EFFECT OF VENETIAN BLIND RETROFITS ON HOUSEHOLD ENERGY REQUIREMENT FOR HEATING AND COOLING IN CANADA

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ABSTRACT

This paper presents an overview of a comprehensive study that was conducted to assess the potential impact of introducing solar technologies and solar technology integration strategies on the end-use energy consumption and the associated greenhouse gas (GHG) emissions of the Canadian housing stock, and reports detailed results of the study on the impact of Venetian blinds. The study was conducted using the new Canadian hybrid residential end-use energy and emissions model CHREM, which is representative of the Canadian housing stock.

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).

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). Consequently in order to be effective, any national policy to reduce energy consumption and the associated GHG emissions must address the residential sector.

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, retrofitting existing houses with solar technologies provides one of the substantial opportunities for reducing energy consumption and GHG emissions in Canada's residential sector. Therefore, a comprehensive research work was conducted to assess the techno-economic impact of a variety of solar energy technology retrofits on the end-use energy consumption and GHG emissions of the Canadian housing stock (Nikoofard, 2012).

Due to the wide range of solar technologies available, as well as 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 differ dramatically in Canada from region to region. Therefore, this study was conducted using the Canadian Hybrid Residential End-use Energy and Emission model (CHREM) (Swan, et al. 2008, Swan, 2010, Swan, et al. 2011). In this paper, the technoeconomic analysis for Venetian blinds (VB) is presented. Complete documentation of the entire study is given in Nikoofard (2012).

Overview of CHREM

CHREM is statistically representative of the Canadian housing stock (CHS). It is based on the Canadian Single-Detached and Double/Row Database (CSDDRD) (Swan, et al., 2009, Swan, 2010), and utilizes the high resolution building energy simulation program ESP-r (ESRU, 2009) as its simulation engine. CSDDRD was developed using the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys, and other available housing databases and consists of close to 17,000 houses representative of the CHS. 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, Farhat and Ugursal, 2010):

- 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 methodology that is used in carrying out this research is depicted in Figure 1.

Solar technologies suitable for the Canadian residential sector

In residential buildings, solar energy is currently used for water and space heating, space cooling and generating electricity. 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. Since the goal of the project was studying the impact of adopting solar technologies on the energy consumption and GHG emissions in the CHS, as well as their cost effectiveness, first the solar technologies that are potentially feasible within the Canadian context were identified through a comprehensive literature review on the performance and feasibility of solar technologies. Based on the findings of this review, the following set of solar technologies were identified to be evaluated in detail (Nikoofard, 2012):

1. Water heating using flat plate solar collector with forced circulation,
2. Direct gain passive solar space heating with window area and type retrofits,
3. Direct gain passive solar space heating with internal, external and between glazing Venetian blinds,
4. Direct gain passive solar space heating with phase change materials,
5. Photovoltaics for electricity generation,
6. Building integrated photovoltaics for electricity generation and space heating.

METHODOLOGY

The methodology that was used in carrying out this research is depicted in Figure 1, and consists of the following steps:

1) Model development/adaption for solar technologies: ESP-r contains models for most of the solar technologies studied. 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 Nikoofard (2012).

2) Parametric study: Before applying each selected solar technology upgrade scenario to the CHREM, a parametric study was carried out to determine the specific variables which have significant effect on the energy performance of the upgrade. However, some upgrades did not require a parametric study due to technology complication, existing standards and previous studies on their performance.

Table 1 Solar technologies for houses

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

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2. Solar space heating
    a. Passive
        i. Direct gain systems
            1. Changing windows area
            2. Changing windows type
            3. Shading devices
                a. Internal, external and between the glazing Venetian blind shading
                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

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

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

To conduct the parametric study, a one-storey detached house commonly found in Canada was 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 resulted in a better energy performance of the house were selected to be considered in batch simulation of the CHS.

3) Estimation of the annual energy savings and the reduction in GHG emissions: Based on the results of the parametric study for each solar technology, the critical parameters were determined and applied to CHREM and the resulting annual heating and cooling energy consumption values were compared with the base case heating and cooling energy consumption to determine the heating and cooling energy savings due to the retrofit. Similarly, the annual GHG emissions with each solar technology were compared to the base case GHG emissions to determine the GHG emission reduction due to each solar technology retrofit.

To determine the annual energy savings and the reduction in GHG emissions associated with each solar technology retrofit scenario, first the houses that could receive the retrofit were identified by screening the houses in the CSDDRD. Then those house files were modified to reflect the retrofit, and batch simulation was conducted. Thus, the annual energy savings associated with the retrofit is determined by subtracting the energy consumption with the retrofit from the base case energy consumption.

Once the annual energy savings with the retrofit was determined, the GHG emission reductions were 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 the GHG emission intensity factor (EIF), which is the level of CO_2e emitted per unit input energy[1]. The GHG EIF is a function of only the type of fuel used and the efficiency of the energy conversion device used for on-site fuel combustion. However, in Canada, it varies with province for electricity generation because the fuel mix used in each province is different. Furthermore, the fuel used for base load and peak (marginal) load power plants are also different. 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, while the changes in GHG emissions due to an energy upgrade is calculated using the marginal GHG EIF of the regional electricity generation. The average and marginal GHG EIFs for different provinces of Canada are given in Farhat and Ugursal (2010).

4. Economic analysis based on tolerable capital cost: Since some of the solar technologies considered for retrofit 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 was adopted which involves the calculation of “tolerable capital cost” (TCC) of the upgrades. TCC 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 an energy upgrade, a reverse payback analysis is conducted (Nikoofard, 2012, Nikoofard, et al. 2012).

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 interest rates used in the analysis were based on the Bank of Canada Prime Rate, which was 1% in September, 2012. 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 rates. The predicted fuel cost escalation rates for each fuel type were 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 were used in the analysis as shown in Table 2.

Table 2 Real fuel escalation type for each fuel type

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

While it is certain that solar technology retrofits to a house increases its market value, the estimation of the increase in market value due to retrofits 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. Nevertheless, the reader needs to be aware that in addition to the reduction in energy consumption and GHG emissions, part of the economic consequence of upgrades is the increase in the market value of a house.

MODELING OF VENETIAN BLINDS

While a range of solar technologies were evaluated for the CHS, it is not possible to present the results for every technology in this paper due to space

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[1] CO_2e is the "equivalent CO_2" emissions from fossil fuel combustion calculated by converting all GHG emissions, such as CO and CH_4, to equivalent CO_2 emissions taking into account their global warming potentials (Swan, 2010).

constraints. Therefore, the results of the component of the work on Venetian blinds (VB) are summarized here as an example. Detailed results of the evaluation of all solar technologies are presented in Nikoofard (2012).

The "Complex Fenestration Construction (CFC) model" added to ESP-r by Lomanowski (2008) is used to model the performance of VB. The CFC model estimates the energy performance of windows with shading devices by carrying out a two-step analysis; a solar analysis followed by a thermal analysis. This approach has been shown to be valid since there is no significant wavelength overlap between solar (short-wave) and thermal (long-wave) radiation. 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. A complete review of the methodology used in modeling the VB is given in Nikoofard (2012).

The VB control which has been added into ESP-r by Lomanowski (2009) is independent of the building and heating/cooling plant control. Currently, there are three types of control available for Venetian blinds: (1) slat angle control, (2) shade retract/deploy (on/off) control, and (3) schedule control for both slat angle and shade retract/deploy. The control strategies evaluated in this work are described in detail in Nikoofard (2012) and are summarized in the following section.

VENETIAN BLINDS - CASE STUDY

As described above, first a case study was conducted to select the suitable parameters for Venetian blind upgrades for the CHS. The base case house was assumed to be located in Toronto and have no blinds. The case study evaluated the effects of following parameters:

1. Effect of slat angle from 0° (fully open) to 90° (fully closed) in increments of 15°,

2. Effect of slat type (light, medium and dark color; 12.5 and 25 mm width, aluminium and vinyl) and VB placement (inside, outside and between glazing),

3. Effect of slat curvature: flat and curved slats,

4. Effect of slat orientation: horizontal and vertical (louver-drape) slats,

5. Effect of shading orientation: horizontal and vertical slat orientations on east, west, north and south,

6. Effect of control strategy: four control schemes to simulate automatic lowering/raising of the VB and closing/opening of the slats based on solar radiation and zone temperature as follows:

- In all seasons, the blinds are closed during the night time,
- In the heating only season, the blinds are open during the day to take advantage of the solar gain through windows.
- During cooling season, four basic control schemes were used: (1) a control scheme to simulate the automatic lowering/raising of the blind based on zone temperature - below 21˚C raise and above 24°C lower blinds; (2) similar to (1) but instead of raising/lowering blinds, open/close the slats; (3) a control scheme to simulate the automatic lowering/raising of the blind based on solar radiation[1] - below 200 W/ m^2 raise and above 233 W/m^2 lower blinds; (4) similar to (3) but instead of raising/lowering blinds, open/close the slats.

RESULTS AND DISCUSSION

Based on the results of the parametric study, presented in detail in Nikoofard (2012), the following Venetian blind upgrades were selected to be added to all windows of eligible houses in the CHS:

Retrofit 1: Addition of ½ inch light aluminum Venetian blinds, indoor side and control type 1;

Retrofit 2: Addition of ½ inch dark aluminum Venetian blinds, outdoor side and control type 4.

Addition of the control strategies to the simulations of the CHREM requires a 2-minute resolution of the simulation time-step. Therefore, the simulation's time-step was changed from 10 minutes in the other simulations to 2 minutes in the simulations conducted for the controlled VB modeling. In other words, all of the eligible house files (around 5000 out of 17,000) in CHREM were simulated for an entire year using a 2-minute time step. Due to the small time step, each batch simulation took about 18 hours on one of the Atlantic Computational Excellence Network (ACEnet) clusters[2]. For these simulations, about 200 cores were allocated with about 2GB of RAM per core.

The results of the batch simulations indicate that the addition of dark colored VB on the outdoor side with control type 4 (Retrofit 2) results in an increase in the overall energy consumption of the housing stock of all provinces. While this VB retrofit reduces the energy consumption for cooling, it results in an increase in the energy consumption for heating, and the increase in heating energy consumption is higher than the reduction in cooling energy consumption. Therefore, the overall effect is a net increase in energy consumption, and consequently in GHG emissions. For this reason, no detailed results are shown for Retrofit 2 here. Interested readers will find detailed results in Nikoofard (2012).

The addition of light color VB on the indoor side of windows with control type 1 (Retrofit 1) saves

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[1] Solar irradiance incident on exterior surface of window

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

energy in all provinces of Canada as shown in Tables 3 and 4 where the results are given for each energy source, house type and province[1]. The results show that this VB retrofit would reduce the energy consumption of the CHS by 2.3% (representing 24.3 PJ/year) and GHG emissions by 2.7% (representing 1.3 Mt of CO2 equivalent).

Table 3 Annual energy savings due to VB upgrade (Retrofit 1)

House type or Province		Energy savings (TJ)				
		Electricity	NG*	Oil	Wood	Total
House type	Single Detached	3,538	16,619	1,262	24	21,442
	Double and Row	603	2,113	117	0	2,834
Province	New Brunswick	1	0	0	7	8
	Nova Scotia	2	0	13	0	15
	Quebec	2,062	4	407	16	2,489
	Ontario	1,794	16,731	959	0	19,484
	Alberta	19	321	0	0	339
	Manitoba	87	296	0	0	383
	Saskatchewan	52	864	0	0	917
	British Colombia	125	517	0	0	642
	Canada	4,141	18,732	1,380	24	24,276

* Natural Gas

Table 4 Annual GHG emission reductions due to VB Upgrade (Retrofit 1)

House type or Province		GHG emission reductions (kt of CO_2e)			
		Electricity	NG*	Oil	Total
House type	Single Detached	223	843	89	1,156
	Double and Row	33	107	8	148
Province	New Brunswick	0	0	0	0
	Nova Scotia	0	0	1	1
	Quebec	2	0	29	32
	Ontario	245	849	68	1161
	Alberta	4	16	0	20
	Manitoba	0	15	0	15
	Saskatchewan	4	44	0	47
	British Colombia	1	26	0	27
	Canada	256	950	98	1,304

* Natural Gas

The distributions of energy savings and GHG emission reductions among the provinces are shown in Figure 2. By 4% of the savings, Ontario dominates the annual energy and GHG savings across Canada. This happens due to the fact that Ontario has the highest percentage of eligible houses for this upgrade across Canada as shown in Table .5

Figure 3 shows the national energy consumption and GHG emission reductions specific to end-uses and energy sources. These results indicate that addition of a controllable light color blind inside the windows reduces both space heating and space cooling energy consumption.

While energy savings are possible, the magnitude of energy savings is marginal for most provinces. As shown in Table 6, for an interest rate of 6%, a payback period of 6 years and medium fuel escalation rate, the TCC varies from \$28 to \$68 per m^2 of window area for all provinces except New Brunswick, where the TCC is a more favorable \$122/m^2 of window area. At lower interest rates and longer payback periods, the economic feasibility improves.

CONCLUSION

A methodology developed to conduct a realistic assessment of the cost effectiveness, energy savings and GHG emission reductions of selected solar technologies on the CHS was presented. The methodology is based on the CHREM (Swan, et al. 2011) which uses ESP-r (ESRU, 2009) as its building energy simulation engine. As an example to demonstrate the use of this methodology, the results of a detailed evaluation of retrofitting houses in the CHS with Venetian blinds were presented. The results indicate that while it will be possible to reduce energy consumption and greenhouse gas emissions using light color VB located on the indoor side of windows and equipped with automatic zone temprature control, the savings are economically attractive in most parts of Canada only when payback periods longer than 6 years and interest rates lower than 6% can be realized. Further work is currently being conducted to evaluate the impact of other VB senarios such as installing different type of controlled VB outside of the window.

NOMENCLATURE

AB = Alberta
AL = Appliance and lighting
AT = Atlantic provinces
BC = British Colombia
CFC = Complex Fenestration Construction
CHREM = Canadian Hybrid Residential End-use Energy and Emission model
CHS = Canadian housing stock
CSDDRD = Canadian Single-Detached and Double/Row Database
DHW = Domestic hot water
EIF = Emission intensity factor
GHG = Greenhouse gas
MB = Manitoba
NB = New Brunswick
NS = Nova Scotia
OT = Ontario
QC = Quebec
SC = Space cooling

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[1] Newfoundland and Prince Edward Island are not included in the results because the number of houses with cooling systems that are eligible to receive the VB retrofit in these two provinces is insignificantly small.

SH = Space heating
SK = Saskatchewan
TCC = Tolerable capital cost
VB = Venetian blind

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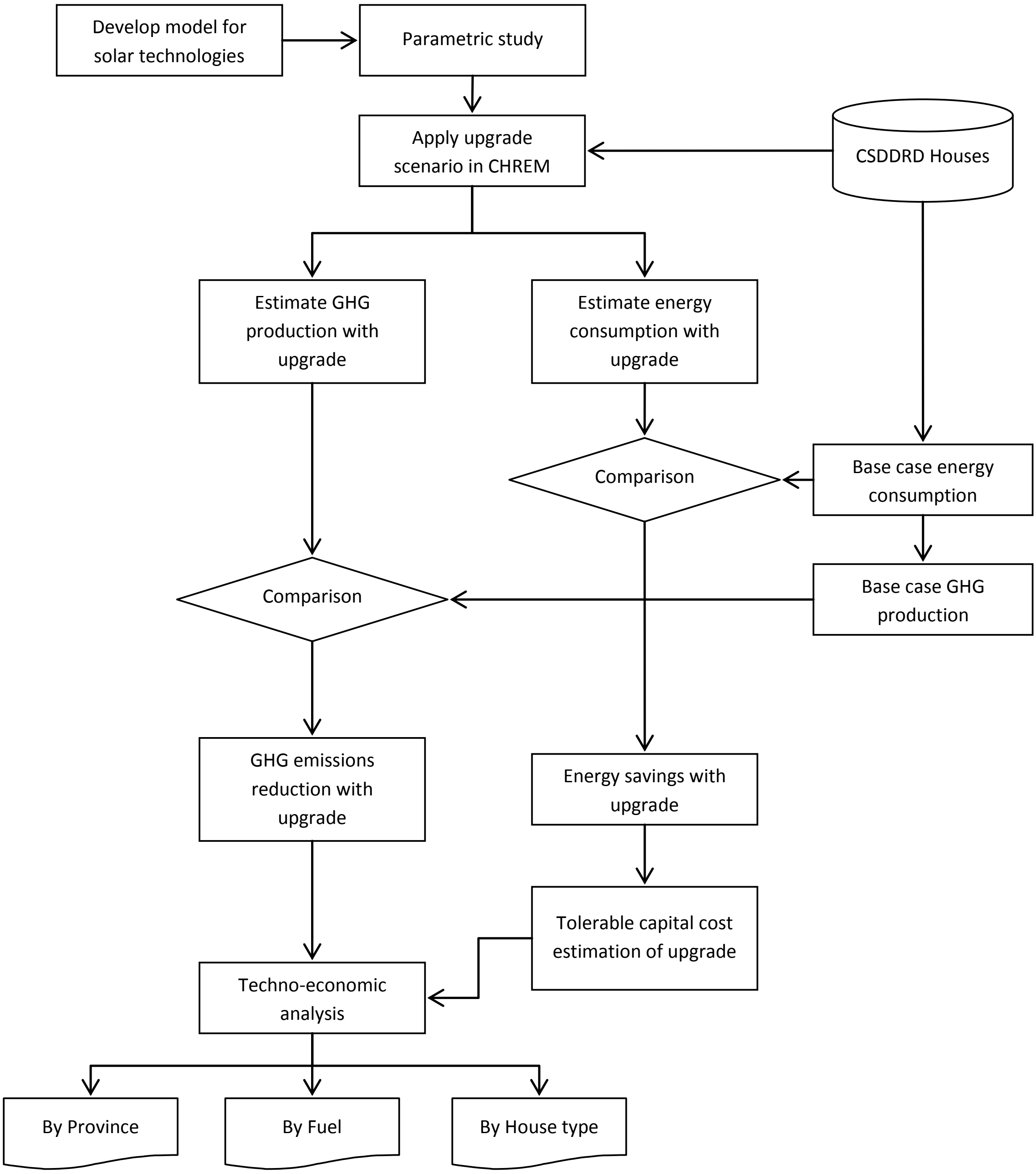

Figure 1 Flow diagram of the overall methodology that is used in this study

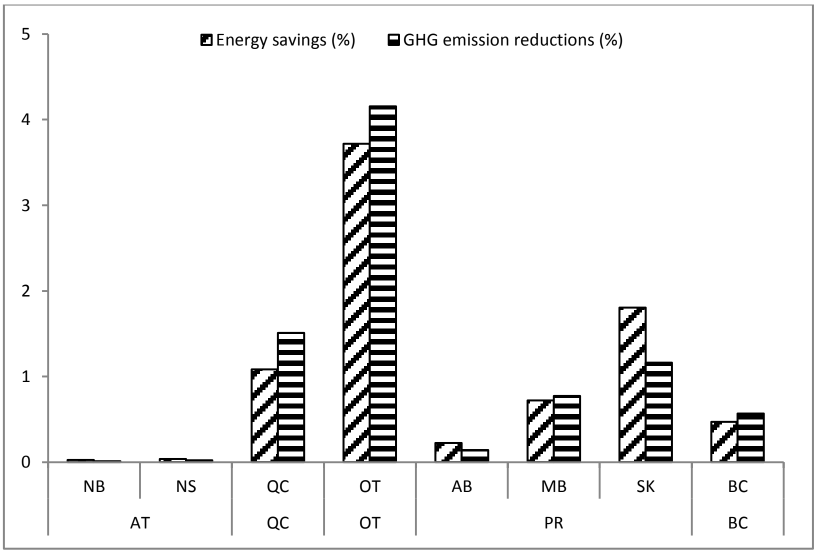

Figure 2 Energy consumption and GHG emission reductions specific to individual provinces of Canada due to Venetian blinds upgrade

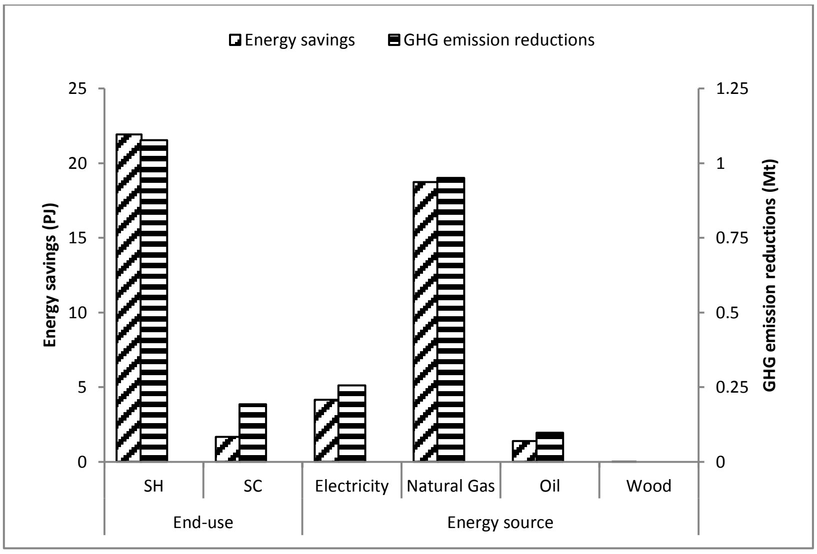

Figure 3 National annual energy consumption and GHG emission reductions specific to end-uses and energy sources due to Venetian blinds Retrofit 1 upgrade

Table 5 The percentage of houses eligible for Venetian blinds Retrofit 1 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

Table 6 Tolerable capital cost per square meter of window for 6 year payback period, 6% interest rate and medium fuel cost escalation rate due to Venetian blinds Retrofit 1 upgrade

Province	NB	NS	QC	OT	AB	MB	SK	BC
TCC*(CAN$) / m^2 of window	122	65	68	37	28	38	37	28

* Tolerable capital cost