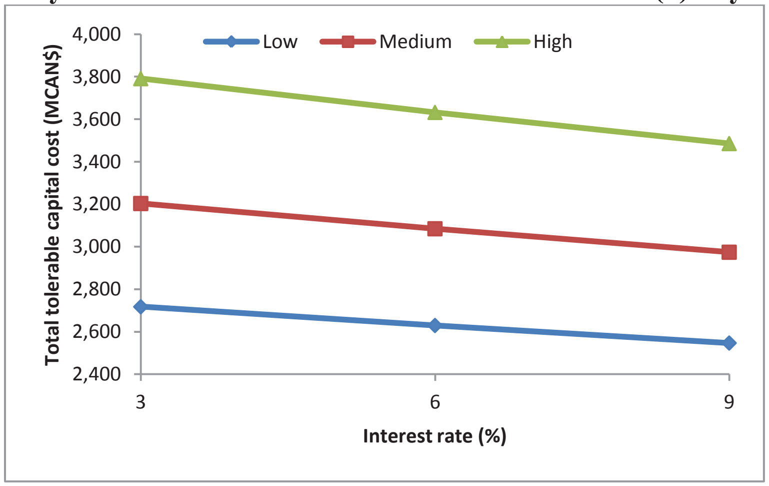
D.7 Upgrade to window type 2110 and window/wall area ratio of 40%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

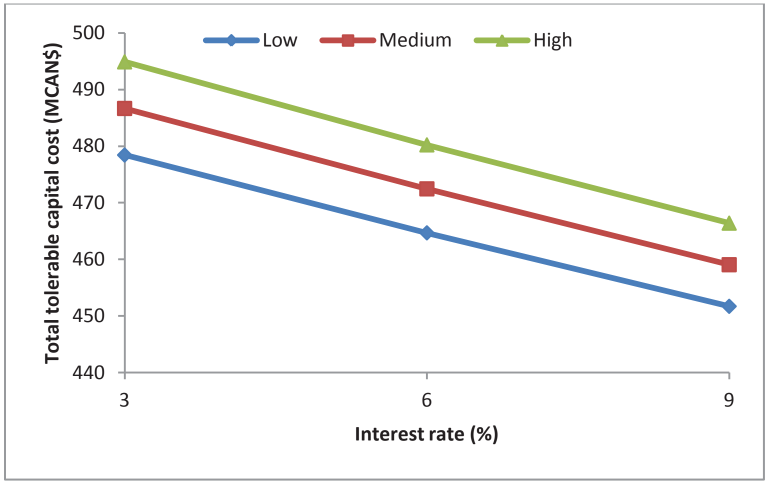
Figure D.7 Total national tolerable capital cost due to window type 2110 and window/wall area ratio of 40% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.7 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2110 and window/wall area ratio of 40% upgrade

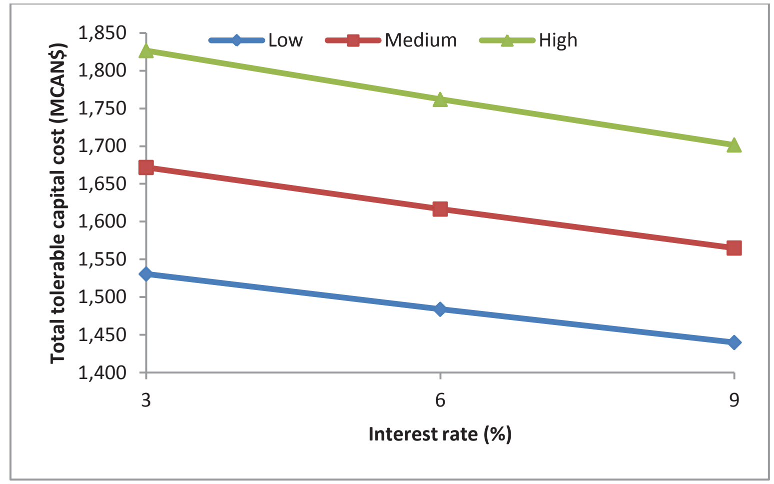
Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	198,117	3,318,911	128	645	38	756	3.8	228	54	275	16.4
NF	153,689	2,582,474	90	583	35	473	3.1	183	19	122	7.2
NS	236,421	4,483,936	129	547	29	719	3.0	160	46	193	10.2
PE	35,310	562,181	16	457	29	106	3.0	189	5	150	9.4
QC	1,435,321	26,882,023	277	193	10	727	0.5	27	19	13	0.7
OT	2,579,160	54,293,219	690	268	13	7,656	3.0	141	421	163	7.7
AB	708,996	12,976,819	77	108	6	2,111	3.0	163	106	150	8.2
MB	179,453	2,627,552	39	215	15	496	2.8	189	21	117	8.0
SK	200,236	2,920,159	38	190	13	623	3.1	213	32	158	10.9
BC	784,101	17,742,234	130	166	7	1,192	1.5	67	55	70	3.1

* Total tolerable capital cost
** Tolerable capital cost

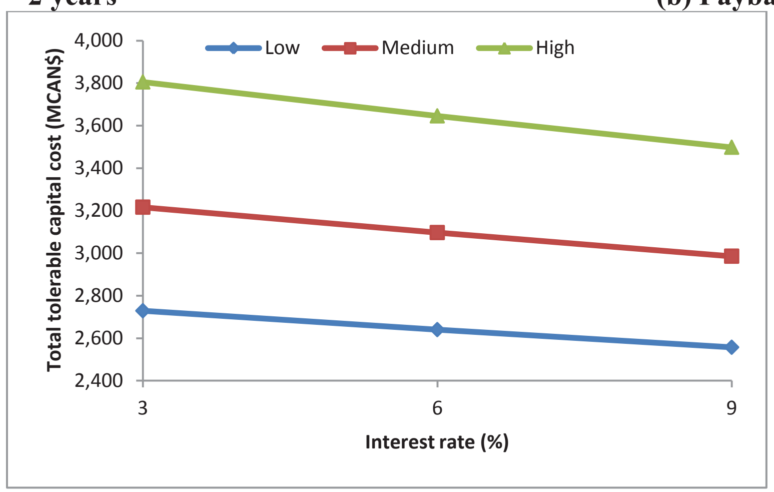
D.8 Upgrade to window type 2110 and window/wall area ratio of 50%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

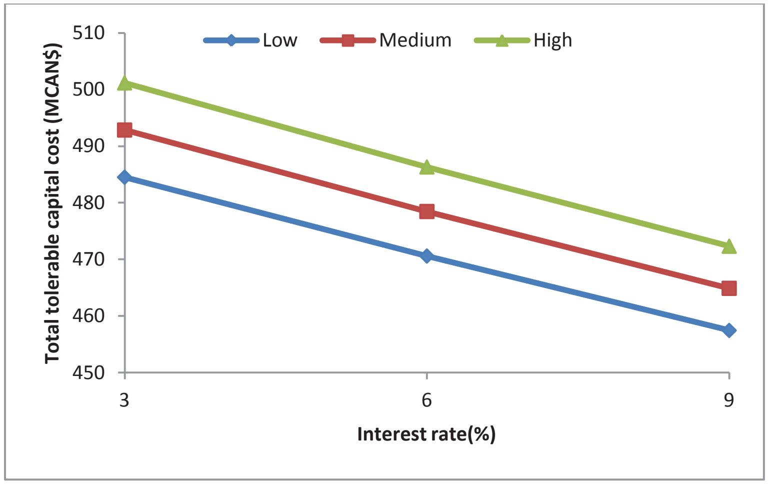
Figure D.8 Total national tolerable capital cost due to window type 2110 and window/wall area ratio of 50% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.8 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2110 and window/wall area ratio of 50% upgrade

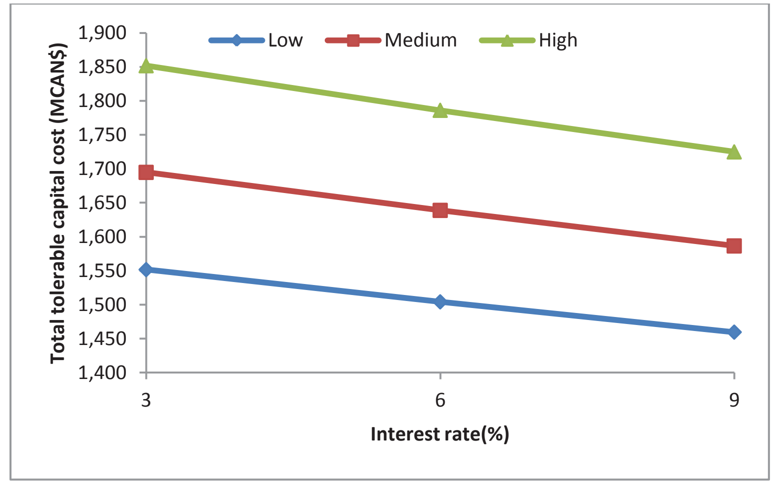
Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	198,117	3,318,911	140	708	42	826	4.2	249	58	293	17.5
NF	153,689	2,582,474	89	576	34	471	3.1	182	19	124	7.4
NS	236,421	4,483,936	139	589	31	772	3.3	172	49	206	10.9
PE	35,310	562,181	17	482	30	111	3.2	198	6	158	9.9
QC	1,435,321	26,882,023	280	195	10	381	0.3	14	17	12	0.6
OT	2,579,160	54,293,219	666	258	12	7,038	2.7	130	339	132	6.2
AB	708,996	12,976,819	77	109	6	2,089	2.9	161	104	147	8.0
MB	179,453	2,627,552	40	224	15	495	2.8	188	21	118	8.1
SK	200,236	2,920,159	38	189	13	596	3.0	204	30	150	10.3
BC	784,101	17,742,234	131	166	7	1,039	1.3	59	49	63	2.8

* Total tolerable capital cost
** Tolerable capital cost

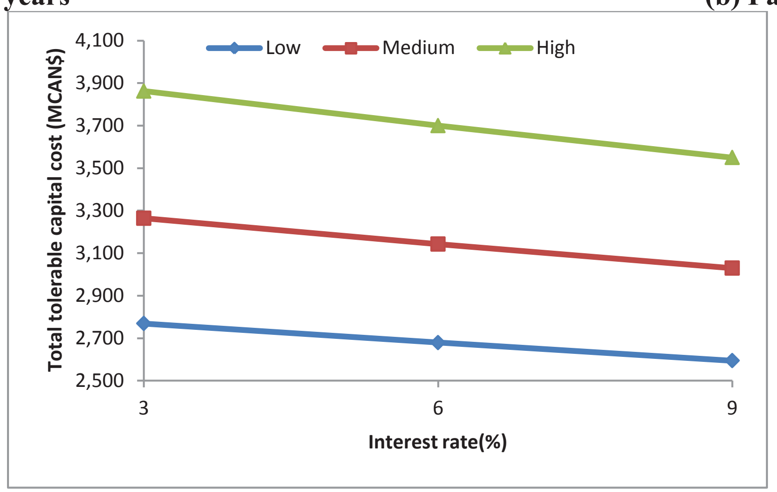
D.9 Upgrade to window type 2110 and window/wall area ratio of 60%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

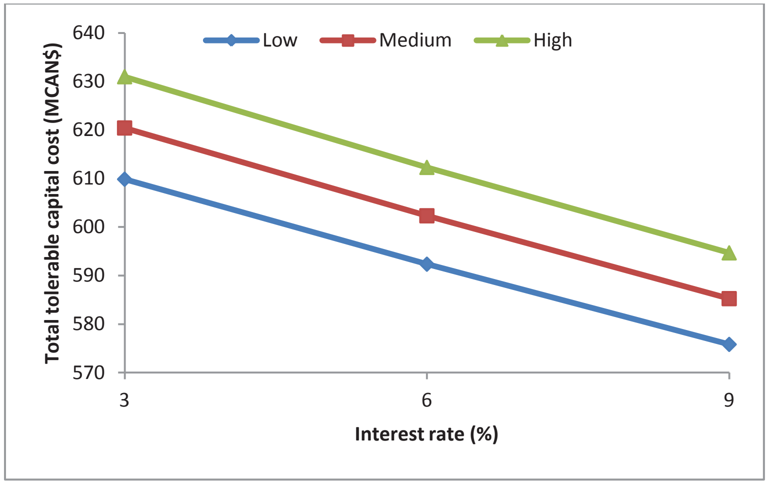
Figure D.9 Total national tolerable capital cost due to window type 2110 and window/wall area ratio of 60% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.9 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 2110 and window/wall area ratio of 60% upgrade

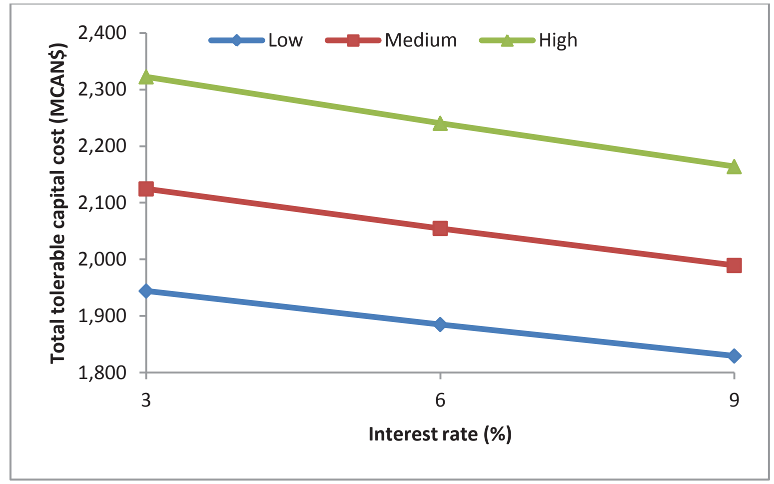
Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	198,117	3,318,911	153	771	46	891	4.5	268	62	310	18.5
NF	153,689	2,582,474	88	571	34	465	3.0	180	19	126	7.5
NS	236,421	4,483,936	149	632	33	821	3.5	183	52	218	11.5
PE	35,310	562,181	18	502	32	116	3.3	206	6	163	10.2
QC	1,435,321	26,882,023	285	198	11	-10	0.0	0	14	10	0.5
OT	2,579,160	54,293,219	658	255	12	6,290	2.4	116	249	97	4.6
AB	708,996	12,976,819	78	110	6	2,024	2.9	156	99	140	7.7
MB	179,453	2,627,552	42	233	16	486	2.7	185	21	118	8.1
SK	200,236	2,920,159	39	194	13	557	2.8	191	28	139	9.5
BC	784,101	17,742,234	130	166	7	849	1.1	48	42	54	2.4

* Total tolerable capital cost
** Tolerable capital cost

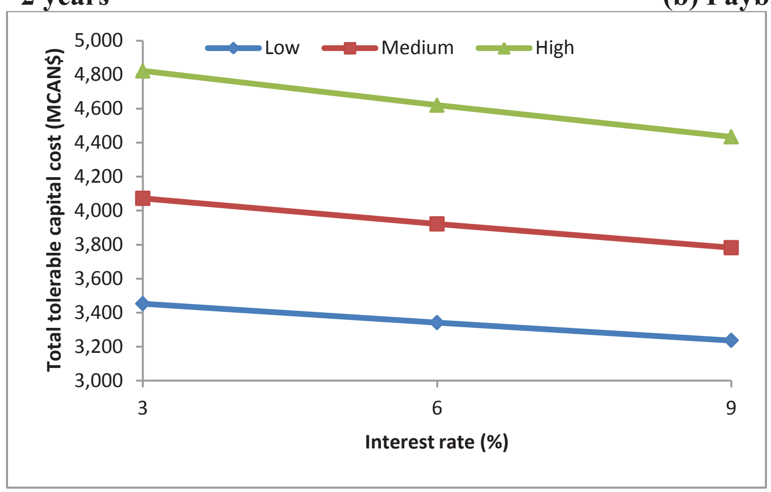
D.10 Upgrade to window type 3210 and window/wall area ratio of 30%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure D.10 Total national tolerable capital cost due to window type 3210 and window/wall area ratio of 30% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

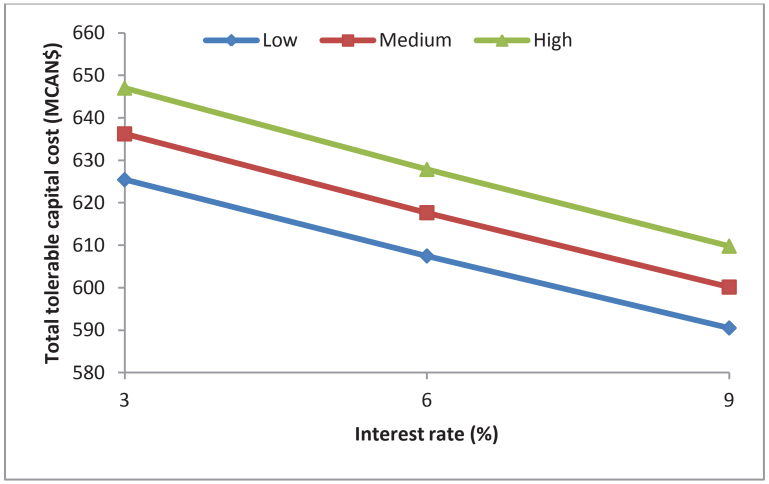
Table D.10 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 and window/wall area ratio of 30% upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	209,261	3,524,726	133	637	38	784	3.7	222	70	334	19.8
NF	162,679	2,792,109	103	635	37	539	3.3	193	82	502	29.2
NS	260,108	4,954,555	142	546	29	784	3.0	158	60	230	12.1
PE	40,538	670,798	20	493	30	130	3.2	194	20	496	30.0
QC	1,688,792	31,784,527	372	220	12	1,713	1.0	54	50	30	1.6
OT	2,949,530	62,477,176	920	312	15	10,094	3.4	162	7	2	0.1
AB	851,528	15,926,256	100	117	6	2,760	3.2	173	31	36	2.0
MB	311,439	4,630,931	63	203	14	791	2.5	171	612	1,964	132.1
SK	275,829	4,159,569	54	196	13	886	3.2	213	140	509	33.7
BC	806,356	18,327,200	147	182	8	1,562	1.9	85	32	40	1.7

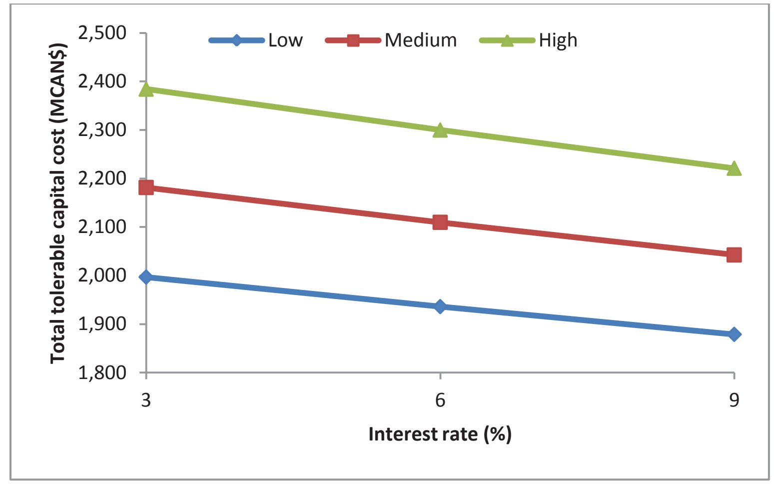
* Total tolerable capital cost

** Tolerable capital cost

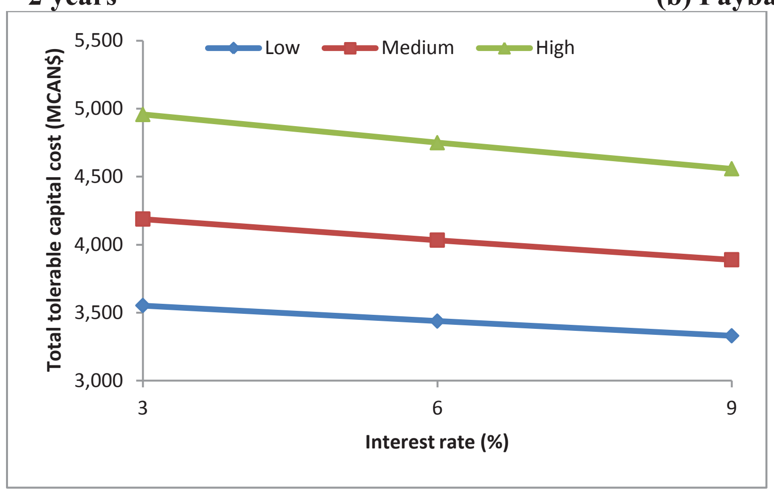
D.11 Upgrade to window type 3210 and window/wall area ratio of 40%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure D.11 Total national tolerable capital cost due to window type 3210 and window/wall area ratio of 40% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

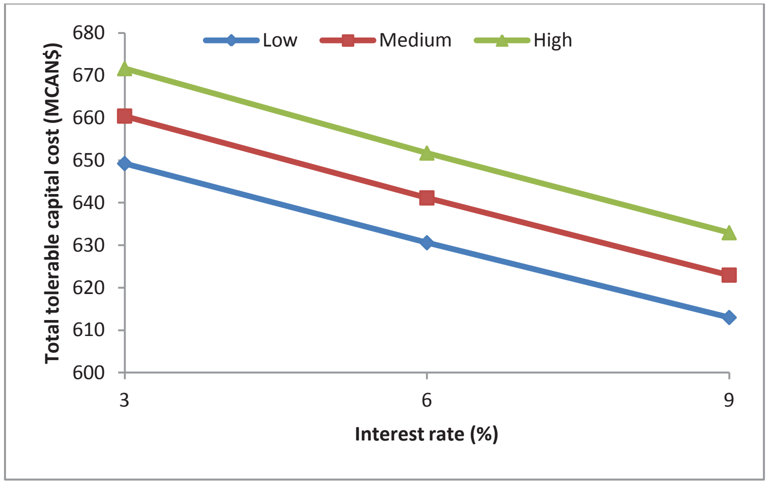
Table D.11 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 and window/wall area ratio of 40% upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	209,261	3,524,726	154	736	44	906	4.3	257	68	325	19.3
NF	162,679	2,792,109	106	654	38	563	3.5	202	22	134	7.8
NS	260,108	4,954,555	160	615	32	888	3.4	179	57	219	11.5
PE	40,538	670,798	22	544	33	143	3.5	213	7	177	10.7
QC	1,688,792	31,784,527	395	234	12	1,579	0.9	50	32	19	1.0
OT	2,949,530	62,477,176	892	302	14	9,955	3.4	159	551	187	8.8
AB	851,528	15,926,256	105	123	7	2,926	3.4	184	147	173	9.2
MB	311,439	4,630,931	69	221	15	851	2.7	184	35	112	7.5
SK	275,829	4,159,569	55	199	13	899	3.3	216	46	165	10.9
BC	806,356	18,327,200	152	189	8	1,505	1.9	82	69	85	3.7

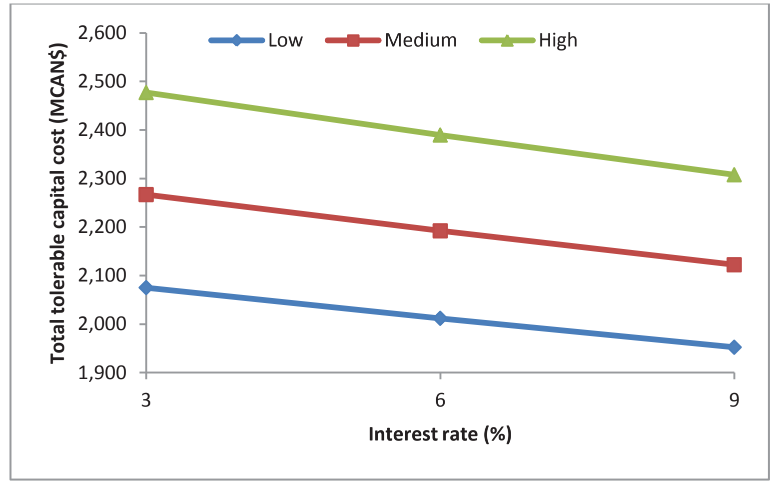
* Total tolerable capital cost

** Tolerable capital cost

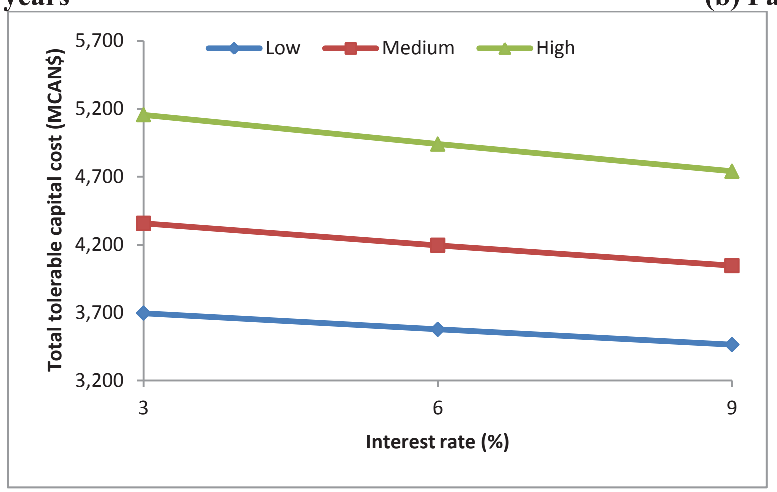
D.12 Upgrade to window type 3210 and window/wall area ratio of 50%



(a) Payback period = 2 years



(b) Payback period = 6 years



(c) Payback period = 10 years

Figure D.12 Total national tolerable capital cost due to window type 3210 and window/wall area ratio of 50% upgrade for different interest rates and fuel cost escalation rates (Low, Medium, High as per Table 2.6)

Table D.12 Total tolerable capital cost and achievable savings per house and per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to window type 3210 and window/wall area ratio of 50% upgrade

Province	No. of houses	Area of windows (m^2)	TTCC* (MCAN$)	TCC** (CAN$)		Total energy saved (TJ)	Energy saved		Total GHG reduced (kt)	GHG reduced (kg)	
				Per house	Per m^2 of window		Per house (GJ)	Per m^2 of window (MJ)		Per house	Per m^2 of window
NB	209,261	3,524,726	173	827	49	1,015	4.8	288	75	359	21.3
NF	162,679	2,792,109	109	670	39	582	3.6	208	23	142	8.3
NS	260,108	4,954,555	177	680	36	974	3.7	196	63	241	12.7
PE	40,538	670,798	24	588	36	154	3.8	229	8	188	11.4
QC	1,688,792	31,784,527	416	246	13	1,384	0.8	44	32	19	1.0
OT	2,949,530	62,477,176	895	303	14	9,675	3.3	155	481	163	7.7
AB	851,528	15,926,256	110	129	7	3,036	3.6	191	151	178	9.5
MB	311,439	4,630,931	75	241	16	896	2.9	193	37	119	8.0
SK	275,829	4,159,569	58	210	14	894	3.2	215	45	162	10.7
BC	806,356	18,327,200	156	193	8	1,416	1.8	77	66	82	3.6

* Total tolerable capital cost
** Tolerable capital cost

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