Development and Analysis of Approaches and Strategies to Facilitate the Conversion of Canadian Houses into Net Zero Energy Buildings

by

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To my Mother.

Your love and support know no bounds.

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Abstract

Conventional building design is not aligned with modern housing requirements. Growing energy demand, international pressure to reduce greenhouse gas (GHG) emissions and increasing cost of energy motivate the building energy research community to provide alternative solutions to improve traditional housing. One of the most popular options for housing is the adoption of net zero energy building (NZEB) concept, which is defined as a building that exports more or equal energy than it imports. So far, majority of research efforts have been focused on finding solutions for the design, construction and operation of new NZE houses. Since the renewal of the housing stock is slow, the impact of introducing NZEBs into the housing stock would not be significant for many years, making the conversion of existing houses into NZE or near NZE buildings an important objective to reduce energy consumption and associated GHG emissions.

Canada has numerous climatic and geographical regions and the Canadian housing stock (CHS) is diversified in terms of vintage, geometry, construction materials, envelope, occupancy, energy sources and heating, ventilation and air conditioning system and equipment. Therefore, strategies to achieve NZE and near NZE status with the current stock of houses need to be devised considering the unique characteristics of the housing stock, the economic conditions and energy mix available in each region. Identifying and assessing pathways to converting existing houses to NZE or near NZE buildings at the housing stock level is a complex and multifaceted problem and requires extensive analysis on the impact of energy efficiency and renewable/alternative energy technology retrofits on the energy use and GHG emissions of households.

To develop and analyze techno-economically feasible approaches and strategies to support the conversion of Canadian houses into NZE and near NZE buildings by implementing energy efficiency and renewable/alternative energy technology retrofits, the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM), a state of the art residential sector energy and GHG emission model statistically representative of the CHS, was expanded and used. For this purpose, a wide range of energy efficiency and renewable/alternative energy technology retrofits including envelope modifications, appliance/lighting upgrade, internal combustion engine and Stirling engine cogeneration, solar combisystem, air to water heat pump, solar assisted heat pump and building integrated photovoltaic and thermal system architectures were developed/adapted and models were incorporated into the CHREM. The impact of the retrofit measures on the energy consumption and GHG emissions of the CHS was investigated. Numerous retrofit scenarios involving various technologies were developed for each province and post-retrofit source energy intensity and GHG emission intensity of houses were determined to evaluate the performance of the retrofit scenarios to achieve NZE and near NZE status for Canadian houses. The results indicate that substantial energy savings and GHG emission reductions are techno-economically feasible for the CHS through careful selection of retrofit options. While achieving large scale conversion of existing houses to NZEB is not feasible, achieving near NZE status is a realistic goal for a large percentage of Canadian houses.

List of Abbreviations and Symbols Used

ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
AR	Roof area (m^2)
ATCCH	Average tolerable capital cost per house (C$)
CO_{2e}	Equivalent CO_2 (kg)
C_{EE}	Cost of electrical energy (C$)
C_{PE}	Cost of primary energy (C$)
c	Specific heat (kJ/kg°C)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
EC	Energy cost (C$)
E_{aux}	Energy consumption of auxiliary heating system (GJ)
E_{RES}	Thermal energy considered from renewable sources (PJ)
E_{ref}	Energy consumption of reference heating system (GJ)
$E_{T,eff}$	Effective irradiance incident on the surface (W/m^2)
$E_{T,ref}$	Reference irradiance (W/m^2)
E_{total}	Total energy consumption (GJ)
$E_{total,ref}$	Total energy consumption of reference system (GJ)
e	Fuel cost escalation rate (decimal)
F	Fuel price per unit of each fuel type (C$/unit)
F_R	Collector heat removal factor
f, f_{sol}	Solar fraction (%)
$f_{sav,ext}$	Extended fractional energy saving (%)
$f_{sav,therm}$	Fractional thermal energy saving (%)
GER	GHG emission reduction (decimal)
GHG_{CHP}	GHG emissions from combined heat and electricity generation in houses eligible for ICE cogeneration retrofit (kg of CO_{2e})
GHG_{CHS}	GHG emissions from separate heat and electricity generation in CHS (kg of CO_{2e})
GHG_{CONV}	GHG emissions from separate heat and electricity generation (kg of CO_{2e})

GHG_{N-E}	GHG emissions from separate heat and electricity generation in houses not eligible for ICE cogeneration retrofit (kg of CO_{2e})
G_T	Solar radiation incident upon the collector (W/m^2)
HDD	Heating degree days (°C)
h_{store}	Storage tank height (m)
H_{ref}	Reference insolation (W/m^2)
I	Circuit output current (A)
I_D	Diode current (A)
I_L	Difference between the light generated current (A)
$I_{mp,ref}$	Maximum power point current (A)
I_{sc}	Short circuit current (A)
$I_{sc,ref}$	Reference short circuit current (A)
i	Interest rate (decimal)
M	Mass of control volume (kg)
m	Number of different fuels used in a house
$\dot{m}$	Mass flow rate (kg/s)
K_{AB}	Heat exchange coefficient between water and working fluids (kW/K)
NH	Number of houses
N_{PV}	Number of PV panels (integer)
n	Acceptable payback period (year)/ Radiator exponent (-)
P_C	Compressor power (kW)
$P_{el,pump.DHW}$	Pump power for DHW heating loop (W)
$P_{el,pump.SH}$	Pump power for heat delivery to the space (W)
P_{in}	Power input (W)
P_{indv}	Nominal power of individual module (W)
P_{mp}	Maximum power (W)
P_{nom}	Nominal power (W)
$P_{nom,burner}$	Nominal capacity of auxiliary boiler (W)
P_0	Power loss when there is a voltage across inverter (W)
PE_{CHP}	Primary energy consumption for cogeneration (GJ)
$PE_{CHS,EE}$	Primary energy consumption for separate electricity production for the CHS (GJ)

$PE_{CHS,th}$	Primary energy consumption for separate heat production for the CHS (GJ)
PE_{conv}	Primary energy consumption of separate heat and electricity generation (GJ)
PE_{ICE}	Primary energy consumption for ICE cogeneration in houses that receive ICE cogeneration retrofit (GJ)
$PE_{N\text{-}E,EE}$	Primary energy consumption for separate electricity production in houses not eligible for ICE cogeneration retrofit (GJ)
$PE_{N\text{-}E,th}$	Primary energy consumption for separate heat production in houses not eligible for ICE cogeneration retrofit (GJ)
PES	Primary energy saving (decimal)
$\dot{Q}$	Rate of energy (W)
Q_{DHW}	Thermal energy for domestic hot water heating (GJ)
Q_{SH}	Thermal energy for space heating (GJ)
Q_{sol}	Thermal energy delivered by solar system (GJ)
Q_{usable}	Gross final thermal energy delivered by heat pump (kJ)
$q_{gen,ss}$	Heat generated by the cogeneration system in one hour (kJ/h)
R_i	Internal resistance of inverter (Ω)
RH_{amb}	Relative humidity of ambient air (%)
SE_{EE}	Electricity use (GJ)
SE_{th}	Secondary energy used for heating (GJ)
SPF_{SAHP}	Seasonal performance factor of solar assisted heat pump
TCC	Tolerable capital cost (C$)
TCCH	Tolerable capital cost of the upgrade for each house (C$)
TTCC	Total tolerable capital cost (C$)
T_{amb}	Ambient temperature (K)
T_{cell}	Cell temperature (°C)
$T_{cell,ref}$	Reference cell temperature (°C)
T_{co}	Cold side temperature (°C)
T_h	Hot side temperature (°C)
T_{in}	Collector inlet temperature (K)
T_{ref}, T_c	Reference temperature (°C)
T_{ret}, T_1	Return water temperature (°C)

T_{sup}	Air supply temperature (°C)
T_w	Water temperature (°C)
t	Time
t_{def}	Defrost time (s)
t_{tr}	Duration of transient operation of boiler (s)
$t_{op,ss}$	Hours of steady state operation (h)
U_s	Set-point voltage (V)
U_{out}	Voltage output (V)
UA	Heat loss coefficient (kW/K)
V	Volume
$V_{mp,ref}$	Maximum power point voltage (V)
V_{oc}	Open circuit voltage (V)
$V_{oc,ref}$	Reference open circuit voltage (V)
V_t	Tank volume (m^3)
$W_{el,SAHP}$	Electricity consumption of solar assisted heat pump (GJ)
W_{HP}	Electricity consumption of heat pump (GJ)
W_{par}	Parasitic power (GJ)
$W_{par,ref}$	Parasitic power of reference system (GJ)

Greek symbols

ρ	Density of water (kg/m^3)
$(\tau\alpha)_n$	Normal-incidence transmittance–absorptance
ΔT	Temperature difference
η	Ratio between total gross production of electricity and the primary energy consumption for electricity generation
η_b	Boiler efficiency
$\eta_{EE,CHP}$	Electrical efficiency of the cogeneration production
$\eta_{EE,conv}$	Efficiency reference value for separate electricity production
η_{el}	Electrical efficiency (inclusive of electricity generation, transmission and distribution efficiency)
$\eta_{th,CHP}$	Thermal efficiency of the cogeneration system

$\eta_{th,conv}$	Efficiency reference value for separate heat production
η_{ref}	Full load boiler efficiency at the reference temperature
α	Temperature coefficient of I_{sc} (K^{-1})
β	Empirical coefficient beta used in calculation of V_{oc} (-)
γ	Temperature coefficient of V_{oc} (K^{-1})
φ	Slope of the efficiency curve

Abbreviations

AB	Alberta
AL	Appliance and lighting
ASHP	Air source heat pump
ASHP-WH	Air source heat pump water heating
AT	Atlantic provinces (i.e. NF, NS, PE and NB)
AWHP	Air to water heat pump
BC	British Columbia
BIPV/T	Building integrated photovoltaic and thermal
CDD	Cooling Degree Days
CHREM	Canadian Hybrid Residential End-Use Energy and GHG Emissions model
CHP	Combined heat and power
CHS	Canadian housing stock
COP	Coefficient of performance
CSDDRD	Canadian single detached and double/row database
C$	Canadian dollar
DHW	Domestic hot water
EIF	Emission intensity factor
FC	Fuel cell
GHG	Greenhouse gas
HP	Heat pump
HHV	Higher heating value
HVAC	Heating, ventilation and air conditioning
HWT	Hot water tank

IC	Internal combustion
ICE	Internal combustion engine
IEA	International energy agency
LHV	Lower heating value
MB	Manitoba
NB	New Brunswick
NF, NL	Newfoundland and Labrador
NG	Natural gas
NPCC	Northeast power coordinating council
NS	Nova Scotia
NZE	Net zero energy
NZEB	Net zero energy building
NZEH	Net zero energy house
NZEm	Net zero emission
NZEmB	Net zero emission building
OEE	Office of energy efficiency
OT	Ontario
PCM	Phase change material
PE, PEI	Prince Edward Island
PR	Prairie provinces (i.e. MB, SK and AB)
PV	Photovoltaic
PV/T	Photovoltaic thermal
QC	Quebec
SAHP	Solar assisted heat pump
SBRN	Solar building research network
SDHW	Solar domestic hot water
SE	Stirling engine
SHC	Solar heating and cooling
SK	Saskatchewan
SNEBRN	Smart net-zero energy buildings strategic research network

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Chapter 1 Introduction

An important component of the overall efforts to reduce energy consumption and associated emissions is the adoption of low energy residential buildings, such as the passive house and the net zero energy building (NZEB) in place of traditional housing. A widely accepted definition of NZEB is "*an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy*" (NIBS, 2015). Amongst the variety of low energy building concepts, the NZEB has attracted much attention because of the alternative/renewable energy generation aspect that complements the minimized energy requirement.

NZEB design is a complicated and multifaceted problem. There are a number of ways to achieve net zero energy (NZE) status for buildings. Their feasibility is affected by a variety of parameters including building size, envelope, and heating, ventilation and air conditioning (HVAC) equipment as well as parameters such as climatic conditions, socio-economic conditions and primary energy availability and mix. The effects of these parameters and retrofit choices have highly inter-related and complex consequences on the energy performance of buildings. Several authors, such as Kapsalaki *et al.* (2012), Chlela *et al.* (2009), Salom *et al.* (2014) and Noris *et al.* (2014), developed methodologies for the design, performance evaluation and grid interaction of NZEBs. Numerical analysis (e.g. building performance simulation) is the suitable tool to examine the design options for NZEB and evaluate approaches for achieving NZE status at the housing stock level. Simulation tools were used by several researchers to study different aspects of NZEB in the planning, design, construction and operation phase. Attia *et al.* (2012) presented a simulation based design tool for planning stages of NZEB which promotes informed decision making in the early stages of design. Cellura *et al.* (2015) used building performance simulation to evaluate the performance of an existing near NZEB in Italy and to propose redesign scenarios to reach net zero electricity and net zero primary energy use. Deng *et al.* (2011) conducted a simulation based analysis to evaluate energy supply options for a typical residential building to achieve NZE status in Madrid (dry) and Shanghai (humid) climates. Analysis showed that PV generation can satisfy the electricity demand of the building in both climates. Nielsen and Möller (2012) studied the impact of thermal energy trade between NZEBs and district heating in Denmark. The results indicated that the excess heat generated by the solar thermal system may benefit the district heating system by replacing the thermal energy generation of fossil fuel based plants. Seasonal thermal energy storage might be necessary for further performance improvement during the summer. Mohamed *et al.* (2014b) studied the feasibility of a series of heating systems to achieve NZE status for a typical passive and a standard house in Finland. Results showed that the required effort to achieve net zero status was minimum for CO_2 emission, followed by primary energy, energy cost and end-use energy. The most suitable scenario may vary by house type, heating system option and parameters used for NZE balance. Marszal *et al.* (2012) evaluated the onsite and offsite renewable energy supply options including PV, micro-cogeneration and renewable electricity from the grid for NZEBs in Denmark. The results indicate that energy efficiency is an important factor for onsite energy supply options. Mohamed *et al.* (2014a) studied micro-cogeneration systems for NZEB considering a variety of thermal and electrical tracking strategies.

The success in designing and construction of NZEBs in different regions motivates and justifies the promotion of low energy design for new construction. However, the annual new construction is a small percentage of the housing stock in each country. Thus, relying on new construction to substantially decrease residential energy consumption and GHG emissions is likely unrealistic for short-term and mid-term plans. Most of the common techniques used for planning, design and construction phases of new NZEBs are not applicable to existing houses. For example, as a common practice the roof of a new NZEB is designed to provide the maximum suitable area in the proper direction to enhance PV electricity generation. Similarly, properly designed roof angle increases the PV electricity generation and reduces snow accumulation. Also, new NZEBs are usually extremely air tight and benefit from the maximum daylight to reduce the lighting load. Adding these features into an existing house can impose considerable retrofit costs that might not be economically justifiable and/or practicable.

Also, the amount of capital investment for massive retrofit scenarios that apply to large subsets of the housing stock is considerably large. Thus, various stakeholders may desire to evaluate the outcomes of such scenarios from energy, emission and economic perspectives prior to any decision for implementation. Additionally, building codes and government initiatives are essential to regulate the low energy building market. Large scale analysis at building stock level is necessary to provide the answers to those questions. For example, Schimschar *et al.* (2011) evaluated the impact of existing and future energy policies of the European Union (EU) and Germany on the development of very high energy performance buildings. The impact of such scenarios on the energy requirement and GHG emissions of the German building sector was investigated. Annunziata *et al.* (2013) conducted a survey to evaluate the integration of energy efficiency and renewable energy, as well as economic feasibility of energy savings in twenty seven EU countries. They concluded that due to various energy regulation authorities, traditional building codes and different background and maturity level in implementation of energy efficiency measures, EU countries consider different approaches to define national regulations. As a result, the building stock energy analysis should be conducted for individual countries.

In Canada, the housing stock spreads from the Atlantic to the Pacific coasts over a variety of climatic and geographical conditions and socio-economic characteristics. Furthermore, the availability and price of fuels and energy sources are also diverse. Consequently, the housing stock in each region exhibits unique characteristics in terms of vintage, geometry, construction materials, envelope, occupancy, energy sources and HVAC systems and equipment, as well as primary and secondary GHG emissions due to end-use energy consumption. This high level of diversity requires unique approaches, policies and strategies to achieve, encourage and support the conversion of Canadian houses into NZEBs.

To develop renewable/alternative energy technologies and to identify pathways that will result in reduced energy consumption and GHG emissions in the Canadian building sector, the NSERC Smart Net-Zero Energy Building Strategic Network (SNEBRN) was established in 2011. When established SNEBRN was the major research effort of building research community of Canada in smart NZEBs which brought together researchers from 15 universities across Canada, Natural Resources Canada (NRCan) and Hydro-Québec (SNEBRN, 2011).

The SNEBRN Network research is classified into the following five themes:

Theme I: Integrated Renewable Energy Systems and Heating/Cooling Systems for Buildings

Theme II: Dynamic Building Envelope Systems and Passive Solar Concepts

Theme III: Mid-to Long-Term Thermal Storage for Buildings and Communities

Theme IV: Smart Building Operating Strategies

Theme V: Technology Transfer, Design Tools and Input to National Policy

The fifth theme, of which this research is a part of, includes many facets: the coordination and implementation of demonstration projects and technology transfer as well as development of design tools and guidelines and input to standards, codes and national policy (SNEBRN, 2012).

1.1. Background

To identify feasible approaches, policies and strategies to reduce the energy consumption and associated GHG emissions of Canadian houses in the different regions of Canada, comprehensive evaluations need to be conducted separately for each region. The Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM), is a state of the art of residential sector energy consumption and GHG emissions model that was developed to conduct such analysis (Crawley, 2008; Kavgic *et al.*, 2010; Swan and Ugursal, 2009; Swan *et al.*, 2009, 2011, 2013). The main strengths of CHREM include its housing database (Canadian Single-Detached and Double/Row House Database (CSDDRD)), which represents the Canadian housing stock (CHS), as well as its advanced modeling and simulation capabilities. The CSDDRD contains detailed data from 16,952 actual houses in Canada (Swan *et al.*, 2009). CHREM utilizes an engineering/neural network hybrid approach to estimate the end-use energy consumption and GHG emissions of the CHS. This approach combines the strengths of the neural network and engineering modeling methods to estimate the energy consumption for domestic hot water heating, lighting and appliances and space cooling (Aydinalp-Koksal and Ugursal, 2008; Swan *et al.*, 2011). CHREM can assess the reduction in energy consumption and GHG emissions for each end-use and energy source due to the adoption of a wide variety of alternative and renewable energy technologies at various levels of penetration.

The objective of this research project is to identify and develop economically and technically feasible approaches, as well as policies and strategies to support the conversion of Canadian houses into NZEB. Therefore, as a prerequisite of this project CHREM was expanded to incorporate renewable/alternative energy technologies that are suitable to achieve NZE status, and the expanded CHREM was used to conduct a wide range of studies to achieve the objective of this project.

The CHREM uses ESP-r as its building energy simulation engine (ESRU, 2013). ESP-r is an advanced and thoroughly validated building performance simulation program that is capable of modelling the building thermal domain, including the building envelope and passive systems pertinent to NZEBs. ESP-r is also capable of conducting simulations at minute scale time steps required to study NZEB technologies (SNEBRN, 2012).

1.2. Potential Technologies

Potential strategies to reduce the energy consumption in the housing stock should include energy efficiency and renewable/alternative energy technologies. A wide variety of renewable/alternative energy technologies were studied in the literature as summarized in Table 1.1. Since the goal of this project is to introduce strategies to achieve NZE status for existing Canadian houses, it is necessary to consider technologies that possess four characteristics:

i. *Suitable for Individual Houses (SIH)*: The operating conditions of a potential renewable/alternative energy technology must be compatible with an individual house. For example, the operating temperature of a solid oxide fuel cell (SOFC) is typically around 600°C – 1000°C; thus the SOFC is generally used for long-term steady state operation which cannot tolerate frequent on-off cycles. Therefore, in an individual house where heat demand is continuously varying and thermal storage capacity is limited, the SOFC is not a suitable technology. Micro gas turbine is another example for a technology that is not suitable individual house, because the nominal capacity of a micro turbine is generally beyond the thermal demand of an individual household.

ii. *Easily Integrated into the CHS (EICHS)*: As discussed earlier, CHS contains a wide range of construction, geometry, occupancy and climatic conditions as well as geographical locations. Thus, a suitable technology must easily fit in an existing building in spite of the building location and climatic conditions. For example, hot water seasonal thermal energy storage system require a large space for system installation. In an existing house those systems are likely installed in an unused area on building premises. In locations with high population density, presence of an unused area is less likely rendering installation of such systems infeasible. Radiant floor system is another example which requires extensive renovation and is not a realistic retrofit for existing houses.

iii. *Commercially Available in the Residential Market (CARM)*: A pre-requisite for wide adoption of renewable/alternative energy systems is technology maturity and commercial availability. Some emerging technologies require further research to achieve reliable performance prior to attaining market share. For example, proton exchange membrane fuel cell (PEMFC) is not released as a reliable and commercially available product for residential customers.

iv. *Reliable Model for Energy Simulation (RMES)*: This study is conducted with CHREM, which use ESP-r as its simulation engine. Development, testing and validation of a new model for a given technology requires extensive effort and is beyond the timing and scope of this research. Thus, this project relies on existing reliable models for energy simulations in ESP-r.

Table 1.1 was populated by a wide range of technologies based on previous studies reported in the literature and the experience of other countries in the implementation of energy conservation programs (Asaee, 2014; Asaee *et al.*, 2016a; Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b; Asaee *et al.*, 2017a; Asaee *et al.*, 2017b; Asaee *et al.*, 2014; Banister, 2015; Beausoleil-Morrison, 2008; Chen *et al.*, 2009; Han *et al.*, 2009; Hepbasli *et al.*, 2009; Nikoofard, 2012; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d; Onovwiona and Ugursal, 2006; Pinel *et al.*, 2011; Self *et al.*, 2013). The list of potential technologies was filtered using the four criteria given above to identify the suitable technology retrofits to achieve NZE and near NZE status for Canadian houses.

Table 1.1 Energy efficiency and renewable/alternative energy technology retrofit options

Technologies	Remarks				References
	SIH	EICHS	CARM	RMES	
Cogeneration					
1. Internal combustion engine	√	√	√	√	(Asaee *et al.*, 2015a, 2015c)
2. Micro turbine			√		(Beausoleil-Morrison, 2008; Onovwiona and Ugursal, 2006)
3. Fuel cell	√	√		√	(Beausoleil-Morrison, 2008; Choudhury *et al.*, 2013; Onovwiona and Ugursal, 2006)
4. Stirling engine	√	√	√	√	(Asaee *et al.*, 2015b)
Solar based technologies					
1. Water heating					(Nikoofard, 2012)
a. Flat plate collector					
I. Thermo-syphon	√		√	√	
II. Active	√	√	√	√	(Nikoofard *et al.*, 2014b)
b. Evacuated tube					
I. Thermo-syphon	√		√		
II. Active	√		√		
2. Space heating					(Nikoofard, 2012)
a. Passive					
I. Direct gain systems					
i. Window modification	√	√	√	√	
ii. Shading devices	√	√	√	√	
a) Fixed internal or external shading (venetian blind)	√	√	√	√	

Technologies	Remarks				References
	SIH	EICHS	CARM	RMES	
b) Fixed external shading (overhang)	√	√	√	√	
II. Indirect gain systems					(Nikoofard, 2012)
i. Trombe wall	√		√	√	
ii. Distributed thermal mass	√		√	√	
iii. Phase change materials (PCM)	√	√	√	√	(Nikoofard *et al.*, 2014c)
III. Isolated gain					
i. Sunspace	√		√	√	
b. Active					
I. Active solar space heating					
i. Liquid based					
a) Flat plate collector	√	√	√	√	
b) Evacuated tube	√		√		
c) Concentrating collector			√		
ii. Air based					
II. Controlled internal and external shading devices	√	√	√	√	
3. Space cooling					(Nikoofard, 2012)
a. Thermally activated cooling systems (TACS)					
I. Solar absorption cooling system	√		√		
II. Solar desiccant technology	√		√		
4. Solar combisystem	√	√	√	√	(Asaee *et al.*, 2016b; Asaee *et al.*, 2014)
5. Photovoltaic					(Nikoofard, 2012)

Technologies	Remarks				References
	SIH	EICHS	CARM	RMES	
a. PV electricity generation	√	√	√	√	(Nikoofard, 2012)
b. Building integrated photovoltaic thermal (BIPV/T) system	√	√	√	√	(Asaee *et al.*, 2016a)
Storage					
1. Thermal					
a. Sensible heat storage					(Pinel *et al.*, 2011)
I. Water storage					
i. Water tank(s)	√	√	√	√	(Han *et al.*, 2009)
ii. Aquifer					
iii. Solar pond	√				
II. Rock bed (or gravel)	√		√		(Tatsidjodoung *et al.*, 2013)
III. Ground					
i. Soil	√	√	√		
ii. Solid rock	√		√		
IV. Storage walls	√		√		
b. Latent heat storage					(Pinel *et al.*, 2011)
I. Phase change material					
i. Organic PCMs					
a) Paraffin	√				
b) Non-paraffin	√				
ii. Inorganic PCMs					
a) Salt hydrates	√				
b) Metallic	√				
iii. Eutectics					
a) Organic eutectic	√				

Technologies	Remarks				References
	SIH	EICHS	CARM	RMES	
b) Inorganic eutectic	√				
c. Seasonal energy storage					(Pinel *et al.*, 2011)
I. Aquifer thermal energy storage	√				
II. Borehole thermal energy storage	√		√		
III. Hot water thermal energy storage	√		√		
IV. Gravel water thermal energy storage	√				
d. Chemical energy storage					(Pinel *et al.*, 2011)
I. Magnesium sulphate	√				
II. Silicon oxide	√				
III. Iron carbonate	√				
IV. Iron hydroxide	√				
V. Calcium sulphate	√				
2. Electrical					
a. Battery					(Chen *et al.*, 2009)
I. Lead acid battery	√	√	√		
II. Nickel cadmium battery	√		√		
III. Sodium sulfur battery			√		
IV. Lithium ion battery					
Ground source heat pump					
1. Closed loop system					(Bayer *et al.*, 2012; Carvalho *et al.*, 2015; Self *et al.*, 2013)

Technologies	Remarks				References
	SIH	EICHS	CARM	RMES	
a. Direct circulation system	√		√		(Fannou *et al.*, 2014; Guo *et al.*, 2012; Hakkaki-Fard *et al.*, 2015; Wang *et al.*, 2013; Yang, 2013)
b. Indirect circulation system					
i. Horizontal closed loop	√		√		(Chong *et al.*, 2013; Esen *et al.*, 2007; Sanaye and Niroomand, 2010; Tarnawski *et al.*, 2009)
ii. Pond and lake loops	√		√		(Self *et al.*, 2013)
iii. Vertical closed-loop arrays			√		(Bakirci *et al.*, 2011; De Carli *et al.*, 2014; Michopoulos *et al.*, 2013; Yang *et al.*, 2010)
2. Open loop system	√		√		(Self *et al.*, 2013)
Heat pump space and water heating					
1. Air to water heat pump	√	√	√	√	(Asaee *et al.*, 2017b)
2. Air to air heat pump	√	√	√		(De Swardt and Meyer, 2001; Ito and Miura, 2000; Li, 2015)
3. Solar assisted heat pump	√	√	√	√	(Asaee *et al.*, 2017a; Banister, 2015; Ozgener and Hepbasli, 2007)
4. Gas engine driven heat pump	√	√			(Hepbasli *et al.*, 2009)
Installation					
1. Radiant floor	√		√	√	(Athienitis, 1997; Olesen, 2002; Ren *et al.*, 2010)
2. Envelope modifications	√	√	√	√	(CMHC-SCHL, 2011; Energy Star, 2016c, 2016d; Nikoofard *et al.*, 2013)
3. Energy efficient appliances and lighting	√	√	√	√	(Energy Star, 2016a; Gardner and Stern, 2008; Young, 2008)

1.2.1. *Selected Retrofit Options for the Canadian Housing Stock*

Amongst the energy efficiency and renewable/alternative energy technologies given in Table 1.1, those that satisfy all four criteria discussed in Section 1.2 are the following:

(i) *Window modification*
(ii) *PCM thermal storage*
(iii) *Envelope modification*
(iv) *Appliance and lighting upgrade*
(v) *Internal combustion engine cogeneration*
(vi) *Stirling engine cogeneration*
(vii) *Solar combisystem*
(viii) *Air to water heat pump*
(ix) *Solar assisted heat pump*
(x) *Building integrated photovoltaic and thermal (BIPV/T)*

These technologies satisfy all four criteria mentioned in Section 1.2 and are chosen for detailed evaluation in this work to identify feasible paths to convert Canadian houses into NZE and near NZE buildings.

1.3. Research Objectives

The principal objective of this dissertation is to develop feasible approaches, policies and strategies to achieve, encourage and support the conversion of Canadian houses into NZE and near NZE building. To achieve this objective, first it is required to expand the capabilities of CHREM to model the complex plant and electrical systems and controls required in NZEBs. Thus, the project has three inter-connected objectives:

(i) Expansion of CHREM to include capability to model technologies required to achieve NZE status, including internal combustion engine and Stirling engine cogeneration, solar combisystem, solar-assisted heat pump, air to water heat pump and building integrated photovoltaic and thermal (BIPV/T) systems.
(ii) Techno-economic analysis for each individual technology retrofit.
(iii) Development of feasible approaches, policies and strategies to achieve, encourage and support the conversion of existing Canadian houses into NZE and near NZE buildings.

CHREM is uniquely suitable to conduct such analysis because of its housing database (CSDDRD) that is representative of the Canadian housing stock, as well as due to its advanced modeling and simulation capabilities.

To achieve the objective of this project, the following tasks need to be completed:

1. A series of studies needs to be conducted to assess the techno-economic impact of individual retrofit options on the energy consumption and GHG emission of the CHS,
2. Based on the results of techno-economic analysis, the most suitable retrofit scenarios in the CHS need to be identified,
3. Retrofit scenarios need to be developed to achieve NZE and near NZE status for Canadian houses and techno-economic analysis need to be conducted to evaluate the impact of those scenarios on the source energy consumption and GHG emissions of the CHS.
4. Taking into consideration the results of techno-economic studies, policies and strategy recommendations need to be developed to achieve, encourage and support the conversion of Canadian houses into NZE and near NZE buildings.

The objective of this work is to provide a clear understanding of the options and types of technologies, strategies as well as policy tools that could be used to achieve source energy and GHG emission reductions in individual houses in the different regions of Canada.

This dissertation is organized such that each selected renewable/alternative energy technology retrofit option is evaluated in a separate chapter (Chapter 2 to Chapter 9). In Chapter 10 scenarios that consist of energy efficiency, thermal storage and renewable/alternative energy technologies are evaluated and policy recommendations are made.

Chapter 2 Techno-Economic Evaluation of Internal Combustion Engine Based Cogeneration System Retrofits in Canadian Houses – A Preliminary Study

This section was previously published as:

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

2.1. Abstract

A preliminary techno-economic evaluation of retrofitting reciprocating internal combustion engine based cogeneration into existing Canadian houses for the purpose of achieving or approaching net-zero energy rating is presented. Primary energy and electricity consumption, associated greenhouse gas emissions and tolerable capital cost are used as indicators. A whole building simulation model was used to simulate the performance of a commonly used cogeneration system architecture with thermal storage in “typical” single storey houses located in Halifax, Montreal, Toronto, Edmonton and Vancouver, representing the five major climatic regions of Canada. The system is assumed to sell excess electricity to the grid at the purchase price. A high efficiency auxiliary boiler is included to supply heat when cogeneration unit capacity is not sufficient to meet the heating load. The effect of thermal storage capacity, interest rate and acceptable payback period on the overall performance was evaluated through a sensitivity analysis. The findings suggest that internal combustion engine based cogeneration provides a promising option to achieve net-zero energy rating for Canadian houses, and therefore more detailed studies focusing on the entire Canadian housing stock are needed.

2.2. Introduction and Literature Review

The Canadian residential sector is responsible for 17% and 16% of the national energy consumption and greenhouse gas (GHG) emissions, respectively (OEE, 2006). Therefore, reducing residential energy consumption will have a substantial contribution to the efforts to reduce overall energy consumption and GHG emissions in Canada. In this respect, research on technologies that would approach or achieve net-zero energy rated buildings has gained impetus (SNEBRN, 2012). Cogeneration (i.e. combined heat and power - CHP) systems that generate electrical and thermal energy simultaneously from a single source of fuel are of interest because of their higher efficiency compared to conventional systems that generate electricity and thermal energy in two separate processes. While the energy conversion efficiency of a cogeneration unit is close to 80% (based on the fuel's lower heating value, and the sum of thermal and electrical output), the efficiency of a conventional fossil fuel based electricity generation unit is about 30-35% (Onovwiona and Ugursal, 2006). In contrast to photovoltaic and wind systems, the ability to control the electricity generation is a key benefit of CHP systems, providing an opportunity to achieve net zero energy status for residential applications (Voss and Musall, 2011). Onovwiona and Ugursal (2006) classified micro cogeneration units into four major categories: reciprocating internal combustion (IC) engine based, micro turbine based, fuel cell (FC) based and reciprocating external heat source Stirling engine (SE) based. As part of a comprehensive effort to evaluate the feasibility of all four types of cogeneration systems for the Canadian housing sector to achieve or approach net-zero rating, the IC engine based system is considered in this work due to the mature technology, fuel adaptability and ubiquitous presence of IC engines in the market.

In an IC engine based cogeneration system the engine is connected to an electricity generator and recovered heat from the engine is supplied to the building to satisfy the thermal energy requirement for the space and domestic hot water (DHW) heating. Usable heat is mainly recovered from engine jacket cooling water, exhaust gas and lube oil cooling water. Thermal storage in the form of one or more water tanks is incorporated into the cogeneration system to increase the duration of the high-efficiency steady state operation of the engine. Where possible (based on electric utility company policies), a cogeneration system may use the grid as electrical storage to export and import electricity when the electricity generation of the CHP unit is not equal to the building demand.

Thermal and electrical load following operating strategies are commonly used with IC engine based cogeneration systems. In both strategies, the IC engine operation period is governed by the energy requirement of the building and storage capacity. To be able to accurately simulate the performance of the cogeneration plant it is therefore necessary to integrate CHP electricity and heat generation with building energy requirements through a whole building simulation method. Thus, numerous studies of IC engine based cogeneration systems conducted using whole building simulation approach have been reported in the literature. For example, Onovwiona *et al.* (2007) developed a parametric model that can be incorporated into a building energy simulation program to evaluate the techno-economic performance of residential scale reciprocating IC engine based cogeneration systems. The model includes IC engine, water based thermal energy and battery based electrical energy storage system as well as required control algorithms. Simulation results showed that size of the system components (IC engine, thermal and electrical storages) as well as control scenario significantly affect overall cogeneration system performance. Beyer and Kelly (2008) studied the performance of an IC engine based domestic cogeneration system for different UK housing types using a model that was validated by comparing the results of simulations with actual measurement data. Various operating strategies for the cogeneration system, with and without thermal storage, were considered. The presence and size of thermal storage were found to have significant effects on the performance of micro cogeneration system. Aussant *et al.* (2009) modeled a series of test case houses using a building performance simulation program and studied the efficiency and economic performance of residential scale IC engine based cogeneration system in Canada. Electrical and thermal loads, climatic conditions and construction characteristics of the house were found to have strong influence on the overall performance of the micro cogeneration system. Also, it was found that GHG emissions increased with the cogeneration system if the provincial electricity emission factor was lower than 400 gCO_2eq/kWh. Rosato *et al.* (2013) conducted a study to evaluate energetic, economic and environmental performance of natural gas (NG) fed reciprocating IC engine based micro cogeneration system integrated to a three storey multifamily house located in Naples, Italy. Investigation was carried out for thermal and electrical load following strategies, and the cogeneration system performance was contrasted to that of a conventional system generating heat and electricity separately. The results showed primary energy and operating cost savings as well as reduction of GHG emissions. It was concluded that compared to the electrical load following strategy, the heat load following is more beneficial in terms of primary energy consumption and GHG emissions but not operating cost.

There are also numerous experimental studies focusing on the performance of IC engine based residential cogeneration systems. For example, Possidente *et al.* (2006) conducted an experimental study to evaluate the energetic, economic and environmental performance of three different micro cogeneration systems (electric power≤15kW). They used primary energy consumption, CO_2 emissions and payback period as indicators, and compared the performance of the cogeneration systems to that of conventional generation of electricity and heat in two separate processes. A reduction of 25% and 40% in primary energy consumption and GHG emissions, respectively, were achieved using micro cogeneration while the capital cost was found to be the main obstacle to implement the cogeneration system in small scale applications. Rosato and Sibilio (2013) conducted experiments to assess the energy, exergy and environmental performance of a 6 kWe IC engine based cogeneration unit under the electrical load following strategy in Italy. They used a realistic load profile representing Italian domestic non-HVAC electrical energy requirement of a multifamily house of five dwellings. The results showed that GHG emissions decreased by 2% while the primary energy and irreversibilities decreased by 3.2% and 3.9%, respectively, compared to the conventional generation of electricity and heat in separate processes. Entchev *et al.* (2013) studied an IC engine based cogeneration system installed in a typical grid connected Canadian detached house at the Canadian Centre for Housing Technology (CCHT, 2013) to supply the required electrical and thermal energy. A high efficiency furnace was added to supply heat when the thermal energy requirement of the house exceeded the engine maximum thermal capacity. Measurements show that close to 65% of electrical load was supplied by the CHP unit while the remainder was imported from the grid. The results confirmed the energy saving during the heating season for the cogeneration system integrated with a high efficiency furnace in comparison to a conventional furnace system. It was concluded that a well sized IC engine based cogeneration system can reliably meet thermal and electrical energy requirement of the house even in Canada's extremely cold climate.

2.3. Problem Statement and Solution Methodology

This paper aims to investigate the energetic, GHG emissions and economic performance of IC engine based cogeneration system for Canadian houses based on whole building simulation. This simulation-based study is the first part of a comprehensive study to evaluate the techno-economic performance and feasibility of IC engine based cogeneration systems for the Canadian housing stock with the objective of achieving or approaching net-zero energy rating. The purpose of this study is to gain a preliminary understanding of IC engine based cogeneration system performance in the Canadian climatic conditions and to identify the suitable size of thermal storage. Based on the findings of this work, detailed simulation studies will be conducted using the Canadian Hybrid Residential Energy End-use and Emissions Model (CHREM) (Swan *et al.*, 2009, 2011) for the entire Canadian housing stock. CHREM is based on the Canadian Single-Detached and Double/Row Database (CSDDRD) (Swan *et al.*, 2009, 2011), and utilizes the high resolution building energy simulation program ESP-r (ESRU, 2015) as its simulation engine. CSDDRD is statistically representative of the Canadian housing stock (CHS). It was developed based on the available data from the EnerGuide for Houses database (SBC, 2006), Statistics Canada housing surveys (OEE, 2006), and other available housing databases. CSDDRD consists of approximately 17,000 unique house records with detailed information on geometry, construction material and air-tightness as well as heating, cooling and ventilation system (Swan *et al.*, 2009). The occupant related household energy consumption (e.g. for appliances and lights) of the house is based on a neural network model that was verified against actual data from Canadian houses (Swan *et al.*, 2011).

The ESP-r building performance simulation software and the IC engine based cogeneration system model developed within IEA/ECBCS Annex 42 based on empirical data and incorporated into ESP-r (Beausoleil-Morrison, 2008; Kelly and Beausoleil-Morrison, 2007) were used. The cogeneration system model was validated through a set of tests to evaluate the results for different modes of operation (Beausoleil-Morrison and Ferguson, 2007; Ferguson *et al.*, 2009; Rosato and Sibilio, 2012). ESP-r is an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. ESP-r has been validated through a vast amount of research results (Strachan *et al.*, 2008).

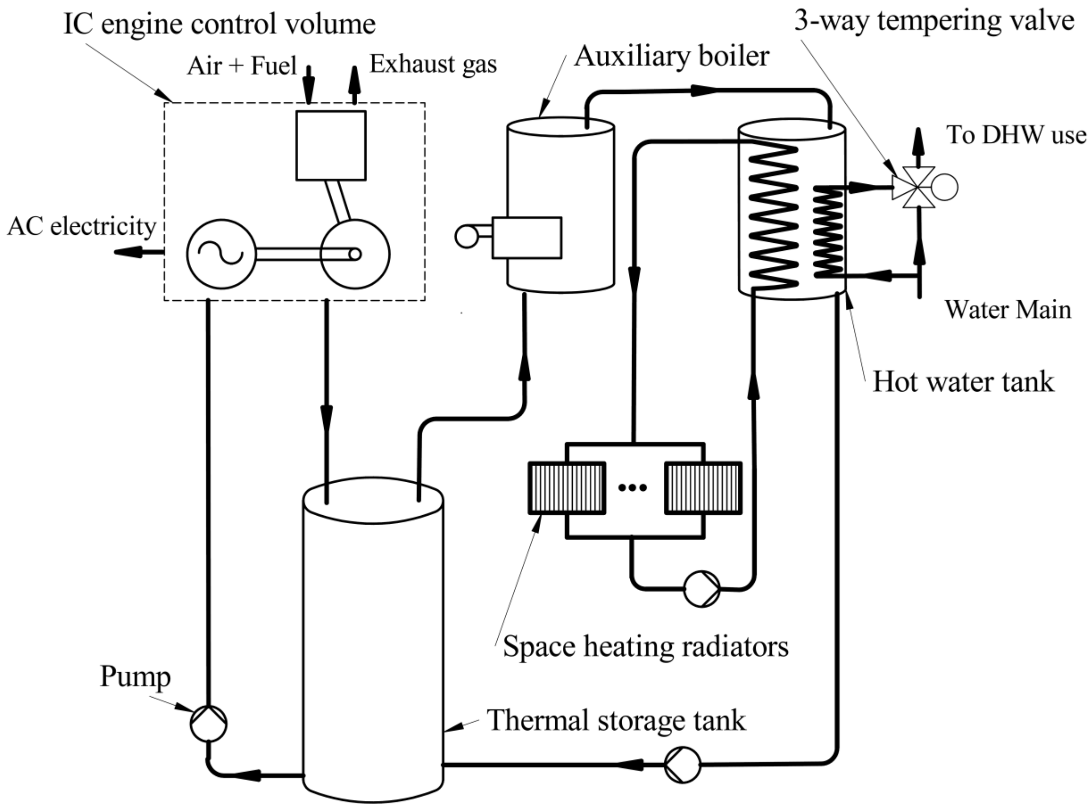

Figure 2.1 IC engine based cogeneration system architecture.

The IC engine based cogeneration system shown in Figure 2.1 is considered for retrofit to a one storey single family house under five primary climate conditions in Canada, namely, Atlantic, East, Central, Prairies and Pacific. This architecture is based on the IC engine based cogeneration system used in IEA/ECBCS Annex 42 subtask B (Kelly and Beausoleil-Morrison, 2007) and is capable of providing space and DHW heating as well as electricity to the house. The system includes a thermal storage tank for the purpose of allowing the IC engine to work for extended periods at full load and steady state to minimize fuel consumption by reducing the low efficiency operation during engine warm-up and stray losses during cool-down. An auxiliary boiler is included to provide heat when the available energy in the thermal storage tank is not sufficient to meet the thermal energy demand for space and DHW heating. A hot water tank is added to the system to store high temperature water required for space and DHW heating. Two heat exchanger coils are considered in the hot water tank to heat DHW and the circulated water in the space heating radiators. The DHW heat exchanger coil is sized based on the maximum flow rate. To avoid overheating the DHW when the flow rate is less than the maximum value, a tempering valve is used to maintain the DHW temperature at 55°C. To avoid unnecessary complexity in plant simulation within ESP-r, the three-way tempering valve is modeled using a fully mixed and adiabatic tank. The temperature of the tank is kept at 55°C and the DHW is withdrawn from the tank. Space heating is done by a hydronic system that circulates heat to radiators.

As discussed in the previous section, building load is a key parameter in the design and optimization of IC engine based cogeneration systems. Since space heating load is governed by outdoor temperature, simulations were conducted for five major climatic regions representing the Canadian climate: Halifax weather was used to represent the climate of the Atlantic region, Montreal to represent the climate of the Quebec region, Toronto to represent the climate of the Ontario region, Edmonton to represent the climate of the Prairies region and Vancouver to represent the climate of the Pacific region. The location and basic weather data for these cities are given in Table 2.1.

Table 2.1 Basic weather data for studied cities (Canadian weather for energy calculations, 2008).

Parameter		Halifax	Montreal	Toronto	Edmonton	Vancouver
Longitude		63.6	73.6	79.4	114.1	123.2
Latitude		44.6	45.5	43.7	53.5	49.2
HDD[a] (°C)		4031	4519	3570	5708	2927
Monthly average temperature (°C)	Jan	-4	-10	-7	-11	3
	Feb	-5	-9	-6	-10	5
	Mar	-2	-2	-1	-4	6
	Apr	3	6	6	4	9
	May	8	13	13	12	12
	Jun	13	18	18	15	15
	Jul	17	21	21	18	17
	Aug	18	20	20	16	17
	Sep	14	15	16	11	14
	Oct	10	9	10	5	10
	Nov	4	2	4	-6	6
	Dec	-4	-7	-4	-11	3

[a] Annual heating degree days based on 18°C

As reported in the literature, the size of system components has a significant effect on overall cogeneration system performance. Although increasing thermal storage size extends the duration of steady state operation of the IC engine, as size of the storage system increases the area of the mechanical room as well as the overall capital cost of the system increase. Thus, a sensitivity analysis was conducted to evaluate the effect of storage system size on primary energy consumption and GHG emissions.

An accurate performance evaluation of the IC engine based cogeneration system requires the simulation of the space and DHW heating loads of the house with electricity and heat generation of the CHP unit. Hence, a detailed building/plant model was developed in ESP-r to evaluate the dynamic building loads and energy supply of the cogeneration system.

The detailed building/plant model developed in ESP-r conducts an annual simulation (January 1 to December 31) with 10-minute time steps. Thus, the building model calculates the electricity as well as space and domestic hot water heating loads of the house for each 10-minute time step and passes this information to the IC engine based cogeneration plant model. The plant model, using the performance and control algorithms described below, calculates the energy input/output of the cogeneration system and the auxiliary heater, as well as the electricity import/export values. The simulation is run in this fashion for the entire year, and the results are calculated and accumulated at 10-minute time steps.

2.4. Building Model

A "typical" one-storey house, with a basement and an attic, for each city was selected from the CSDDRD as the case study house for simulations. Construction characteristics (floor area, vintage, window area, envelope thermal resistance and air tightness) and operating parameters (number of occupants, HVAC equipment type, and fuel type for heating as well as space and DHW heating system efficiencies) were used to select the case study houses. The house selected for each city has these parameters close to the average values seen in the city. The heating fuel for the study houses in Toronto, Edmonton and Vancouver is natural gas (NG) since this is the most commonly used fuel in these cities. In Halifax and Montreal, the most commonly used space heating fuel is electricity (OEE, 2014a), however the case study houses in Halifax and Montreal were selected from oil heated houses (oil is the second most common fuel in Halifax and Montreal) because retrofitting a cogeneration system into an electrically heated house would require installation of a completely new heating system (air handling unit, ducts, etc. for a water-air system, or piping, baseboard convection units, etc. for a hydronic system), rendering cogeneration retrofit infeasible. The architectural characteristics and operating parameters of the houses are given in Table 2.2 and Table 2.3.

Table 2.2 Architectural characteristics of the houses (A = area, m^2; U = heat transfer coefficient, W/m^2K; M = main zone; B = basement)

		Wall direction				Roof	Floor	Window direction			
		S	W	E	N			S	W	E	N
Halifax											
A	M	26	26	26	26	115	111*	3	8	9	2
	B	26	26	26	26	--	115	--			
U	M	0.33	0.33	0.33	0.33	0.19	--	1.9	1.9	1.9	1.9
	B	0.38	0.38	0.38	0.38	--	2.5	--			
Montreal											
A	M	32	21	21	32	110	107*	12	9	0	21
	B	32	17	17	32	--	110	--			
U	M	0.25	0.25	0.25	0.25	0.19	--	1.9	1.9	1.9	1.9
	B	0.45	0.45	0.45	0.45	--	2.5	--			
Toronto											
A	M	32	27	27	32	144	138*	10	4	3	9
	B	22	27	27	22	--	144	--			
U	M	0.42	0.42	0.42	0.42	0.15	--	1.9	1.9	1.9	1.9
	B	0.60	0.60	0.60	0.60	--	2.5	--			
Edmonton											
A	M	29	23	23	29	114	110*	1	5	8	4
	B	25	20	20	25	--	114	--			
U	M	0.33	0.33	0.33	0.33	0.18	--	1.9	1.9	1.9	1.9
	B	0.38	0.38	0.38	0.38	--	2.5	--			
Vancouver											
A	M	30	30	30	30	150	146*	16	4	4	10
	B	30	30	30	30	--	150	--			
U	M	0.47	0.47	0.47	0.47	0.21	--	1.9	1.9	1.9	1.9
	B	1.40	1.40	1.40	1.40	--	2.5	--			

* Conditioned floor area

The case study houses were modeled as three thermal zones representing the main floor, basement and attic. All thermal zones are conditioned using the HVAC system except the attic, which allowed to "free float". The basement zone and the ground are connected using the BASESIMP model (Beausoleil-Morrison and Mitalas, 1997) and the air infiltration is modeled with the AIM-2 model (Walker and Wilson, 1990). The DHW volume draw profile developed by Swan *et al.* (2009) is used.

Table 2.3 Operating data of the houses

Parameter	Halifax	Montreal	Toronto	Edmonton	Vancouver
Vintage	2000	1988	1990	1990	1992
Occupancy (people)	4	4	4	4	4
AC/h at 50 Pa depressurization	6.2	5.5	6.7	5	7
DHW usage (m^3/year)	77.5	96.6	51.4	75.9	57.9
DHW heating fuel	Elec	Elec	NG	NG	NG
DHW heating efficiency (%)	82	82	55	55	55
Space heating set-point (°C)	21	21	21	21	21
Space heating efficiency (%)	80	73	81	77	77
Space heating fuel	Oil	Oil	NG	NG	NG

2.5. Plant Model

The IC engine based cogeneration system presented in Figure 2.1 was modeled using the component models and control algorithms available in ESP-r. The ESP-r component models used are given in Table 2.4.

Table 2.4 Components used in the cogeneration system

Component name	ESP-r type description
IC engine	Annex 42 model for ICE CHP systems
Thermal storage tank	Stratified tank with up to 100 layers; 2 node model
Hot water tank (HWT)	Stratified tank with 2 immersed HXs; 3 node model
Radiator	domestic hot water radiator VO ~ 2 m^2; 2 node model
Pump	Variable speed domestic WCH pump; 1 node model
Auxiliary boiler	Non-condensing boiler & aquastat control; 2 node IEA Annex model Condensing boiler & ON/OFF control; 2 node model

The strategies used to control the cogeneration unit as well as space and DHW heating are ON/OFF algorithms. The sensor and actuator parameters for each control loop are listed in Table 2.5.

"IC engine | Tank pump" control loop as shown in Table 2.5, controls the IC engine mode and power generation as well as pump of the tank (i.e. when the IC engine starts, so does the pump). The cogeneration unit is controlled to follow the thermal load. The control parameters used in the simulations were chosen to be compatible with the space heating systems used in the residential buildings in Canada. Thus, the IC engine runs to maintain the thermal storage tank temperature in the range of 85-95°C. When the thermal storage tank temperature at supply line to the boiler drops below 85°C, the IC engine and circulating pump are turned on. HWT pump and boiler control loops sense the water temperature of the hot water tank at the supply line to the zones. The supply temperature to the radiators is maintained in the range of 88-92°C. If the IC engine capacity is not enough to balance the heat requirement, auxiliary heater supplies energy to the water.

Table 2.5 Control parameters used

Actuator	Period		Sensor location	Setpoint	
	start	end		on	off
IC engine | Tank pump	1 Jan	31 Dec	Thermal storage tank outlet to boiler	85	95
Hot water tank pump	1 Jan	31 Dec	Hot water tank outlet to zone	88	92
Boiler	1 Jan	31 Dec	Hot water tank outlet to zone	75	85
DHW Pump	1 Jan	31 Dec	DHW tank	54	56
DHW tank	1 Jan	31 Dec	DHW draw	--	--
Radiator pump	1 Jan	1 Apr	Zone main 1	20	22
	2 Apr	3 Jun		20	22
	4 Jun	16 Sep		0	1[a]
	17 Sep	7 Oct		20	22
	8 Oct	31 Dec		20	22

[a] The heating system will not turn on due to the low temperature setpoint during the cooling only season

DHW control loops are assigned to run the DHW pump and keep the DHW temperature at 55°C. The DHW consumption is controlled by patterns provided in boundary conditions and applied to the system as water draw to DHW tank.

Radiator pump control loop senses the main zone temperature and supplies hot water to radiators to maintain the zone temperature in desired range. Other zones of the house are slave of the main zone. Five periods are considered to address the heating only, cooling only and heating-cooling seasons as shown in Table 2.5.

2.5.1. IC Engine

The empirical IC engine model developed and incorporated into the ESP-r within IEA/ECBCS Annex 42 subtask B for residential cogeneration devices (Beausoleil-Morrison, 2008; Kelly and Beausoleil-Morrison, 2007) is used. The size of the cogeneration unit is selected based on the design heating load of the house from the list of commercially available cogeneration units given in Table 2.6 (BAXI, 2013; ENER-G, 2013). A cogeneration unit that just matches or is slightly undersized for the design heating load is assigned to each house, with the balance to be made up by auxiliary heat. The thermal load following method is assumed in all cases.

Table 2.6 Technical details of micro cogeneration units used

Series name	Rated output (kW)		Efficiency (%)	
	Electrical	Thermal	Electrical	Thermal
ENER-G 4Y	3.87	8.38	26.7	57.8
Dachs G 5.5	5.50	12.50	24.2	54.8
ENER-G 10Y	10.0	17.30	30.7	53.5
ENER-G 25Y	25.0	38.40	33.5	51.5

The effect of start-up and shut-down losses are ignored in the simulations based on a sensitivity analysis conducted to determine the magnitude of these losses over an entire heating season. Thus the electrical and thermal efficiencies are treated as constants. Thus, the flow rate and temperature dependency coefficients of the Annex 42 model were set to zero.

Since the smallest thermal storage tank capacity was selected to store heat generated by the IC engine over a two-hour operation, the IC engine operates for at least two hours once started, rendering the effect of start-up and shut-down losses negligible. With larger thermal storage tanks, the effect becomes increasingly smaller.

2.5.2. Water Tanks

As shown in Figure 2.1, two cylindrical tanks are used in the system: a thermal storage tank and a hot water tank.

2.5.2.1. Thermal Storage Tank

One of the objectives of this work is to determine the thermal storage tank capacity that results in the best performance of the cogeneration system. Therefore, three sizes of thermal storage tanks are considered based on the rated thermal output of the cogeneration system, i.e. capacity sufficient to store heat generated in 10, 5 and 2 hours of steady state operation of the cogeneration system, calculated using Equation (2.1).

$$V_t = \frac{q_{gen,ss} t_{op,ss}}{\rho C \Delta T_{tank}} \tag{2.1}$$

where V_t is the tank capacity (m^3), $q_{gen,ss}$ is heat generated by the cogeneration system in one hour (kJ/h), $t_{op,ss}$ is hours of steady state operation (h), ρ is density of water (kg/m^3), C is specific heat of water (kJ/kg°C) and ΔT_{tank} tank temperature range, i.e. difference between the high- and low-temperature set points for the tank, set to 10°C.

The stratified tank model implemented in the plant domain of ESP-r by Thevenard & Haddad (2010) is used. In order to minimize heat losses to the environment, the height is made equal to the diameter to minimize surface area, with the constraint that the tank height must be no greater than the basement height.

2.5.2.2. Hot Water Tank

The purpose of hot water tank is to provide heat for space and DHW heating as shown in Figure 2.1. It is sized and modeled the same way as the thermal storage tank, except its capacity is sufficient to store the heat generated by 1 hour of steady state operation of the cogeneration system. The heating coils for space and DHW heating are assumed to have the same height as the tank, and diameters 0.8 and 0.2 times, respectively, of the tank diameter.

2.5.3. Auxiliary Boiler

The condensing/non-condensing boiler models implemented in the plant domain of ESP-r by Hensen (1991) is used. The model simulates a gas fired conventional or condensing boiler. For the regions that NG is not available (i.e. Halifax), a non-condensing oil boiler is used. The nominal heating capacity for the auxiliary heating unit is selected based on the difference between design heating load of the house and heat generation of the cogeneration system during full load operation mode. Input parameters for condensing and non-condensing boilers are given in Table 2.7.

Table 2.7 Input parameters for auxiliary boiler

Parameter		Unit	Value
Component total mass		kg	50
Mass weighted average specific heat		J/kgK	1000
Upper temperature limit		°C	95
Full load efficiency	Non-condensing boiler	%	80
	Condensing boiler	%	90

2.5.4. *Space Heating Radiator*

The radiator model implemented in the plant domain of ESP-r by Hensen (1991) is used. The radiator properties derived from actual measurements (ESRU, 2015) tabulated in Table 2.8 are used. Although the nominal hot water supply and exit temperatures given in Table 2.8 are high for condensing type boilers, the same heat emission value of 1030 W per radiator is used in the model since the same heat transfer rate can be achieved with lower water temperatures and a radiator that has the same thermal mass but larger surface area. The required number of radiators for each zone is obtained by dividing the heating requirement by the nominal heat emission of the radiator.

Table 2.8 Radiator properties (ESRU, 2015)

Parameter		Unit	Value
Mass		kg	20.9
Mass weighted average specific heat		J/kgK	1350
Nominal	heat emission	W	1030
	supply temp	°C	89.7
	exit temp	°C	68.5
	environment temp	°C	22

2.5.5. *Fuel Options for the Cogeneration and Auxiliary System*

NG is available in all provinces of Canada except in the Atlantic region (NS, NB, PEI and NL) where there is very limited availability of NG for residential customers. In the Atlantic region furnace oil is the commonly used fuel source for space heating. Hence NG is considered as the primary energy source for space and DHW heating purposes in Montreal, Toronto, Edmonton and Vancouver, while the oil is considered for Halifax. Adjusted for heating value, the wholesale price of NG in Canada was 45% of the price of heating oil during the 2000's and 14% in 2013 (NRCan, 2013), as given in Table 2.9.

ESP-r calculates the heating value and CO_2 emissions for NG based on fuel composition. The typical composition of NG available in Canada (Uniongas, 2013) given in Table 2.9 is used in this work. For oil, the lower heating value and carbon intensity (kg CO_2 emission per unit weight of fuel) are used as inputs.

Table 2.9 Fuel properties

Property		NG	Oil
Mole fraction (%) [a]	Methane	95	--
	Ethane	3.2	--
	Propane	0.2	--
	Butane	0.06	--
	Pentane	0.02	--
	Carbon dioxide	0.5	--
	Nitrogen	1	--
	Oxygen	0.02	--
Lower heating value (J/kg)		--	4.6×10^7
Density (Kg/m^3)		--	840
Carbon intensity (Kg/kg)		--	3.24
Price (C$/GJ) [b]	2000-2010	5.84	12.99
	2013 (Jan-Aug)	3.10	21.83

[a] Uniongas (2013)
[b] Natural Resources Canada (2013)

2.6. Performance Evaluation Parameters

In order to estimate techno-economic performance of IC engine based cogeneration system, three metrics are used: primary energy savings index, GHG emission reduction index and tolerable capital cost.

2.6.1. Primary Energy Saving (PES) Index

To quantify the potential benefits of cogeneration in terms of the amount of primary energy savings provided, the European Parliament and Council published in Directive 2004/8/EC (OJEU, 2004) the "primary energy savings" (PES) index given by Equation (2.2). The value of PES varies between 0 and 1, with values closer to 1 indicating higher savings.

$$\mathrm{PES}=1-\frac{1}{\frac{\eta_{th,CHP}}{\eta_{th,conv}}+\frac{\eta_{EE,CHP}}{\eta_{EE,conv}}} \tag{2.2}$$

where $\eta_{th,CHP}$ = heat efficiency of the cogeneration production defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration, $\eta_{th,conv}$ = efficiency reference value for separate heat production, $\eta_{EE,CHP}$ = electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration, $\eta_{EE,conv}$ = efficiency reference value for separate electricity production.

The Directive specifies that the efficiency reference values are to be calculated according to the following principles:

- The comparison with separate electricity production shall be based on the principle that the same fuel categories are compared.
- Each cogeneration unit shall be compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit.
- The efficiency reference values for separate electricity production and heat production shall reflect the climatic differences due to location.

The PES index given by Equation (2.2) becomes meaningless if separate electricity generation is from a renewable energy source such as hydro since the term $\eta_{EE,conv}$ is undefined for renewable energy sources. This is the case for Montreal, a city in the province of Quebec, where close to 100% of the electricity production is from hydro resources (Hydro-Quebec, 2014a). However, Quebec is a member of the Northeast Power Coordinating Council (NPCC) (2014) and all surplus electricity generation in Quebec is exported to the New England and New York states (Hydro-Quebec, 2014a) where there is substantial electricity generation from fossil fuels. Thus, while the PES is undefined for Montreal within the Canadian context, a PES can be calculated for Montreal within the NPCC context using the reference efficiency of fossil fuel based electricity generation in the U.S. portion of NPCC.

Two approaches that reflect the spirit of the directive are used in this work to calculate the PES. The first approach uses efficiency parameters that reflect the best available and economically justifiable conditions in Canada and the second approach uses efficiency parameters that reflect the current conditions in Canada. In both cases, it is assumed that electricity generated by the cogeneration system replaces utility electricity generated from fossil fuels.

2.6.1.1. Approach 1

To calculate the PES that reflects the best available and economically justifiable technology used in residential heating systems and fossil fuel based electricity generation in Canada, hereafter referred to as PES(CANA), the following values were used:

$\eta_{th,CHP}$	Determined from ESP-r model simulations,
$\eta_{th,conv}$	87.4% (based on HHV) for the seasonal efficiency of the best available and economically justifiable residential scale furnace oil fired boiler on the market in Canada (Viessmann, 2015b),
	98% (based on HHV) for the seasonal efficiency of the best available and economically justifiable residential scale furnace NG fired boiler on the market in Canada (Viessmann, 2015a),
$\eta_{EE,CHP}$	Determined from ESP-r model simulations,
$\eta_{EE,conv}$	Determined based on fuel mixture for utility electricity generation from fossil fuels in each province (Statistics Canada, 2014a, 2014b) and best available efficiency of the pulverized coal, oil and NG fired power plants in North America. While NG is largely unavailable for residential customers, it is used for electricity generation in Nova Scotia.

The $\eta_{EE,conv}$ values for each province were calculated based on the 45% and 60% energy efficiency for advanced steam power (pulverized coal (International Energy Agency, 2012) and oil fired) and NG fired combined cycle (Bartos, 2011) power plants, respectively, as shown in Table 2.10. The fuel mixture was calculated based on the most recent data available for Canadian provinces, which is for 2011 and 2012 (Statistics Canada, 2014a, 2014b). The electricity transmission and distribution losses in the grid (Farhat and Ugursal, 2010) were also taken into consideration in the calculation of the PES index.

Table 2.10 Efficiency reference value for separate electricity production (%)

Scenario	Halifax	Montreal	Montreal-NPCC	Toronto	Edmonton	Vancouver
CANA	47	N/A	55	54	46	58
CANB	31	N/A	41	35	30	40

Siler-Evans *et al.* (2012) evaluated the marginal emission factors and the fuel mixture for the U.S. electricity generation from fossil fuel sources. The average fuel mixture for marginal electricity generation from fossil fuel based thermal plants within the period 2006 to 2011 in U.S. section of NPCC is used to calculate the efficiency reference value for the calculation of the PES within the Montreal-NPCC context.

2.6.1.2. Approach 2

To calculate the PES that reflects the current state of technology used in residential heating systems and fossil fuel based electricity generation in Canada, hereafter referred to as PES(CANB), the following values were used:

$\eta_{th,CHP}$	Determined from ESP-r model simulations,
$\eta_{th,conv}$	As given in Table 2.3,
$\eta_{EE,CHP}$	Determined from ESP-r model simulations,
$\eta_{EE,conv}$	Determined based on fuel mixture for utility electricity generation in each province (Statistics Canada, 2014a, 2014b) and actual efficiency of fossil fuel fired electricity generation in each region of Canada (Statistics Canada, 2007, 2009a, 2009b).

The $\eta_{EE,conv}$ values for electricity generation using fossil fuels in each province were calculated based on the most recent data from Statistics Canada as shown in Table 2.10. While the fuel mixture is calculated based on the 2011 and 2012 data (Statistics Canada, 2014a, 2014b), the reference efficiencies are calculated based on the average efficiencies of electric utility thermal plants for the period of 2005 to 2007 (Statistics Canada, 2007, 2009a, 2009b). This is due to the lack of efficiency data for the period 2011 to 2012. The electricity transmission and distribution losses in the grid (Farhat and Ugursal, 2010) were also considered in the calculation of the PES index.

The efficiency reference value for the Montreal-NPCC context was calculated based on the average fuel mixture and GHG intensity factors for marginal electricity generation from fossil fuel based thermal plants within the period 2006 to 2011 in the U.S. section of the NPCC (Siler-Evans *et al.*, 2012).

2.6.2. GHG Emission Reduction Index

To quantify the potential benefits of cogeneration in terms of the reduction in GHG emissions, a GHG emission reduction (GER) index was developed in this work. The GER is similar to the PES, and compares the GHG emissions with cogeneration to the GHG emissions with separate heat and electricity generation. Thus:

$$GER=\frac{GHG_{CONV}-GHG_{CHP}}{GHG_{CONV}} \quad (2.3)$$

where GHG_{CONV} = GHG emissions from separate heat and electricity generation, GHG_{CHP} = GHG emissions from combined heat and electricity generation.

As in the case of PES, the value of GER varies between 0 and 1, with values closer to 1 indicating larger reductions.

The same two approaches used in the calculation of PES were used to calculate GER, as follows.

2.6.2.1. Approach 1

Similar to the PES Directive principles to determine the efficiency reference values, the GHG emission values for separate generation of heat and electricity were calculated based on the following principles:

- The GHG emissions for the same fuel categories are compared.
- The GHG emissions of the cogeneration unit are compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit.

To calculate the GER that reflects the best available state of technology available in residential heating systems and fossil fuel based electricity generation in Canada, hereafter referred to as GER(CANA), the following values were used:

- The best available and economically justifiable heating technology for separate production of heat using oil in Canada is the high efficiency boiler with a seasonal efficiency of 87.4% (based on HHV, as provided by the manufacturer) (Viessmann, 2015b). The GHG emission for this boiler is 0.081 kg/MJ thermal output.
- The best available and economically justifiable heating technology for separate production of heat using NG in Canada is the high efficiency condensing boiler with a seasonal efficiency of 98% (based on HHV) (Viessmann, 2015a). The GHG emission for this boiler is 0.051 kg/MJ thermal output.

The GHG intensity factors were calculated using the best available and justifiable technology for separate electricity generation as presented in the previous section and the fuel mixture calculated based on the most recently available data for the period 2011 to 2012 (Statistics Canada, 2014a, 2014b).

To evaluate the GHG intensity factor for the Montreal-NPCC context, the average fuel mixture for marginal electricity generation from fossil fuel based thermal plants within the period 2006 to 2011 in the U.S. section of NPCC was used (Siler-Evans *et al.*, 2012). The resulting GHG emission values are given in Table 2.11.

Table 2.11 GHG intensity factors for electricity generation

Scenario	Unit	Halifax	Montreal	Montreal-NPCC	Toronto	Edmonton	Vancouver
CANA	kg/MWh	601	N/A	385	386	618	323
	g/MJ	167	N/A	107	107	172	90
CANB	kg/MWh	848	N/A	489	590	1020	448
	g/MJ	236	N/A	136	164	283	124

2.6.2.2. Approach 2

To calculate the GER that reflects the current state of technology used in residential heating systems and fossil fuel based electricity generation in Canada, hereafter referred to as GER(CANB), the efficiency values for space heating equipment given in Table 2.3 were used. The corresponding GHG emissions for the equipment are given in Table 2.12.

The GHG intensity factors were calculated using the current technology for separate electricity generation as presented in the previous section. The resulting GHG emission values are given in Table 2.11.

Table 2.12 GHG intensity factors for space and DHW heating (g/MJ)

	Halifax	Montreal	Montreal-NPCC	Toronto	Edmonton	Vancouver
Space	91	99	99	62	65	65
DHW	287	N/A	269	91	91	91

2.6.3. Economic Evaluation Using Tolerable Capital Cost

IC engine based cogeneration, especially at residential scale, is an emerging technology in Canada as it is in the USA. Hence, capital cost estimates are difficult to obtain. Although commercial scale units are more common than residential scale units, their capital costs are also difficult to estimate due to a variety of reasons. The 2014 edition of "Catalog of CHP Technologies" published by the U.S. Environmental Protection Agency states "it should also be noted that installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control requirements, prevailing labor rates, and whether the system is a new or retrofit application" (US EPA, 2014). In the absence of reliable capital cost estimates, it is not practical to use conventional cost-benefit analysis methods to evaluate the economic feasibility of residential scale IC engine based cogeneration systems. Therefore, the feasibility of IC engine based cogeneration systems is evaluated here using the tolerable capital cost (TCC) approach suggested by Nikoofard *et al.* (2014a). The TCC approach evaluates the economic feasibility of energy upgrades for buildings from the perspective of the building owner. TCC is the capital cost that building owner is able to pay for an energy upgrade based on the number of years considered acceptable for pay-back, the annual savings, and the applicable annual interest and fuel cost escalation rates.

Considering the equal value for energy cost escalation rate and interest rate, Equation (2.4) is used to evaluate the TCC for the IC engine based cogeneration system upgrade in studied houses.

$$\mathrm{TCC}=\mathrm{ACS}\times n(1+i)^{-1} \tag{2.4}$$

where ACS is the net annual cost savings due to energy upgrade (C$), n is the acceptable payback period (year) and i is the interest rate for borrowing (decimal).

Net annual cost saving is the difference between the energy cost of conventional heating system and the energy cost of the cogeneration system. Energy cost of the building is determined using Equation (2.5).

$$\mathrm{EC}=\mathrm{C}_{\mathrm{EE}}+\mathrm{C}_{\mathrm{PE}} \tag{2.5}$$

where EC is the energy cost (C$), C_{EE} is the cost of electrical energy (C$) and C_{PE} is the cost of primary energy (C$).

The unit electricity prices used in this study were obtained from 2013 edition of annual Hydro-Quebec report on electricity bills of costumers of various utilities in 21 major North American cities (Hydro-Quebec, 2014b). TCC were calculated for three scenarios including case 1 (i=3%, n=2), case 2 (i=6%, n=6) and case 3 (i=9%, n=10) to minimize effects of uncertainty in estimating the future interest rates. The maximum payback period of 10 years used in this work is within the economical lifetime of 15 years reported by the International Energy Agency (ETSAP, 2010). The fuel prices that are used in this study are presented in Table 2.13.

Table 2.13 Fuel prices in each city

	Halifax	Montreal	Toronto	Edmonton	Vancouver
Electricity[a] (cents/kWh)	16.22	7.89	14.30	15.55	9.55
Natural gas[b] (cents/m^3)	N/A	46.41	29.87	17.26	42.45
Home heating oil[‡] (cents/litre)	113.1	121.2	127.2	N/A	128.3

[a] Hydro-Quebec (2014b)
[b] Statistics Canada handbook (2014b)

2.7. Results and Discussion

The fuel and electricity consumption for the conventional heating system and the IC engine based cogeneration system for each city are given in Table 2.14.

Table 2.14 Fuel and electricity consumption with the conventional

City	Electricity from the grid (kWh)		NG (m^3)		Oil (L)	
	Conv	CHP	Conv	CHP	Conv	CHP
Halifax	14,824	4,029	-	-	1,470	2,058
Montreal	14,358	-3,469[a]	-	3,710	2,635	-
Toronto	7,103	-4,309	2,561	3,116	-	-
Edmonton	6,989	-3,094	2,981	3,157	-	-
Vancouver	16,773	7,027	2,289	2,870	-	-

[a] Negative values indicate electricity is exported to the grid

The oil consumption of the IC engine based cogeneration system is 145% of its value for the conventional system in Halifax while the cogeneration system supplies 70% of the electricity demand. The lower thermal efficiency of the cogeneration unit compared to the thermal efficiency of the conventional heating system yields higher fuel consumption to satisfy the building thermal load. The fuel source for the conventional space and DHW heating system of the house in Montreal is oil. As discussed in the previous section, the fuel source for the IC engine based cogeneration system in the present study for the house in Montreal is set to NG. The net amount of electricity generation is negative for the house in Montreal which indicates that the electricity generation of the system is higher than the electricity demand of the house, and the surplus electrical energy is exported to the grid. For the conventional heating system used in the house in Toronto, the fuel source is NG and efficiency is 81% which is in the same range as the total cogeneration efficiency. Thus, the fuel consumption to supply the heating demand of the building is higher for the cogeneration system compared to the conventional heating system. The NG consumption of the IC engine based cogeneration system for the house located in Edmonton is 1.2 of its value for the conventional heating system. Similar to the houses in Toronto and Montreal, the electricity generation of the cogeneration system exceeds the house electrical energy requirement. The NG consumption of the IC engine based cogeneration system exceeds the value of these parameters for a conventional heating system in Vancouver. Also, the total electricity generation of the IC engine is less than the electrical energy requirement of the house.

The annual operational hours of auxiliary heating system in all cities except Montreal is negligible. In Montreal the auxiliary boiler operates forty hours per year. This result indicates that the IC engine based cogeneration system has sufficient capacity to meet the heating load of the building.

In following sections, the techno-economic assessment of the IC engine based cogeneration system retrofit is evaluated using the metrics presented in Section 2.6.

2.7.1. Primary Energy Savings

The PES index calculated for each house based on the two approaches presented in Section 2.6.1 are given in Table 2.15. As discussed in Section 2.6, PES(CANA) illustrates the perspective of primary energy savings using the IC engine based cogeneration system as an alternative to the best available fossil fuel based conventional heat and electricity generation system in Canada.

Table 2.15 PES index for studied houses

Scenario	Halifax	Montreal	Montreal-NPCC	Toronto	Edmonton	Vancouver
CANA	0.25	N/A	0.19	0.14	0.21	0.12
CANB	0.41	N/A	0.36	0.38	0.44	0.36

The maximum PES(CANA) index is achieved for Halifax followed by Edmonton. This is due to the higher coal portion in the fuel mixture for electricity generation in Nova Scotia (Halifax) and Alberta (Edmonton) compared to its value in the other provinces of Canada(Statistics Canada, 2014a, 2014b). Thus, the efficiency reference value for Halifax and Edmonton are the lowest among the five cities, as shown in Table 2.10. Additionally, the efficiency of the oil fired furnace used in Halifax is lower compared to the NG fired ones used in Edmonton. While the PES for Montreal is undefined within the Canadian context, the PES calculated for the Montreal-NPCC context indicates a substantial opportunity for primary energy savings within the NPCC as shown in Table 2.15. While the efficiency of conventional electricity generation in Quebec, Ontario and British Columbia are in the same range, the PES(CANA) is higher in Montreal-NPCC compared to Toronto and Vancouver. This is due to the lower efficiency of the oil fired furnace used for space heating in Montreal compared to NG fired furnace for space heating in Vancouver and Toronto. Since the geometric and operational parameters for the studied houses were the average values of existing Canadian houses, these results confirm the potential role of IC engine based cogeneration system to reduce primary energy consumption in the Canadian housing stock.

PES(CANB) was calculated based on the efficiency of actual technology used for electricity generation and heating purposes in Canada. While the PES(CANA) varies considerably in five cities studied in this paper, the variation of PES(CANB) is about 20% among the cases that only consider fossil fuel for electricity generation. This result shows the importance of considering the actual status of electricity generation in the evaluation of primary energy savings due to cogeneration retrofit.

As discussed earlier PES(CANB) represents the most realistic scenario to calculate the primary energy saving due to IC engine based cogeneration upgrade. The significant difference between PES(CANA) and PES(CANB) show the effect of efficiency of conventional heat and electrical energy generation on the potential role of the CHP system to reduce primary energy consumption. Thus, any strategy to encourage manipulating cogeneration system in the residential sector should consider the existing technologies for energy conversion. The value of PES(CANB) for the houses considered in this study show the effectiveness of using IC engine based cogeneration systems to approach net zero energy status in existing Canadian houses.

2.7.2. *GHG Emission Reduction*

The portion of the GHG emission that is associated with electricity generation compensates the total GHG emission of the cogeneration system and the overall GHG emissions of the building is reduced. The results of GER index calculations based on the two approaches given in Section 2.6.2 are presented in Table 2.16.

Table 2.16 GER index for studied houses

Scenario	Halifax	Montreal	Montreal-NPCC	Toronto	Edmonton	Vancouver
CANA	0.34	-0.13	0.51	0.35	0.52	0.10
CANB	0.45	0.06	0.63	0.63	0.78	0.28

As discussed in Section 2.6.2, The GER(CANA) approach provides the GHG reduction due to using IC engine based cogeneration system to replace the best available conventional heat and electricity generation system in Canada. Due to this fact the amount of GHG reduction as a result of IC engine based cogeneration system retrofit is lower compared to the CANB scenario that considers actual fossil fuel based conventional heat and electricity generation. The highest GHG emission reduction is associated with the cogeneration retrofit in Montreal-NPCC and Edmonton. The considerable amount of coal in the fuel mixture for electricity generation in Alberta provides a favorable opportunity for IC engine based cogeneration retrofit to reduce GHG emissions in Edmonton. As shown in Table 2.11, the GHG intensity factor for conventional electricity generation in Montreal-NPCC is the second lowest. Thus, the GHG emissions reduction as a result of exporting electricity to the grid is less effective in the Montreal-NPCC context compared to the Halifax, Toronto and Edmonton cases. The main reason for the high value of GER(CANA) index in the Montreal-NPCC context is switching the fuel source from oil to NG. Also, the efficiency of the original heating system in Montreal is the lowest compared to the other houses. While the GHG intensity factor for electricity generation in Toronto is about 60% of its value in Halifax, as shown in Table 2.11, the GER(CANA) is in the same range for these two cities. This is due to the considerable amount of electrical energy saving as a result of using CHP system in the house in Toronto. Diversely, the cogeneration unit for the house in Vancouver yields 10% reduction in GHG emissions. This is because of the small value of GHG intensity factor for the conventional electricity generation in British Columbia. The

GER(CANA) index is positive for all of the cases which is evidence that cogeneration is beneficial from an environmental point of view for the Canadian housing stock. However, the negative value of GER(CANA) for Montreal case shows that the IC engine based cogeneration system is not environmentally beneficial in Montreal, if the electricity export from Quebec to New York and New England states is ignored.

The GER(CANB) is the most realistic approach to evaluate the GHG emissions reduction caused by replacing the existing fossil fuel based heat and electricity generation by IC engine based cogeneration. In contrast to the results of GER(CANA) scenario, the GER(CANB) is approximately neutral for Montreal. The GHG emission reduction due to IC engine based cogeneration retrofit in Edmonton is the maximum among five major Canadian cities studied in this paper. As discussed before, this is due to the high portion of coal in fuel mixture for electricity generation in Alberta. Within the Montreal-NPCC context, the IC engine based cogeneration retrofit approximately cuts half of GHG emissions.

2.7.3. Economic Evaluation Using Tolerable Capital Cost

The TCC for three payback periods and interest rates for the IC engine based cogeneration system upgrade are presented in Table 2.17. The results show that while the electricity and NG prices in Montreal are the lowest and the highest values in Canada, respectively, the TCC of the house located in Montreal is the highest. The main reason for the considerable difference in the TCC in Montreal and other cities is the changing of the fuel source from furnace oil to NG and substantially higher price per energy content of furnace oil compared to NG, as shown in Table 2.9. While the electricity price in Halifax is the highest in Canada the TCC for the house in Halifax is less than TCC in Toronto and Edmonton. This is due to the fact that the cogeneration unit burns NG in all cities except Halifax. As mentioned before, the price per energy content of oil is much higher than that of NG, which increases the fuel cost of the house in Halifax. Since the low cost NG is available in Alberta and conventional electricity generation cost is relatively high, the TCC for the house in Edmonton is the second highest. The low energy cost in British Columbia yields the minimum TCC for the house in Vancouver.

Table 2.17 Tolerable capital cost for cogeneration upgrade (C$)

City	Case 1	Case 2	Case 3
Halifax	2,109	6,147	9,963
Montreal	5,589	16,293	26,407
Toronto	2,847	8,299	13,451
Edmonton	2,985	8,703	14,106
Vancouver	1,328	3,872	6,276

Overall, the calculated TCC provides a promising outlook for the cogeneration system in existing Canadian houses. The next step for this study is to conduct a comprehensive study in provincial and national scale to estimate the potential role of IC engine based cogeneration unit to approach net zero energy status in existing Canadian houses.

2.7.4. Sensitivity Analysis

To evaluate the effect of storage size on energetic and environmental performance of IC engine based cogeneration system, the size of the thermal storage tank was changed while other parameters were kept at baseline values. The results of the sensitivity analysis are presented in Table 2.18.

Table 2.18 Effect of storage size on fuel and electricity consumption and GHG emissions

City	Electricity (kWh)		NG (m^3)		Oil (L)		GHG emission (kg)	
	Small tank	Large tank	Small tank	Large tank	Small tank	Large tank	Small tank	Large tank
Halifax	4,057	3,584	-	-	2,053	2,206	9,378	9,431
Montreal	-3,275[a]	-4,330	3,651	3,974	-	-	7,497	8,173
Toronto	-4,143	-4,726	3,065	3,243	-	-	5,627	5,874
Edmonton	-2,829	-3,883	3,085	3,411	-	-	4,545	4,177
Vancouver	7,694	5,860	2,679	3,209	-	-	5,706	6,766

[a] Negative values indicate electricity exported to the grid.

Three sizes of thermal storage tank were evaluated. The "small" storage tank is sized to store heat produced during 2.5 hours (2.7 m^3) of IC engine operation, while the "medium" tank is sized for 5 hours (5.4 m^3), and the "large" tank for 10 hours (10.8 m^3) of operation. The medium storage size represents the volume of thermal storage tank used in the previous sections. While the small storage tank may be considered to be uncommonly large for a conventional heating system in a single-family house, it is selected in this work to provide sufficient thermal energy storage capacity in order to utilize the thermal potential of the cogeneration system.

The results show that increasing the size of storage tank yields a higher oil and NG consumption as well as higher electricity generation. The thermal energy required to fully charge a large tank is higher compared to smaller tank. The IC engine operates to fully charge the tank during each cycle and the tank is discharged by space and DHW heating requirement and heat losses. While during the heating season energy demand is mainly governed by space heating, in cooling season the DHW heating is the only thermal energy requirement of the building. Thus, during the cooling season the discharge process of the storage tank is mainly governed by DHW heating energy requirement and the tank heat losses to the environment. The cogeneration system is sized to address the peak heating energy demand of the house; therefore the energy stored in a fully charged tank is much higher than the thermal energy requirement for DHW heating. Thus, enlarging the volume of storage tank increases the discharge period and yields to greater heat losses during the cooling season. As a result, the total CHP unit operational hours and fuel consumption is higher for a large tank compared to the small tank. An increase in operational hours of the IC engine enhances the electricity generation of the cogeneration system and the unit energy cost of the IC engine based cogeneration system slightly decreases as the storage tank volume increase. The operational period of auxiliary system in Montreal increased to 60 hours per year by decreasing the thermal storage size; however, the fuel consumption of auxiliary boiler compared to IC engine fuel consumption is insignificant. Thus, the overall cogeneration system NG consumption increased by enlarging the thermal storage tank volume in Montreal. The results of the sensitivity analysis in this study are in agreement with the results of similar studies in the literature. Haeseldonckx *et al.* (2007) show that increasing the size of storage tank yields to higher operational hours of the IC engine. They conclude that there is no benefit to use a small or large storage tank able to store the generated heat during less than 1 hour or more than 2 hours of engine operation. Bianchi *et al.* (2012) conducted an analytic study and show that the storage tank with a capacity to store the generated heat during more than 2 hours of IC engine operation has no effect on CHP operating hours. The effect of heat losses which has a negative role was not considered in that study. In another study, Barbieri *et al.* (2012) evaluated the effect of thermal storage size for micro cogeneration unit with different prime movers. They showed that increasing the size of storage tank yields to higher CHP operating hours and NG consumption.

The environmental impact of storage tank volume is not similar for all houses studied in this work. The GHG emissions are clearly increased by enlarging the storage size for the cogeneration systems installed in Montreal, Toronto and Vancouver, while the GHG emissions are reduced by enlarging the storage tank volume in Edmonton while it remains approximately the same for the house in Halifax. As discussed before, the total operating hours and fuel consumption of IC engine is higher for a cogeneration system that utilizes a large storage tank compared to a system with small size tank. This means that the GHG emissions associated with the IC engine operation increase by enlarging the storage volume. In regions that fossil fuels are used to generate electricity, reduction of GHG emissions associated with the electricity generation by the cogeneration unit is significant. Thus, in Edmonton, the total GHG emission of cogeneration unit does not increase by increasing the size of storage tank.

Table 2.19 Tolerable capital cost of IC engine based cogeneration system for two thermal storage tank sizes and economic parameters given in section 2.4 (C$)

City	Small tank			Large Tank		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Halifax	2,111	6,153	9,973	1,924	5,608	9,089
Montreal	5,612	16,361	26,518	5,483	15,984	25,906
Toronto	2,830	8,251	13,373	2,889	8,422	13,650
Edmonton	2,930	8,540	13,842	3,139	9,149	14,829
Vancouver	1,362	3,971	6,436	1,265	3,689	5,978

The TCC using the same scenarios considered in Section 2.6.3 for the cogeneration system with small and large thermal storage tanks are presented in Table 2.19. The results show that the highest TCC in Toronto and Edmonton is associated with large tank while the small tank has the highest TCC in Halifax, Montreal and Vancouver. As mentioned before, the IC engine connected to a large tank consumes more oil compared to other cases in Halifax. Since the oil price is substantiality high, the excess electricity generation of cogeneration unit coupled to a large thermal storage tank is not sufficient to reduce the energy cost of system; therefore the TCC increases with enlarging the thermal storage tank size. Due to the availability of low-cost electricity in Montreal and Vancouver, the excessive generated electricity of cogeneration unit cannot justify the price of additional NG used for operation of cogeneration unit that utilizes large storage tank.

2.8. Conclusion

An IC engine based cogeneration system is studied to evaluate the techno-economic performance of this system in actual houses in five major climatic conditions of Canada. Primary energy saving index, GHG emission reduction opportunity and tolerable capital cost are used for evaluation of energetic, environmental and economic performance of IC engine based cogeneration systems. A high efficiency boiler is added to the plant to supply heat to the house during the days that cogeneration unit capacity is not sufficient to meet heating load. Based on the fuel availability in each jurisdiction, NG and furnace oil are the fuel choice for the cogeneration unit and auxiliary burner. Simulations are conducted for Halifax, Montreal, Toronto, Edmonton and Vancouver representing the five major climatic conditions of Canada (Atlantic, Quebec, Ontario, Prairies and Pacific). Two approaches are used to evaluate the PES and GER indexes for each house. Tolerable capital cost was calculated under three combinations of annual interest rate and payback period. A sensitivity analysis was conducted to estimate the effect of storage on the overall performance of the cogeneration system.

As discussed earlier in this paper, several earlier and comprehensive studies that focus on the feasibility of IC engine based cogeneration systems have been reported in the literature. This paper presents a new and unique perspective for the Canadian housing sector due to the following unique innovations:

(i) The case study houses are selected from a statistically representative database of the Canadian housing stock. As such, the results of this work can be used with confidence in evaluating the potential of IC engine based cogeneration systems in the Canadian context.

(ii) The architecture of the IC engine based cogeneration system used in this work is based on the system developed by Annex 42 Subtask B of IEA/ECBCS and contains a thermal storage tank to maximize the efficiency of the system.

(iii) Since the installed cost of residential scale cogeneration systems is difficult to obtain, and highly variable in different parts of Canada, it is not possible to conduct a reliable economic analysis using conventional economic analysis methods. Therefore, in this study the Tolerable Capital Cost analysis approach is used to estimate the capital cost that will be found "tolerable" under a range of economic parameters.

(iv) This is the first time the PES index is used to quantify the potential benefits of a cogeneration system in the Canadian context. To adapt the European based PES index to the Canadian context, this work developed two new approaches in defining the PES index.

(v) A new GER index, similar in principle to the PES index, was developed in this work to quantify the potential benefits of cogeneration in terms of reducing GHG emissions.

Results of simulations indicate that from the primary energy saving perspective the IC engine based cogeneration upgrade is beneficial for existing Canadian houses in all regions excluding Quebec due to the predominance of hydro generated electricity in that province. However, the IC engine based cogeneration system retrofit in Montreal yields lower primary energy consumption within the NPCC scale. From environmental point of view, the IC engine based cogeneration system is a favorable alternative for conventional energy conversion systems in all of the houses in the five climatic regions of Canada. However, in order to evaluate the environmental impact of IC engine based cogeneration systems in regional and national scale, a more comprehensive study based on the entire CSDDRD is required.

The tolerable capital cost analysis indicates that the potential for IC engine based cogeneration system in Canadian houses is economically acceptable. Results of the sensitivity analysis done to evaluate the impact of increasing the thermal storage tank volume to enhance the total operational hours of IC engine show that the large storage tank is not a suitable option from energetic and environmental point of view in most cities. The

TCC is used to evaluate effect of thermal storage tank size on the energy cost and required capital cost of the cogeneration system. It is concluded that the TCC of large storage tank is not sufficient to encourage using a bulky storage tank; thus, small size storage tank is preferable in Canadian housing stock. Future studies will be focused on overall energetic, economic and environmental impact of IC engine based cogeneration system in regional and national scale for Canadian houses. The proposed study will be conducted by manipulating the results of this study in the Canadian Hybrid Residential Energy End-use and Emissions Model.

Chapter 3 An Investigation of the Techno-Economic Impact of Internal Combustion Engine Based Cogeneration Systems on the Energy Requirements and Greenhouse Gas Emissions of the Canadian Housing Stock

This section was previously published as:

Asaee, S.R., Ugursal, V.I. and Beausoleil-Morrison, I., 2015. An investigation of the techno-economic impact of internal combustion engine based cogeneration systems on the energy requirements and greenhouse gas emissions of the Canadian housing stock. *Applied Thermal Engineering*, *87*, pp.505-518. doi: http://dx.doi.org/10.1016/j.applthermaleng.2015.05.031

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

3.1. Abstract

This study provides a techno-economic evaluation of retrofitting internal combustion engine (ICE) based cogeneration systems in the Canadian housing stock (CHS). The study was conducted using the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM). CHREM includes close to 17,000 unique house files that are statistically representative of the Canadian housing stock. The cogeneration system performance was evaluated using a high resolution integrated building performance simulation software. It is assumed that the ICE cogeneration system is retrofitted into all houses that currently use a central space heating system and have a suitable basement or crawl space. The GHG emission intensity factor associated with marginal electricity generation in each province is used to estimate the annual GHG emissions reduction due to the cogeneration system retrofit. The results show that cogeneration retrofit yields 13% energy savings in the CHS. While the annual GHG emissions would increase in some provinces due to cogeneration retrofits, the total GHG emissions of the CHS would be reduced by 35%. The economic analysis indicates that ICE cogeneration system retrofits may provide an economically feasible opportunity to approach net/nearly zero energy status for existing Canadian houses.

3.2. Introduction

Energy use in Canada increased by 22.3 percent between 1990 and 2010. According to the Office of Energy Efficiency (OEE), in 2010 Canadian households were responsible for 16 percent of the total national energy use and 14 percent of the greenhouse gas (GHG) emissions, and spent $26.3 billion on their energy needs (OEE, 2013). Of the total energy use in the Canadian residential sector, 80 percent is associated with space and domestic hot water (DHW) heating and 18 percent is for appliances and lighting (OEE, 2013). Thus, there is increasing interest to reduce the energy consumption and associated GHG emissions of the Canadian housing stock by retrofitting individual houses and communities with advanced and renewable energy options to approach or achieve net-zero energy (NZE) status. To facilitate a national scale research effort in identifying feasible technologies and paths to approach or achieve NZE status, the Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN) initiative was recently established (SNEBRN, 2012).

Cogeneration (i.e. combined heat and power - CHP) systems that generate electrical and thermal energy simultaneously from a single source of fuel are of interest because of their higher efficiency compared to conventional systems that generate electricity and thermal energy in two separate processes. Onovwiona and Ugursal (2006) classified micro cogeneration units into four major categories: reciprocating internal combustion (IC) engine based, micro turbine based, fuel cell (FC) based and reciprocating external heat source Stirling engine (SE) based. As part of a comprehensive effort to evaluate the feasibility of different cogeneration systems for the Canadian housing sector to achieve or approach net-zero rating, the IC engine based system is considered in this work due to the mature technology, fuel adaptability and ubiquitous presence of IC engines in the market. Several authors used experimental and numerical approaches to study residential scale ICE cogeneration systems. For example, Aussant *et al.* (2009) developed a series of test case house models using a building performance simulation program to assess the economic feasibility and efficiency of residential scale ICE cogeneration system in Canada. It was concluded that electrical and thermal loads as well as climatic conditions and construction characteristics of the house may have strong influence on the overall performance of the micro cogeneration system. It was also found that the increase in the fuel cost of household due to the cogeneration system could be justified by the electricity trade with the grid.

Aliabadi *et al.* (2010) conducted a study to compare three natural gas powered micro cogeneration systems (i.e. ICE, SE and FC) from energy, exergy and marginal efficiency perspectives. The analysis showed that for all three systems, the ICE cogeneration system energy and exergy efficiencies increase with heat use. Caresana *et al.* (2011) modeled a 28 kW_e natural gas fired ICE cogeneration system to investigate the constant and variable speed operation modes. Techno-economic analysis showed that good energy and economic performances compared with a conventional heat and electricity generation system can be achieved in a 10-flat apartment building. Beausoleil-Morrison (2008) and Ferguson *et al.* (2009) developed a model for residential scale ICE cogeneration system as part of IEA/ECBCS Annex 42. The model was implemented into a series of whole building simulation programs including EnergyPlus, ESP-r and TRNSYS. Measured data were used for the model calibration and validation of the predicted results. Rosato and Sibilio (2012) used the test results of a natural gas fired ICE cogeneration system to calibrate and validate the IEA/ECBCS Annex 42 model. The results of the study showed a good agreement in the predictions of net electricity and heat generation as well as fuel consumption of the micro cogeneration unit. Entchev *et al.* (2013) studied an ICE cogeneration system performance in a typical grid connected Canadian detached house at the Canadian Centre for Housing Technology (CCHT, 2013). The cogeneration system was coupled with a high efficiency furnace to supply heat when the thermal energy requirement of the house exceeded the thermal capacity of the cogeneration system. Measurements showed that close to 65% of electrical load was supplied by the cogeneration unit while the remainder was imported from the grid. The results confirmed the energy savings during the heating season for the cogeneration system integrated with a high efficiency furnace in comparison to a conventional furnace system. It was concluded that a well sized ICE cogeneration system can reliably meet thermal and electrical energy requirements of the house even in Canada's extremely cold climate.

A series of studies were focused on the impact of implementing cogeneration systems on both gas and electricity grid as well as home owners. For example, Peacock and Newborough (2006) studied the effects of micro cogeneration retrofit into both single and group of dwellings in the UK. The data of gas and electricity consumption on a 1-min time base over a full year was used in calculations. The results indicate that a micro cogeneration system with a thermal load following scenario reduced the daily load factor for electricity network, while increasing prime mover capacity, efficiency and daily run time yielded lower load factor. It was concluded that the highly efficient large cogeneration systems with a low penetration level might have the similar effect on the daily grid electricity requirement as high penetration deployment of small low efficient systems. Boait *et al.* (2006) used a simple computer model to integrate the time distribution and use of the electricity generation of micro cogeneration system with a stochastic model of the electricity demand in a UK dwelling. The study was conducted for six scenarios including three different house types and two levels of occupancy and appliance use. The results showed that based on the thermal characteristics of the house and occupant behaviour, up to 62% of generated electricity by the cogeneration system might be exported to the grid. It was concluded that the economic feasibility of micro cogeneration systems was affected by the thermal characteristics of the building, as well as occupant behaviour, including heating time and thermostat settings. Costa and Matos (2009) used an analytical model to assess the impact of micro cogeneration on the avoided electrical losses in the grid. The results showed that implementation of micro cogeneration systems may significantly avoid electricity losses in the grid. Vandewalle and D'haeseleer (2014) studied the effects of high penetration levels of micro cogeneration systems on the gas supply system. It was shown that using generic heat demand profiles yields overestimated results. Also, the results indicated that increasing the size of thermal storage tank may reduce the gas demand at peak periods. It was concluded that large scale implementation of micro cogeneration systems might not cause any problems in the gas network, even at a massive penetration levels.

Energy saving and high efficiency energy technology retrofits if implemented in large scale may yield reduction of energy consumption and greenhouse gas (GHG) emissions in the residential sector. Accurate housing stock models are likely required to assess any potential scenarios. Nikoofard *et al.* (2013, 2014b, 2014c, 2014d) studied the impact of retrofitting a series of solar technologies including window and windows shading upgrade as well as solar domestic hot water (SDHW) heating and manipulation of phase change materials (PCM) on energy consumption and GHG emissions of CHS. These studies show that such retrofits have the potential to significantly reduce the energy consumption and GHG emissions of the Canadian residential sector. Firth *et al.* (2010) developed the Community Domestic Energy Model (CDEM) to estimate the GHG emissions of English housing stock and studied the potential methods to reduce the GHG emissions. The results showed the significant impact of underperformance of energy-efficiency measures on the GHG emissions. Ren *et al.* (2012) developed a bottom-up model to estimate annual energy consumption (with an hourly resolution) of a housing stock at a local community level in New South Wales, Australia. The model predicted hourly electricity consumption and peak demand which can be used for grid planning and local energy efficiency strategies. Ampatzi *et al.* (2013) studied the opportunities to supply the space and DHW heating using active hydronic solar technologies in houses in Northern Europe. A model including twelve typical dwelling representative of half of the Welsh housing stock was developed. It was shown that high solar fraction might be achieved using large collector area and storage capacities.

As discussed earlier, a potential scenario to a NZEB might be achieved by a combination of energy demand reduction options through energy efficiency measures as well as electricity and thermal energy generation by means of on-site and off-site energy supply options (Sartori *et al.*, 2012). Thus as part of the research efforts of the SNEBRN, Asaee *et al.* (2015c; 2014) recently conducted a series of case studies to evaluate the impact of solar combisystem and residential internal combustion (IC) engine based cogeneration system retrofits on energy consumption and GHG emissions of existing houses in major climatic regions of Canada. The latter study showed that ICE cogeneration systems provide a promising option to approach or achieve NZE rating. While this favourable finding is encouraging, due to the substantial differences in climate, primary fuel availability, fuels used in electrical generation, as well as the differences in construction, heating/cooling equipment and appliance characteristics in the different regions of Canada, a comprehensive evaluation is required to determine with confidence the techno-economic impact of large scale implementation of ICE cogeneration system retrofits in the CHS. This study was therefore conducted using the Canadian Hybrid Residential End-Use Energy and Emissions Model (Swan, 2010; Swan *et al.*, 2013).

3.3. Methodology

Due to the wide range of climatic, geographical and economic conditions as well as the availability and price of fuels and energy sources in different regions, the CHS exhibits a high diversity in geometry and construction materials as well as heating, cooling and ventilation systems. Thus, this study was conducted using CHREM (Swan, 2010; Swan *et al.*, 2013), which is based on the Canadian Single-Detached Double/Row Database (CSDDRD) (Swan *et al.*, 2009) and is statistically representative of the CHS. CHREM utilizes the high-resolution building energy simulation program ESP-r (ESRU, 2015) as its simulation engine, an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. ESP-r has been validated through a vast amount of research results (Strachan *et al.*, 2008). 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 unique 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:

- The Canadian Single-Detached & Double/Row Housing Database (Swan *et al.*, 2009),
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households (Swan *et al.*, 2011),
- 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 (Farhat and Ugursal, 2010),
- A model to estimate GHG emissions from fossil fuels consumed in households.

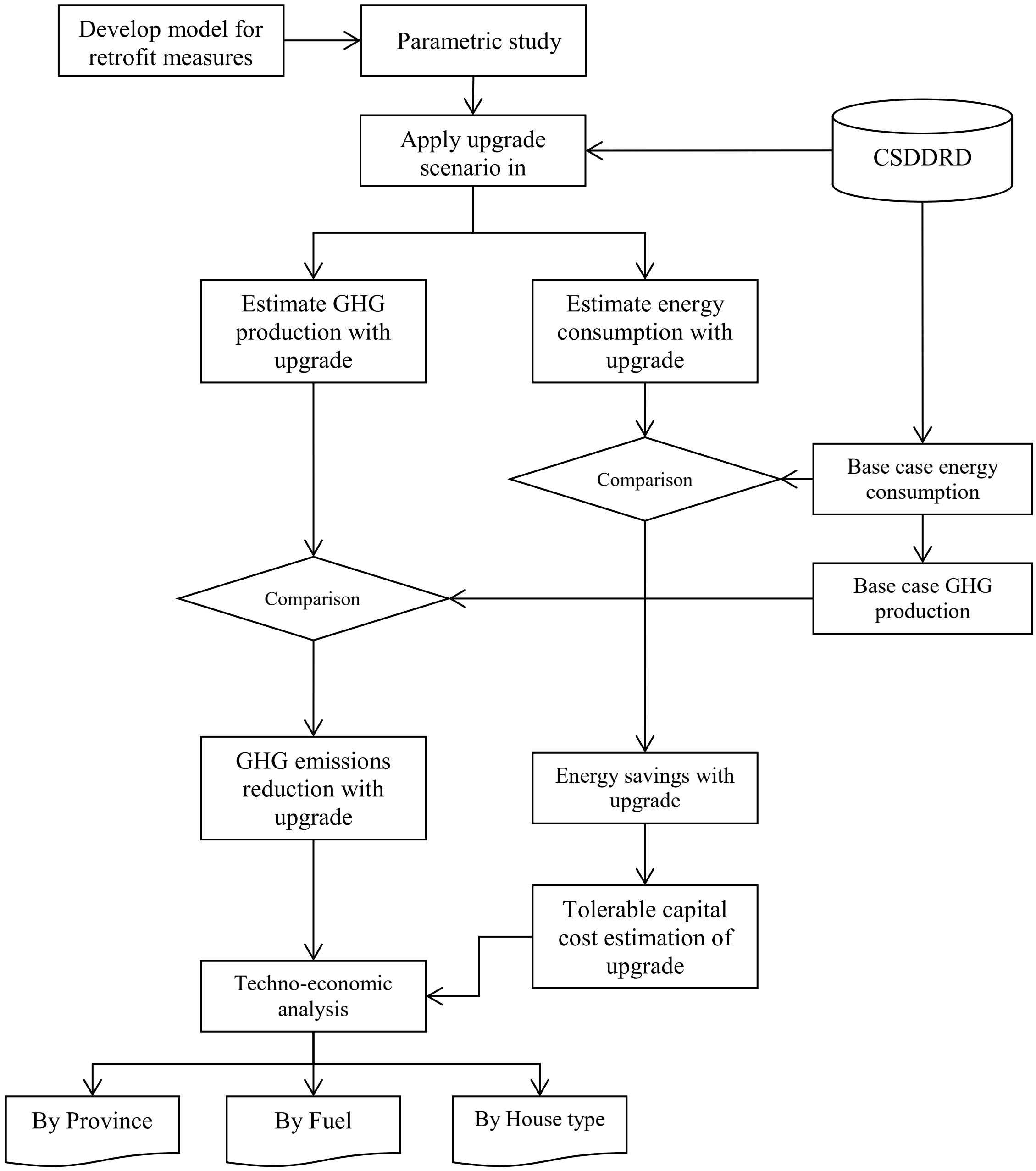

Figure 3.1 Flow diagram of the overall methodology that is used in this study (Nikoofard *et al.*, 2014).

As shown in Figure 3.1, the energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as cogeneration systems, can be estimated using CHREM as follows:

(i) Identify houses suitable to receive the upgrade/technology: For IC engine cogeneration system retrofit, only houses with a basement or a mechanical room would be suitable. Therefore, a search has to be conducted in the CSDDRD to identify such houses.

(ii) Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.

(iii) Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the "base case" (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010). Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

CHREM has so far been used to evaluate the energy, economic and emissions performance of window and window shading upgrades, PCM for thermal energy storage and solar domestic hot water heating system retrofits in the CHS (Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

3.3.1. Modeling the ICE Cogeneration System

The ICE cogeneration system shown in Figure 3.2 is considered for retrofitting existing and eligible Canadian houses. This architecture is based on the ICE cogeneration system used in IEA/ECBCS Annex 42 subtask B (Kelly and Beausoleil-Morrison, 2007) and is capable of providing space and DHW heating as well as electricity to the house. The system includes a thermal storage tank for the purpose of allowing the IC engine to work for extended periods at full load and steady state to minimize fuel consumption by reducing the low efficiency operation during engine warm-up and stray losses during cool-down. The size of the cogeneration unit is selected based on the design heating load of the house from the list of commercially available cogeneration units given in Table 3.1 (Asaee *et al.*, 2015c; BAXI, 2013; ENER-G, 2013). A cogeneration unit that just matches or is slightly undersized for the design heating load is assigned to each house, with the balance to be made up by auxiliary heat. The thermal load following method is assumed in all cases.

Table 3.1 Technical details of micro cogeneration units used (Asaee *et al.*, 2015)

Series name	Rated output (kW)		Efficiency (%)	
	Electrical	Thermal	Electrical	Thermal
ENER-G 4Y	3.87	8.38	26.7	57.8
Dachs G 5.5	5.50	12.50	24.2	54.8
ENER-G 10Y	10.0	17.30	30.7	53.5
ENER-G 25Y	25.0	38.40	33.5	51.5

The effect of start-up and shut-down losses are ignored in the simulations based on a sensitivity analysis that was conducted to quantify the impact of start-up and shut-down transient losses on the annual performance of residential scale ICE cogeneration units in the Canadian climate. The results of the analysis indicated that the impact of these losses is in the order of 5% in the Canadian context over the course of a year. Consequently, it was decided to neglect the start-up and shut-down transients and treat the electrical and thermal efficiencies as constants.

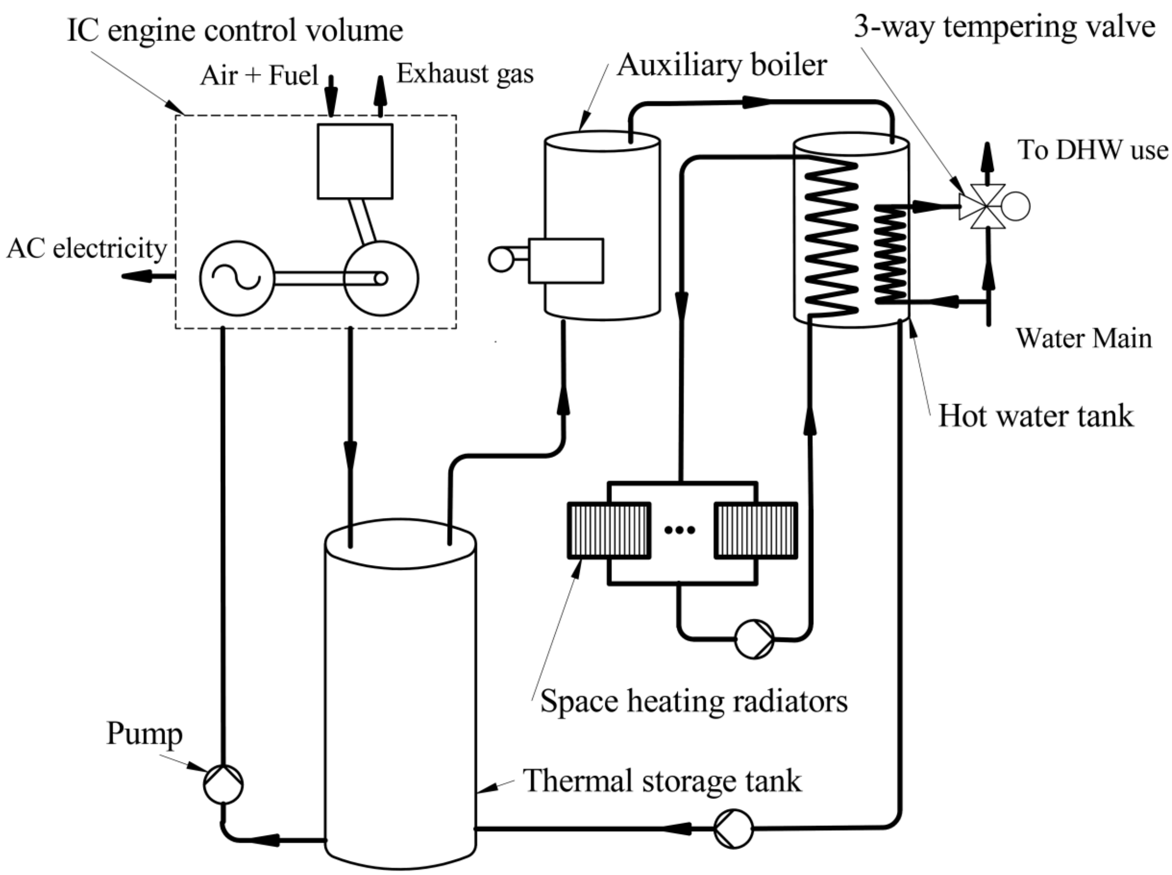

Figure 3.2 IC engine based cogeneration system architecture (Asaee *et al.*, 2015c).

An auxiliary boiler is included to provide heat when the available energy in the thermal storage tank is not sufficient to meet the thermal energy demand for space and DHW heating. A hot water tank is added to the system to store high temperature water required for space and DHW heating. Two heat exchanger coils are considered in the hot water tank to heat DHW and the circulated water in the space heating radiators. The DHW heat exchanger coil is sized based on the maximum flow rate. To avoid overheating the DHW when the flow rate is less than the maximum value, a tempering valve is used to maintain the DHW temperature at 55°C. Space heating is accomplished by a hydronic system that circulates heat to radiators.

The ICE cogeneration system presented in Figure 3.2 was modeled using the component models and control algorithms available in ESP-r to determine the primary energy consumption of the cogeneration system. The ICE cogeneration system presented in Figure 3.2 was modeled using the component models and control algorithms available in ESP-r to determine the primary energy consumption of the cogeneration system. The IC engine model developed within IEA/ECBCS Annex 42 and incorporated into the ESP-r is used (Kelly and Beausoleil-Morrison, 2007). This model utilizes three control volumes to model the operation of the ICE. These are (i) the energy conversion control volume, which determines the fuel consumption for the required engine output as well as the temperature, mass flow rate and specific heat of the combustion gases, (ii) thermal mass control volume, which represents the thermal mass of the engine and heat exchanger block, and (iii) cooling water control volume, which calculates the thermal energy content in the circulating cooling water. The energy balance for the thermal mass control volume includes thermal energy stored within the engine, recovered heat from combustion, heat transfer to cooling water and heat losses to the environment (Kelly and Beausoleil-Morrison, 2007). The thermal storage tank model developed and incorporated into ESP-r by Thevenard and Haddad (2010) is used. The model represents a stratified tank with immersed helical heat exchangers. The stratified model divides the storage tank into a maximum of 100 control volumes. Continuity and energy equations are solved for each control volume. Forced convection and conduction governs the heat transfer inside and through the walls of immersed heat exchangers, respectively. The heat transfer outside the heat exchangers is assumed to be mixed free and forced convection (Thevenard and Haddad, 2010). Further details of the ICE cogeneration system model as well as the input data used are given in Asaee *et al.* (2015c).

The capacity of the ICE cogeneration system as well as the size of the thermal storage tank for each eligible house were selected based on the design heating load of the house. The capacity of the ICE cogeneration system was determined such that the cogeneration system heating capacity meets or slightly below the design heating load. The size of thermal storage tank was selected based on the capacity of the ICE cogeneration system such that the thermal storage tank has the capacity to store the heat generated in five hours of steady state operation of the IC engine. The five-hour storage capacity was determined to be the best choice considering the energetic, environmental and economic performance in an earlier investigation that studied the effect of thermal storage capacity on the performance of ICE cogeneration systems in the Canadian context (Asaee *et al.*, 2015c).

The building/plant model developed in ESP-r conducts an annual simulation (January 1 to December 31) with 10-minute time steps. Thus, the building model calculates the electricity as well as space and domestic hot water heating loads of the house for each 10-minute time step and passes this information to the IC engine based cogeneration plant model. The plant model, using the performance and control algorithms, calculates the energy input/output of the cogeneration system and the auxiliary heater, as well as the electricity import/export values. The simulation is run in this fashion for the entire year, and the results are calculated and accumulated at 10-minute time steps.

The fuel used in ICE cogeneration systems depends on the province. In all provinces except the Atlantic Provinces of NF, NB, NS and PE, Natural gas (NG) is widely available for residential customers. Therefore, it is assumed that in all provinces except these four, the fuel used in ICE cogeneration is NG. In the four Atlantic Provinces, home heating oil is used for cogeneration.

3.3.2. Methodology to Select Houses Eligible for ICE Cogeneration System Retrofit

The presence of a basement or mechanical room is necessary to install an ICE cogeneration system in a house. Existence of mechanical room in the houses that do not have a basement is not specified in CSDDRD. Thus, two criteria are considered to evaluate the suitability of a house for ICE cogeneration upgrade:

1. The presence of a basement.
2. The presence of a heating system that requires a mechanical room.

Thus, all houses that have basements, or utilize natural gas or heating oil fired heating systems, electric furnaces, or wood furnace/boilers are considered eligible for cogeneration retrofits.

Based on these eligibility criteria, 71% of the houses in the CHS were found to be eligible for the ICE cogeneration system retrofit as shown in Table 3.2.

Table 3.2 Portion of houses eligible for IC engine cogeneration retrofit (% of total) and range of thermal efficiency values (%) of space and DHW heating systems encountered in the CHS

Province	Percent of Eligible houses	NG		Oil		Wood	
		Min	Max	Min	Max	Min	Max
NF	50	N/A	N/A	65	83	50	70
NS	69	N/A	N/A	70	87	50	80
PE	87	N/A	N/A	66.5	87	50	74
NB	51	N/A	N/A	60	87	50	78
QC	19	N/A	N/A	58	87	50	75
OT	90	55	98	55	87	N/A	N/A
MB	72	58	96.6	N/A	N/A	N/A	N/A
SK	91	55	96.3	N/A	N/A	N/A	N/A
AB	100	60	94	N/A	N/A	N/A	N/A
BC	79	50	96.6	N/A	N/A	50	78

3.3.3. Estimation of the GHG Emissions Intensity Factor for Electricity Generation in Each Province of Canada[1]

Once the houses to be retrofitted with a cogeneration system were identified, those house files were modified to reflect the retrofit, and a batch simulation was conducted. The resulting energy consumption reflects the energy savings associated with the ICE cogeneration system retrofit. Thus, the annual energy savings associated with the retrofit is

[1] Provinces of Canada, from east to west, are: Newfoundland (NF), Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (OT), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). NF, PE, NS and NB are collectively referred to as Atlantic Provinces (AT) while MB, SK and AB are referred to as Prairie Provinces (PR).

determined by subtracting the energy consumption with cogeneration from the base case energy consumption.

Once the annual energy savings with the ICE cogeneration system 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 losses.

Table 3.3 The average and marginal GHG intensity factors (g CO_{2eq}/kWh) for each province of Canada (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 $EIF_{Marginal}$		837	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%

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, the GHG EIF for electricity generation varies from province to province in Canada because of the different fuel mixture used in each province.

[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 (Farhat and Ugursal, 2010).

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 Table 3.3 (Farhat and Ugursal, 2010).

3.4. Performance Evaluation Parameters

Asaee et al (2015c) used three metrics including primary energy savings index, GHG emission reduction index and tolerable capital cost to evaluate techno-economic performance of cogeneration system upgrade in Canadian houses. These metrics are also used here to estimate the techno-economic performance of ICE cogeneration system retrofit in CHS.

3.4.1. Primary Energy Savings Index

To quantify the potential benefits of cogeneration in terms of the amount of primary energy savings provided, the European Parliament and Council published in Directive 2004/8/EC (OJEU, 2004) the "primary energy savings" (PES) index given by Equation (3.1). The maximum value of PES can be +1, with values closer to +1 indicating higher savings.

$$PES=1-\frac{1}{\frac{\eta_{th,CHP}}{\eta_{th,conv}}+\frac{\eta_{EE,CHP}}{\eta_{EE,conv}}} \quad (3.1)$$

where:

$\eta_{th,CHP}$ = thermal efficiency of the cogeneration system defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration,

$\eta_{th,conv}$ = efficiency reference value for separate heat production,

$\eta_{EE,CHP}$ = electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration,

$\eta_{EE,conv}$ = efficiency reference value for separate electricity production.

The Directive specifies that the efficiency reference values are to be calculated according to the following principles:

- The comparison with separate electricity production shall be based on the principle that the same fuel categories are compared.

- Each cogeneration unit shall be compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit.
- The efficiency reference values for separate electricity production and heat production shall reflect the climatic differences due to location.

The PES index given by Equation (3.1) is based on the fundamental definition of primary energy savings due to the replacement of separate heat and electricity generation systems with cogeneration systems[1]:

$$PES=\frac{PE_{conv}-PE_{CHP}}{PE_{conv}} \tag{3.2}$$

where:

PE_{conv} = primary energy consumption of separate heat and electricity generation
PE_{CHP} = primary energy consumption of cogeneration system

Since Equation (3.1) contains only efficiencies, it is suitable to be used for individual houses. To use Equation (3.1) for the entire housing stock, it is necessary to calculate weighted average efficiency values for the entire housing stock, which does not have a practical meaning. Thus, the PES index for the CHS is calculated here based on its definition given in Equation (3.2):

$$PES=\frac{PE_{CHS,th}+PE_{CHS,EE}-(PE_{ICE}+PE_{N\text{-}E,th}+PE_{N\text{-}E,EE})}{PE_{CHS,th}+PE_{CHS,EE}} \tag{3.3}$$

where:

$PE_{CHS,th}$ = primary energy consumption for separate heat production for the CHS,

$PE_{CHS,EE}$ = primary energy consumption for separate electricity production for the CHS,

PE_{ICE} = primary energy consumption for ICE cogeneration and imported electricity generated by the utility in houses that receive ICE cogeneration retrofit,

$PE_{N\text{-}E,th}$ = primary energy consumption for separate heat production in houses not eligible for ICE cogeneration retrofit,

$PE_{N\text{-}E,EE}$ = primary energy consumption for separate electricity production in houses not eligible for ICE cogeneration retrofit.

In conformance with the Directive principles, only electricity production from fuel categories suitable for cogeneration, i.e. fossil fuels, is considered in the calculation of the PES index.

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[1] The derivation of Equation (3.1) is given in Section 3.7.

Two approaches that reflect the spirit of the Directive are used in this work to calculate the PES index. The first approach calculates the PES(CANA) index that reflects the best available and economically justifiable technology used in residential heating systems and fossil fuel based electricity generation in Canada. The efficiency values used to calculate PES(CANA) are given in Table 3.4 (Bartos, 2011; EnerGuide, 2003; International Energy Agency, 2012; Viessmann, 2015a, 2015b). The second approach calculates the PES(CANB) index that reflects the current state of technology used in the residential heating systems and fossil fuel based electricity generation in Canada. The efficiency values used to calculate PES(CANB) are those used in CHREM and given in Table 3.2 and Table 3.5.

Table 3.4 Efficiency values for the best available state of technology available in residential heating systems and fossil fuel based electricity generation in Canada

Primary energy source	Efficiency (%)	Reference
	Residential heating	
NG	98	Condensing boiler based on HHV (Viessmann, 2015a)
Oil	87.4	Boiler based on LHV (Viessmann, 2015b)
Wood	80	High-tech stove based on LHV (EnerGuide, 2003)
	Electricity generation (based on LHV)	
NG*	60	Brayton-Rankine combined cycle (Bartos, 2011)
Oil	45	Advanced Rankine cycle (International Energy Agency, 2012)
Pulverized coal	45	Advanced Rankine cycle (International Energy Agency, 2012)

* While NG is largely unavailable for residential customers in the AT region, it is used for electricity generation

The most recent data for primary energy sources used in electricity generation (Statistics Canada, 2014a, 2014b) and the average efficiencies of fossil fuel-fired electric utility thermal plants (Statistics Canada, 2007, 2009a, 2009b) used as reference efficiencies along with the electricity grid transmission and distribution losses (Farhat and Ugursal, 2010) used in calculating the PES index for each province are given in Table 3.5.

Table 3.5 Energy source and reference efficiency values for each province reflecting the current status of separate electricity generation and distribution losses in Canada as of 2011-2012

Province	Energy source (%)					Reference efficiency[a]
	Coal	NG	Oil	Hydro	Nuclear	(%)
NF	0	0	2.4	97.6	0	N/A[b]
NS	56.4	23.2	11.2	9.2	0	32
PE	23.9	21.2	18.3	34.3	2.3	36
NB	23.9	21.2	18.3	34.3	2.3	36
QC	0	0.1	0.3	97.4	2.2	N/A
OT	3.1	15.8	0.2	23.1	57.8	37
MB	0.2	0.1	0	99.7	0	N/A
SK	59.8	18.3	0	21.9	0	32
AB	74.5	21.4	0	4.1	0	31
BC	0	2.9	0.1	97.0	0	N/A

[a] Average efficiency of electricity generation from fossil fuels
[b] Reference efficiency for fossil fuel electricity generation is not reported due to the negligibly small contribution of fossil fuels to electricity generation

3.4.2. GHG Emission Reduction Index

To quantify the potential benefits of cogeneration in terms of the reduction in GHG emissions, a GHG emission reduction (GER) index was developed by Asaee et al (2015c). The GER is similar to the PES, and compares the GHG emissions with cogeneration to the GHG emissions with separate heat and electricity generation. Thus:

$$GER=\frac{GHG_{CHS}-(GHG_{CHP}+GHG_{N-E})}{GHG_{CHS}} \quad (3.4)$$

where,

GHG_{CHS} = GHG emissions from separate heat and electricity generation in CHS,

GHG_{CHP} = GHG emissions from combined heat and electricity generation in houses eligible for ICE cogeneration retrofit,

GHG_{N-E} = GHG emissions from separate heat and electricity generation in houses not eligible for ICE cogeneration retrofit.

As in the case of the PES index, the maximum value of the GER index can be +1, with values closer to +1 indicating larger reductions.

The same two approaches used in the calculation of the PES were used to calculate the GER. Thus, GER(CANA) is calculated using GHG intensity factors that reflect the best available state of technology for residential heating systems and fossil fuel based electricity generation given in Table 3.4, while GER(CANB) is calculated based on the current GHG emission levels calculated by CHREM as given in Table 3.2 and Table 3.5.

3.4.3. Economic Analysis Based on Tolerable Capital Cost

Accurate estimation of cogeneration system capital costs, at residential as well as commercial scale, is difficult. In the 2014 edition of "Catalog of CHP Technologies", the U.S. Environmental Protection Agency states that for commercial scale cogeneration systems "installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control requirements, prevailing labor rates, and whether the system is a new or retrofit application" (US EPA, 2014). For the same reasons, the purchase and installation costs of cogeneration systems in Canada vary substantially from manufacturer to manufacturer and location to location. Thus, it is not practicable to estimate realistic total investment costs for ICE cogeneration systems and to conduct a conventional economic feasibility analysis. Therefore, an alternative approach to conventional economic feasibility analysis is adopted here which involves the calculation of the "tolerable capital cost" (TCC) of the upgrades (Nikoofard *et al.*, 2014a). TCC is the capital cost for an energy saving upgrade that will be recovered based on the annual savings, the number of years allowed for payback, and the estimated annual interest and fuel cost escalation rates. Thus, to estimate the tolerable capital cost of an upgrade a reverse payback analysis is conducted as follows:

1. The annual fuel and electricity savings for each upgrade is estimated (C$).
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:

$$\text{TCCH}=\begin{cases}\text{ACSH}\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e \\ \text{ACSH}\times n(1+i)^{-1} & \text{for} \quad i=e\end{cases} \tag{3.5}$$

$$\text{ACSH}=\sum_{j=1}^{m}(\text{F}\times\text{E})_j \tag{3.6}$$

where:

TCCH	Tolerable capital cost of the retrofit for the house (C$)
n	Acceptable payback period (year)
i	Interest rate (decimal)
e	Fuel cost escalation rate (decimal)
ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
F	Fuel price per unit of each fuel type (C$/unit)
m	Number of different fuels used in a house

The additional maintenance cost of the ICE cogeneration system over and above that of the replaced system is assumed to be included in the TCC as a present value of the annual maintenance cost over the lifetime of the cogeneration system.

It is not useful or practical to report the TCC for each house in the CSDDRD, or for that matter within the CHS, because from a macro level of interest, data on individual houses have no utility. Thus, the "average tolerable capital cost per house" (ATCCH) is used to evaluate the economic feasibility of the ICE cogeneration system retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$\text{ATCCH}=\text{TTCC}/\text{NH} \tag{3.7}$$

where, TTCC is the total tolerable capital cost as a result of the cogeneration system upgrade (C$), calculated as follows:

$$TTCC=\sum_{i=1}^{NH} TCCH_i \tag{3.8}$$

NH = number of houses that received the upgrade.

To take into consideration the uncertainty associated with the future of interest and fuel price escalation rates, a sensitivity analysis was conducted. The interest rates used in the analysis are based on the Bank of Canada Prime Rate (BOC, 2015), which was 1% in June, 2014. 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.

For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 4.6 are used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada (NEB, 2014) and Energy Escalation Rate Calculator (WBDG, 2014).

For each province, fuel prices for residential customers for natural gas, heating oil, electricity and wood were obtained to calculate the energy cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 3.7.

Payback periods of six and ten years are used in the sensitivity analysis. Both values are comfortably within the economical lifetime of 15 years for ICE cogeneration systems reported by the International Energy Agency (ETSAP, 2010).

It is likely that a cogeneration retrofit would increase the market value of a house. However, the estimation of the increase in market value due to such a retrofit is not straightforward 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.

Table 3.6 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
Mixed wood§	3	6	9

* National Energy Board of Canada (NEB, 2014)

‡ Energy Escalation Rate Calculator (EERC) (WBDG, 2014)

§ Equal to interest rate as there is no source for its escalation rate

Table 3.7 Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[a]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	cents/MJ	365.8	450.6	470.8	371.1	219.2	397.2	242.5	420.0	431.9	265.3
Natural gas[b]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	cents/MJ	N/A	N/A	N/A	N/A	124.1	79.9	82.3	77.7	46.2	113.5
Home heating oil[c]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	cents/MJ	296.3	284.2	291.7	307.6	312.5	328.0	303.3	293.7	N/A	330.8
Wood[d]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	cents/MJ	112.0	112.0	112.0	156.9	114.3	134.4	116.5	112.0	224.0	107.5

[a] Hydro-Quebec (Hydro-Quebec, 2014b)

[b] Statistics Canada handbook (Statistics Canada, 2013)

[c] Statistics Canada Handbook (Statistics Canada, 2013)

[d] Local companies

3.5. Results and Discussion

The CHREM estimates of current annual end-use energy consumption by the CHS and the associated GHG emissions are given in Table 3.8 (Swan *et al.*, 2013). The values presented in the table constitute the "Base Case" (i.e. current) end-use energy consumption and GHG emissions for the CHS. The ICE cogeneration system shown in Figure 3.2 was integrated into the eligible houses in CHREM and simulations were conducted to determine the energy end-use consumption and GHG emissions assuming that all eligible houses are retrofitted with the ICE cogeneration system. The number of houses eligible for retrofit as well as the energy savings and GHG emission reductions due to the retrofits are given in Table 3.9. The results are discussed in detail in the following sections.

3.5.1. Impact of ICE Cogeneration System Retrofit on the Energy Consumption of the CHS

For each province, the annual end-use energy consumption of the houses eligible and ineligible for the ICE cogeneration retrofit are given in Table 3.10. As shown in Table 3.10, the retrofit of ICE cogeneration systems in all provinces except in PE and BC result in net electricity exports to the grid. While there is no net export in these two provinces, in BC close to 80% and in PE 100% of the electricity consumption of the eligible houses is satisfied by the cogeneration systems. In other provinces, ICE cogeneration retrofit provides more favourable results. For example, in OT where 90% of the houses are eligible for the ICE cogeneration retrofit, the ICE cogeneration systems satisfy all of the electricity requirements of the houses that receive the retrofit (96.6 PJ as shown in Table 3.10) and export 50.3 PJ of electricity to the grid. The amount of exported electricity is more than the electricity required by all of the houses ineligible for the cogeneration retrofit (50.3 PJ > 40.6 PJ); thus, retrofitting all eligible houses in OT with an ICE cogeneration system results in turning the entire housing stock into a net electricity exporter to the grid with a total electricity production of 146.9 PJ (96.6PJ + 50.3PJ) of which 9.7 PJ exported to the grid[1].

[1] Whether the electricity system could support such a scenario is a question that must be investigated in future research.

Table 3.8 CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 3.9 Annual energy savings and GHG emission reductions due to ICE cogeneration retrofits in the CHS

Province	No of houses eligible for retrofit	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
		Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	88,207	5.2	0	-4.7	2.7	3.2	0.042	0	-0.331	-0.289
NS	205,181	10.0	0	-7.2	3.7	6.5	1.160	0	-0.506	0.654
PE	38,997	1.4	0	-0.7	0.8	1.5	0.004	0	-0.049	-0.045
NB	122,070	7.8	0	-9.3	6.8	5.3	1.617	0	-0.654	0.963
QC	382,595	30.0	-55.5	30.3	2.9	7.7	0.044	-2.806	2.131	-0.632
OT	3,082,265	146.9	-107.7	47.2	0	86.4	16.454	-5.445	3.319	14.328
MB	243,288	12.8	-6.0	0	0	6.8	-0.001	-0.303	0	-0.305
SK	287,895	12.5	-1.9	0	0	10.6	0.766	-0.096	0	0.670
AB	970,120	38.3	-11.3	0	0	27.0	8.937	-0.571	0	8.366
BC	877,789	33.3	-15.8	0	0.4	17.9	0.173	-0.799	0	-0.626
Canada	6,298,407	298.2	-198.2	55.6	17.3	172.9	29.196	-10.020	3.910	23.084

Table 3.10 CHREM estimates of annual energy consumption (PJ) with existing (Exist) and ICE cogeneration systems retrofit (ICER) in houses eligible (EL) and houses not eligible (N-E) for ICE cogeneration retrofit

	Electricity			NG[a]		Oil[a]		Wood			Total		
	N-E	EL						N-E	EL		N-E	EL	
Province		Exist	ICER	Exist	ICER	Exist	ICER		Exist	ICER		Exist	ICER
NF	10.9	4.3	-0.9[b]	0.0	0.0	9.6	14.3	0.6	2.7	0.0	11.5	16.6	13.4
NS	9.1	8.6	-1.4	0.0	0.0	22.6	29.8	2.3	3.7	0.0	11.4	34.9	28.4
PE	0.4	1.4	0.0	0.0	0.0	4.0	4.7	0.7	0.8	0.0	1.1	6.2	4.7
NB	12.7	6.0	-1.8	0.0	0.0	9.7	19.0	3.9	6.8	0.0	16.6	22.5	17.2
QC	181.7	23.6	-6.4	1.0	56.5	30.3	0.0	7.5	2.9	0.0	189.2	57.8	50.1
OT	40.6	96.6	-50.3	337.4	445.1	47.4	0.2	0.0	0.0	0.0	40.6	481.4	395.0
MB	12.1	6.8	-6.0	33.6	39.6	0.0	0.0	0.0	0.0	0.0	12.1	40.4	33.6
SK	3.1	7.5	-5.0	40.2	42.1	0.0	0.0	0.0	0.0	0.0	3.1	47.7	37.1
AB	0.0	28.3	-10.0	119.8	131.1	0.0	0.0	0.0	0.0	0.0	0.0	148.1	121.1
BC	23.2	41.4	8.1	83.9	99.7	0.0	0.0	1.7	0.4	0.0	24.9	125.7	107.8
Canada	293.8	224.5	-73.7	615.9	814.1	123.6	68.0	16.7	17.3	0.0	310.5	981.3	808.4

[a] All houses that use NG or oil as onsite fuel are eligible for cogeneration upgrade

[b] Negative values indicate electricity exported to the grid

The fuel used by the ICE cogeneration systems in OT to generate this electricity is NG. Since most houses that currently use oil fired heating systems are also eligible to be retrofitted with ICE cogeneration, the oil consumption is drastically reduced, from 47.4 PJ to 0.2 PJ as shown in Table 3.10. As a result of the substitution of heat produced by conventional NG and oil systems and the electricity produced by conventional fossil fired power plants with heat and electricity produced by the ICE cogeneration systems using NG, the NG consumption in OT increases from 337.4 PJ to 445.1 PJ. Thus, the total energy consumption by the housing stock of OT reduces from 522 PJ (40.6 PJ + 481.4 PJ) to 435.6 PJ (40.6 PJ + 395 PJ), resulting in a savings of 16.6%.

Depending on the proportion of the houses eligible for retrofit and the type of fuels used for electricity generation and heating, the energy savings in each province is different as shown in Table 3.9 and Table 3.10. These results show that retrofitting ICE cogeneration in all eligible houses yields a 13% reduction in the end-use energy consumption of the CHS. The highest potential for energy savings is in PE, SK, AB and OT, while the lowest energy savings are in QC. This is because of the high proportion of houses that use baseboard electric convectors for space heating in QC, resulting in a relatively smaller proportion of eligible houses compared to the rest of Canada as shown in Table 3.2.

3.5.2. Primary Energy Savings

The PES index calculated for each province based on the two approaches presented in Section 3.4.1 are given in Table 3.11.

Table 3.11 PES index and GER index for each province of Canada

Province	PES		GER	
	CANA	CANB	CANA	CANB
NF	-0.42	-0.16	-0.56	-0.39
NS	0.22	0.34	0.22	0.32
PE	0.27	0.39	0.27	0.38
NB	0.18	0.27	0.14	0.22
QC	-0.89	-0.53	-0.47	-0.23
OT	0.24	0.46	0.31	0.51
MB	-0.54	-0.18	-0.53	-0.18
SK	0.27	0.53	0.45	0.69
AB	0.26	0.54	0.47	0.73
BC	-0.66	-0.18	-0.57	-0.14

Both the PES(CANA) and PES(CANB) indexes for NF, QC, MB and BC are all negative, indicating that ICE cogeneration systems result in an increase in the consumption of fossil primary energy sources, in this case, NG and oil. This is because close to 100% of electricity generation in all four provinces is from hydro sources as shown in Table 3.5. Thus, when hydro generated electricity is replaced with electricity generated using a technology such as ICE cogeneration that requires a fossil fuel primary energy source, the result is unfavourable in terms of fossil fuel primary energy use.

In all other provinces, i.e. in NS, PE, NB, OT, SK and AB, a substantial proportion of electricity generation is from fossil fuel primary energy sources as shown in Table 3.5. Also, a high proportion of the houses are eligible for ICE cogeneration retrofit as shown in Table 3.2. Consequently, both the PES(CANA) and PES(CANB) indexes are positive indicating a favourable potential for cogeneration system upgrade. As to be expected, the values of the PES(CANB) index are substantially higher than PES(CANA) for every province because the efficiency of the current energy conversion systems is substantially lower in comparison to the efficiency of the best available and justifiable technologies as shown in Table 3.4 and Table 3.5.

These findings underline the importance of considering the actual status of energy generation in the evaluation of primary energy savings due to cogeneration retrofits.

3.5.3. Impact of ICE Cogeneration System Retrofit on GHG Emissions of the CHS

The annual GHG emissions reduction in the CHS due to ICE cogeneration upgrade in eligible houses is presented in Table 3.9 for each energy source and province. Since CO_2 emissions of biogenic material combustion will return to the atmosphere the CO_2 that was originally removed by photosynthesis, CO_2 emissions from biogenic materials are considered as a complement of the natural carbon cycle (Farhat and Ugursal, 2010). Thus the GHG intensity factor for wood is considered to be zero and emissions due to wood consumption is omitted from Table 3.8 and Table 3.9.

To evaluate the total GHG emissions of upgraded houses, the GHG emissions associated with the electricity generation of ICE cogeneration system are deducted from the total GHG emissions of the CHS. Percent GHG emission reductions due to the ICE cogeneration retrofit relative to base case GHG emissions is presented in Table 3.12.

Table 3.12 Annual energy savings and GHG emission reductions due to ICE cogeneration retrofits in the CHS if (i) eligible houses are selected based on the criteria presented in Section 4.3.2, and (ii) houses with wood burning heating system are removed from eligible

Province	Case (i)		Case (ii)	
	Energy Savings (%)	GHG emission reductions (%)	Energy Savings (%)	GHG emission reductions (%)
NF	11.4	-36.5	7.1	-18.2
NS	14.0	12.2	10.4	13.7
PE	20.5	-11.8	16.4	1.0
NB	13.6	31.3	5.4	28.5
QC	3.1	-24.8	2.6	-19.8
OT	16.6	50.2	16.6	50.2
MB	13.0	-17.2	13.0	-17.2
SK	20.9	14.9	20.9	14.9
AB	18.2	61.3	18.2	61.3
BC	11.9	-13.4	11.7	-13.1
Canada	13.4	35.4	12.8	35.9

The results of the simulations show that the ICE cogeneration retrofit yields a 35% reduction in annual GHG emissions of the CHS. However, the reductions vary by province, and in NF, PE, QC, MB and AB emissions increase. In NF, QC, MB and BC, marginal electricity generation is primarily from hydro resources (Farhat and Ugursal, 2010) with negligibly small GHG emissions as shown in Table 3.3. Therefore, retrofitting fossil fuel fired ICE cogeneration systems increase GHG emissions as electricity production by an ICE results in GHG emissions, which do not exist with hydroelectricity. The GHG intensity of marginal electricity generation in PE is similarly negligibly small, resulting in an increase in GHG emissions with the ICE retrofit.

A comparison of the energy savings and GHG emission reductions shown side-by-side in Table 3.12 indicate that energy savings due to ICE cogeneration retrofits do not necessarily result in GHG emission reductions. Depending on the source of marginal electricity generation, ICE cogeneration systems may increase GHG emissions although resulting in energy savings. For example, while relative energy savings in NF and NS are about the same, there is a reduction in GHG emissions in NS but a substantial increase in NF. Every kWh generated by the ICE cogeneration systems in NS replaces largely fossil fuel generated electricity, resulting in a decrease in GHG emissions. However, in NF, electricity generated by ICE cogeneration replaces hydroelectricity with zero GHG emissions, resulting in an increase in GHG emissions. Thus, the desirability of ICE cogeneration retrofit depends on the objective. If the objective is to reduce overall energy consumption, then these systems are desirable in every province; but, if the objective is to reduce GHG emissions, then the desirability varies from province to province.

As shown in Table 3.8, wood provides more than 10% of the residential end-use energy consumption in the eastern provinces of Canada (NF, NS, PE, NB) and smaller amounts in QC and BC. While it is technically feasible and beneficial from an end-use energy savings perspective, replacing wood with fossil fuels for space and DHW heating may increase or decrease the GHG emissions of retrofitted houses depending on the fuel mix used in marginal electricity generation. To assess the GHG emission implications of ICE cogeneration retrofit in place of wood burning heating systems, houses that use wood as a source of primary energy were removed from the set of eligible houses, and the energy and GHG emissions of the CHS was estimated using CHREM. The energy savings and GHG emission reductions for the modified eligibility condition are presented in Table 3.12.

As shown in Table 3.8, close to 30% of residential energy requirement in NB is supplied by wood. Therefore, excluding houses that use wood for heating purposes from the set of houses eligible for ICE cogeneration retrofit significantly reduces the energy savings in NB, from 14% to 5%, as shown in Table 3.12, respectively. However, because of the large value of the marginal GHG EIF in NB compared to its average value (Table 3.3), retrofitting ICE cogeneration systems in houses with wood burning heating systems is favourable, providing 31% reduction in GHG emissions as opposed to only 29% reduction if these houses are excluded from the retrofit as shown in Table 3.12. In all other provinces, excluding wood heated houses is preferable from the GHG emissions perspective although energy savings shrink, as shown in Table 3.12. Thus, the decision to promote ICE cogeneration in houses that burn wood depends on the ultimate objective, i.e. whether to reduce energy consumption or GHG emissions.

3.5.4. GHG Emissions Reduction Index

The results of GER index calculations based on the two approaches given in Section 3.4.2 are presented in Table 3.11.

The GER(CANA) approach provides the GHG reduction due to ICE cogeneration system retrofit in place of the best available conventional heat and electricity generation systems in Canada. Thus, the GER(CANA) is lower compared to the GER(CANB) scenario which considers the current status of fossil fuel based conventional heat and electricity generation. The highest GHG emissions reduction is associated with the cogeneration retrofit in SK and AB because of the considerable amount of coal in the fuel mixture of electricity generation in these provinces, in addition to the large proportion of eligible houses. In contrast, the GER index is negative for both CANA and CANB scenarios for NF, QC, MB and BC because of the very high proportion of hydro generated electricity with no GHG emissions. Thus, with the exception of the provinces where electricity generation is almost exclusively from hydro resources, ICE cogeneration provides favourable GER indexes.

3.5.5. Economic Feasibility of ICE Cogeneration Retrofit for the CHS

As discussed in Section 3.4.3, the economic feasibility of ICE cogeneration system is assessed using the tolerable capital cost. The average tolerable capital costs per house for each province under the payback period, interest rate and fuel cost escalation rate assumptions are given in Table 3.13.

The TCC values presented in Table 3.13 indicate the substantial differences among the provinces regarding the economic feasibility of ICE cogeneration systems. It is precisely this level of complexity that makes this work useful and interesting. Without the detailed and housing stock level simulations carried out here, it would not be possible to develop or predict these results. For the same reasons, it is not possible to generalize or extrapolate the findings. For different assumptions and conditions, new simulations need to be carried out to find the unique results.

Table 3.13 Average TCC per house (C$/house)

Province	Payback (yr)	Interest rate 3%			6%			9%		
		Fuel cost escalation rate								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	5,876	6,735	7,767	5,176	5,887	6,736	4,601	5,194	5,899
	6	4,367	4,755	5,183	3,985	4,326	4,701	3,654	3,955	4,285
NS	10	11,319	13,334	15,797	9,803	11,446	13,442	8,578	9,930	11,564
	6	7,414	8,136	8,936	6,736	7,369	8,068	6,150	6,708	7,322
PE	10	12,140	14,330	17,005	10,467	12,247	14,409	9,120	10,581	12,346
	6	7,669	8,415	9,239	6,958	7,611	8,332	6,345	6,920	7,553
NB	10	4,544	4,835	5,126	4,088	4,344	4,604	3,703	3,930	4,162
	6	3,886	4,141	4,415	3,560	3,785	4,027	3,277	3,477	3,691
QC	10	27,520	33,808	41,667	23,420	28,493	34,800	20,151	24,284	29,396
	6	15,551	17,405	19,476	14,047	15,666	17,472	12,754	14,175	15,758
OT	10	20,571	24,700	29,797	17,624	20,966	25,070	15,263	17,995	21,332
	6	12,325	13,627	15,072	11,160	12,298	13,560	10,156	11,157	12,264
MB	10	9,973	11,992	14,489	8,565	10,201	12,215	7,435	8,774	10,414
	6	6,100	6,754	7,480	5,528	6,100	6,734	5,035	5,538	6,095
SK	10	16,474	19,671	23,606	14,148	16,740	19,912	12,282	14,403	16,987
	6	10,077	11,114	12,262	9,132	10,039	11,042	8,317	9,115	9,995
AB	10	15,352	18,334	22,004	13,184	15,602	18,561	11,445	13,424	15,834
	6	9,390	10,357	11,429	8,510	9,355	10,291	7,751	8,494	9,316
BC	10	7,503	9,044	10,954	6,444	7,693	9,233	5,593	6,616	7,869
	6	4,589	5,087	5,642	4,158	4,595	5,079	3,788	4,171	4,596

The results presented in Table 3.13 indicate that for the parameters chosen in the simulations, QC provides the largest opportunity for the ICE cogeneration retrofit due to the highest TCC. At the high end of the spectrum, a home owner in QC who is prepared to accept a 10 year payback period, could justify the substantial capital outlay of C$ 41,700 if the interest rate for the loan to purchase the system can be obtained at 3% interest rate and the fuel price escalation rate remains at the high level. Even if the fuel price escalation rate is expected to remain at the low level, the tolerable capital outlay is substantial at C$27,500. This favourable result is largely due to the large monetary savings achieved by switching from expensive oil fired space heating (C$ 3.12/MJ as shown in Table 3.7) with additional charges for the electrical consumption (C$ 2.19/MJ as shown in Table 3.7) to substantially less expensive NG (C$1.24/MJ as shown in Table 3.7) fired ICE cogeneration. As the economic conditions change, the TCC reduces, to a minimum of C$ 12,750 for a 6-year payback, a high interest rate of 9% and a low fuel price escalation rate.

The lowest TCC is seen in NB, although the energy savings in this province is the highest amongst all. While this result may appear to be counter-intuitive, it is in fact rational considering that in NB close to 30% of the residential energy consumption is from inexpensive wood (C$1.56/MJ as shown in Table 3.7), and the ICE cogeneration retrofit requires the substitution of this inexpensive fuel with almost twice as expensive oil (C$ 3.08/MJ as shown in Table 3.7). Thus, in the most favourable conditions of 10-year payback, 3% interest rate and high fuel price escalation rate, a homeowner could justify a capital outlay of C$ 5,100 for this retrofit. If this is not enough to cover the capital and installation costs of an ICE cogeneration system, and if the government wishes to promote cogeneration, then it may be necessary to devise a rebate or subsidy program that would provide funding to the homeowners to cover the shortfall.

The results for the other provinces show the TCC under different conditions, providing economic guidance for homeowners and governments alike in considering ICE cogeneration retrofits.

The total TCC for the range of interest and fuel escalation rates and payback periods are given in Figure 3.3 for the entire CHS. The results show that the effects of interest rate and fuel cost escalation rate on the total TCC increase with payback period. For example, for a

10-year payback period, 3% interest rate and low fuel cost escalation rate, the total tolerable capital cost is about 160 Billion Canadian dollars for the CHS, which is almost twice as high as the value for the 6-year payback period. This result indicates that education of home-owners regarding the long-term benefits and expected lifetime of cogeneration systems would be helpful to convince them to make the switch to cogeneration.

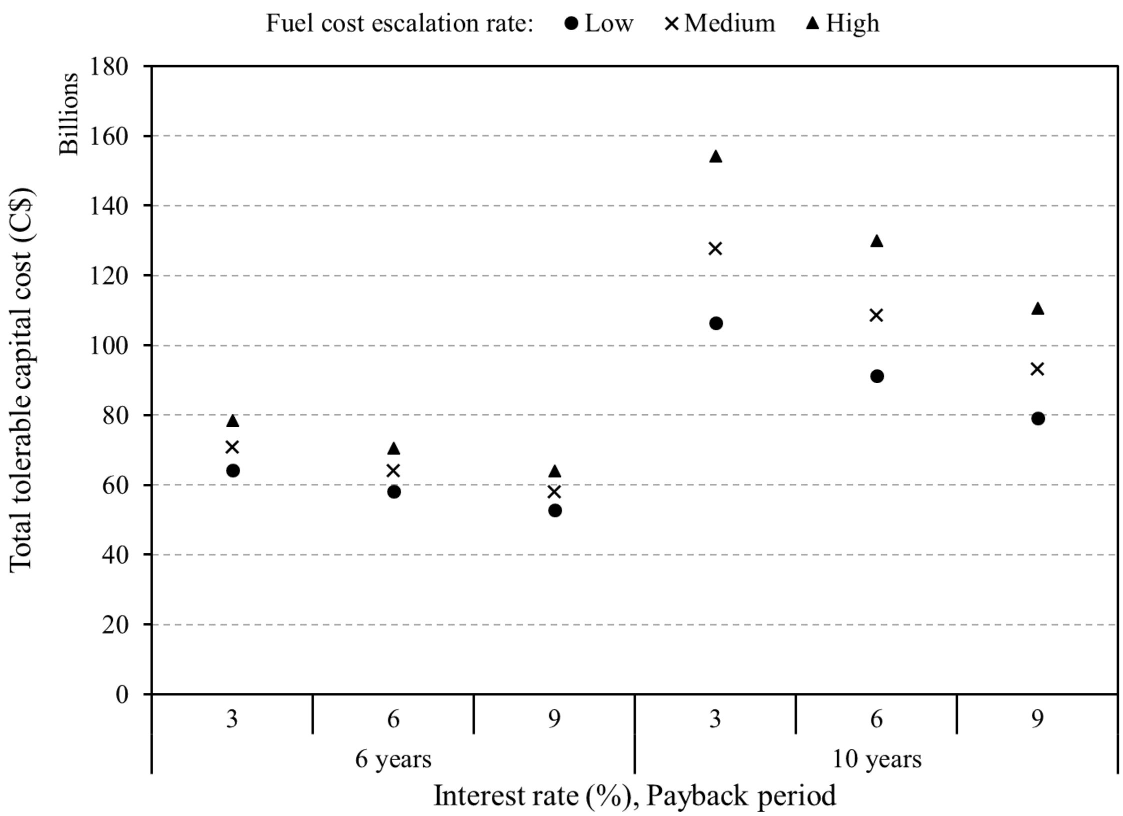

Figure 3.3 Total national tolerable capital cost due to IC engine based cogeneration system upgrade for different interest rates and fuel cost escalation rates (Low, Medium and High as per Table 3.6).

3.6. Conclusion

The results of a comprehensive study conducted to estimate the techno-economic impacts of ICE cogeneration retrofits for the CHS were presented. The study was conducted using the CHREM, a versatile end-use and emissions energy model of the CHS. The study is part of a large-scale effort to develop approaches, incentive measures and strategies to facilitate conversion of existing Canadian houses into net zero energy buildings under Smart Net-Zero Energy Buildings Strategic Research Network. The study is a follow-up on a preliminary system performance evaluation study that was conducted previously (Asaee *et al.*, 2015c).

Energy savings, GHG emission reductions, PES and GER indexes are used to assess the impact of the ICE cogeneration system upgrade on the energy consumption and GHG emissions of the CHS. Tolerable capital cost is used as a measure to estimate the economic feasibility of the ICE cogeneration retrofit in existing Canadian houses.

The main conclusions are the following:

- The ICE cogeneration upgrade reduces energy use in all provinces across Canada. If all of the eligible houses receive the proposed cogeneration upgrade, the energy use of CHS would be decreased by 13%. However, the savings vary substantially from province to province. Thus, the overall national savings do not translate to similar levels of savings in individual provinces. Similarly, the consumption of certain fuels decrease while others increase. Thus, there is no generalizable result in terms of energy savings.
- The ICE cogeneration retrofit reduces GHG emissions of the CHS by close to 35%. However, the reductions vary significantly across Canada due to the widely different fuel mixtures used for electricity generation in each province. Due to the dominance of hydro-electricity in several provinces, ICE cogeneration retrofit would actually increase GHG emissions in those provinces. Thus, as in the case of energy savings, there is no generalizable result regarding GHG emissions.
- The PES and GER indexes also vary widely across Canada as a result of the fuels used for space heating and electricity generation. Depending on the reference used for calculating these indexes (best vs. current technology), the results show substantial differences.
- The economic feasibility of ICE cogeneration also varies widely across Canada as a result of the largely different fuel mixes used and fuel prices. In some provinces, home owners would likely be more inclined to switching to ICE cogeneration due to the large monetary savings while in others government incentives may be necessary to promote their adoption.

The results of this study indicate that depending on the province, retrofitting existing houses in the CHS could result in substantial energy savings and GHG reductions in an economically feasible fashion. Further studies are needed to study the impacts and feasibility of incorporating other energy efficiency and renewable energy technologies to achieve or approach net zero energy status in existing Canadian houses.

3.7. Derivation of the PES Index Equation

The primary energy saving index due to cogeneration retrofit is defined as:

$$PES=\frac{PE_{conv}-PE_{CHP}}{PE_{conv}}=1-\frac{PE_{CHP}}{PE_{th,conv}+PE_{EE,conv}} \quad \text{(i)}$$

where:

PE_{conv} = primary energy consumption of separate heat and electricity generation

PE_{CHP} = primary energy consumption of cogeneration system

The primary energy consumption is a function of fuel efficiency definition, and can be calculated as follows.

$$PE_{th,conv}=\frac{SE_{th}}{\eta_{th,conv}} \quad \text{(ii)}$$

$$PE_{EE,conv}=\frac{SE_{EE}}{\eta_{EE,conv}} \quad \text{(iii)}$$

$$\left.\begin{aligned}\eta_{th,CHP}&=\frac{SE_{th}}{PE_{CHP}}\\ \eta_{EE,CHP}&=\frac{SE_{EE}}{PE_{CHP}}\end{aligned}\right\}\Rightarrow PE_{CHP}=\frac{SE_{th}}{\eta_{th,CHP}}=\frac{SE_{EE}}{\eta_{EE,CHP}} \quad \text{(iv)}$$

where:

SE_{th} = secondary energy used for heating

SE_{EE} = electricity use

$\eta_{th,CHP}$ = Thermal efficiency of the cogeneration system defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration,

$\eta_{th,conv}$ = efficiency reference value for separate heat production,

$\eta_{EE,CHP}$ = electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration,

$\eta_{EE,conv}$ = efficiency reference value for separate electricity production

Substituting Equations (ii-iv) in Equation (i) gives

$$PES=1-\frac{1}{\frac{PE_{th,conv}}{PE_{CHP}}+\frac{PE_{EE,conv}}{PE_{CHP}}}=1-\frac{1}{\frac{\frac{SE_{th}}{\eta_{th,conv}}}{\frac{SE_{th}}{\eta_{th,CHP}}}+\frac{\frac{SE_{EE}}{\eta_{EE,conv}}}{\frac{SE_{EE}}{\eta_{EE,CHP}}}}=1-\frac{1}{\frac{\eta_{th,CHP}}{\eta_{th,conv}}+\frac{\eta_{EE,CHP}}{\eta_{EE,conv}}} \quad \text{(v)}$$

Chapter 4 Stirling Engine Based Cogeneration System Retrofit Impact on the Energy Requirement and Greenhouse Gas Emissions of the Canadian Housing Stock

This section was previously published as:

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Rasoul Asaee is the principal researcher and author of the article. He conducted the research as part of his PhD. Thus, while he received supervision and guidance from his supervisors Drs. Ugursal and Beausoleil-Morrison, he carried out the work, wrote the published article, and carried out the necessary revisions before publication. Minor editorial changes have been made to integrate the article within this dissertation.

4.1. Abstract

Energy end-use and greenhouse gas (GHG) emission impact of retrofitting Stirling engine based cogeneration systems in existing Canadian houses is studied using the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM). CHREM includes close to 17,000 unique house files that are statistically representative of the Canadian housing stock (CHS). The cogeneration system performance was evaluated using a high resolution integrated building performance simulation software. It is assumed that the Stirling engine cogeneration system is retrofitted into all houses that currently use a central space heating system and have a suitable basement or crawl space. A high efficiency auxiliary boiler is included to supply heat when cogeneration unit capacity is not sufficient to meet the heating load. The GHG emission intensity factor associated with marginal electricity generation in each province is used to estimate the annual GHG emissions reduction due to the cogeneration system retrofit. The results show that cogeneration retrofit would yield substantial energy savings and GHG emission reductions in the CHS.

4.2. Introduction

If widely implemented, energy saving and high efficiency energy technology retrofits in the housing stock have the potential to reduce energy consumption and greenhouse gas (GHG) emissions of the residential sector. Cogeneration (i.e. combined heat and power - CHP) systems that generate electrical and thermal energy simultaneously from a single source of fuel are of interest because of their higher efficiency compared to conventional systems that generate electricity and thermal energy in two separate processes. While the energy conversion efficiency of a cogeneration unit is close to 80% (based on the fuel's lower heating value, and the sum of thermal and electrical output), the efficiency of a conventional fossil fuel based electricity generation unit is about 30-35% (Onovwiona and Ugursal, 2006). Onovwiona and Ugursal (2006) classified micro cogeneration units into four major categories: reciprocating internal combustion (IC) engine based, micro turbine based, fuel cell (FC) based and reciprocating external heat source Stirling engine (SE) based. As part of a comprehensive effort to evaluate the feasibility of all four types of cogeneration systems for the Canadian housing stock (CHS) to achieve or approach net-zero rating, the Stirling engine based system is considered in this work due to the high efficiency, fuel flexibility, low emissions, low noise and vibration as well as decent performance at partial load. Since the heat source for Stirling engine is external, a wide range of energy sources can be used for this application (Lombardi *et al.*, 2010; Onovwiona and Ugursal, 2006).

Several authors studied the performance of residential scale SE cogeneration systems using experimental and numerical techniques. Entchev *et al.* (2004) conducted an experiment to assess building integration, design issues and performance characteristics of a 6.5 kW_{th} (736 W_{el}) natural gas fired SE cogeneration system installed in a demonstration house at the Canadian Centre for Housing Technology. Tests were conducted for two different setups and scenarios during the winter/spring of 2003. It was shown that the micro cogeneration system satisfied the total thermal demand of the building including space and domestic hot water (DHW) heating. While the significant portion of electricity requirement of the house was supplied through SE cogeneration system, the excess electricity was exported to the grid. Kelly and Beausoleil-Morrison (Beausoleil-Morrison, 2008; Kelly and Beausoleil-Morrison, 2007) developed a simulation model to characterize the thermal and energy performance of combustion-based micro-cogeneration devices, including those that are SE based, within Annex 42 of the International Energy Agency’s Energy Conservation in Buildings and Community Systems Programme (IEA/ECBCS). The IEA Annex 42 model for cogeneration systems can be used with high resolution building energy simulation tools including ESP-r, TRNSYS and EnergyPlus. The IEA/ECBCS Annex 42 cogeneration system model was validated through a set of tests to evaluate the results for different modes of operation (Beausoleil-Morrison and Ferguson, 2007; Ferguson *et al.*, 2009). Lombardi *et al.* (2010) calibrated the IEA Annex 42 model for SE based cogeneration systems based on a comprehensive experimental study Lombardi conducted (Lombardi, 2008). Alanne *et al.* (2010) studied a SE based cogeneration system using the IEA Annex 42 model to evaluate and optimize strategies for the integration of this system with residential buildings. Ribberink *et al.* (2009) modeled a SE based cogeneration system in a single detached house with average heat demand in Ontario, and found that the SE based cogeneration system yields fuel savings as well as GHG and NOx emission reductions compared to high efficiency conventional heating systems. Based on these findings, it was concluded that the SE cogeneration system is a favourable option to reduce energy consumption and GHG emissions in Ontario. Conroy *et al.* (2013) presented a model for SE based cogeneration system. The model includes transient (start-up and shutdown) and steady state period of operations for SE. The model was validated using the measured data from a unit installed in a dwelling in Northern Ireland. The model is capable of predicting thermal and electrical energy of the cogeneration system with acceptable accuracy. González-Pino *et al.* (2014) conducted a study to assess the operational and economic viability of SE cogeneration system in single-family houses in three different climatic zones of Spain. It was assumed that the SE cogeneration system supplied the space and DHW heating demands. A sensibility analysis was carried out to estimate the effects of initial investment costs as well as fuel and electricity price variations on the economic results. It was concluded that that SE cogeneration system might not be suitable in single-family dwellings sited in any climatic zone of Spain. However, if the capital cost decreases, the micro cogeneration system could become viable in the coldest zone of study. Bouvenot *et al.* (2014) developed a model for SE micro cogeneration system to assess their energy performance. The model incorporates a limited number of parameters with the goal to be suitable for annual building energy simulations. The modelling approach is based on an energy balance on the device and on empirical expressions for the main inputs and outputs. Valenti *et al.* (2014) presented an experimental and numerical analysis of 8 kW_{th} (1 kW_{el}) commercial SE cogeneration system. The results showed that the electrical and thermal efficiency (based on the higher heating value - HHV) of the SE system is close to 9% and 90%, respectively. If the cogeneration water inlet temperature rises from 30°C to 70°C, the thermal efficiency decreases to about 84%. Cacabelos *et al.* (2014) developed a model to study the dynamic performance of a commercial micro SE cogeneration system under different mass flow inputs. A theoretical analysis was carried out to assess the performance of the engine with the variation of the heat source temperature. The simulation results conclude that an important saving could be obtained when the electrical to thermal ratio is tracked for the power or thermal demands from a dwelling.

As this brief review of literature indicates, SE based cogeneration systems present a potential for energy savings and GHG emission reductions in the residential sector depending on climate, building and system characteristics. Since no comprehensive study was conducted to evaluate the effects of large-scale implementation of SE based cogeneration systems in the Canadian residential sector so far, this study was conducted within the Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN) initiative (SNEBRN, 2012) to develop detailed information regarding the potential role of SE based micro cogeneration systems to achieve the objective of converting existing Canadian houses into net/nearly zero energy buildings (NZEB).

4.3. Methodology

This study was conducted using a representative model of the CHS that incorporates a whole building simulation approach. The methodology used in the study is discussed below.

4.3.1. Modeling the Canadian Housing Stock

Due to the wide range of climatic, geographical and economic conditions as well as the availability and price of fuels and energy sources in different regions of Canada, the CHS exhibits a high diversity in geometry and construction materials as well as heating, cooling and ventilation systems. Thus, this study was conducted using CHREM (Swan, 2010; Swan *et al.*, 2013), which is based on the Canadian Single-Detached Double/Row Database (CSDDRD) (Swan *et al.*, 2009) and is statistically representative of the CHS.

CHREM utilizes the high-resolution building energy simulation program ESP-r (ESRU, 2015) as its simulation engine, an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. ESP-r has been validated through a vast amount of research results (Strachan *et *al.*, 2008). 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 unique 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:

- The Canadian Single-Detached & Double/Row Housing Database (Swan *et al.*, 2009),
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households (Swan *et al.*, 2011),
- 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 (Farhat and Ugursal, 2010),
- A model to estimate GHG emissions from fossil fuels consumed in households.

As discussed in detail elsewhere (Asaee *et al.*, 2015c; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d), the energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as cogeneration systems, can be estimated using CHREM as follows:

i. Identify houses suitable to receive the upgrade/technology: For Stirling engine cogeneration system retrofit, only houses with a basement or a mechanical room would be suitable. Therefore, a search has to be conducted in the CSDDRD to identify such houses.
ii. Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.
iii. Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the "base case" (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated

using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010). Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

CHREM has so far been used to evaluate the energy, economic and emissions performance of window and windows shading upgrade as well as solar domestic hot water (SDHW) heating, manipulation of phase change materials (PCM) and ICE cogeneration retrofit in the CHS (Asaee *et al.*, 2015c; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

4.3.2. Modeling the SE Cogeneration System

The SE cogeneration system shown in Figure 4.1 is considered for retrofitting existing and eligible Canadian houses. This architecture is based on the SE cogeneration system used in IEA/ECBCS Annex 42 subtask B (Kelly and Beausoleil-Morrison, 2007) and is capable of providing space and DHW heating as well as electricity to the house. The system includes a thermal storage tank for the purpose of allowing the SE to work for extended periods at full load and steady state to minimize fuel consumption by reducing the low efficiency operation during engine warm-up and stray losses during cool-down. The size of the cogeneration unit is selected based on the design heating load of the house and the thermal and electrical efficiencies are assumed as 80% and 10%, respectively. A cogeneration unit that just matches or is slightly undersized for the design heating load is assigned to each house, with the balance to be made up by auxiliary heat. The thermal load following method is assumed in all cases. The effect of start-up and shut-down losses are ignored in the simulations based on a sensitivity analysis that was conducted to quantify the impact of start-up and shut-down transient losses on the annual performance of residential scale cogeneration units in the Canadian climate. The results of the analysis indicated that the impact of these losses is in the order of 5% in the Canadian context over the course of a year. Consequently, it was decided to neglect the start-up and shut-down transients and treat the electrical and thermal efficiencies as constants.

An auxiliary boiler is included to provide heat when the available energy in the thermal storage tank is not sufficient to meet the thermal energy demand for space and DHW heating. A hot water tank is added to the system to store high temperature water required for space and DHW heating. Two heat exchanger coils are considered in the hot water tank to heat DHW and the circulated water in the space heating radiators. The DHW heat exchanger coil is sized based on the maximum flow rate. To avoid overheating the DHW when the flow rate is less than the maximum value, a tempering valve is used to maintain the DHW temperature at 55°C. Space heating is accomplished by a hydronic system that circulates heat to radiators.

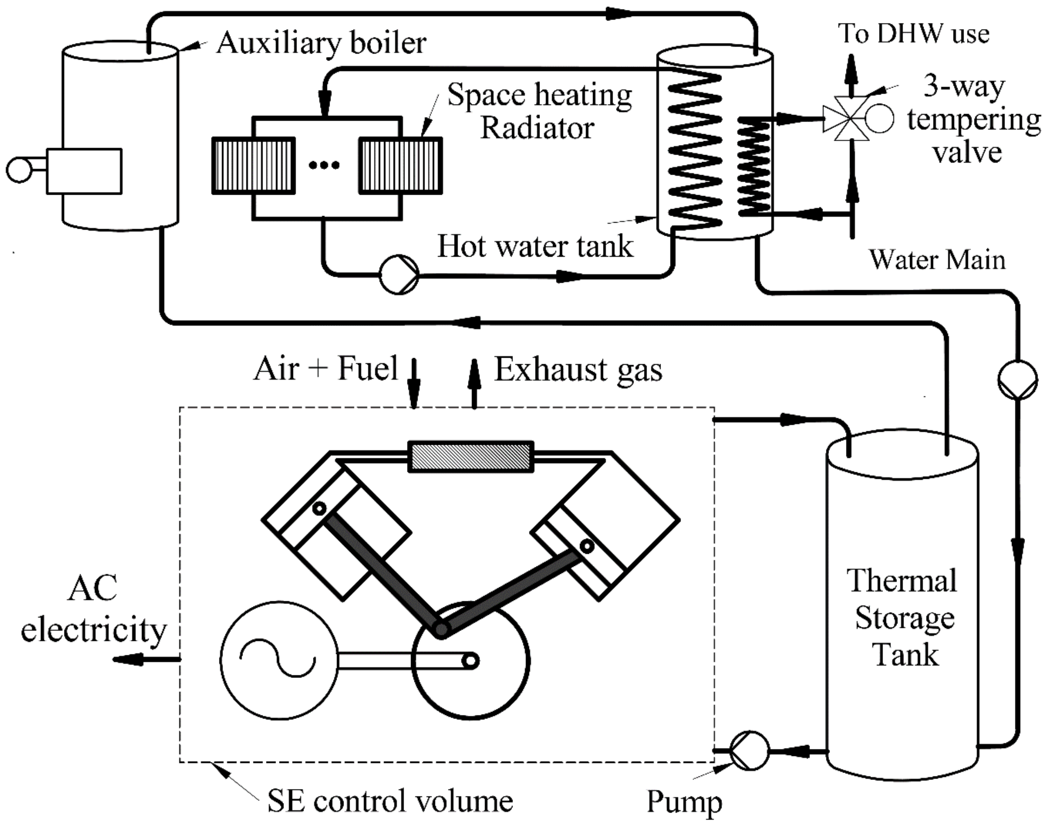

Figure 4.1 Stirling engine based cogeneration system architecture.

The SE cogeneration system presented in Figure 4.1 was modeled using the component models and control algorithms available in ESP-r to determine the fuel consumption of the cogeneration system. The capacity of the SE cogeneration system for each eligible house is determined according to the design heating load of the house. The building/plant model developed in ESP-r conducts an annual simulation (January 1 to December 31) with 10-minute time steps. Thus, the building model calculates the electricity as well as space and domestic hot water heating loads of the house for each 10-minute time step and passes this information to the SE cogeneration plant model. The plant model, using the performance and control algorithms, calculates the energy input/output of the cogeneration system and the auxiliary heater, as well as the electricity import/export values. The simulation is run in this fashion for the entire year, and the results are calculated and accumulated at 10-minute time steps.

The fuel used in SE cogeneration systems depends on the province. In all provinces except the Atlantic Provinces of NF, NB, NS and PE, Natural gas (NG) is widely available for residential customers. Therefore, it is assumed that in all provinces except these four, the fuel used in SE cogeneration is NG. In the four Atlantic Provinces, home heating oil is used for cogeneration.

4.3.3. Methodology to Select Houses for SE Cogeneration System Retrofit

The presence of a basement or mechanical room is necessary to install a SE cogeneration system in a house. Existence of mechanical room in the houses that do not have a basement is not specified in CSDDRD. Therefore, all houses that utilize natural gas or heating oil fired heating systems, electric furnaces, or wood furnace/boilers are considered to have a mechanical room and are eligible for cogeneration retrofits.

Based on these eligibility criteria, 71% of the houses in the CHS were found to be eligible for the SE cogeneration system retrofit as shown in Table 4.1.

Table 4.1 Portion of houses eligible for SE engine cogeneration retrofit (% of total)

NF	NS	PE	NB	QC	OT	MB	SK	AB	BC	Canada
50	69	87	51	19	90	72	91	100	79	71

4.3.4. Estimation of the GHG Emission Intensity Factor for Electricity Generation in Each Province of Canada

Once the houses to be retrofitted with a cogeneration system were identified, those house files were modified to reflect the retrofit, and a batch simulation was conducted. The resulting energy consumption reflects the energy savings associated with the SE cogeneration system retrofit. Thus, the annual energy savings associated with the retrofit is determined by subtracting the energy consumption with cogeneration from the base case energy consumption.

Once the annual energy savings with the SE cogeneration system 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 losses.

Table 4.2 The average and marginal GHG intensity factors (g CO_{2eq}/kWh) for each province of Canada (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 $EIF_{Marginal}$		837	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%

The GHG emissions were calculated using the GHG emission intensity factor (EIF), which is the level of CO_{2e} emitted per unit input energy. 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, the GHG EIF for electricity generation varies from province to province in Canada because of the different fuel mixture used in each province. 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 Table 4.2 (Farhat and Ugursal, 2010).

4.4. Results and Discussion

The CHREM estimates of current annual end-use energy consumption by the CHS and the associated GHG emissions are given in Table 4.3 (Swan *et al.*, 2013). The values presented in the table constitute the "Base Case" (i.e. current) end-use energy consumption and GHG emissions for the CHS by province and fuel type.

Table 4.3 CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source (Swan *et al.*, 2013)

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

The SE cogeneration system shown in Figure 4.1 was integrated into the eligible houses in CHREM and simulations were conducted to determine the energy end-use consumption and GHG emissions assuming that all eligible houses are retrofitted with the SE cogeneration system. The number of houses eligible for retrofit as well as the energy savings and GHG emission reductions due to the retrofits are given in Table 4.4. The results are discussed in detail in the following sections.

Table 4.4 Energy savings and GHG emission reductions per house due to SE cogeneration retrofit

Province	No of houses eligible for retrofit	Total Energy saved (PJ)	Energy saved per house (GJ)	Total GHG reduced (Mt)	GHG reduced per house (kg)
NF	88,207	4.3	49	0.01	101
NS	205,181	8.9	43	0.55	2,655
PE	38,997	1.9	49	0.05	1,262
NB	122,070	6.8	56	0.30	2,416
QC	382,595	11.5	30	0.23	599
OT	3,082,265	120.3	39	8.81	2,859
MB	243,288	11.1	46	0.35	1,455
SK	287,895	13.9	48	0.64	2,211
AB	970,120	38.4	40	2.68	2,761
BC	877,789	28.2	32	1.03	1,175
Canada	6,298,407	245.2		14.65	

4.4.1. Impact of SE Cogeneration System Retrofit on the Energy Consumption of the CHS

The breakdown of annual end-use energy consumption of the houses eligible and ineligible for the SE cogeneration retrofit are given in Table 4.5 for each energy source and province. Electricity and fuel consumption in houses eligible for SE cogeneration retrofit are presented for existing and retrofit conditions. The energy consumption for the CHS is determined by adding the energy consumption of houses not eligible for the SE cogeneration retrofit to these data for existing and retrofit scenario, respectively. The results show that the retrofit of SE cogeneration system reduced the fuel consumption in all provinces except in the QC and OT while the electricity generation of SE is not sufficient to supply the full demand in any region. In QC the existing heating systems are oil fired, however, due to wide availability of NG for residential customers the NG fired SE cogeneration system assumed for retrofit.

Table 4.5 CHREM estimates of annual energy consumption (PJ) with existing (Exist) and SE cogeneration retrofit (SER) systems in houses eligible (EL) and houses not eligible (N-E) for SE cogeneration retrofit

	Electricity			NG[a]		Oil[a]		Wood			Total		
	N-E	EL						N-E	EL		N-E	EL	
Province		Exist	SER	Exist	SER	Exist	SER		Exist	SER		Exist	SER
NF	10.9	4.3	2.4	0.0	0.0	9.6	9.9	0.6	2.7	0.0	11.5	16.6	12.3
NS	9.1	8.6	5.8	0.0	0.0	22.6	20.2	2.3	3.7	0.0	11.4	34.9	26.0
PE	0.4	1.4	1.1	0.0	0.0	4.0	3.2	0.7	0.8	0.0	1.1	6.2	4.3
NB	12.7	6.0	2.8	0.0	0.0	9.7	12.9	3.9	6.8	0.0	16.6	22.5	15.7
QC	181.7	23.6	7.1	1.0	39.2	30.3	0.0	7.5	2.9	0.0	189.2	57.8	46.3
OT	40.6	96.6	59.6	337.4	301.5	47.4	0.0	0.0	0.0	0.0	40.6	481.4	361.1
MB	12.1	6.8	3.8	33.6	25.5	0.0	0.0	0.0	0.0	0.0	12.1	40.4	29.3
SK	3.1	7.5	5.5	40.2	28.3	0.0	0.0	0.0	0.0	0.0	3.1	47.7	33.8
AB	0.0	28.3	23.7	119.8	86.0	0.0	0.0	0.0	0.0	0.0	0.0	148.1	109.7
BC	23.2	41.4	34.0	83.9	63.5	0.0	0.0	1.7	0.4	0.0	24.9	125.7	97.5
Canada	293.9	224.4	145.8	615.9	544.0	123.6	46.2	16.7	17.3	0.0	310.6	981.2	736.0

[a] All houses that use NG or oil as onsite fuel are eligible for cogeneration upgrade

Table 4.6 Annual energy savings and GHG emission reductions due to SE cogeneration retrofits in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	1.9	0	-0.3	2.7	4.3	0.03	0.00	-0.02	0.01
NS	2.8	0	2.4	3.7	8.9	0.39	0.00	0.16	0.55
PE	0.3	0	0.8	0.8	1.9	0.00	0.00	0.05	0.05
NB	3.2	0	-3.2	6.8	6.8	0.52	0.00	-0.23	0.30
QC	16.5	-38.2	30.3	2.9	11.5	0.03	-1.93	2.13	0.23
OT	37	35.9	47.4	0	120.3	3.78	1.71	3.32	8.81
MB	3	8.1	0	0	11.1	0.0	0.35	0.00	0.35
SK	2	11.9	0	0	13.9	0.04	0.60	0.00	0.64
AB	4.6	33.8	0	0	38.4	1.00	1.68	0.00	2.68
BC	7.4	20.4	0	0.4	28.2	0.04	0.99	0.00	1.03
Canada	78.6	71.9	77.4	17.3	245.2	5.83	3.40	5.41	14.65

Depending on the proportion of the houses eligible for retrofit and the type of fuels used for electricity generation and heating, the energy savings in each province is different as shown in Table 4.6 and Table 4.7. These results show that retrofitting SE cogeneration in all eligible houses yields a 19% (representing 245.2 PJ/year) reduction in the end-use energy consumption of the CHS. The highest potential for energy savings is in SK, PE, AB and OT, while the lowest energy savings are in QC. This is because of the high proportion of houses that use baseboard electric convectors for space heating in QC, resulting in a relatively smaller proportion of eligible houses compared to the rest of Canada as shown in Table 4.1.

Table 4.7 Annual energy savings and GHG emission reductions due to SE cogeneration retrofits in the CHS if eligible houses selected based on the criteria presented in Section 4.3.3

Province	Energy Savings (%)	GHG emission reductions (%)
NF	15	1
NS	19	10
PE	26	13
NB	17	10
QC	5	9
OT	23	31
MB	21	20
SK	27	14
AB	26	20
BC	19	22
Canada	19	22

4.4.2. Impact of SE Cogeneration System Retrofit on GHG Emissions of the CHS

The annual GHG emissions reduction in the CHS due to SE cogeneration upgrade in eligible houses is presented in Table 4.6 for each energy source and province. Since CO_2 emissions of biogenic material combustion will return to the atmosphere the CO_2 that was originally removed by photosynthesis, CO_2 emissions from biogenic materials are considered as a complement of the natural carbon cycle (Farhat and Ugursal, 2010). Thus the GHG intensity factor for wood is considered to be zero and emissions due to wood consumption is omitted from Table 4.3 and Table 4.6. Percent GHG emission reductions due to the SE cogeneration retrofit relative to base case GHG emissions is presented in Table 4.7.

Due to the high efficiency of simultaneous electricity and heat generation, the SE cogeneration retrofit results the overall reduction of GHG emissions of the CHS; however, the reduction is not the same for all provinces. Because of differences in fuel mixture for electricity generation and space heating the energy savings and GHG reduction distribution are not the same in Canadian provinces. For example while the NF exhibits 15% (representing 4.3 PJ/year) energy saving due to SE cogeneration retrofit the GHG reduction is almost negligible. As shown in Table 4.6, wood has a significant portion (2.7 PJ) of end-use energy savings. As discussed before, the GHG EIF of the wood is assumed to be zero, thus, replacing the wood fired space heating system with oil burned SE cogeneration system increase the annual GHG emissions. However, the increase in GHG emissions is cancelled by the GHG emissions reduction due to electricity production of cogeneration system.

The results provided in Table 4.7 illustrates that retrofitting SE cogeneration in all eligible houses yields a 22% (representing 14.65 Mt of CO_{2e}/year) reduction in the GHG emissions of CHS. From environmental perspective OT, BC, AB and MB show the most attractive condition for SE cogeneration retrofit.

4.5. Conclusion

The results of a comprehensive study conducted to estimate the impacts of SE cogeneration retrofits on the energy consumption and GHG emissions of the CHS were presented. The study was conducted using the CHREM, a versatile end-use and emissions energy model of the CHS. The study is part of a large-scale effort to develop approaches, incentive measures and strategies to facilitate conversion of existing Canadian houses into net zero energy buildings under Smart Net-Zero Energy Buildings Strategic Research Network.

Energy savings and GHG emission reductions are used to assess the impact of the SE cogeneration system upgrade performance in the CHS. The results of this study indicate that retrofitting existing houses in the CHS could result in 19% of energy savings and 22% of GHG emissions reductions. The suitability of SE cogeneration retrofit depends on the fuel mixture used for space heating and electricity generation as well as status of existing heating system in different provinces. Further studies are needed to study the impacts and feasibility of incorporating other energy efficiency and renewable energy technologies to achieve or approach net zero energy status in existing Canadian houses.

Chapter 5 Preliminary Study for Solar Combisystem Potential in Canadian Houses

This section was previously published as:

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Rasoul Asaee is the principal researcher and author of the article. He conducted the research as part of his PhD. Thus, while he received supervision and guidance from his supervisors Drs. Ugursal and Beausoleil-Morrison as well as Dr. Ben-Abdallah, he carried out the work, wrote the published article, communicated with the editor of the journal, and carried out the necessary revisions before publication. Minor editorial changes have been made to integrate the article within this dissertation.

5.1. Abstract

Solar combisystems that are capable of providing space heating and cooling as well as domestic hot water heating present a promising alternative to conventional systems to achieve net zero energy status in residential buildings. To determine whether or not the performance of such systems would be suitable in the northerly Canadian context, a preliminary study was conducted to evaluate the thermal performance of a solar combisystem with space heating, cooling, domestic hot water heating and thermal storage capability for houses in the four climate regions of Canada (Atlantic, Central, Prairies and Pacific) based on simulations conducted using models developed within the TRNSYS 17.1 energy simulation software. For days without sufficient sunshine, auxiliary heating and cooling systems are included. The operation of the solar combisystem and the auxiliary systems is controlled using a realistic control algorithm. Sensitivity analysis is conducted to determine effects of solar collector area and storage capacity on solar combisystem performance. The results show that solar combisystems can provide a substantial fraction of the space heating, cooling and domestic hot water heating energy requirement of a simple house in all major climatic regions of Canada. As to be expected, climatic conditions have an important impact on solar combisystem performance. The results also show that increasing solar collector area enhances solar fraction, and the solar fraction curve peaks at a specific storage capacity. Based on the favorable results found in this study, it is clear that further and more detailed studies are warranted on solar combisystem applications in

Canada. The next step in this work will be a much more detailed evaluation using the Canadian Hybrid Residential Energy End-use and Emissions Model.

5.2. Introduction

Canada is one of the highest per capita energy consumers in the world, with about 17% of the national energy consumption in the residential sector. The greenhouse gas emissions associated with this energy consumption represent about 16% of the national emissions. Therefore, there is pressure on Canada to reduce its residential energy consumption. In this respect, research in net zero energy buildings research has gained impetus over the past years. One technology that presents a high potential to achieve net zero energy status is the solar combisystem. A solar combisystem provides space heating and cooling as well as domestic hot water (DHW) heating supplied by an array of solar collectors and an absorption-cooling device. Additional auxiliary heating and cooling systems are included for back up on days with insufficient sunshine. Naturally, with the additional subsystems for space heating and cooling capability, solar combisystems are more complex than simple solar DHW heating systems. It is therefore necessary to evaluate the performance of solar combisystems in houses through detailed computer simulations. This work is a preliminary study to assess the potential of solar combisystems for the Canadian housing stock. Based on the findings of this work, a larger scale study will be conducted using the Canadian Hybrid Residential Energy End-use and Emissions Model (CHREM) (Swan *et al.*, 2008) and the ESP-r/TRNSYS co-simulator (Beausoleil-Morrison *et al.*, 2012).

In a combisystem there are at least two energy sources that supply heat to space and DHW heating and absorption cooling: the solar collectors deliver heat as long as solar power is available, and the auxiliary energy source supplies heat when the solar power is not available. The main challenge in the design of a solar combisystem is combining the different requirements of heat suppliers and heat consumers into one single, cost effective, durable and reliable heating and cooling system, achieving the most benefit from each installed square meter of collector (Weiss, 2003).

Parameters that affect annual energy requirement for space heating and cooling include the climate, building size and envelope characteristics, ventilation, passive solar use and internal heat loads as well as the number of occupants. The annual energy requirement for

DHW heating depends on the number of occupants and mains water temperature. Commonly, 10-40% of the building heat load is for DHW heating (Weiss, 2003).

Since the design of a solar combisystem needs a wide range of computations for both building load and system performance predictions, computer simulation is a suitable tool for this purpose. Thus, numerous articles have been reported in the literature on solar combisystem studies conducted using computer simulations.

In one of the earliest works, Klein *et al.* (1976) developed a simulation model to estimate the performance of residential solar space and water heating systems. A graphical design method for solar heating systems was presented based on the information gained from a series of simulations.

Drück and Hahne (1998) studied four types of hot water storage tanks to be used with solar combisystems. They concluded that the thermal insulation of storage, solar loop heat exchanger capacity and the size of the auxiliary heating system are important parameters in solar combisystem performance.

Braun *et al.* (1981) conducted a study on thermal storage for space heating using water as the storage medium. A transient simulation model based on TRNSYS software (2013) was used to investigate interrelationships between collector area, storage volume, and system performance. A series of case studies was conducted to examine the effects of load heat exchanger size, tank insulation, collector slope, and year-to-year weather variations on system design.

Jordan and Vajen (2001) studied the influence of DHW load profiles for a solar combisystem. A numerical simulation using a model based on the TRNSYS software was carried out with a variety of simplified and realistic load profiles.

Bales and Persson (2003) studied seven different external DHW units, comprising of flat plate heat exchanger and flow control, to determine the method that produced the best performance with solar combisystems. They considered a reference method for preparing hot water and compared each of external DHW units with the base case for a reliable evaluation. A numerical model was developed within the PRESIM/TRNSYS simulation environment. The results show that the hot water load profile strongly influences the energy savings.

Lund (2005) presented an analytical daily model to predict the solar combisystem performance. The study indicates that increasing the collector area in a solar combisystem for higher solar fractions could be economically justified in average or older building stock in northern and central Europe but not yet in low energy or very energy efficient buildings, nor in a more southern climate. Increasing the size of the heat storage much beyond the daily capacity proved not to be well justified with solar combisystems.

Thür *et al*. (2006) used TRNSYS 16 to simulate the performance of a solar combisystem combined with a condensing natural gas boiler. Simulations were conducted for a single family house located in Stockholm with two combisystem sizes, a small (6m^2 solar collector and total 300 L/auxiliary 90 L solar tank volume) and a large (20m^2 solar collector and total 1000 L/auxiliary 300 L solar tank volume) system. Results show that the energy savings were 33% for the small system and 88% for the large system compared to a traditional boiler system with no solar input.

Leckner and Zmeureanu (2011) conducted a numerical study to investigate solar combisystem to reach the goal of net zero energy house (NZEH) in the cold climate of Montreal. The results show that in terms of the life cycle energy use, the energy payback time is 8.4–8.7 years when the NZEH is compared with an average house that complies with the provincial code. However, the life cycle cost analysis of the NZEH shows that due to the high cost of the solar technologies and the low cost of electricity in Montreal, financial payback is never achieved.

Kacan and Ulgen (2012) ran a series of experiments to evaluate and improve the performance of an existing solar combisystem in Turkey. The measurements were done from December 2010 until May 2011. The study revealed that the annual solar fraction of the system was approximately 83%.

Rodríguez-Hidalgo *et al*. (2012) developed a transient model to size a solar DHW system for apartment buildings with focus on the size of storage components. They showed that storage size may strongly affect solar DHW system performance.

Enteria *et al*. (2010) developed a novel solar hot water heating and space cooling system. Measurement results indicated that the available solar energy is not sufficient during the early hours of the day to supply the energy requirement of the house and stored thermal energy were used for system operation. Results show that the solar space cooling system was able to satisfy the latent and sensible cooling loads with little contribution from the auxiliary cooling system.

Jing *et al*. (2012) studied a solar heating and cooling system with natural gas operated auxiliary system. Primary energy consumption and emissions were measured among different operation strategies. A numerical study was conducted for a commercial building in Beijing, China and concluded that thermal energy following is the preferable operation strategy operation strategy.

Chow *et al*. (2012) developed a TRNSYS model to study a solar assisted heat pump for space and water heating for a swimming pool application. Energy performance of the system was calculated using winter time operation schedule. They concluded that the solar assisted heat pump resulted in energy savings close to 79% with a payback period of less than 5 years.

In the present study, a novel architecture for a solar combisytem is considered to supply heating and cooling as well as DHW heating to a simple house consisting of a single thermal zone under the four primary climate conditions in Canada. This simulation based study is the first part of a comprehensive study to evaluate the techno-economic performance and feasibility of solar combisystem for the Canadian housing stock. The purpose of this preliminary study is to gain a preliminary understanding of solar combisystem performance in the Canadian climatic conditions. Based on the results of this study, suitable ranges of sizing and design parameters for solar combisystems will be determined for Canadian houses and detailed simulation studies will be conducted.

5.3. Problem Statement

This work aims to investigate the energy performance of solar combisystem for Canadian houses based on simulations conducted using a model developed within the TRNSYS building simulation software environment. Simulations are conducted for Canadian houses in the four climate conditions (Atlantic, Central, Prairies and Pacific) to study energy savings possible with solar combisystems. The specific objectives are:

a. To propose a suitable architecture for solar combisystems for Canadian houses.

b. To simulate the performance of solar combisystem for heating, cooling and DHW for Canadian houses in four major climatic regions of Canada; Atlantic, Central, Prairies and Pacific. Halifax weather was used to represent the climate of the Atlantic region, Montreal to represent the climate of the Central region, Edmonton to represent the climate of the Prairies region and Vancouver to represent the climate of the Pacific region. The location and basic weather data for these cities are given in Table 5.1.
c. To perform sensitivity analysis on solar combisystems for space heating, cooling and DHW heating to evaluate effect of collector area and storage capacity on solar combisystem performance.

Table 5.1 Basic weather data for studied cities

Parameter		Halifax	Montreal	Edmonton	Vancouver
Longitude		63.6	73.6	114.1	123.2
Latitude		44.6	45.5	53.5	49.2
HDD (°C, annual) Base Temp= 18°C		4031	4519	5708	2927
CDD (°C, annual) Base Temp= 18°C		106	242	29	45
Monthly average temperature					
	J	-4	-10	-11	3
	F	-5	-9	-10	5
	M	-8	-2	-4	6
	A	3	6	4	9
	M	8	13	12	12
	J	13	18	15	15
	J	17	21	18	17
	A	18	20	16	17
	S	14	15	11	14
	O	10	9	5	10
	N	4	2	-6	6
	D	-4	-1	-11	3

5.4. Methodology

An accurate performance evaluation of the solar combisystem requires the prediction of the space heating, cooling, and DHW heating loads of the house. Hence, a detailed building model was developed in TRNSYS 17.1 software to obtain these loads, which were then used as input to the solar combisystem plant model, also developed within the TRNSYS software.

The house used in the case studies was selected from the Canadian Single-Detached and Double/Row House Database (CSDDRD) (Swan *et al.*, 2009). CSDDRD is statistically representative of the Canadian housing stock. It was developed based on the available data from the EnerGuide for Houses database (SBC, 2006), Statistics Canada housing surveys (OEE, 2006) and other available housing databases. CSDDRD consists of approximately 17,000 unique house records with detailed information on geometry, construction material and air-tightness as well as heating, cooling and ventilation system (Swan *et al.*, 2009). The selected house is a commonly encountered one-story single family house. The occupant related household energy consumption (e.g. for appliances and lights) of the house is based on a neural network model that was verified against actual data from Canadian houses (Swan *et al.*, 2011).The architecture of the house was simplified for simulations using the TRNSYS component (type 19) that models the thermal behavior of a building with single thermal zone. The basic architectural characteristics of the house are given in Table 5.2.

Table 5.2 Basic architectural characteristics of the house

Parameter	Unit	House						
		Wall				Roof	Floor	Window South
		S	W	E	N			
Area	m^2	24	30	30	24	80	80	6
Thermal conductivity	W/m^2K	0.55	0.55	0.55	0.55	0.8	2.4	3
Infiltration rate	kg/h	30						
Occupancy	people	2						

The methodology used to develop the combisystem model consisted of three main parts:

a. A comprehensive literature review was conducted to survey and gather a data bank of results for validation as well as guidelines for parametric studies.
b. Based on the solar combisystem architecture in Figure 5.1, the solar combisystem was modeled using the available component models in TRNSYS 17.1 as summarized in Table 5.3. The model includes component models for the flat plate collector, storage tanks, heat exchangers, absorption refrigeration unit, hydronic components, auxiliary heating and cooling units, heating and cooling coils, control units and thermostat, and makes use of the appropriate weather data files.

c. Parametric studies were conducted to study the performance characteristics of solar combisystems and to evaluate the thermal performance of these systems in Canadian houses located in four major climate regions.

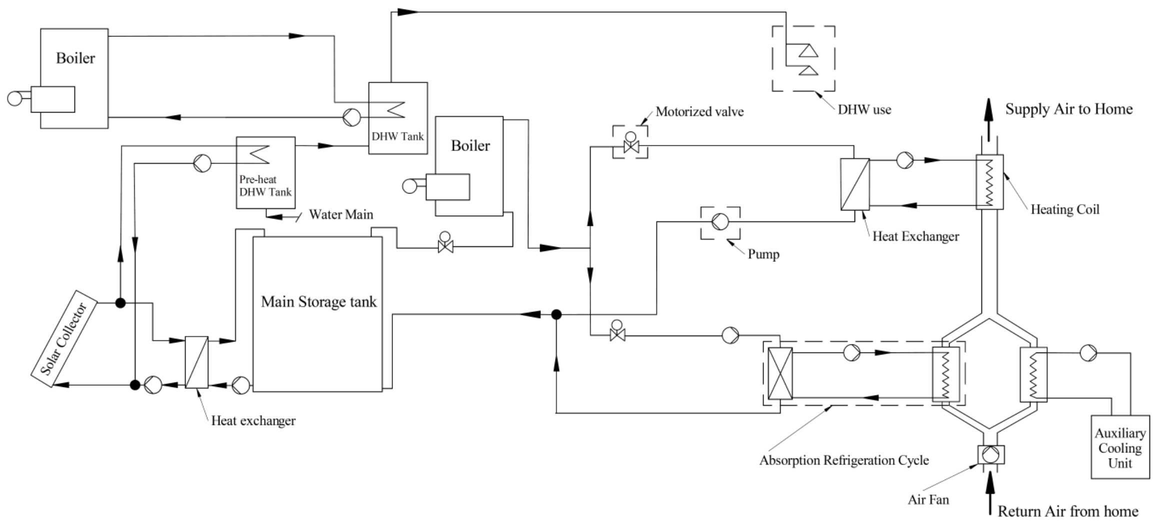

Figure 5.1 Solar combisystem architecture.

Table 5.3 TRNSYS types used in this study

Component name	TRNSYS type	
	Number	Name
Solar collector	1	Solar collector
Heat exchanger	5	Counter flow heat exchanger
Main storage tank	4	Storage tank; variable inlets
Preheat DHW tank	4	Storage tank; variable inlets
DHW tank	4	Storage tank; variable inlets
Boiler	6	Auxiliary heater
Absorption refrigeration cycle	107	Hot water fired single effect absorption chiller
Auxiliary cooling unit	92	Auxiliary cooling device
Heating coil	670	Heating coil with hot side bypass to keep air side outlet below its setpoint
Cooling coil	52	Cooling coil: detailed coil
Pump	3	Pump
Fan	111	Variable speed fan/blower

5.5. System Architecture and Components

The solar combisystem architecture used is presented in Figure 5.1 and list of its components are given in Table 5.3 and Table 5.4. This architecture is based on the solar combisystem 14 from Task 26 of IEA-SHC (Suter *et al.*, 2000) and is capable of providing space heating and cooling as well as DHW heating to the house, either directly or from its thermal storage. When there is insufficient solar radiation and the thermal storage heat is depleted, the auxiliary systems satisfy the loads. The primary difference between the architecture used here and the IEA-SHC Task 26 architecture is the cooling cycle and extra storage tanks. These changes are applied to achieve a suitable system for both space heating and cooling. Space cooling is provided by an absorption refrigeration cycle. The major components of the solar combisystem are described below, while the capacities and sizes of major components are given in Table 5.4.

Table 5.4 Capacity and size of major components

Type	Unit	Value
Solar collector (G32, by Thermo-Dynamic Ltd. www.thermo-dynamics.com)		
Module area	m^2	3
Collector slope	deg	45
Number of modules in parallel	–	8
Performance curve	–	http://www.thermo-dynamics.com/technical_specs/G_series_technical.html
Main storage tank		
Volume	m^3	3
Surface area	m^2	8.7
Thermal conductivity of insulation	W/mK	0.042
Insulation thickness	m	0.15
DHW storage tank		
Pre-heat tank volume	m^3	0.2
Surface area	m^2	1.6
Thermal conductivity of insulation	W/mK	0.042
Insulation thickness	m	0.05
Solar HX capacity	W/K	750
Auxiliary heater capacity	W/K	750
Auxiliary heating and cooling		
Rated capacity - auxiliary heating	kJ/h	3,000
Rated capacity – auxiliary cooling	kJ/h	5,000
Absorption chiller		
Rated capacity	kJ/hr	5,000
Rated COP	–	7.5
Auxiliary electric power	kJ/hr	2,000

5.5.1. Solar Collector

The solar collector used in the simulations is a flat plate collector with a gross module area of $3m^2$. In the base case runs, eight collectors connected in parallel are used. The performance data used in the simulations is the same as that of the G-32 flat plate collector provided by Thermo-Dynamics Ltd (Thermo Dynamics Ltd).

5.5.2. Auxiliary Systems

Auxiliary systems are necessary to support the solar combisystem in the case of low solar radiation, such as on cloudy days. In the case that solar produced heat is not sufficient to satisfy the space heating requirement, auxiliary heat is directly delivered to the space. Similarly, auxiliary cooling is available for the days when solar irradiation is insufficient to generate the required heat for the absorption cooling cycle.

5.5.3. Storage Tanks

Three thermal storage tanks are included in the system to increase the solar energy utilization to periods when solar radiation is insufficient or unavailable.

The main storage tank is used to store solar generated heat when available generated heat is greater than the space heating or cooling requirement. The volume of the main storage tank is a key parameter in the performance of a solar combisystem (Weiss, 2003).

Two DHW storage tanks are included in the system to store heated water for future use. Due to different temperature requirements for space and DHW heating, a separate DHW tank is used to pre-heat water. Pre-heated water flows into the second DHW storage tank. When necessary, heat is supplied by the auxiliary heater to the second DHW storage tank to elevate water temperature to the desired value (60°C).

5.5.4. Heat Exchangers

As shown in Figure 5.1, heat exchangers are used to transfer heat from the working fluid to the end use applications. Four types of heat exchangers are used in the proposed system:

- A plate heat exchanger is used is used to transfer heat from the solar collector to the main storage tank in the proposed design.
- Two immersed coil heat exchangers are used to deliver the heat produced in the solar collector and by the auxiliary burner to the DHW tank. This type of heat

exchanger is widely used for DHW applications. Thus, accurate models are available to predict the heat transfer rate for this configuration.

- As shown in Figure 5.1, the return air from the house passes through the heating and cooling coils, and is then supplied to the house for space heating and cooling purposes. Chilled water is supplied to the cooling coil either from the absorption refrigeration cycle or the auxiliary cooling unit. Hot water supply from main storage tank delivers heat to the heating coil.

5.5.5. Control Strategy

A thermostat controls the zone temperature and maintains it in a desired range. Heating set-point temperature is 21°C and cooling set-point is 24°C with a dead band of ±0.5°C to avoid rapid ON/OFF cycles.

Different control strategies are used for the heating and cooling season operation. Seasons are defined based on average outside temperature. Months where the average outside temperature is less than 18°C are considered winter and months with average temperature above this temperature are considered summer. The control strategies for the two seasons are as follows.

Heating Season:

- Because of the lower price of electricity at night, auxiliary heater provides required heat to DHW tank to heat DHW to maximum allowable temperature.
- After sunrise, priority is given to space heating and heat generated by solar power is delivered to the main storage tank to provide required heat to the water for space heating.
- If the available solar energy exceeds the space heating energy requirement, heat produced by solar power is supplied to the DHW storage tank in the rest of the day to heat the water to the maximum allowable temperature.
- When there is not sufficient heat to satisfy the space heating or the DHW heating requirement, the auxiliary systems are energized.

Cooling Season:

- Priority is given to the DHW tank, which is heated to the maximum allowed temperature when solar energy is available.
- After heating the DHW tank, the solar energy is used to heat the water in the main storage tank.
- An auxiliary cooling unit is included to support the absorption refrigeration cycle. In case of solar energy shortage, auxiliary cooling unit is used to satisfy the cooling requirement.
- The heat stored in the main storage tank supplies the heat requirement of the absorption refrigeration cycle. In a case that water temperature in main storage tank drops below the required heat source temperature of the absorption refrigeration cycle, the auxiliary heater is not implemented to supply the heat to the cooling system.

5.6. Results and Discussion

Annual simulations were conducted for the house equipped with the solar combisystem using the climate data of Halifax, Montreal, Edmonton and Vancouver representing the four climate regions of Canada.

The variation of the temperature of the DHW supplied to the house (T_DHW), pre-heat storage tank outlet temperature (T_PHT) and main water temperature (T_main-water) are plotted for an entire year (from hour 0 = January 1, 00:00 to hour 8760 = December 31, 24:00) in Figure 5.2.

Since the DHW usage pattern in the house is the same for all cities, the lower main water temperature results in a larger DHW heating demand. It can be seen that solar energy is not always sufficient to heat the DHW in the preheat tank to the desired supply temperature of 60°C. Therefore, the auxiliary heater elevates DHW temperature to the desired value (with a tolerance of 0.5°C, set by the control unit). As seen in Figure 5.2, solar energy is able to provide a substantial part of the DHW heating from March/April to September/October in all four cities.

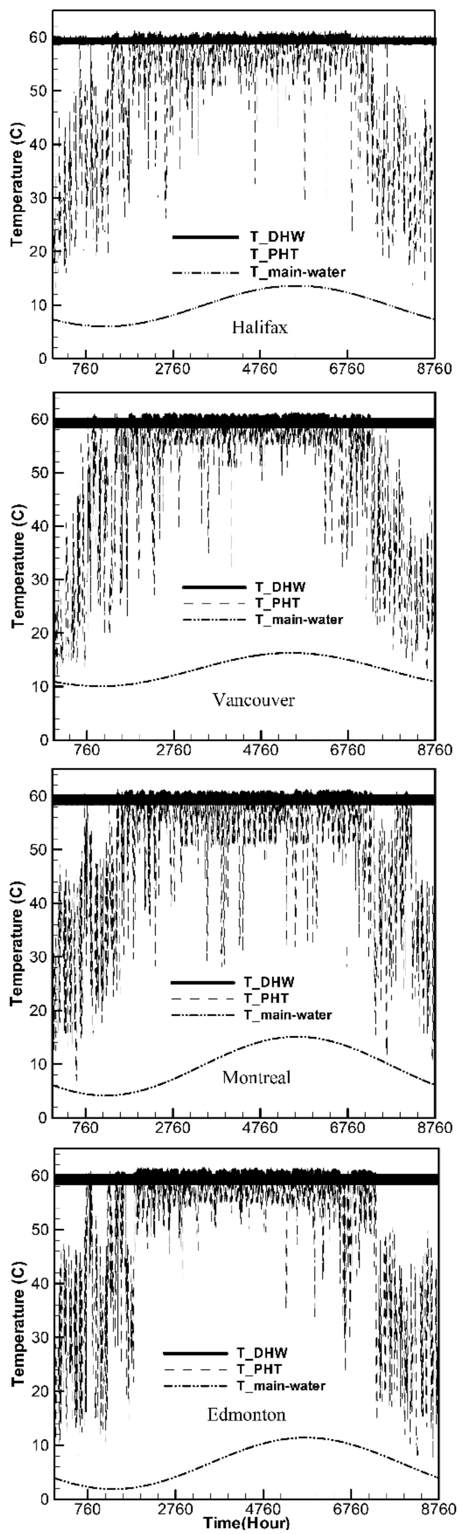

Figure 5.2 DHW and main water temperatures.

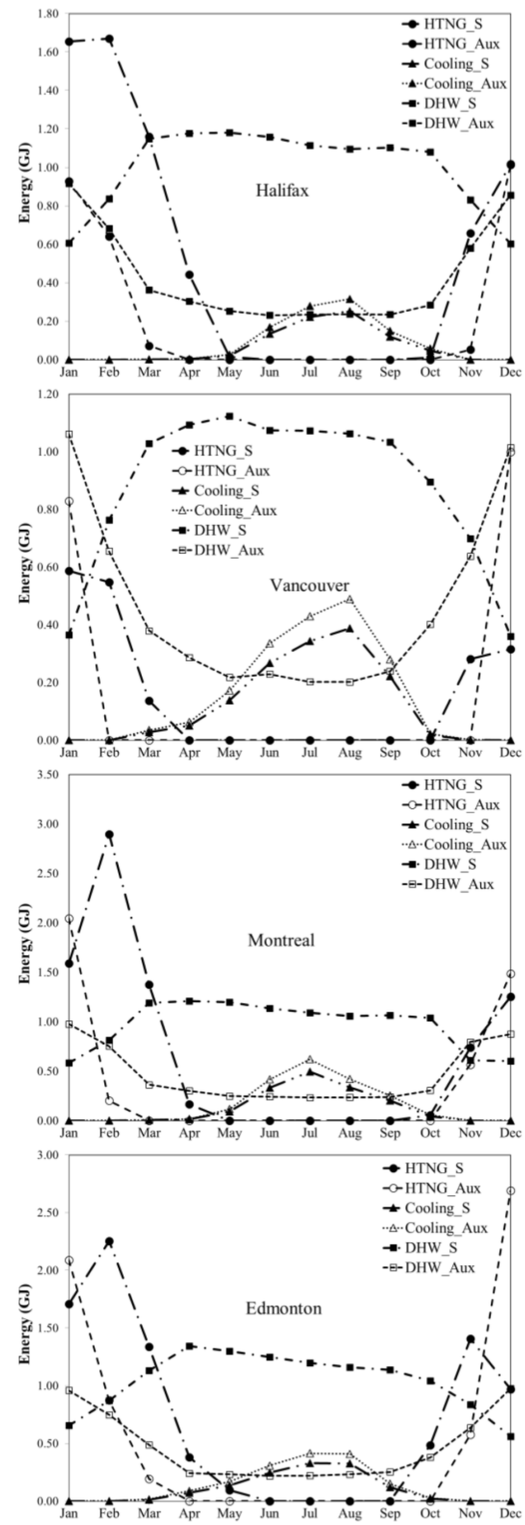

Figure 5.3 Energy supplied by the solar combisystem and the auxiliary systems.

Annual solar fraction is used to compare solar combisystem performance in Halifax, Montreal, Edmonton and Vancouver. Annual solar fraction (*f*) is the ratio of solar energy contribution to the total load, calculated using Equation (5.1):

$$f = \frac{\int_{t=0}^{t=8760} \dot{Q}_s dt}{\int_{t=0}^{t=8760} \dot{Q}_s dt + \int_{t=0}^{t=8760} \dot{Q}_{aux} dt} \tag{5.1}$$

The annual and monthly solar fractions for the four cities are given in Table 5.5, and the monthly quantities of heating, cooling and DHW heating energy supplied by the solar combisystem and the auxiliary systems are shown in Figure 5.3.

These results collectively indicate that solar combisystems are capable of providing a substantial portion of the heating, cooling and DHW energy needs of the test house in all four cities. As shown in Table 5.5 and Table 5.6, Edmonton has the highest solar energy contribution although its solar fraction is the lowest. The reason for this is the highest space and DHW heating energy requirement.

The results of the sensitivity analysis conducted to study the effect of solar collector area and storage volume on solar combisystem performance are presented in Figure 5.4 to Figure 5.7.

Table 5.5 Solar fractions

Solar fraction	Halifax	Vancouver	Montreal	Edmonton
Jan	0.62	0.47	0.48	0.48
Feb	0.73	0.80	0.81	0.69
Mar	0.90	0.89	0.92	0.85
Apr	0.93	0.92	0.92	0.91
May	0.93	0.92	0.91	0.90
Jun	0.91	0.88	0.86	0.87
Jul	0.89	0.87	0.83	0.86
Aug	0.88	0.87	0.85	0.86
Sep	0.91	0.89	0.88	0.89
Oct	0.91	0.86	0.90	0.88
Nov	0.79	0.74	0.56	0.67
Dec	0.50	0.34	0.48	0.32
Annual	0.82	0.78	0.78	0.76

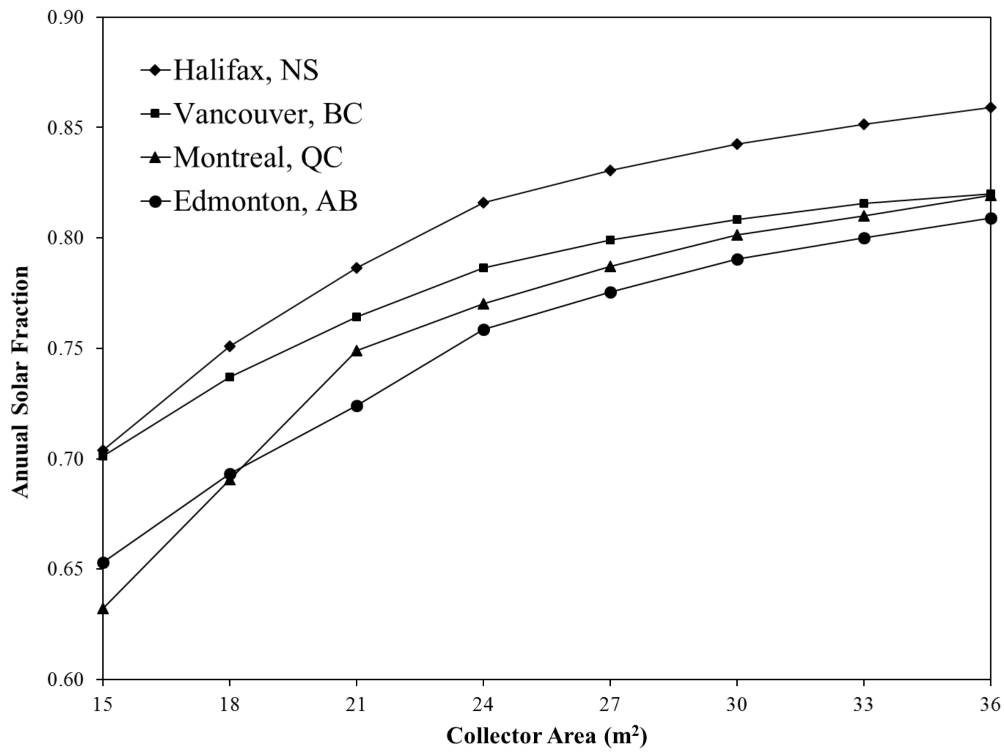

Figure 5.4 Effect of solar collector area on annual solar fraction.

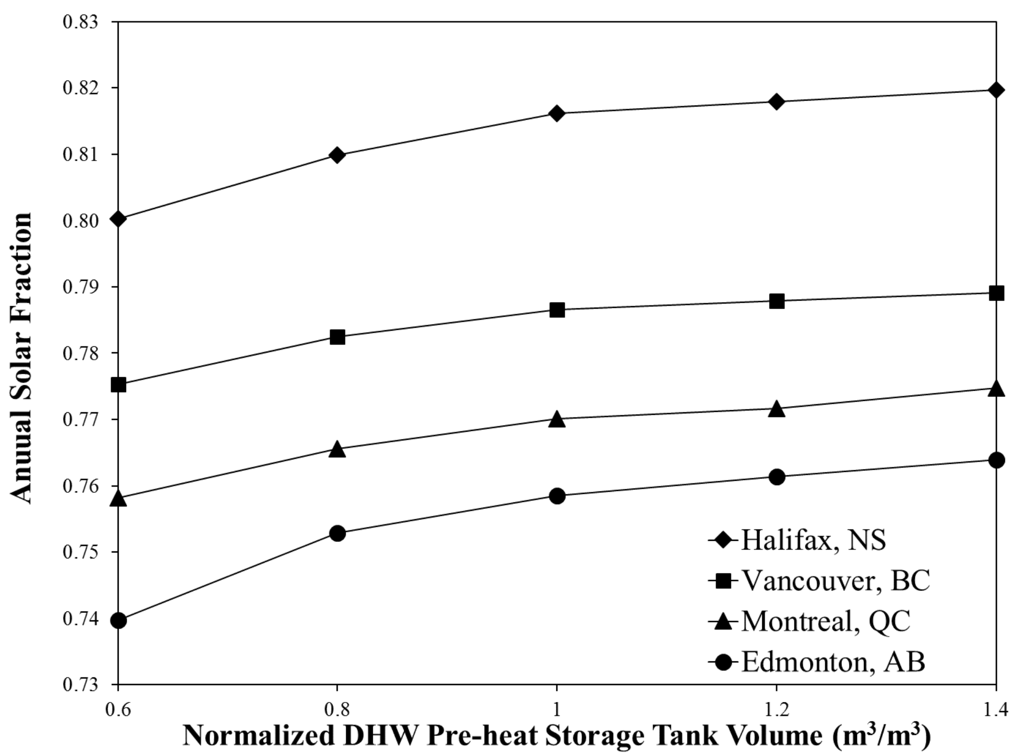

Figure 5.5 Effect of DHW storage tank volume on annual solar fraction.

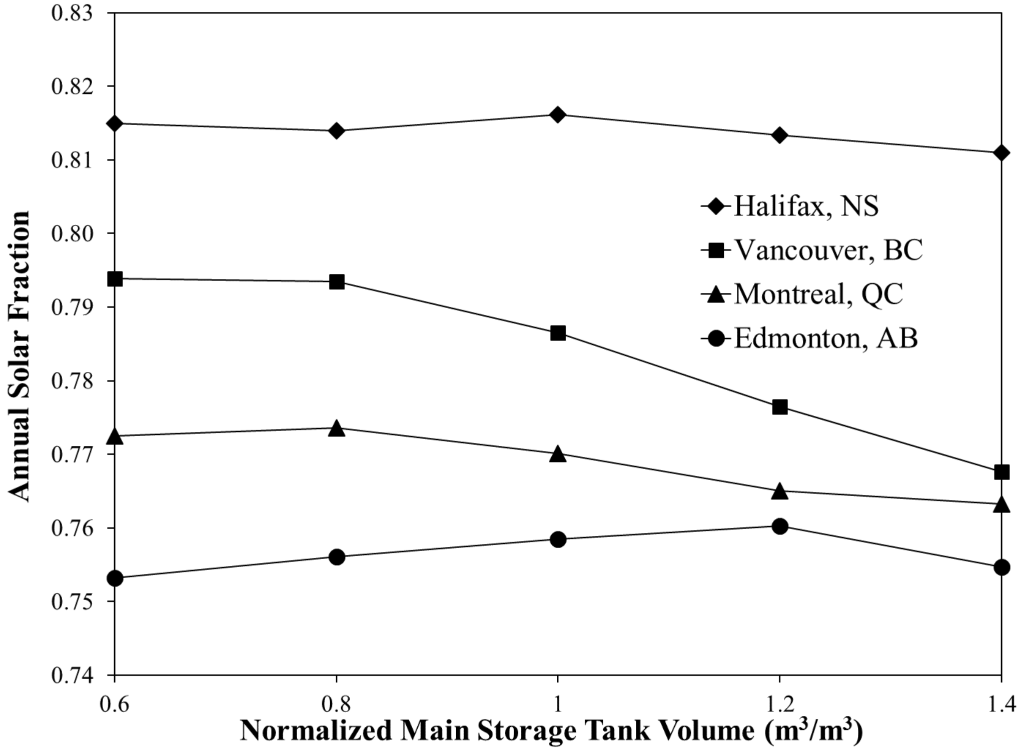

Figure 5.6 Effect of main storage tank volume on annual solar fraction.

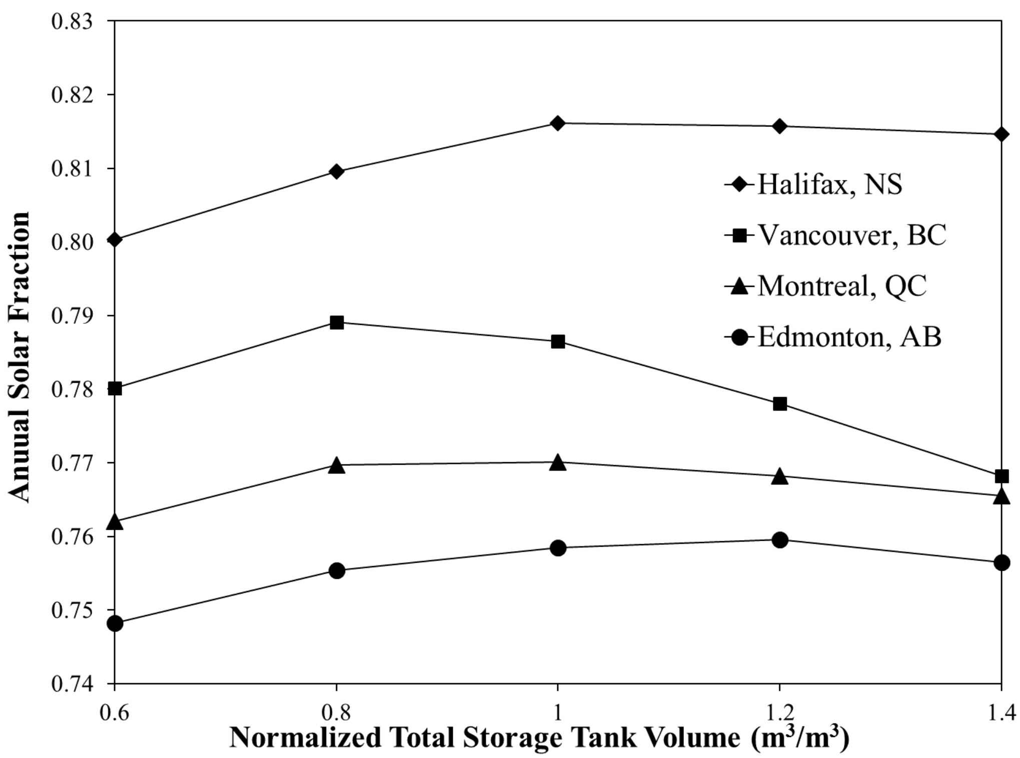

Figure 5.7 Effect of changing the volume of both storage tanks on annual solar fraction.

Table 5.6 Annual energy provided (GJ)

Source	Halifax	Vancouver	Montreal	Edmonton
Solar energy	22	18	25	27
Auxiliary energy	5	5	7	9

5.6.1. Effect of Collector Area on Combisystem Performance

Since the module size of the solar collector is 3 m^2, the area of collectors considered in the sensitivity analysis is a multiple of 3 m^2. Figure 5.4 illustrates solar fraction for the eight collector areas and four cities investigated (Trend lines are added to Figure 5.4 to Figure 5.7 to help visualize the treads).

It is observed from Figure 5.4 that increasing solar collector area increases solar fraction. However, the marginal increase in solar fraction becomes smaller with each incremental increase in solar collector area, thus the incremental benefit decreases as the collector area increases. However due to the differences in solar angle, sunshine hours and loads, the variation of solar fraction with solar collector area is different for each city. Halifax benefits most from increasing collector area because of its lower latitude, longer winter daylight hours, and higher loads compared to Vancouver.

5.6.2. Effect of Thermal Storage Capacity on Combisystem Performance

The effect of thermal storage capacity on combisystem performance was studied by changing:

- (i) only the DHW pre-heat tank volume,
- (ii) only the main storage tank (used to supply space heating and cooling system) volume,
- (iii) the volumes of both the DHW pre-heat tank and the main storage tank.

The tank volumes were changed by the same fraction with respect to the baseline values given in Table 5.4. Therefore, the results of the sensitivity analyses are presented in terms of normalized tank volume, which is given by Equation (5.2).

$$\text{Normalized tank volume} = \text{Volume/Baseline Volume} \tag{5.2}$$

Results of sensitivity analysis on the DHW pre-heat tank volume are plotted in Figure 5.5. As mentioned before, the DHW pre-heat storage tank as well as the main storage tank receive energy from the solar collector.

It is observed that increasing DHW pre-heat tank volume improves the solar fraction at a decreasing rate. This is because of the heating capacity of the solar system as well as the DHW loads. The benefit from thermal storage size becomes limited by the amount of energy available for storage and the amount of energy draw from the tank.

Figure 5.6 indicates that the annual solar fraction reaches a different maximum value for each city as the normalized main storage tank volume is varied. As the heating/cooling loads and the amounts of solar energy available for storage changes with location, the size of the storage tank that maximizes solar fraction also changes. Thus, if the storage capacity exceeds available solar energy, its temperature decreases. In this case auxiliary heater provides heat to elevate water temperature to desired value. Under these circumstances solar fraction declines if the storage capacity increases.

In order to put all of these effects together, a sensitivity analysis was conducted to determine the effect of varying the capacities of both storage tanks supplied by solar energy (main tank and DHW pre-heat tank).

Table 5.7 Comparison of solar combisystem performance from various studies

Ref.	Description	Location		Solar fraction (%)
present study	Residential	Canada	Atlantic	82
			Central	78
			Prairies	76
			Pacific	78
(Thür *et al.*, 2006)	Residential	Sweden		83
(Kacan and Ulgen, 2012)	Residential	Turkey		83
(Rodríguez-Hidalgo *et al.*, 2012)	Residential	Spain		61[a]
(Chow *et al.*, 2012)	Swimming pool	Hong Kong		73[b]

[a] solar collector used was 9 years old when it was used in the experiments and its area relative to building size is smaller in comparison to those used in other studies
[b] for the months of November to March

As shown in Figure 5.7, the solar fraction for each city has a maximum for a specific normalized total storage volume. This is because of the effects of increasing both the main storage tank and DHW pre-heat tank volumes are combined. The normalized volume at which maximum solar fraction is obtained is the same for this case and previous one. This indicates that the effect of main storage tank is dominant on solar fraction.

The predicted performance of the solar combisystems used in the present study is compared to the performance of similar systems reported in the literature in Table 5.7. While the system characteristics and climates used in the studies are different, the savings due to solar combisystems are in the 70-80% range, indicating the favourable potential of solar combisystems in a variety of climates and houses/system combinations.

5.7. Conclusion

The thermal performance of a solar combisystem with space heating, cooling, domestic hot water heating and thermal storage capability was evaluated for houses in the four climate regions of Canada (Atlantic, Central, Prairies and Pacific) based on simulations conducted using models developed within the TRNSYS 17.1 energy simulation software. For days without sufficient sunshine, auxiliary heating and cooling systems were included. The operation of the solar combisystem and the auxiliary systems was controlled using a realistic control algorithm. Sensitivity analysis was conducted to determine effects of solar collector area and storage capacity on solar combisystem performance. The results show that solar combisystems can provide a substantial fraction of the space heating, cooling and domestic hot water heating energy requirement of a simple house in all major climatic regions of Canada. As to be expected, climatic conditions have an important impact on solar combisystem performance. The results also show that increasing solar collector area enhances solar fraction, and the solar fraction curve peaks at a specific storage capacity. Based on the favorable results found in this study, it is clear that further and more detailed studies are warranted on solar combisystem applications in Canada. Therefore, our next step will be to conduct a detailed techno-economic evaluation using the CHREM (Swan *et al.*, 2008) and the ESP-r/TRNSYS co-simulator (Beausoleil-Morrison *et al.*, 2012).

Chapter 6 Techno-Economic Study of Solar Combisystem Retrofit in the Canadian Housing Stock

This section was previously published as:

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

6.1. Abstract

Techno-economic feasibility of retrofitting solar combisystems to houses in the Canadian housing stock (CHS) is investigated using the Canadian Hybrid Residential End-Use Energy and Emissions Model (CHREM). Solar combisystem architecture and sizing is based on the systems and guidelines provided by the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 26. Houses with sufficient roof area facing south, south-east or south-west, and a basement or mechanical room to contain solar combisystem components, including the thermal storage tank, auxiliary boiler and pumps, are considered eligible to receive the retrofit. A hydronic heat delivery system is used to supply heat to the thermal zones. Solar collector area is sized to match the nominal capacity of the existing heating system in each house. Reductions in energy consumption and greenhouse gas (GHG) emissions are evaluated. Results show that close to 40% of houses in the CHS are eligible for solar combisystem retrofit, and if all eligible houses are retrofitted, the annual energy consumption and GHG emissions of the CHS would be reduced by about 19%. The tolerable capital cost varies significantly amongst provinces, and governmental subsidies or incentive programs may be required to promote solar combisystems in some provinces.

6.2. Introduction

Solar thermal systems for space and domestic hot water (DHW) heating, commonly referred to as solar combisystems, has been gaining attention in the residential market over the last decade as an alternative to conventional systems due to their low operating costs and clean energy production. Depending on the system design, heating load and climatic conditions, solar energy can supply 10-100% of the thermal energy demand of a building (Weiss, 2003). However, the feasibility of solar thermal systems in extremely cold climates, such as that of Canada, is uncertain because buildings are mainly heating load dominated. The most common use of solar energy in northerly climates is for domestic hot water (DHW) heating. Techno-economic evaluations of solar DHW systems have been conducted using both experimental and modeling approaches. For example, Hobbi and Siddiqui (2009) studied a solar water heating system for a single-family residential unit in Canada using the TRNSYS simulation platform (TRNSYS, 2013). The system was optimized to maximize solar fraction. The results show that the system may provide a solar fraction of 83-97% during the summer and 30-62% during the winter months. Bernando *et al.* (2012) used TRNSYS to estimate the feasibility of solar water heating system retrofit in a single family house in Sweden. The effect of system configuration and control strategy on the annual solar fraction was evaluated. It was concluded that the solar water heating system with multiple storage tanks can achieve 50% solar fraction. Wallin *et al.* (2012) also used a TRNSYS based model to study the performance of solar thermal systems in four different buildings in Sweden and Canada. Their results showed that the effectiveness of the solar system is higher in buildings with a higher thermal load. Mori and Kawamura (2014) studied the design methods for solar water heating systems for a cold region in Japan where temperature in the winter months is around -10°C. They developed a numerical model using measured data from a solar water heating system combined with a heat pump installed in a house in Kushiro city, Japan and used the model to study the performance of a proposed solar water heating system in a single detached house. They concluded that a system with multiple tanks is more efficient compared to a system with a single thermal storage tank.

The presence of additional subsystems in hybrid solar and solar combisystems increase the level of complexity compared to solar domestic hot water (SDHW) systems, requiring in-depth studies focusing on performance and economic evaluations. For example, Jordan and Vajen (2001) studied the impact of domestic hot water load profiles with a fixed annual thermal energy demand on the performance of a solar combisystem using a TRNSYS model. They concluded that the impact of DHW load profiles should not be ignored because the draw profile may affect the stratification in thermal storage tanks. Andersen *et al.* (2004) studied the thermal performance of solar combisystems in single-family houses in Denmark based on measured data from actual systems with different collector areas and thermal storage tank volumes. The results show that the thermal performance may increase if there is space heating demand during the summer, and stratification in the thermal storage tank may significantly affect system performance. Lund (2005) studied the sizing and applicability of solar combisystems using an analytical model with a 24-hour time step. The results indicate that increasing collector area improves solar fraction and economic feasibility of solar combisystem retrofits in the old building stock in northern and central Europe. However, increasing the size of the thermal storage tank beyond the size that can store energy that exceeds daily demand was found to be economically unattractive. Hugo *et al.* (2010) investigated the performance of a solar combisystem with seasonal thermal energy storage in Canada using a TRNSYS model. They found that the solar combisystem can supply the total thermal energy for space and DHW heating demand from the beginning of the second year of operation, and the initially invested embodied energy of the solar combisystem can be recovered within six years through thermal energy savings. Lundh *et al.* (2010) used a TRNSYS model to investigate the effects of primary and auxiliary thermal storage volume configurations on the performance of medium sized solar combisystems. The results show that the dimensions of thermal storage tank in large solar combisystems may deviate from the generally recommended dimensions, and yet the fractional energy savings remains in the acceptable range. Rad *et al.* (2013) conducted a study to predict the performance of a hybrid solar thermal system with a ground source heat pump for a building in Canada in which the thermal load is a significant part of the energy demand. A TRNSYS model, validated using the experimental data, was used to estimate the annual performance of the system. It was concluded that the hybrid solar thermal system is a feasible option for heating purposes in the Canadian climate, and thermal energy supplied by solar energy may yield a significant reduction in the ground heat exchanger length. Hin and Zmeureanu (2014) used an optimization model to minimize the life cycle cost, energy use and exergy destroyed of a solar combisystem in an energy efficient house in Montreal, Canada. The result show that life cycle cost, energy use and exergy destroyed was reduced 19%, 34%

and 33%, respectively. The energy payback period and exergy payback period was less than 7 years.

Considering the potential of solar combisystems, the International Energy Agency (IEA) formed Task 26 within the Solar Heating and Cooling (SHC) Programme in 1998. The aim was to improve designs and solutions of solar combisystems in detached single-family houses, groups of single-family houses and multi-family houses through testing, analysis and optimization (Hadorn *et al.*, 2002). Letz *et al.* (2009) developed a fractional solar consumption model to characterize solar combisystems based on the IEA SHC Task 26 results. The model considers climatic conditions and thermal energy load as well as size, orientation and tilt angle of the solar collector. They introduced a dimensionless fractional solar consumption parameter to characterize solar combisystems. The results show that the fractional energy saving is a quadratic function of the fractional solar consumption.

Canadian housing stock (CHS) exhibits a high diversity in geometry and construction materials as well as heating, cooling and ventilation systems because of the wide range of climatic, geographical and economic conditions as well as the availability and price of fuels and energy sources in different regions. To facilitate a national scale research effort in increasing energy efficiency and promoting renewable energy use in buildings, first the Solar Buildings Research Network was established in 2005 (SNEBRN, 2012), followed by the Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN), which was established in 2011 with the objective of identifying feasible technologies and paths to approach or achieve net zero energy (NZE) ranking (SNEBRN, 2012). Both of these networks were funded by the government and private sector sources and brought together researchers from numerous Canadian universities and government laboratories. One of the projects initiated within the SBRN and is continuing under the SNEBRN is the development, refinement and utilization of the Canadian Hybrid Residential End-Use Energy and Emissions Model (CHREM) (Swan, 2010; Swan *et al.*, 2013). CHREM is a housing stock model that is capable of accurately estimating the energy saving and greenhouse gas (GHG) emission reductions due to large-scale implementation of energy efficiency and renewable energy technologies in the Canadian housing stock (CHS). Using CHREM, Nikoofard *et al.* (2013, 2014b, 2014c, 2014d) studied the impact of retrofitting a series of solar technologies, including window and windows shading upgrades, solar DHW, phase change materials (PCM) energy storage and PV applications, and Asaee *et al.* (2015a, 2015c) studied the techno-economic impact of internal combustion (IC) engine based cogeneration systems on the energy consumption and GHG emissions of the CHS. These studies show that such retrofits have the potential to significantly reduce the energy consumption and GHG emissions of the Canadian residential sector.

Asaee *et al.* (2014) developed a numerical model to estimate the performance of solar combisystem in major Canadian climatic conditions. The study showed that high solar fraction is achievable with solar combisystems in Canadian climates. Based on this favourable finding, a comprehensive evaluation was conducted to determine with confidence the techno-economic impact of large-scale implementation of solar combisystem retrofits in the CHS using the CHREM. These results are presented here.

6.3. Modeling of the CHS

Parameters that affect the energy consumption and GHG emissions of the housing stock have complex and inter-related effects. Thus, comprehensive housing stock models are required to accurately investigate techno-economic impact of large scale implementation of energy retrofits (Swan *et al.*, 2013). The latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys and other available housing databases were used to develop Canadian Single-Detached and Double/Row Database (CSDDRD). The CSDDRD consists of close to 17,000 unique houses which statistically represent the CHS (Swan *et al.*, 2009). Swan *et al.* (2013) used a bottom-up approach to build the CHREM using the house data available in CSDDRD. ESP-r, a whole building simulation software for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings, was used as simulation engine in CHREM. ESP-r has been validated through a wide range of research results (Strachan *et al.*, 2008). Thus, CHREM is capable to assess the techno-economic impact of massive implementation of energy efficiency and renewable energy technology retrofits into the CHS.

Six interconnected components that work together form the structure of CHREM to evaluate the end-use energy consumption and GHG emission of the CHS. These components are:

- The CSDDRD that provide the detailed data of geometry, construction, equipment, occupancy and air infiltration (Swan *et al.*, 2009),
- The bottom-up neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian household (Swan *et al.*, 2011),
- A series of load profiles representing the AL and DHW usage profiles in Canadian households,
- A high-resolution whole building energy simulation software (ESP-r) to accurately predict the energy consumption of each house file in CSDDRD,
- A model to estimate GHG emissions associated with the marginal electricity generation in each province of Canada and for each month of the year based on the fuel mixture (Farhat and Ugursal, 2010),
- A model to estimate GHG emissions associated with onsite fossil fuels consumption in households.

The work flow of assessing the techno-economic impact of energy efficiency upgrade or renewable/alternative energy technology retrofits, such as solar thermal systems in this study, is shown in Figure 6.1. The methodology to estimate energy savings and GHG emissions reductions associated with retrofits include several steps and can be summarized as follows:

(i) Identify eligible houses for the upgrade/technology retrofit: For solar combisystem retrofit, only houses with a basement or a mechanical room and proper roof direction would be suitable. Therefore, an algorithm has to be developed to identify such houses in the CSDDRD.

(ii) Modify the CHREM to reflect the energy/technology upgrade in the input files of the selected houses for use in the ESP-r simulation software.

(iii) Compare the energy consumption and GHG emissions of the upgraded CHREM with the adopted upgrade/technology and the "base case" (i.e. current) values to evaluate the change in energy consumption and GHG emissions of the CHS due to the retrofit. The change in GHG emissions associated with the change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010). Since CSDDRD is statistically representative of the

CHS, the impact of retrofit on energy consumption and GHG emissions estimated by CHREM can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

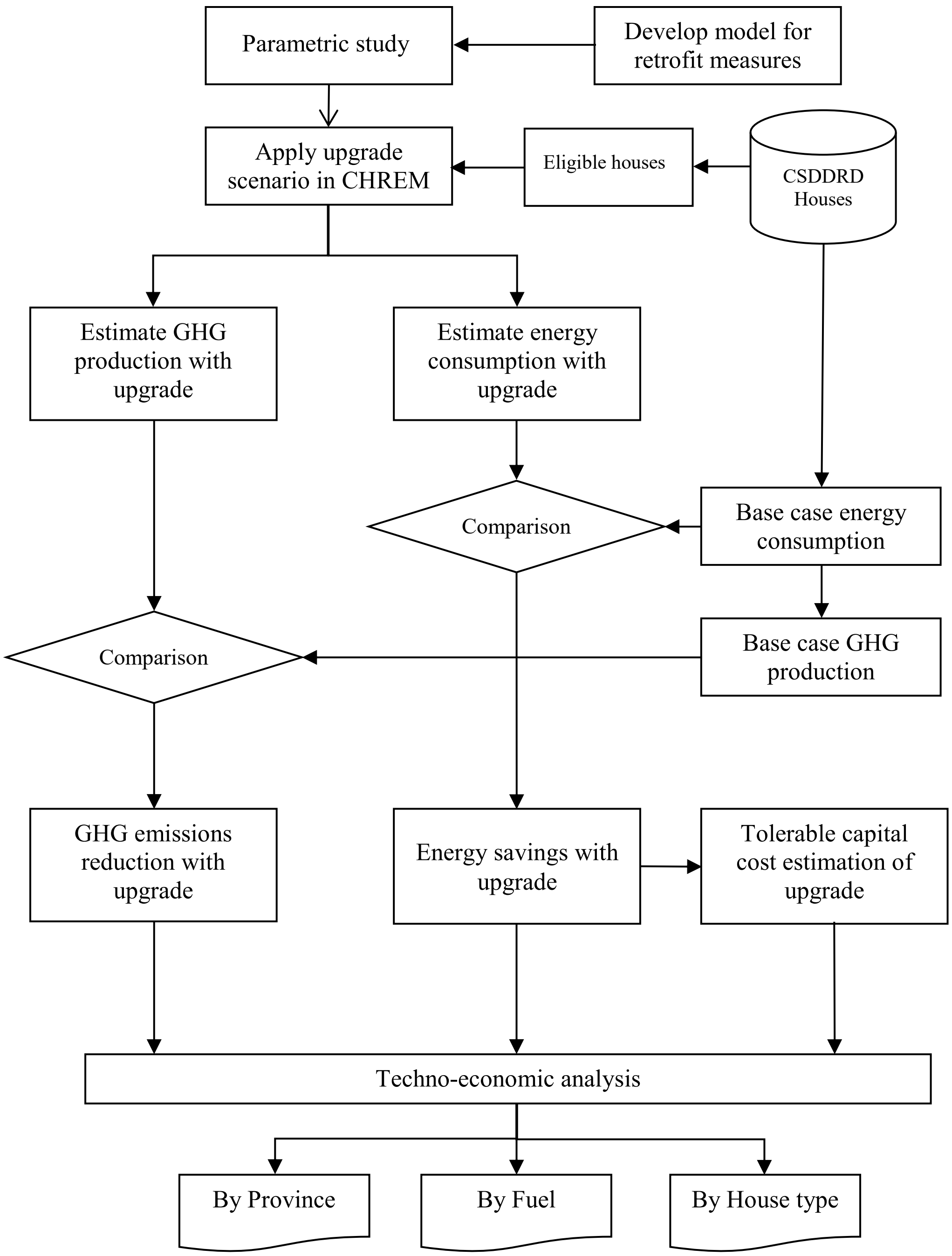

Figure 6.1 Flow diagram of the overall methodology that is used in this study (Nikoofard *et al.* 2014a).

CHREM has so far been used to evaluate the energy, economic and emissions performance of window and window shading upgrades, PCM for thermal energy storage, solar domestic hot water heating system and IC engine based cogeneration retrofits in the CHS (Asaee *et al.*, 2015a; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

6.4. Modeling of Solar Combisystems

The solar combisystem architecture presented in Figure 6.2 is modeled here using the component models and control algorithms available in ESP-r. The model is adopted from IEA SHC Task 26 system 6, and represents a customary system for space and DHW heating with solar and thermal storage tanks as well as an auxiliary heating system (Weiss, 2003). This solar combisystem has been used in the Dutch market since 1999. The DHW tank in the original IEA SHC Task 26 plant is replaced here with a large hot water tank (tank A – see Figure 6.2) with internal heat exchangers for space and DHW heating. The auxiliary boiler is located between the solar storage tank B and hot water tank A for "topping off" solar energy with auxiliary energy as suggested by Duffie and Beckman (2006) for DHW systems. Five modes of operation of the solar combisystem is considered (Duffie and Beckman, 2006):

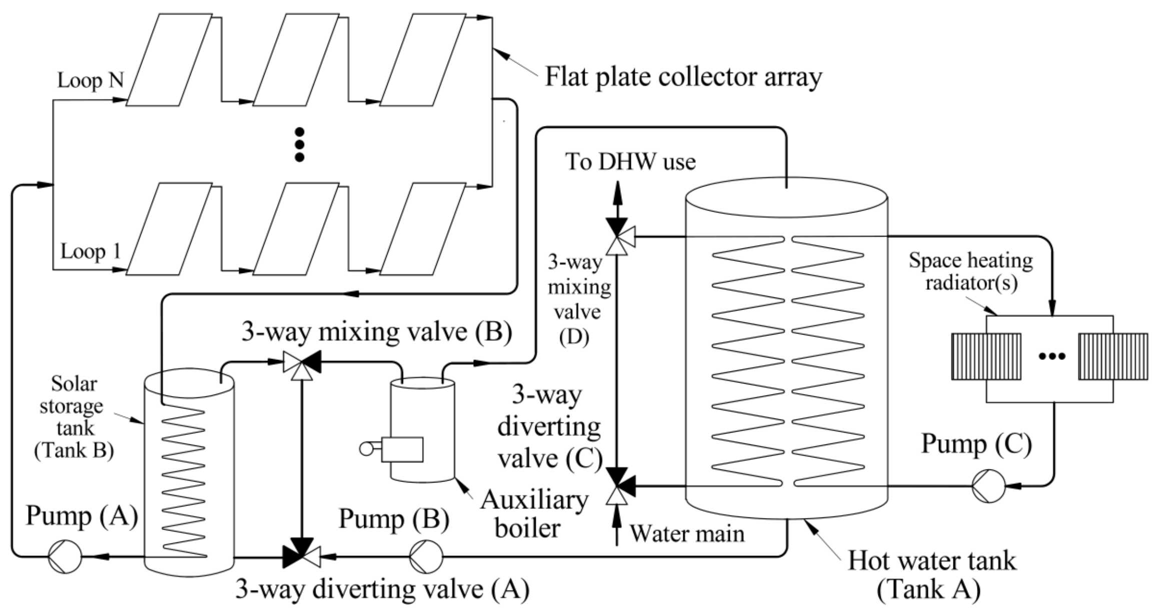

Figure 6.2 Solar combisystem architecture.

A. Solar energy is available but there is no thermal load on the system, thus the energy gain is added to the storage tank B,

B. Solar energy is available and there is thermal load on the system, thus the energy gain is used to supply the demand,
C. Solar energy is not available and heat stored in tank B exceeds the thermal load on the system; thus, the stored energy is used to supply the demand,
D. Solar energy is not available and heat stored in tank B is depleted while there is thermal load on the system; thus, auxiliary energy is used to supply the demand,
E. Solar energy is available and tank A is fully charged while there is no thermal load on the system; thus, the absorbed energy is discarded.

A small (100 L) solar storage tank B is connected to the flat plate collector array to harvest the solar energy. To avoid rapid on-off cycles, the circulation pump A (see Figure 6.2) starts when temperature difference between the flat plate collector and the solar tank B exceeds 5°C, and stops when the temperature difference drops to 1°C. The thermostat setting for the thermal storage tank A may affect the energy performance of a solar heating system (Weiss, 2003). Thus, the maximum temperature of the hot water tank A is set to 55°C as required for the DHW heating to avoid potential problems with bacteria growth. When the space heating supply temperature drops below the 50°C, the hot water tank pump B (see Figure 6.2) is turned on. If the temperature of solar storage tank B is larger than the temperature of the hot water tank A, the 3-way valve A (see Figure 6.2, outlets are shown by solid black) leads the circulating water to the solar tank B. However, to avoid heating the solar storage tank B by auxiliary energy, the 3-way valve A is closed when the temperature of the solar storage tank B is below the temperature of the hot water tank A. The auxiliary heating system operates in the range of 50-55°C. The main zone temperature is maintained in the range of 21±1°C during the heating season while other zones, including the basement, are slave of the main zone. Thus the supply temperature to the space heating radiator is set to 55°C to ensure the required temperature difference between radiator and desired zone temperature. To adjust the DHW temperature at the desired value, a 3-way tempering valve C (see Figure 6.2, outlets are shown by solid black) is considered in the DHW loop. To avoid unnecessary complexity in the components and control algorithms of plant simulation using ESP-r, the three way tempering valve C and mixing valve D collectively are modeled using a fully mixed and adiabatic tank. For this purpose a fully mixed adiabatic tank model is used and the temperature of the tank is kept at 55±0.5°C as shown in Figure 6.3. The hot water is supplied from hot water tank A to the adiabatic tank. The DHW draw is from top of the adiabatic tank and the same amount of main water is supplied to the bottom of adiabatic tank to maintain the mass balance. The energy balance equation for the adiabatic tank includes heat transfer between hot water flow from hot water tank A and main water supply. Thus, energy balance equation represent the same scenario as the three way diverting valve C and the three way mixing valve D acting collectively. The DHW consumption is controlled by patterns provided in boundary conditions and applied to the system as water draw from the adiabatic tank. Table 6.1 provides the details of the control algorithms including the sensor and actuator locations as well as control periods and temperature setpoints.

Table 6.1 Control parameters used

Actuator	Period		Sensor location	Setpoint	
	start	end		on	off
Solar pump A	1 Jan	31 Dec	ΔT between solar storage tank B & solar collector	5	1
Hot water tank pump B	1 Jan	31 Dec	Hot water tank A outlet to zone	50	55
Boiler	1 Jan	31 Dec	Boiler outlet	50	55
Auxiliary valve A	1 Jan	31 Dec	ΔT between hot water tank A & solar tank B	1	0
DHW Pump	1 Jan	31 Dec	DHW tank	54	56
DHW tank	1 Jan	31 Dec	DHW draw	--	--
Radiator pump	1 Jan	1 Apr	Zone main 1	20	22
	2 Apr	3 Jun		20	22
	4 Jun	16 Sep		0	1[a]
	17 Sep	7 Oct		20	22
	8 Oct	31 Dec		20	22

[a] The heating system will not turn on due to the low temperature setpoint during the cooling only season

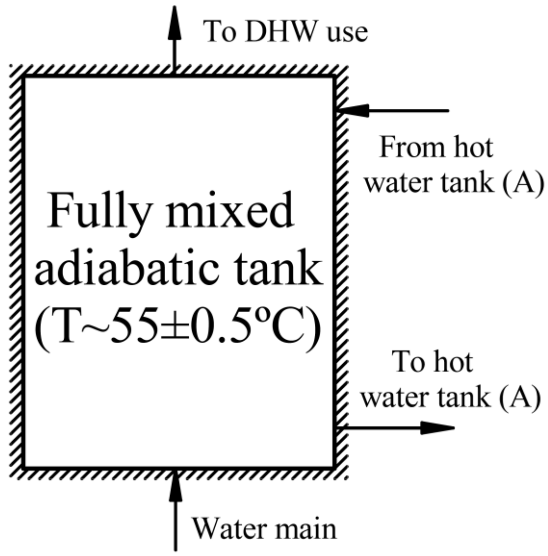

Figure 6.3 Fully mixed adiabatic tank model that represents the 3-way diverting valve (C) and 3-way converging valve (D) collectively.

The modeling strategy and sizing of main components of solar combisystem are described below.

6.4.1. Flat Plate Collector

The empirical flat plate collector model incorporated into the ESP-r by Thevenard *et al.* (2004) is used. The model is based on the energy balance on the collector using an empirical quadratic collector efficiency. The collector efficiency is presented in Equation (6.1).

$$\eta=F_R(\tau\alpha)_n-a\frac{\Delta T}{G_T}-b\frac{\Delta T^2}{G_T} \tag{6.1}$$

$$\Delta T=T_{in}-T_{amb} \tag{6.2}$$

The equation predicts collector efficiency, η, as a function of the collector heat removal factor, F_R, normal-incidence transmittance–absorptance, $(\tau\alpha)_n$, collector inlet temperature, T_{in}, ambient temperature, T_{amb}, and the solar radiation incident upon the collector, G_T, (Duffie and Beckman, 2006). The model includes considerations for flow rate and incidence angle correction during the collector operation in off-test conditions. The flat plate collector test data are given in Table 6.2.

The arrangement of the flat plate collector array may affect water outlet temperature. To achieve the desired water temperature and flowrate, the flat plate collectors are arranged in an array. Edwards (2014) suggested to use three collectors connected in series in each parallel loop for solar combisystem application in Canadian climates. The flat plate collector used in this study is a G 32-P model provided by Thermo-Dynamics Ltd. (2013). The collector gross and aperture areas are 2.982 m^2 and 2.870 m^2, respectively. Thus, the total aperture area in each parallel loop is 8.61 m^2 with about 9 m^2 space requirement for installation.

Table 6.2 Flat plate collector parameters[a]

Parameter	Unit	Value
Weight	kg	43.5
Test flow rate	kg/s	0.059
Efficiency constant coefficient, $F_R(\tau\alpha)_n$	–	0.689
Efficiency square coefficient, a	W/m^2K	3.8475
Efficiency quadratic coefficient, b	W/m^2K^2	0.01739
Incidence angle modifier coefficient (b_0)	–	0.154

[a] http://www.thermo-dynamics.com/technical_specs/G_series_technical.html

To reach the maximum solar energy contribution in thermal energy demand of the CHS, the total collector area is defined based on the existing heating system capacity and available roof area for each house. Three types of roof exist in CHREM for single detached and double/row house type (Swan, 2010). Three types of roofs exist in CHREM for single detached and double/row houses: hip, gable and flat (Swan, 2010). For all three types of roofs, the net area available to install solar collectors is less than the gross roof area. In hip and gable roofs, obstructions such as chimneys and dormers affect the net area available for solar collector installation. Due to the trapezoidal shape of the exposed area of hip roofs, the area available for solar collectors is further reduced compared to gable roofs. With flat roofs gaps between solar collector rows are required to avoid the shade from one row covering the one behind. Since there is no specific information in the CHREM database (Swan *et al.*, 2009) on the nature or size of such obstructions, the following "reasonable" assumption was made to determine the net area available for solar collector installation: 90% of gable roof, 80% of hip roof and 50% of flat roof area is available for collector installation. Since solar insolation in the northern hemisphere is maximum in the south direction, hip and gable roof surfaces that face the south, southeast or southwest direction are considered for collector installation. The number of collector loops are defined based on the guidelines provided in Table 6.3 with the constraint that available roof area is not exceeded.

Table 6.3 Number of collector loops based on the existing heating system capacity (kW) and available roof area (m^2)

Available roof area	Existing heating system capacity			
	below 10	10-15	15-20	above 20
27-45	3	3	3	3
45-63	3	5	5	5
63-81	3	5	7	7
above 81	3	5	7	9

6.4.2. Storage Tank

Thermal storage size significantly affects the performance of solar combisystem. A large storage tank increases the opportunity to save absorbed energy when it exceeds the thermal load while heat losses of the storage system increases with size (Weiss, 2003). If the ratio of storage volume to collector area increases, the thermal energy demand to maintain the water at 55°C increases while the supplied solar energy remains constant. Thus, the auxiliary energy consumption may increase for large values of storage volume to collector area ratio. A sensitivity analysis was conducted within IEA SHC Task 26 on the effects of the storage volume to collector area ratio on the performance of solar combisystems. The results revealed that for storage volume to collector area ratios greater than 150 l/m^2, the potential savings may decline as a result of increased heat losses from the storage volume. It was recommended to keep the thermal storage volume between 50-100 litres per each square meter of flat plate collector area (Weiss, 2003). The results of preliminary study on the performance of solar combisystem in Canadian climate by the Asaee *et al.* (2014) yielded a similar conclusion. Thus, based on commercial availability in Canada, 700, 1000, 1500 and 1750 USG (2650, 3785, 5680 and 6625 L) storage tank volumes are used here with 3, 5, 7 and 9 collector loops, respectively.

According to the recommendation of IEA SHC Task 26, thermal storage tank height is determined using Equation (6.3). Insulation material with thermal conductivity of 0.04 W/mK and maximum thickness of 15 cm (Edwards, 2014) is used as suggested by Weiss (2003).

$$h_{store} = max\left[min\left(2.2, 1.78 + 0.39 \ln\frac{V_{store}}{m^3}\right), 1.25\right] \quad (6.3)$$

The storage tank model developed and incorporated into ESP-r by Thevenard and Haddad (2010) is used. The model represents a stratified tank with immersed helical heat exchangers. The model divides the storage tank into a maximum of 100 control volumes to simulate the stratification. Conservation of mass and energy equations are solved for each control volume. The heat transfer inside and through the walls of immersed heat exchangers are governed by forced convection and conduction, respectively. Mixed free and forced convection governs the heat transfer outside the heat exchangers.

6.4.3. Auxiliary Boiler

Natural gas fired condensing and oil fired non-condensing boilers are used based on the fuel and commercial availability in each province. The IEA SHC Task 26 used 15 and 24 kW boiler sizes for single and multiple family houses (Weiss, 2003). In this study, the auxiliary heat rating is defined according to the capacity of existing heating system in each house. The wall mounted gas fired condensing boilers with maximum rated heating output of 11, 19, 26 and 35 kW (Viessmann, 2015a) and oil fired boilers with maximum rated heating output of 18, 27 and 33 kW (Viessmann, 2015b) are selected. For each house, the auxiliary heating system that matches or slightly exceeds the existing heating system rating is selected.

The boiler model implemented into the plant domain of ESP-r by Hensen (1991) is used. The model includes two nodes for connection to boiler input and output. Continuity and energy equations are solved for both nodes. The heat input to the water and thermal energy loss to the environment appears in the energy balance equation between the two nodes. The boiler efficiency is defined using Equation (6.4).

$$\eta_b = \left[\eta_0 - tan\,\varphi \times (T_c - T_1)\right]\left(\frac{\Delta t - t_0}{\Delta t}\right)_{1^{st}\_ON} \quad (6.4)$$

where η_0 is the full load water side efficiency expressed as a decimal at condensing temperature; $tan\,\varphi$ is the tangent of the efficiency curve; T_c and T_1 are the condensing and return temperatures; t_0 is the normalized start-stop loss and Δt is the simulation time step. The start-stop loss is considered during the first time step after turning the boiler on. For the case of condensing boiler, the water vapour in the flue gases will condensate when the return water temperature is below condensing temperature, which is assumed to be 50°C. To consider condensing effects, two values for the tangent of the efficiency curve are used, -0.25 and -0.15. These values are associated with the cases where the return temperature is below and above the condensing temperature.

6.4.4. Space Heating Radiator

The radiator model implemented into the plant domain of ESP-r by Hensen (1991) is used. The model has two nodes for connection to supply and return flow. Continuity and conservation of energy equations are solved for both nodes. The heat transfer to the environment is considered in the energy balance equation between the internal nodes. Radiator heat emissions to the environment, Q_R, is defined by Equation (6.5).

$$\frac{Q_R}{Q_0} = \left(\frac{\Delta T_R}{\Delta T_0}\right)^n \tag{6.5}$$

$$\Delta T = \frac{T_s - T_r}{ln\left(\frac{T_s - T_{env}}{T_r - T_{env}}\right)} \tag{6.6}$$

where Q_0 is the radiator heat emission under nominal temperature difference conditions ΔT_0; ΔT_R is the radiator log mean temperature difference; n is the radiator exponent; T_s, T_r and T_e are supply, return and environment temperatures, respectively. The radiator nominal characteristics adapted from Express Radiant Ltd product catalogue (Express Radiant Ltd, 2015) are given in Table 6.4. The required number of radiators for each zone is obtained by dividing the heating requirement by the nominal heat emission of the radiator.

Table 6.4 Radiator properties

Parameter		Unit	Value
Mass		kg	49
Mass weighted average specific heat		J/kgK	1350
Nominal	heat emission, Q_0	W	967
	supply temp	°C	55
	exit temp	°C	35
	environment temp	°C	21

6.4.5. *Pumps*

The IEA SHC Task 26 used Equations (6.7) to (6.9) to obtain pump power for the solar collector, space and DHW heating loops, respectively. The power for any other pump used in the system is assumed to be 50 W (Weiss, 2003). The same guidelines are used in this study to evaluate the parasitic electricity demand of pumps.

$$P_{el,pump,solar}=\left[0.3\left(\frac{A_{col}}{m^2}\right)^2 -2.5\left(\frac{A_{col}}{m^2}\right)+50\right]\ \mathrm{W} \tag{6.7}$$

$$P_{el,pump.SH}=90\mathrm{W}+2\times10^{-4}P_{nom,burner} \tag{6.8}$$

$$P_{el,pump.DHW}=49.4\mathrm{W}\times exp\left(0.0083\frac{P_{nom,burner}}{kW}\right) \tag{6.9}$$

6.4.6. *Fuel Options for the Auxiliary System*

NG is widely available across Canada except in the Atlantic region (NS, NB, PEI and NL) where there is very limited availability of NG for residential customers, and furnace oil is commonly used for space heating purposes. Therefore, NG is assumed to be the main fuel source for auxiliary systems in all provinces except the Atlantic provinces where home heating oil is used for auxiliary heating.

6.4.7. *Methodology to Select Houses Eligible for Solar Combisystem Retrofit*

Since solar combisystems require large collector area, the integration of solar collector in the roof is an advantageous design (Weiss, 2003). The houses in Canada have cold roofs as attics are ventilated and their temperature follows the ambient temperature. Solar collector integration into the cold roof adds no additional condensation problem since the collector array temperature is mainly higher than that of the standard roof (Weiss, 2003). Thus, the integration of solar collector into the roof is selected as the installation method, provided that the roof offers sufficient roof area and faces south, south-east or south-west.

The area of flat plate collector selected for this study is 3 m^2 and can be integrated into most roof sizes and shapes. As discussed in Section 6.4.1, three roof types exist in CSDDRD including gable, hip and flat. Flat plate collectors are assumed to be installed directly on gable and hip roof types, while a structure is needed to install solar collectors on flat roofs to provide the required inclination, and it is assumed that half of a flat roof is available for collector installation to avoid shading. For residential heating in adverse climates Iqbal (1979) recommends to use “latitude−10°” in case of 10-20% solar contribution in thermal load supply and linearly increase it to "latitude+15°" for 80% solar contribution. Major Canadian cities are located in a latitude range of 45-55°. Thus, 45° is selected as the collector tilt angle for installation on flat roofs. The number of collector loops is defined based on the roof area and existing heating system rating. As shown in Table 6.3, a minimum available roof area of 27 m^2 is required for solar combisystem retrofit. The solar insolation in northern hemisphere is maximum in the south direction. Thus, the eligible houses should have the required roof area in the south, southeast or southwest direction for collector installation.

Solar combisystem components including storage tanks, boiler and pumps are likely installed indoors. These components are traditionally installed in the basement or mechanical room. The presence of a mechanical room is not identified in the CSDDRD. However, based on the type of the existing heating system, the existence of mechanical room can be presumed. Thus, it is considered that all houses without a basement that utilize a natural gas or oil fired heating system, electric furnace or wood furnace/boiler have a mechanical room.

All houses that satisfy the conditions above are identified as eligible for solar combisystem retrofit. Based on the eligibility criteria, 37% of the houses in the CHS were found to be eligible for the solar combisystem retrofit as shown in Table 6.5.

Table 6.5 Portion of houses eligible for solar combisystem retrofit (% of total)

NF	NS	PE	NB	QC	OT	MB	SK	AB	BC	Canada
35	44	54	30	13	47	32	47	52	37	37

6.4.8. Estimation of the GHG Emissions Associated with Residential Energy Consumption in Each Province of Canada[1]

The GHG emission of the residential sector consist two parts: (i) GHG emission due to onsite fossil fuel consumption, and (ii) GHG emission directly attributable to electricity

[1] Provinces of Canada, from east to west, are: Newfoundland and Labrador (NF), Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (OT), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). NF, PE, NS and NB are collectively referred to as Atlantic Provinces (AT) while MB, SK and AB are referred to as Prairie Provinces (PR).

production, inclusive of transmission losses. Thus, to evaluate the GHG emissions of the CHS a batch simulation was conducted using the current status of CHREM to obtain the base case energy consumption. Based on the energy consumption, the associated GHG emissions were calculated using the GHG emission intensity factor (EIF). The GHG EIF is defined as the level of CO_{2e} emitted per unit input energy[1] including fossil fuels and electricity. The GHG EIF for onsite fossil fuels is a function of only the type of the fuel used and the efficiency of the energy conversion device. The GHG EIF associated with electricity consumption depends on the fuel mixture used for power generation, the efficiency of the energy conversion process and the transmission and distribution losses. In Canada each province has a self-governing utility that uses a different fuel mixture for electricity generation. Farhat and Ugursal (2010) reviewed the fuel mixture for electricity generation in each province of Canada and defined the average provincial GHG EIF as presented in Table 6.6.

Table 6.6 The average and marginal GHG intensity factors (g CO_{2eq}/kWh) for each province of Canada (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 $EIF_{Marginal}$		837	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%

[1] CO_{2e} is the "equivalent CO_2" emissions of fossil fuel combustion defined by converting all GHG emissions, such as CO and CH_4, to equivalent CO_2 emissions taking into account their global warming potentials (Farhat and Ugursal, 2010).

To estimate the impact of wide scale retrofit of solar combisystems on GHG emissions of the CHS, the eligible houses were retrofitted and a batch simulation was conducted using the updated CHREM. The result is the energy consumption of the eligible houses for solar combisystem retrofit together with the energy consumption of houses not eligible for retrofit. The GHG emission associated with onsite fossil fuel consumption is defined using the GHG EIF for each fuel type and efficiency of the energy conversion device. However, the fuel mixture for base load and peak (marginal) load power plants are not the same. Therefore, the same GHG EIF used for base case electricity generation is not suitable to evaluate the GHG emissions due to the electricity consumption of upgraded CHS. Thus, the GHG emission reduction (or increase) associated with change in electricity consumption due to solar combisystem retrofit is calculated using the marginal GHG EIF of the regional electricity generation. The marginal GHG EIFs for provinces of Canada are given in Table 6.6 (Farhat and Ugursal, 2010).

6.5. Performance Evaluation Indicators

The techno-economic performance of solar combisystem assessment is conducted using a set of three indicators, including fractional thermal energy savings, extended fractional energy savings and tolerable capital cost.

6.5.1. Fractional Thermal Energy Savings

To quantify the impact of solar combisystem retrofit on onsite fossil fuel consumption the IEA SHC Task 26 introduced the indicator called fractional thermal energy savings (Weiss, 2003). This indicator is defined as the ratio of the auxiliary energy consumption of the solar combisystem to the energy consumption of a reference system as given by Equation (6.10). The maximum value of the fractional thermal energy savings can be +1, with the values closer to +1 indicating higher savings.

$$f_{sav,therm} = 1 - \frac{E_{aux}}{E_{ref}} \tag{6.10}$$

where $f_{sav,therm}$, E_{aux} and E_{ref} represent fractional thermal energy savings, fuel consumption of auxiliary system and fuel consumption of reference heating system, respectively. Boiler efficiencies of both solar combisystem and reference system has a significant impact on the fractional thermal energy savings. If an electric based heating system exist in the house before retrofit, the provincial efficiency of electricity generation is used to estimate the fossil fuel consumption in the reference scenario.

6.5.2. Extended Fractional Energy Savings

To quantify the impact of solar combisystem retrofit on total fossil fuel consumption, including onsite fuel consumption and fuel use for electricity generation, the IEA SHC Task 26 defined the indicator called extended fractional energy savings (Weiss, 2003). With this indicator, the fractional thermal energy savings definition is extended to include both thermal and electrical energy used in the space heating system as shown in Equation (6.11) (Weiss, 2003). The maximum value of the extended fractional energy savings can be +1, with the values closer to +1 indicating higher savings.

$$f_{sav,ext}=1-\frac{E_{total}}{E_{total,ref}}=1-\frac{E_{aux}+\frac{W_{par}}{\eta_{el}}}{E_{ref}+\frac{W_{par,ref}}{\eta_{el}}} \tag{6.11}$$

where $f_{\mathrm{sav,ext}}$, W_{par} and η_{el} represent extended fractional energy savings, parasitic power and electrical efficiency, respectively. Electricity generation efficiency is included in the electrical efficiency to obtain the savings based on the primary energy consumption. Thus, for each house the provincial electricity generation efficiency is multiplied by the pump efficiency given in Equations (6.7) to (6.9).

6.5.3. Economic Analysis Based on Tolerable Capital Cost

Several authors defined and used a series of metrics to evaluate the economic feasibility of solar thermal systems for different purposes (Duffie and Beckman, 2006). Most of conventional economic metrics are not suitable for macro scale evaluations. For example break-even cost, which is the point that net present cost including initial investment and operating cost of the system equals the net present benefit of the system, is a function of several parameters including solar resource, local energy cost, space and DHW heating demand, and available incentives (Cassard *et al.*, 2011). Thus, a considerable variation can be expected in these measures in the Canadian context where these factors are controlled regionally. Thus, it is not practicable to conduct a conventional economic feasibility analysis for the objective of this study.

Nikoofard *et al.* (2014a) introduced the “tolerable capital cost” (TCC) of the energy upgrades as an alternative approach to conventional economic feasibility analysis. TCC is defined as the capital cost for an energy saving or renewable technology upgrade that one would be willing to spend under the given fiscal constraints of annual interest and fuel cost escalation rates, the number of years to achieve payback, as well as annual operating cost savings. Based on these parameters the maximum "tolerable" initial investment is determined.

To assess the economic feasibility of solar combisystem the annual operating cost saving is calculated using the results of batch simulation conducted for the base case and the retrofit upgraded case by CHREM. Energy prices for residential customers including natural gas, heating oil, electricity and wood in each province of Canada were obtained to calculate the annual cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 6.7. The additional maintenance cost of the solar combisystem over and above that of the existing heating system is assumed to be included in the TCC as a present value of the annual maintenance cost over the lifetime of the solar combisystem.

Based on the market condition a realistic cost of money (interest rate) for residential customers borrowing money to finance the retrofit and fuel cost escalation rate is assumed. The Bank of Canada Prime Rate of 1% in June 2014 (BOC, 2015) was used as an indicator of the Canadian market for borrowing money. A sensitivity analysis on interest rate is necessary to consider the uncertainty associated with market fluctuations. 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. For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 6.8 were used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada (NEB, 2014) and Energy Escalation Rate Calculator (WBDG, 2014).

A realistic payback period should be less than or equal to the life expectancy of the solar thermal system and satisfy the residential customer expectations. A short payback period might be more acceptable for home owners but reduces the cap for initial investment. Thus, a sensitivity analysis with six and ten year payback periods are conducted to study the impact of investment period on the economic feasibility of solar combisystems. Using these assumptions the reverse payback analysis is conducted to determine the tolerable capital cost of the solar combisystem for each house (TCCH):

$$\text{TCCH}=\begin{cases}\text{ACSH}\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e\\ \text{ACSH}\times n(1+i)^{-1} & \text{for} \quad i=e\end{cases} \tag{6.12}$$

$$\text{ACSH}=\sum_{j=1}^{m}(\text{F}\times\text{E})_{j} \tag{6.13}$$

where:

TCCH	Tolerable capital cost of the retrofit for the house (C$)
n	Acceptable payback period (year)
i	Interest rate (decimal)
e	Fuel cost escalation rate (decimal)
ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
F	Fuel price per unit of each fuel type (C$/unit)
m	Number of different fuels used in a house

It is not useful or practical to report the TCC for each house in the CSDDRD, or for that matter within the CHS, because from a macro level of interest, data on individual houses have no utility. Thus, the "average tolerable capital cost per house" (ATCCH) is used to evaluate the economic feasibility of the solar combisystem retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$\text{ATCCH}=\text{TTCC}/\text{NH} \tag{6.14}$$

where, TTCC is the total tolerable capital cost as a result of the solar combisystem upgrade (C$), calculated as follows:

$$\text{TTCC}=\sum_{i=1}^{\text{NH}}\text{TCCH}_{i} \tag{6.15}$$

NH = number of houses that received the upgrade.

It is likely that the market value of a house would increase due to a solar thermal retrofit. However, the impact of energy retrofit on market value of a house depends on a number of parameters including buyer perception and sophistication, market forces, and energy prices. Thus, this issue was not considered in this work because of the complex nature of the impact of upgrades on the market value of a house.

Table 6.7 Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[a]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	C$/GJ	36.58	45.06	47.08	37.11	21.92	39.72	24.25	42.00	43.19	26.53
Natural gas[b]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	C$/GJ	N/A	N/A	N/A	N/A	12.41	7.99	8.23	7.77	4.62	11.35
Home heating oil[c]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	C$/GJ	29.63	28.42	29.17	30.76	31.25	32.80	30.33	29.37	N/A	33.08
Wood[d]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	C$/GJ	11.20	11.20	11.20	15.69	11.43	13.44	11.65	11.20	22.40	10.75

[a] Hydro-Quebec (Hydro-Quebec, 2014b)

[b] Statistics Canada handbook (Statistics Canada, 2013)

[c] Statistics Canada Handbook (Statistics Canada, 2013)

[d] Local companies

Table 6.8 Real fuel escalation type for each fuel type

	Low	Medium	High
Electricity[a]	2	6	10
Natural gas[b]	2	5	8
Light fuel oil[b]	6	10	14
Mixed wood[c]	3	6	9

[a] National Energy Board of Canada (NEB, 2014)

[b] Energy Escalation Rate Calculator (EERC) (WBDG, 2014)

[c] Equal to interest rate as there is no source for its escalation rate

6.6. Results and Discussion

The annual integrated energy simulation was conducted using CHREM for the current status of the CHS, hereafter called "base case". The annual energy consumption and associated GHG emissions of the base case is presented in Table 6.9 by fuel source and province (Swan *et al.*, 2013). To estimate the techno-economic impact of solar combisystem retrofit on the energy consumption and GHG emissions of the CHS, all eligible houses were upgraded. The energy simulation was conducted once again using the upgraded CHREM model. Total number of retrofitted houses, saved energy and reduced GHG emissions in each province are presented in Table 6.10.

A detailed discussion on the techno-economic performance of solar combisystem retrofit based on annual energy consumption, energy savings and GHG emission reductions, as well as tolerable capital cost is presented in the following sections.

6.6.1. Annual Energy Consumption

The annual energy consumption of the eligible houses with existing heating system and solar combisystem retrofit, as well as the annual energy consumption of the houses that are not eligible for solar combisystem retrofit are presented in Table 6.11 by energy source and province. Annual energy savings depend on the energy source used for space and DHW heating as well as the penetration factor (percent eligible houses) of solar combisystem in each province. The annual energy savings and associated GHG emission is presented in Table 6.12. As shown in Table 6.12, electricity consumption in eligible houses decrease with solar combisystem retrofit in all provinces except SK (-0.3 PJ electricity saving) and AB (-1.6 PJ electricity saving). Electricity is used for appliances and lighting as well as for space and DHW heating in some provinces. Although replacing electrical energy used for space and DHW heating system with solar thermal energy may reduce electricity consumption, the electrical usage of solar combisystem components impose additional electrical load to the houses. Thus, solar combisystem retrofit may yield a higher electricity usage in provinces that heating demand is mainly supplied by fossil fuels.

Table 6.9 CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 6.10 Energy savings and GHG emission reductions for the CHS due to solar combisystem retrofit

Province	No of houses eligible for retrofit	Total Energy saved (PJ)	Average energy saving per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
NF	60,662	5.0	82	0.18	3,014
NS	131,393	9.6	73	0.66	5,026
PE	24,175	1.7	70	0.08	3,491
NB	72,060	7.0	97	0.24	3,309
QC	254,126	18.3	72	0.84	3,304
OT	1,608,866	121.5	76	6.61	4,107
MB	108,944	8.4	77	0.40	3,713
SK	148,106	12.7	86	0.62	4,168
AB	508,451	37.6	74	1.56	3,072
BC	408,534	24.2	59	1.19	2,921
Canada	3,325,316	246.0		12.39	

Table 6.11 CHREM estimates of annual energy consumption (PJ) with existing (Exist) and solar combisystems retrofit (SCSR) in houses eligible (EL) and houses not eligible (N-E) for solar combisystem retrofit

	Electricity			NG			Oil			Wood			Total		
	N-E	EL		N-E	EL		N-E	EL		N-E	EL		N-E	EL	
Province		Exist	SCSR		Exist	SCSR		Exist	SCSR		Exist	SCSR		Exist	SCSR
NF	12.3	2.9	2.3	0.0	0.0	0.0	2.9	6.7	4.1	1.5	1.8	0.0	16.7	11.4	6.4
NS	12.2	5.5	4.8	0.0	0.0	0.0	8.1	14.5	7.1	4.5	1.5	0.0	24.8	21.5	11.9
PE	0.9	0.9	0.9	0.0	0.0	0.0	1.7	2.3	1.1	1.0	0.5	0.0	3.6	3.7	2.0
NB	15.3	3.4	2.4	0.0	0.0	0.0	4.2	5.5	4.1	6.1	4.6	0.0	25.6	13.5	6.5
QC	189.8	15.5	6.9	0.2	0.8	13.1	9.8	20.5	0.0	8.9	1.5	0.0	208.7	38.3	20.0
OT	87.9	49.3	44.6	162.3	175.1	80.2	25.5	21.9	0.0	0.0	0.0	0.0	275.7	246.3	124.8
MB	15.8	3.1	2.7	19.4	14.2	6.2	0.0	0.0	0.0	0.0	0.0	0.0	35.2	17.3	8.9
SK	6.8	3.8	4.1	20.2	20.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	27.0	23.8	11.1
AB	13.6	14.7	16.3	57.7	62.1	22.9	0.0	0.0	0.0	0.0	0.0	0.0	71.3	76.8	39.2
BC	46.3	18.3	17.5	46.7	37.2	13.8	0.0	0.0	0.0	2.1	0.0	0.0	95.1	55.5	31.3
Canada	400.9	117.4	102.5	306.5	309.4	143.2	52.2	71.4	16.4	24.1	9.9	0.0	783.7	508.1	262.1

Table 6.12 Annual energy savings and GHG emission reductions due to solar combisystem retrofits in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	0.6	0.0	2.6	1.8	5.0	0.00	0.00	0.18	0.18
NS	0.7	0.0	7.4	1.5	9.6	0.14	0.00	0.52	0.66
PE	0.0	0.0	1.2	0.5	1.7	0.00	0.00	0.08	0.08
NB	1.0	0.0	1.4	4.6	7.0	0.14	0.00	0.10	0.24
QC	8.6	-12.3	20.5	1.5	18.3	0.02	-0.62	1.44	0.84
OT	4.7	94.9	21.9	0.0	121.5	0.27	4.80	1.54	6.61
MB	0.4	8.0	0.0	0.0	8.4	0.00	0.40	0.00	0.40
SK	-0.3	13.0	0.0	0.0	12.7	-0.04	0.66	0.00	0.62
AB	-1.6	39.2	0.0	0.0	37.6	-0.42	1.98	0.00	1.56
BC	0.8	23.4	0.0	0.0	24.2	0.01	1.18	0.00	1.19
Canada	14.9	166.2	55.0	9.9	246.0	0.12	8.40	3.87	12.39

Fossil fuel consumption is reduced collectively in all provinces due to solar combisystem retrofit. Oil and NG consumption of the CHS is reduced by about 45% and 27%, respectively. As shown in Table 6.9, in Atlantic Provinces and QC oil is the dominant fossil fuel source of existing heating systems, while in this study NG fired burner is used as the auxiliary system everywhere except in the Atlantic provinces. As shown in Table 6.12, this assumption adds extra demand of NG (-12.3 PJ saving) and reduce oil demand in QC due to solar combisystem retrofit. Also, the penetration factor of solar combisystem is not the same in all provinces. As shown in Table 6.11, NG demand of existing heating systems in houses eligible and not eligible for solar combisystem retrofit is about the same. However, oil demand of existing heating systems in eligible houses is about 1.4 times the oil demand of the houses not eligible for solar combisystem retrofit. Thus, the impact of solar combisystem retrofit on oil savings is more significant compared to NG because the energy consumption of houses not eligible for solar combisystem retrofit remains unchanged in the retrofit scenario compared to base case. Analogously, impact of solar combisystem retrofit is less significant on wood consumption due to low penetration factor of solar combisystem in houses that use wood for space and DHW heating purposes. For example as shown in Table 6.11, in BC all of the houses that use wood for heating purposes are not eligible for solar combisystem retrofit.

Table 6.13 Annual energy savings and GHG emission reductions due to solar combisystem retrofits in the CHS

Province	Energy Savings (%)	GHG emission reductions (%)
NF	18	23
NS	21	12
PE	23	22
NB	18	8
QC	7	33
OT	23	23
MB	16	23
SK	25	14
AB	25	11
BC	16	26
Canada	19	19

As shown in Table 6.12 and Table 6.13, the total annual energy savings (246 PJ) is about 19% of the total energy consumption of the CHS (1291.8 PJ), and the average energy saving per house, shown in Table 6.10, is between 60 and 100 GJ/year. These savings are considerably higher compared to other retrofit options considered in earlier studies (Asaee *et al.*, 2015a; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

6.6.2. *Energy Savings*

To determine the energy savings, the existing (base line) energy consumption and the energy consumption with the solar combisystem retrofit are calculated as shown in Equations (6.16) and (6.17).

$$E_{B\text{-}L}=E_{E,EXIST}+E_{N\text{-}E} \tag{6.16}$$

$$E_{UPGR\text{-}SC}=E_{E,SCSR}+E_{N\text{-}E} \tag{6.17}$$

where,

$E_{B\text{-}L}$= Existing (base line) primary energy consumption of the CHS

$E_{E,EXIST}$= Primary energy consumption of the houses eligible for the solar combisystem retrofit at present

$E_{N\text{-}E}$= Primary energy consumption of the houses not eligible for the solar combisystem retrofit

$E_{UPGR\text{-}SC}$= Primary energy consumption of the CHS with the solar combisystem retrofit

$E_{E,SCSR}$= Primary energy consumption of the houses eligible for the solar combisystem retrofit after solar combisystems retrofit is implemented

As discussed in Sections 6.5.1-6.5.2, only primary energy (i.e. fossil fuel) consumption is considered to determine the primary energy savings. Thus, the amount of fossil fuel used for electricity generation shown in Table 6.11, is determined based on the average efficiency of each provincial utility for electricity generation. In the case of electricity generation from renewable resources, the primary energy consumption is considered to be zero.

Fractional thermal energy saving and extended fractional energy saving for the CHS are presented in Table 6.14. As shown in Table 6.13 and Table 6.14, the values of the fractional thermal energy saving indicator is larger than the percent energy savings in all provinces because of main impact of solar combisystem on fossil fuel consumption in the CHS. For example, in AB and SK solar combisystem retrofit increases electricity usage compared to the base case while the fossil fuel consumption is reduced. Also, since the energy consumption of houses not eligible for the solar combisystem retrofit is considered in all energy saving evaluations as shown in Equations (6.16) and (6.17), the percent of eligible houses in each province shown in Table 6.5 also affects the difference between fractional thermal energy saving indicator (expressed as a percentage) and percent energy savings. For example, in QC about 87% of houses that mainly use electricity for heating purposes are not eligible for solar combisystem retrofit. Since hydroelectricity is the main source of electricity generation in QC, the equivalent fossil fuel consumption for electricity use in QC houses is zero.

Table 6.14 Energy saving indicators for solar combisystem (expressed in percent)

Province	Fractional thermal energy saving (%)	Extended fractional energy saving (%)
NF	34	34
NS	23	21
PE	31	27
NB	18	16
QC	23	23
OT	27	25
MB	24	24
SK	28	24
AB	33	28
BC	27	27
Canada	27	25

Similarly in NF, MB and BC since electricity generation is mainly from renewable resources, the equivalent fossil fuel consumption for electricity use in houses is close to zero. However, the impact of this factor in NF, MB and BC is less significant compared to that in QC because fewer houses use electricity for heating purposes. The lowest fractional thermal energy saving is associated with NB due to the considerable amount of energy from wood (10.7PJ) in the annual energy consumption of the NB residential sector (39.1PJ). This is because retrofitting close to 43% of existing wood burning heating systems (corresponding to 4.6PJ) with solar combisystems that utilize oil fired auxiliary heating systems increases fossil fuel consumption. However, as shown in Table 6.11 and Table

6.12, the overall impact of solar combisystem retrofit on oil saving in NB is positive, and fractional thermal energy saving indicator remains the same as percent energy savings.

Extended fractional energy saving indicator estimates the fossil fuel savings associated with electricity used in mechanical systems as well as the fossil fuel savings in the heating system. Thus, extended fractional energy saving indicator is likely smaller than the fractional thermal energy saving indicator. In NF, QC, MB and BC where electricity generation is mainly from renewable resources and fossil fuel consumption for electricity generation is negligible, the extended fractional energy saving indicator and the fractional thermal energy saving indicator values are equal. As discussed before, electricity consumption increases due to solar combisystem retrofit in AB and SK. Since, electricity generation is mainly from fossil fuels in these provinces, the difference between the extended fractional energy saving and fractional thermal energy saving indicators is the highest compared to other provinces.

Table 6.15 Distribution (%) of eligible houses in each province according to extended fractional energy savings achieved with solar combisystem retrofit

	Extended fractional energy savings					
Province	>70%	60-70%	50-60%	40-50%	30-40%	≤ 30%
NF	7	13	24	41	15	0
NS	6	27	38	26	3	0
PE	5	39	36	16	5	0
NB	33	39	20	8	0	0
QC	4	17	36	11	0	33
OT	7	30	47	14	2	0
MB	4	35	41	15	4	2
SK	5	34	47	13	1	0
AB	4	18	52	23	3	0
BC	22	45	23	7	1	2

The distribution of eligible houses according to the magnitude of extended fractional energy savings that can be achieved with solar combisystem retrofit is given in Table 6.15. The results are very encouraging as in all provinces a large majority of the houses achieve extended fractional energy savings of 40-70%. Based on the percent eligible houses presented in Table 6.15, the lower margin for extended fractional energy savings in Canadian houses is about 40% except in QC and NF where electricity generation is mainly from renewable resources, resulting in lower primary energy savings especially in houses that use electric based space/DHW heating systems.

6.6.3. Annual GHG Emissions

The annual GHG emission reduction due to solar combisystem retrofit in all eligible houses of the CHS is presented in Table 6.12 for each energy source and province. Since CO_2 emissions of biogenic material combustion returns to the atmosphere the CO_2 that was recently removed by photosynthesis, CO_2 emissions from biogenic materials are considered as a complement of the natural carbon cycle (Farhat and Ugursal, 2010). Thus, the GHG intensity factor for wood is considered to be zero and no GHG emission is associated with wood consumption in Table 6.9 and Table 6.12. Percent GHG emission reductions due to the solar combisystem retrofit relative to base case GHG emissions is presented in Table 6.13.

As discussed before, solar combisystem retrofit impact on electricity consumption is not significant in the CHS. The highest electricity reduction due to solar combisystem retrofit occur in QC, however, the associated GHG reduction is negligible. As shown in Table 6.6, the annual and marginal GHG EIF in QC is very low due to the major share of renewable resources, primarily hydro, in the provincial electricity generation. Similarly, the solar combisystem retrofit impact on GHG emission reduction associated with electricity generation in NF, MB and BC is negligible due to the small GHG EIF of these provinces. In AB and SK the provincial GHG EIFs are the highest in Canada. Thus, electricity consumption increase due to solar combisystem retrofit yields a considerable increase in the associated GHG emissions. As shown in Table 6.12, the overall impact of solar combisystem retrofit on GHG emissions associated with electrical energy consumption of the CHS is about 1% (0.12 Mt of CO_{2e}) of total GHG emission reduction (12.39 Mt of CO_{2e}) in the CHS.

Solar combisystem retrofit impact on GHG emission reduction associated with fossil fuel consumption varies amongst provinces based on the percentage of eligible houses and the fuel type. For example, the lowest GHG emission reduction among Atlantic provinces occurs in NB. As shown in Table 6.11, NB has the highest amount of existing wood burning heating systems (equivalent to 4.6 PJ of energy consumption) retrofitted with solar combisystem that utilize a fossil fuel fired auxiliary system. Thus, zero emission wood is replaced, although at a much lower level, with a fossil fuel that has GHG emissions. However, overall impact of solar combisystem retrofit on the annual GHG emission of the NB residential sector is favorable. In QC, the major share of eligible houses for solar combisystem retrofit consume oil as the fuel source in their existing heating systems. Thus, solar combisystem retrofit that utilize a NG fired auxiliary heating system yields a considerable GHG emission reduction (1.44 Mt of CO_{2e}) associated with oil consumption relative to base case, while the GHG emissions associated with NG consumption increase (-0.62 Mt of CO_{2e}).

While the highest provincial GHG emission reduction occurs in OT (6.61 Mt of CO_{2e}), the maximum average GHG reduction per house is in NS (5,026 Kg of CO_{2e}) followed by SK (4,168 Kg of CO_{2e}) and OT (4,107 Kg of CO_{2e}) as shown in Table 6.10. Percent GHG emission reduction due to solar combisystem retrofit in NS and SK relative to base case are among the lowest as shown in Table 6.13. Conversely, provincial GHG emission reduction relative to the base case in BC (26%) is the second highest, the average GHG reduction per house in BC (2,921 kg of CO_{2e}) is the lowest amongst all provinces.

6.6.4. Tolerable Capital Cost

The average provincial tolerable capital cost for solar combisystem retrofit in the CHS for three interest rates, three fuel cost escalation rate and two payback periods are shown in Table 6.16.

The economic feasibility of solar combisystem retrofit in the CHS is not the same for all provinces. The highest fractional thermal energy saving (33% as shown in Table 6.14) and energy saving (25% as shown in Table 6.13), and the lowest TCC for solar combisystem retrofit is seen in AB. This is due to the wide availability of significantly inexpensive NG (17.26 cents/m^3) and fairly expensive electricity (15.12 cents/kWh) compared to the rest of Canada, as shown in Table 6.7. As discussed in Section 6.6.1, solar combisystem retrofit increases the electricity use and decreases NG consumption in AB, which negatively impacts the economic feasibility. For example, even with the most suitable economic condition (i.e. 3% interest rate and high fuel cost escalation rate), a homeowner may only be able to invest about 9,000 C$ for 10 year payback period.

Table 6.16 Average TCC per house (C$/house)

Province	Payback (yr)	Interest rate 3%			Interest rate 6%			Interest rate 9%		
		Fuel cost escalation rate: Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	20,668	24,568	29,328	17,634	20,783	24,610	15,211	17,779	20,885
	6	11,951	13,125	14,419	10,806	11,831	12,960	9,821	10,721	11,711
NS	10	21,214	25,341	30,398	18,079	21,409	25,470	15,576	18,291	21,585
	6	12,138	13,363	14,717	10,970	12,041	13,221	9,966	10,905	11,940
PE	10	18,298	21,802	26,085	15,585	18,412	21,851	13,421	15,724	18,513
	6	10,421	11,455	12,594	9,417	10,319	11,313	8,553	9,345	10,216
NB	10	21,133	24,749	29,105	18,079	21,003	24,511	15,635	18,024	20,876
	6	12,506	13,631	14,864	11,318	12,301	13,378	10,295	11,159	12,103
QC	10	29,914	36,096	43,730	25,472	30,460	36,588	21,929	25,993	30,961
	6	16,993	18,817	20,840	15,353	16,946	18,711	13,943	15,341	16,888
OT	10	10,407	12,213	14,393	8,899	10,359	12,114	7,693	8,885	10,311
	6	6,136	6,693	7,304	5,552	6,039	6,572	5,050	5,478	5,945
MB	10	6,443	7,392	8,510	5,534	6,303	7,207	4,804	5,434	6,171
	6	3,941	4,253	4,590	3,572	3,844	4,139	3,253	3,493	3,752
SK	10	5,547	6,286	7,139	4,764	5,363	6,053	4,135	4,626	5,189
	6	3,393	3,636	3,898	3,075	3,288	3,516	2,800	2,988	3,189
AB	10	2,044	2,266	2,510	1,755	1,935	2,133	1,524	1,671	1,833
	6	1,250	1,324	1,402	1,133	1,198	1,266	1,032	1,089	1,149
BC	10	6,526	7,469	8,575	5,605	6,369	7,263	4,865	5,492	6,221
	6	3,992	4,301	4,636	3,617	3,888	4,181	3,295	3,533	3,790

Oil is the only widely available fossil fuel for residential customers in Atlantic provinces. As shown in Table 6.7, oil cost per unit of energy (~30 C$/GJ) is about 375% of the cost per unit of energy of NG (~8 C$/GJ). Thus, the reduction of thermal energy consumption supplied by fossil fuels by means of solar combisystem retrofit is more economically favorable in the Atlantic provinces compared to others except QC. In QC, the existing oil fired heating systems are substituted with solar combisystem retrofit that utilizes a NG fired auxiliary heating system. In addition to the economic profit gained by the reduction of energy consumption due to solar combisystem retrofit, the fuel change reduces the annual energy cost of the households in QC. Thus, solar combisystem retrofit shows the highest TCC in QC and a homeowner is able to invest about 14,000 C$ to 44,000 C$ based on the economic conditions and desired payback periods.

The results for the other provinces show the TCC under different conditions, providing economic guidance for homeowners and governments alike in considering solar combisystem retrofits.

If the TCC is not sufficient to cover the initial investment required for solar combisystem retrofits and if the government wishes to promote solar thermal systems, then it may be necessary to devise a rebate or subsidy program that would provide funding to the homeowners to cover the shortfall. Thus, a macro scale estimation of total tolerable capital cost might be helpful for governments to plan accordingly. For this purpose, the total TCC for the range of interest and fuel escalation rates and payback periods are given in Figure 6.4 for the entire CHS. The highest TCC for the solar combisystem retrofit in the CHS is about 50 Billion Canadian dollars. The results show that at 10 year payback period, the effect of fuel cost escalation rate and interest rate on the total TCC are more significant. Thus, education of home-owners regarding the long-term benefits and expected lifetime of solar thermal systems would be helpful to convince them to make the switch to solar combisystems.

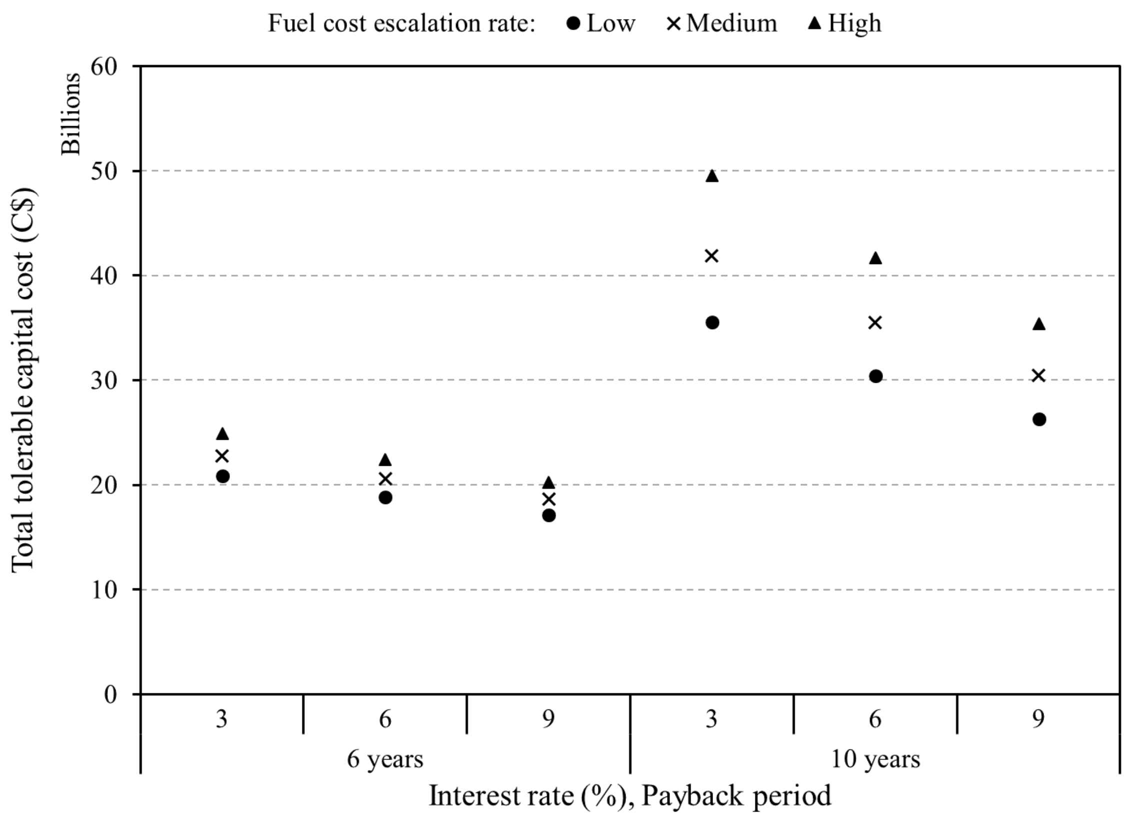

Figure 6.4 Total national tolerable capital cost due to solar combisystem upgrade for different interest rates and fuel cost escalation rates (Low, Medium and High as per Table 6.8).

6.7. Conclusion

A complete techno-economic analysis of solar combisystem retrofit in the CHS is presented as a follow-up on a preliminary system performance evaluation that was conducted previously (Asaee *et al.*, 2014). A hybrid energy modeling approach using the Canadian Hybrid Residential End-Use Energy and GHG Emissions model (CHREM) was used to conduct the analysis. A solar combisystem architecture based on the available systems within IEA SHC Task 26 was assumed for the retrofit. The solar combisystem components including flat plate collector, solar tank, thermal storage tanks, auxiliary heater, radiator, pump and valve as well as control algorithms were modeled using the available models in ESP-r. The eligibility conditions for solar combisystem retrofit were defined and the retrofit was introduced into all eligible houses. The results of upgraded CHREM model and base case were compared and energy saving, fractional thermal energy saving and extended fractional energy saving as well as GHG emission reductions were considered to estimate the performance of solar combisystem retrofit. The economic feasibility of a large scale solar combisystem retrofit in the CHS was evaluated by calculating the tolerable capital cost.

The results show that solar combisystem retrofit will reduce the annual energy consumption and GHG emission of the CHS by 19%. The reduction in energy consumption is not the same in all provinces and solar combisystem impact on annual electricity consumption is less significant compared to fossil fuel usage. The annual GHG emission reduction strongly depends on the fuel source of existing heating system in each province. Fractional thermal energy saving is higher compared to energy saving in all provinces. Extended fractional energy saving due to solar combisystem retrofit is about 25% in the CHS. The tolerable capital cost varies significantly amongst provinces, and governmental subsidies or incentive programs may be required to promote solar combisystems in some provinces.

This study is part of a large-scale effort to develop approaches, incentive measures and strategies to facilitate conversion of existing Canadian houses into net zero energy buildings under Smart Net-Zero Energy Buildings Strategic Research Network. The results of this study will be used in future research to develop paths to achieve or approach net/near zero energy status for existing Canadian houses.

Chapter 7 Techno-Economic Feasibility Evaluation of Air to Water Heat Pump Retrofit in the Canadian Housing Stock

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Rasoul Asaee is the principal researcher and author of the article. He conducted the research as part of his PhD. Thus, while he received supervision and guidance from his supervisors Drs. Ugursal and Beausoleil-Morrison, he carried out the work, wrote the article, and communicated with the editor of the journal. Minor editorial changes have been made to integrate the article within this dissertation.

7.1. Abstract

This study was conducted to assess the techno-economic feasibility of converting the Canadian housing stock (CHS) into net/near zero energy buildings by introducing and integrating high efficient and renewable/alternative energy technologies in new construction and existing houses. Performance assessment of energy retrofit and renewable/alternative energy technologies in existing houses in regional and national scale is necessary to devise feasible strategies and incentive measures. The Canadian Hybrid Residential End-Use Energy and GHG Emissions model (CHREM) that utilizes a bottom-up modeling approach is used to investigate the techno-economic feasibility of air to water heat pump retrofit in the Canadian housing stock. The proposed energy retrofit includes an air to water heat pump, auxiliary boiler, thermal storage tank, hydronic heat delivery and domestic hot water (DHW) heating. Energy savings, GHG emission changes and economic feasibility of the air source heat pump retrofit are considered in this study. Results show that there is a potential to reduce 36% of energy consumption and 23% of GHG emissions of the CHS if all eligible houses undertake the retrofit. Economic analysis indicates that the feasibility of air to water heat pump systems is strongly affected by the current status of primary energy use for electricity generation and space and DHW heating as well as energy prices and economic conditions. Legislation, economic incentives and education for homeowners are necessary to enhance the penetration level of air to water heat pump retrofits in the CHS.

7.2. Introduction

Shrinking the energy footprint of residential buildings is a promising option to reduce national greenhouse gas (GHG) emissions. While developing and implementing improved building codes for new construction is necessary, it is not sufficient to achieve this goal. A housing policy with focus on retrofitting existing houses is an essential part of a strategic plan to reduce the GHG emissions associated with the housing stock (Hens *et al.*, 2001). While the most feasible and effective retrofit options might be improving building skin, installing high efficiency heating systems and incorporating renewable energy systems (Verbeeck and Hens, 2005), adding an air to water heat pump (AWHP) system to a house could also be a suitable option to reduce energy consumption (ASHRAE, 2008). AWHP system can provide space and domestic hot water (DHW) heating energy requirement from a single source. While the AWHP system is well established in Europe and Japan, it is relatively new to the Canadian market (CMHC-SCHL, 2015). Thus, an accurate and comprehensive study is needed to investigate the feasibility of integrating AWHP systems into the Canadian housing stock (CHS). Recently, such studies have been conducted for various regions of the world. For example, Kelly and Cockroft (2011) developed a numerical model to evaluate the performance of AWHP retrofit into a building in Scotland. The simulation results were validated by laboratory data and the model was integrated into a whole building performance simulation software. The model was well representative of the AWHP operating conditions in the field trial. An equivalent condensing natural gas boiler and an electric heating system were used as alternative heating systems for the building, and annual energy consumption of the three systems were compared. The results showed that GHG emissions of AWHP were lower compared to that of the condensing natural gas boiler and the electric heating system. While the operating cost of the AWHP exceeds that of the gas condensing boiler, incentives available for renewable thermal energy may make up the difference. In another study, Kelly *et al.* (2014) used the AWHP model to estimate the effectiveness of integrated AWHP and thermal storage tank with phase change material (PCM) to restrict the AWHP operation to the off-peak periods. The results showed that through manipulation of the PCM chemistry, heat storage tank volume could be reduced by 50% with a minimum impact on heat supply to the building in the UK climate. Cabrol and Rowley (2012) used a numerical model to study the performance of air source heat pump water heating (ASHP-WH) system with hydronic heat delivery in various UK locations. A sensitivity analysis was conducted to evaluate the impact of the building construction materials and off-peak period operation. The GHG emissions and operating cost of ASHP-WH were found to be lower compared to those of an equivalent size gas boiler, and the annual coefficient of performance (COP) of the ASHP-WH was found to be about 3.5 and 4 for cold and mild UK climates, respectively. Johnson (2011) found that in the UK context the heat pump GHG emissions due to electricity consumption were higher compared to gaseous fuels and lower compared to heating oil. Using a model for ASHP-WH system model based on measured data from a field trial campaign Madonna and Bazzocchi (2013) found that climate has a significant role on the performance of ASHP-WH, and depending on climate, the energy requirement for space heating could be reduced by up to 79% in new buildings in Italy. A study by Hewitt *et al.* (2011) that investigated AWHP retrofit options for existing houses in the UK recommended using variable speed compressor, advanced evaporators and improving heat delivery system to enhance the performance of AWHP in the European maritime climate conditions. Bertsch and Groll (2008) designed, simulated, constructed and tested an ASHP water or air heating system with an operating range of -30°C to 10°C and return water temperature of 50°C for northern US climates. The issues related with the low temperature, high lift operation of the heat pump were dealt with through design choices. The cost of the proposed ASHP system was found to be lower compared to an equivalent ground source heat pump. Ibrahim *et al.* (2014) developed a simulation model to study the performance of ASHP-WH system and its potential for energy savings and GHG emissions reductions in Lebanon. The results showed that COP would vary in the range of 2.9 to 5 for the various climatic conditions of Lebanon. Lund *et al.* (2010) evaluated the role of district heating in the future renewable energy systems of Denmark assuming that Danish energy supply will be entirely from renewable resources by 2060. Assuming a 75% reduction in space heating demand individual heat pump systems were found to be the best alternative to existing fossil fuel systems. The European Parliament and Council also identified the aerothermal, geothermal and hydrothermal energy production of heat pump systems as renewable energy under specific circumstances as published in the Directive 2009/28/EC (EPC-EU, 2009).

To achieve substantial reductions in national energy consumption, massive energy retrofits in building stocks are required. The unique challenges that such massive retrofits require have recently been the focus of researchers. For example, Dall'O' *et al.* (2012) presented a method to estimate the energy savings due to retrofitting existing houses in a building stock and applied it for five municipalities in the province of Milan, Italy. Amstalden *et al.* (2007) studied the cost-effectiveness of energy retrofit options from house owners' point of view in the Swiss housing sector, including the effect of various incentives. They concluded that energy price has the most significant impact on the profitability of retrofit options and efficiency retrofits were economically viable with the current energy prices and future energy cost elevations would improve the feasibility of energy retrofits. Tommerup and Svendsen (2006) assessed the performance of energy saving measures for existing Danish houses. The study was conducted for two typical buildings and results showed that retrofits were economically viable in 30 years in the presence of sufficient education and training for house owners. Nemry *et al.* (2010) studied the life cycle impact of 72 building types with different construction properties in various geographical locations of European Union countries. The results showed that heating demand was the dominant energy consumption component in the life cycle energy consumption of both existing and new buildings. It was also found that in most buildings at least 20% energy savings were cost effective with infiltration reduction by sealing and additional roof and façade insulation.

In order to focus efforts and resources to reduce residential energy consumption and GHG emissions an accurately designed strategy with specific goals is required. For this purpose, so far, a wide range of retrofit options including envelope modifications such as glazing and window shading upgrades, as well as installation of solar domestic hot water (SDHW) systems, phase change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling engine (SE) based cogeneration systems and solar combisystem were studied (Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d) as part of a national effort in Canada (SNEBRN, 2012). In this work, the techno-economic feasibility of AWHP system retrofit in the Canadian housing stock is studied.

7.3. Methodology

Under the current circumstances where GHG emissions are considered to be as important as energy consumption and costs, the evaluation of the feasibility of an energy retrofit measure for a house has to consider house energy consumption, associated GHG emissions and energy costs before and after the retrofit. To evaluate the feasibility of massive implementation of energy efficient retrofits in a regional or national housing stock, a representative and accurate housing stock model is necessary to predict the system-wide energy savings, emission reductions and economic feasibility. Comprehensive reviews of housing stock models and modeling efforts are presented in Swan and Ugursal (2009) and Kavgic *et al.* (2010).

7.3.1. Housing Stock Model

In this work the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) (Swan, 2010; Swan *et al.*, 2013) is used. CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) (Swan *et al.*, 2009). CSDDRD statistically represents the CHS with close to 17,000 unique houses that were extracted from the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys and other available housing databases.

A high-resolution building energy simulation program ESP-r (ESRU, 2015) is used as the simulation engine of CHREM. ESP-r is an integrated modeling tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings which employs a finite difference control volume approach for energy simulation. The building domain is discretized into control volumes and each control volume contain finite difference nodes. Control volumes represent a wide range of building components such as air volume in thermal zones, opaque and transparent structures, solid-fluid interfaces and plant components. Governing equations are discretized based on the Crank-Nicolson finite difference method for all nodes in the control volume. The system of algebraic equations is solved using a simultaneous direct solution approach based on matrix partitioning and Gaussian elimination in each time step (Beausoleil-Morrison, 2000; Clarke, 2001). The system of linearized mass balance equations is solved using the Newton-Raphson iterative method. ESP-r has been validated through a vast amount of research results (Strachan *et al.*, 2008).

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:

- The Canadian Single-Detached & Double/Row Housing Database (Swan *et al.*, 2009),
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households (Swan *et al.*, 2011),
- 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 (Farhat and Ugursal, 2010),
- A model to estimate GHG emissions from fossil fuels consumed in households.

The energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as AWHP systems, can be estimated using CHREM as follows:

(i) Identify houses suitable to receive the upgrade/technology: For AWHP system retrofit, only houses with a basement or a mechanical room would be suitable. Therefore, a search has to be conducted in the CSDDRD to identify such houses.

(ii) Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.

(iii) Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the “base case” (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010). Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

Since its initial development, the modeling capability of CHREM has been gradually expanded, to include PCM thermal energy storage, SDHW heating system, ICE and SE engine based cogeneration and solar combisystem (Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

The schematic of the AWHP retrofit considered in this work for existing houses is given in Figure 7.1. The system is capable to deliver heat for space and DHW heating. Cooling is not considered in this study because adding an air handling unit to use the chilled water for space cooling purposes will substantially increase retrofit costs to compromise economic feasibility. Also, an AWHP system cannot provide hot water for DHW heating and chilled water for space cooling simultaneously. Thus only space and DHW heating features are considered for retrofit.

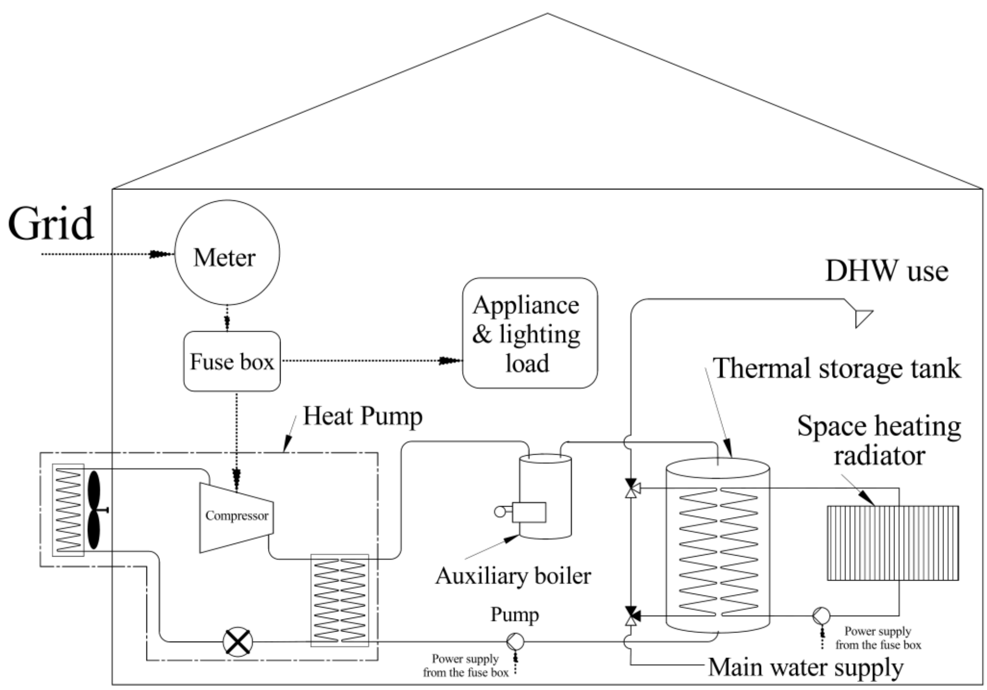

Figure 7.1 A typical house with air to water heat pump retrofit.

To assess the techno-economic feasibility of AWHP integration into the CHS in this work, first an AWHP modeling capability was added to CHREM as discussed in sections 7.3.1.1-7.3.1.7. Then a set of criteria was established to identify houses in CHREM that are suitable for AWHP retrofit. These criteria are presented and discussed in Section 7.3.2. The method used to estimate GHG emissions is presented in Sections 7.3.3. Methodologies for accounting of renewable energy from heat pump and economic feasibility analysis are elaborated in Sections 7.4 and 7.5, respectively.

7.3.1.1. Air to Water Heat Pump

The AWHP model used in this work was developed and added to the ESP-r plant components by Kelly and Cockroft (2011). This model incorporates three control volumes: a functional volume and two lumped mass volumes as shown in Figure 7.2. The functional control volume represents the working fluid loop and auxiliary parts, and calculates the COP of the heat pump and compressor power consumption based on the ambient temperature, return water temperature and the control signal. The total power use of the heat pump is the cumulative power consumption of compressor and auxiliary components. The empirical expressions used for the COP and compressor power consumption of an AWHP are given in Equations (7.1) and (7.2):

$$\mathrm{COP}=a_0+a_1(T_r-T_{amb})+a_2(T_r-T_{amb})^2 \tag{7.1}$$

$$P_C=b_0e^{b_1(T_r-T_{amb})} \tag{7.2}$$

where T_r, T_{amb} and P_C represent the return water temperature (K), ambient temperature (K) and compressor power (kW), respectively. In each time step of the simulation, the COP and P_C are calculated based on the instantaneous water and ambient temperatures. The constants factors ($a_{0\text{-}2}$ and $b_{0\text{-}1}$) are derived based on the empirical data of the AWHP and the values used in this work are given in Table 7.1. The nominal heat supply of the heat pump is then determined as the compressor power consumption multiplied by the COP.

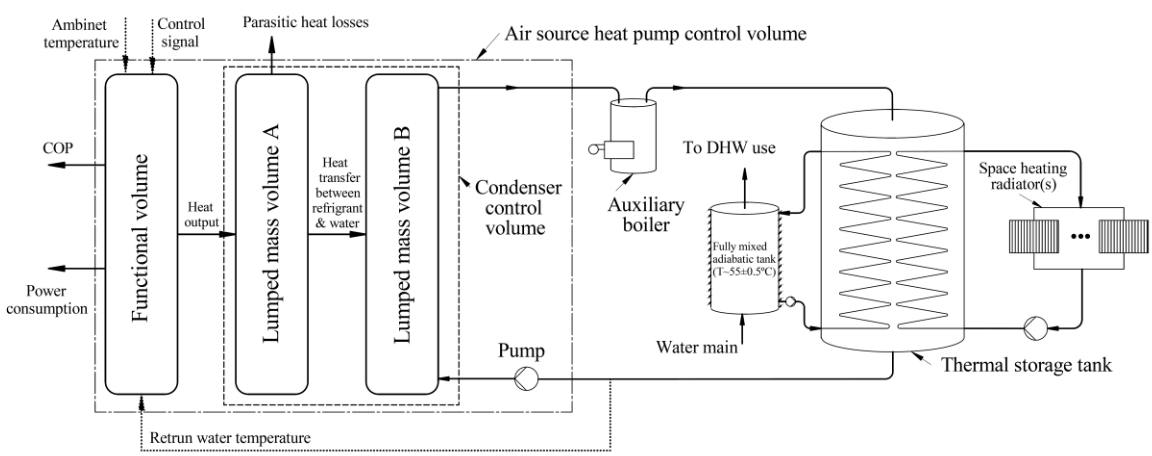

Figure 7.2 Air to water heat pump modeling approach in ESP-r.

Table 7.1 Parameters of AWHP system components based on the existing heating system capacity

ASHP system components	Parameter	Unit	Existing heating system nominal capacity (kW) >21	11-16	<11	Reference
COP	a_0	–	5.2202	5.0948	5.6818	(Viessmann, 2016)
	a_1	K^{-1}	-0.077	-0.0583	-0.0864	
	a_2	K^{-2}	4×10^{-4}	3×10^{-4}	5×10^{-4}	
Compressor power rating	b_0	kW	10.424	7.3568	5.6681	
	b_1	K^{-1}	-0.007	-0.006	-0.007	
Fan power	P_{fan}	W	480	230	190	
Duration of defrost	t_0	s		360		(ASHRAE, 2008; Viessmann, 2016)
	t_1	s/%		2.4		
NG fired boiler	$P_{nom,buner}$	kW	19	19	18	(Viessmann, 2015a)
	$(\tan\varphi)_{T>50^\circ C}$	$^\circ C^{-1}$		-0.15		
	$(\tan\varphi)_{T\leq50^\circ C}$	$^\circ C^{-1}$		-0.25		
Oil fired boiler	$P_{nom,buner}$	kW	18	18	11	(Viessmann, 2015b)
	$\tan\varphi$	$^\circ C^{-1}$		-0.15		
Thermal storage tank	V_{store}	USG	400	260	200	
Radiator	M_{unit}	kg		49		(Express Radiant Ltd, 2015)
	C_{avg}	J/kg K		1350		
	Q_0	W		967		
	$T_{s,0}$	°C		55		
	$T_{r,0}$	°C		35		
	$T_{env,0}$	°C		21		

To model the condenser of the AWHP two lumped capacitance control volumes are used. The lumped capacitance volume (A) represents the working fluid side of the condenser and the lumped capacitance volume (B) represents the water side of the condenser. The nominal heat supply of the AWHP is transferred to the lumped capacitance volume (A). Heat losses from the condenser to the environment are considered in the energy balance of lumped capacitance volume (A). Heat transfer between the working fluid and water is estimated by a heat exchange coefficient between lumped mass volumes (A) and (B). The energy balance equations for lumped mass volumes (A) and (B) are given in Equations (7.3) and (7.4), respectively:

$$M_A c_A \frac{dT_A}{dt} = P_C \times COP - UA(T_A - T_{amb}) - K_{AB}(T_A - T_B) \qquad (7.3)$$

$$M_B c_B \frac{dT_B}{dt} = K_{AB}(T_A - T_B) - \dot{m} c_w (T_w - T_B) \qquad (7.4)$$

where M is the mass of control volume (kg), c is the specific heat (kJ/kgK), UA is the heat loss coefficient (kW/K), K_{AB} is the heat exchange coefficient between water and working fluids (kW/K) and $\dot{m}$ is the water mass flow rate (kg/s). The values of these parameters used in this work are given in Table 7.1.

At low ambient temperature and high relative humidity the evaporator coil may operate below the frost temperature of ambient air. Under these circumstances the frost may accumulate on the evaporator coil surface and reduce the heat transfer between refrigerant and the outside air. Thus, the defrost cycle is considered to melt the frost (ASHRAE, 2008). A defrost algorithm predicts the status of the AWHP in a case that ambient temperature drops below the frost temperature. If the ambient temperature remains below the frost temperature for a long time a defrost lockout duration is considered to dictate an interval between the defrost cycles. If the defrost cycle is turned on the heat supply of heat pump is set to zero. The duration of the defrost cycle is defined using Equation (7.5).

$$t_{def} = t_0 + t_1 \times RH_{amb} \qquad (7.5)$$

where t_{def} is the defrost time (s) and RH_{amb} is the relative humidity of ambient air (%). t_0 (s) and t_1 (s/%) are empirical coefficients determined by experimentation. The values used here are given in Table 7.1. The typical duration of defrost cycle is between 4 to 10 minutes (ASHRAE, 2008).

7.3.1.2. Auxiliary Boiler

The boiler model that was developed and added to the ESP-r plant domain by Hensen (1991) is used. The model can be used for both non-condensing and condensing auxiliary boilers. The governing equations, including conservation of mass and energy, are solved in each time step. The control signal that defines the ON/OFF status of the boiler is set the beginning of each time step, and the boiler remains in that status during a time step. In the case that boiler temperature exceeds the maximum allowable temperature limit, the control signal is discarded and boiler is turned off to determine the new boiler temperature for that time step.

The heat supply of the boiler is determined based on the fuel consumption, fuel heating value and boiler efficiency. Boiler efficiency is a function of temperature with the condensing effect considered for gas-fired boilers as shown in Equation (7.6):

$$\eta_b=\left[\eta_0- tan\,\varphi\times(T_c-T_1)\right] \tag{7.6}$$

where η_b is the boiler efficiency (%), η_0 is the full load boiler efficiency (%) at the reference temperature, φ is the slope of the efficiency curve (%/K), T_c is the reference temperature (K), T_1 is the return water temperature (K). During the start-up and shutdown periods the boiler efficiency is reduced by the $\left(\frac{\Delta t\text{-}t_{tr}}{\Delta t}\right)$ factor, where t_{tr} is the duration of transient operation (i.e. start-up and shutdown) and Δt is the simulation time step (s). For a condensing boiler, the reference temperature is the condensing temperature. The values used a given in Table 7.1.

7.3.1.3. Thermal Storage Tank

The thermal storage tank model developed and incorporated into the ESP-r by Thevenard and Haddad (2010) is used. The model represents a stratified tank with two immersed heat exchangers. The tank is divided into N control volumes, and mass and energy balance equations are solved for each control volume. The energy balance equation for each control volume considers heat losses to the environment, convection and conduction heat transfer with the adjacent control volumes as well as heat transfer due to water flow at inlet/outlet, where applicable.

Asaee *et al.* (2016b) used the approach suggested by Weiss (2003) to define thermal storage tank size for residential solar combisystems. Since the tank height affects stratification and due to similar temperature ranges found in the thermal storage tanks of solar combisystems and AWHP systems, the same approach is used here to estimate the thermal storage tank height as shown in Equation (7.7).

$$h_{store}=max\left[min\left(2.2,1.78+0.39\ln\frac{V_{store}}{m^3}\right),1.25\right] \tag{7.7}$$

where h_{store} is the storage tank height (m) and V_{store} is the storage tank volume (m^3).

7.3.1.4. *Heat Delivery System*

The heat delivery system is assumed to be hydronic, consisting of piping, pumps and radiators.

The radiator and pump models developed and added to the ESP-r plant database by Hensen (1991) are used. Radiator heat emission is estimated based on the nominal heat emissions at reference conditions and actual temperature conditions of radiator and environment based on radiator type, dimensions, connection method and room characteristics. The electricity consumption of the circulation pump defined based on actual mass flow rate, pressure drop, fluid density and pump efficiency with heat losses from the pump added to the energy balance.

The number of radiators for each thermal zone is chosen to satisfy the design heating load and nominal radiator capacities selected from the Express Radiant Ltd product catalogue (Express Radiant Ltd, 2015). The hot water circulation pump power is estimated using empirical equations that Asaee *et al.* (2016b) used to estimate pump power in space and DHW heating loop for solar combisystem applications based on recommendations by Weiss (2003):.

$$P_{el,pump.SH}=90\text{W}+2\times10^{-4}P_{nom,burner} \tag{7.8}$$

$$P_{el,pump.DHW}=49.4\text{W}\times exp\left(0.0083\,\frac{P_{nom,burner}}{kW}\right) \tag{7.9}$$

where $P_{el,pump.SH}$ is the pump power in space heating loop (W), $P_{el,pump.DHW}$ is the pump power in DHW loop (W) and $P_{nom,burner}$ is the nominal power of auxiliary boiler (kW).

7.3.1.5. *Domestic Hot Water System*

The AWHP system architecture shown in Figure 7.1 uses a combination of three-way diverting valve and three-way converting valve to maintain the DHW temperature in the desired range. Since the DHW heating coil is sized for maximum water draw calculated for the house, this architecture prevents overheating the DHW when the water draw is less than the nominal value. To simplify the modeling of this architecture in ESP-r, a fully mixed adiabatic tank with temperature control as shown in Figure 7.2 is used. As the DHW draw and equivalent main water addition is applied to the adiabatic tank, the tank temperature is maintained in the range of 55±0.5°C by circulating hot water from the thermal storage tank to the adiabatic tank. Thus, the energy balance for the adiabatic tank is the same as for the three-way valve combination.

7.3.1.6. AWHP System Sizing

The nominal capacity of AWHP components are defined based on the existing heating system capacity of individual buildings as shown in Table 7.1.

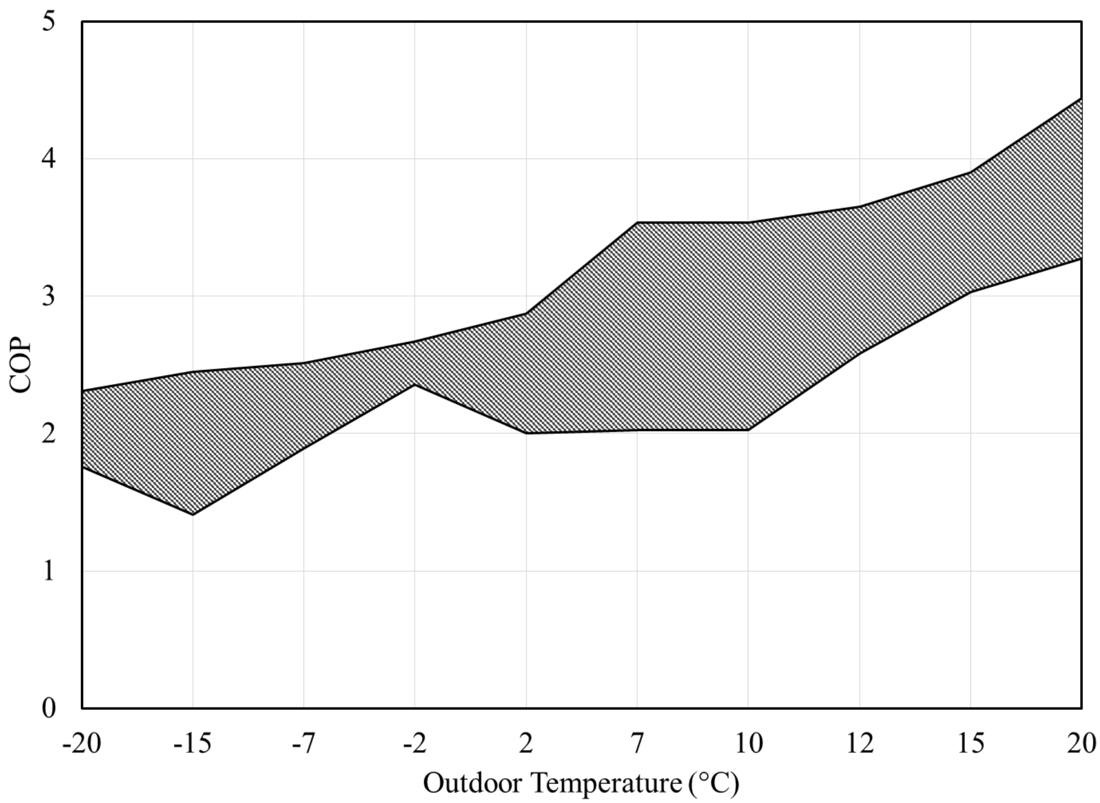

Figure 7.3 COP range of various commercially available AWHP systems (Fujitsu, 2016; Mitsubishi Electric, 2016b; Stiebel Eltron, 2016; Toshiba, 2016; Viessmann, 2016).

Since the goal of this study is to push the CHS towards net zero energy buildings (NZEB) by introducing AWHP retrofit in the existing houses, the COP and power consumption profile are derived for the AWHP systems that represents the most efficient technologies available in the market that fits the Canadian climatic conditions. For this purpose a series of AWHP systems from different manufacturers including Mitsubishi electric, Toshiba, Viessmann, Fujitsu and Stiebel Eltron are reviewed (Fujitsu, 2016; Mitsubishi Electric, 2016b; Stiebel Eltron, 2016; Toshiba, 2016; Viessmann, 2016). The COP range reported by the manufacturers for those AWHP systems is presented in Figure 7.3.

The size and performance parameters of the AWHP units used in this work are based on the Viessmann Vitocal 350-A as given in Table 7.1. Operating temperature, heating capacity and COP of Vitocal 350-A AWHP system is in the similar range with other reviewed products. All of these systems can operate in the Canadian Climatic conditions. The cut-out temperature for the AWHP system is -15°C. The control system deactivates the AWHP at ambient temperature below the cut-out temperature and reverts to the back-up system. The AWHP size for each house is selected such that the AWHP is capable of satisfying major part of the design heating load. The capacity of the thermal storage tank is chosen such that the tank can store the heat generated by the AWHP during a 30 minute long operation at its maximum output. The fuel used in the auxiliary heating system is chosen based on the availability of natural gas. Thus, natural gas (NG) fired boilers are assumed to be the auxiliary heating system in every region of Canada except in the Atlantic region where oil fired boilers are used. The nominal capacity of auxiliary heating system is chosen to be equal to the AWHP nominal capacity (Viessmann, 2015a, 2015b).

7.3.1.7. Control Algorithms

Control algorithms for the AWHP system include the loops that operate the heat pump, auxiliary boiler and pumping system according to the space and DHW temperatures. The detailed control loop data are presented in Table 7.2.

Space and DHW heating are supplied in two stages. The first stage is supplied by the heat pump and the second stage is by auxiliary heat. Due to this dual mode of operation, the water supply to the space heating radiators is between 50°C and 55°C; i.e. the circulation pump is turned on when the temperature drops to 50°C and turned off when the temperature reaches 55°C.

The first control loop operates the AWHP to heat the water up to 50°C. The second loop operates the auxiliary heater. The 50°C hot water leaving the AWHP is heated by the boiler to a maximum 55°C. With this control scheme, it is ensured that the auxiliary heating system is operated only when the AWHP is not capable of meeting the demand.

The third control loop maintains the DHW temperature in the adiabatic tank in the range of 55±1°C by running the DHW pump while the fourth loop controls the DHW draw and equivalent main water supply to the adiabatic tank.

Fifth loop controls the zone temperature by maintaining the space heating pump operation. CHREM provides for four space conditioning periods (winter - heating only, summer - cooling only, and shoulder seasons - heating/cooling are both available). However, since cooling is not available, two periods are used in this work as shown in Table 7.2:

- September 17 to June 3: heating available,
- June 4 to September 16: heating not available.

During the heating period the space heating pump is controlled to maintain the main zone temperature in the range of 20–22°C. The main-slave control strategy is used for temperature control of other zones excluding the attic which is not conditioned. Since attic is free ventilated, its temperature follows the ambient temperature.

Table 7.2 Control strategy for AWHP, space heating and DHW supply

Control loop	Actuator	Period		Sensor location	Setpoint	
		start	end		on	off
Two stage heating	ASHP	1 Jan	31 Dec	Thermal storage tank outlet to zone	45	50
	Boiler	1 Jan	31 Dec	Boiler outlet	50	55
DHW heating and supply	DHW Pump	1 Jan	31 Dec	DHW tank	54	56
	DHW tank	1 Jan	31 Dec	DHW draw	--	--
Space heating	Radiator pump	17 Sep	3 Jun	Zone main 1	20	22
		4 Jun	16 Sep		0	1[a]

[a] The heating system will not turn on due to the low temperature setpoint during the cooling only season

7.3.2. Methodology to Select Eligible Houses for the AWHP System Retrofit

A basement or a mechanical room is necessary to install an AWHP system into a house. While the presence of a basement is noted in the CHREM database, the presence of a mechanical room is not. Therefore, it is assumed in this work that all houses that either have a basement or a heating system that requires a mechanical room are suitable for AWHP retrofit. Based on this assumption, all houses that use NG or oil for space heating are considered to be eligible for the AWHP retrofit. Depending on the type of heating system and the presence of a basement, some houses that use wood or electricity are also eligible for the retrofit. The percentage of houses eligible for the retrofit in each province of Canada[1] is shown in Table 7.8.

7.3.3. Estimation of GHG Emissions

CHREM determines the associated GHG emission due to onsite fossil fuel and electricity consumption separately for each province due to the vast differences in the fuel mix used. GHG emissions are calculated and reported as "equivalent CO_2" (CO_{2e}) emitted per unit input energy. CO_{2e} is calculated by converting all GHG emissions from fossil fuel combustion, such as CH_4 and N_2O, to equivalent CO_2 emissions taking into account their global warming potentials as shown in Equation (7.10) (Farhat and Ugursal, 2010; Swan *et al.*, 2013).

$$CO_{2e}=CO_2+25CH_4+298N_2O \qquad (7.10)$$

Instantaneous GHG emissions due to onsite fuel consumption is calculated in each time step based on the fuel type and efficiency of the energy conversion device. The emission of CO_2 due to wood combustion is not accounted for in this study because it is assumed that combustion of wood returns to the atmosphere the CO_2 that was recently removed by photosynthesis as the tree grew (Farhat and Ugursal, 2010).

To evaluate the GHG emissions related to electricity consumption the GHG emission intensity factor (EIF) is used. The GHG EIF is the level of CO_2 emissions (kg/kWh) generated for the generation and delivery of one kWh electricity to the end-user. In Canada electricity generation is under the jurisdiction of provincial utility companies. Thus, provincial GHG EIF is defined based on the primary energy mixture used for electricity generation and efficiency of energy conversion as well as transmission and distribution losses. Also, typically utilities consider different types of technologies for peak and base electricity generation. Thus, different average and marginal GHG EIFs associated with base

[1] Provinces of Canada, from east to west, are: Newfoundland and Labrador (NF), Prince Edward Island (PE), Nova Scotia (NS), New Brunswick (NB), Quebec (QC), Ontario (OT), Manitoba (MB), Saskatchewan (SK), Alberta (AB), and British Columbia (BC). NF, PE, NS and NB are collectively referred to as Atlantic Provinces (AT) while MB, SK and AB are referred to as Prairie Provinces (PR).

and peak electricity generation are required. The provincial average and marginal GHG EIF developed by Farhat and Ugursal (2010) and given in Table 7.3 are used.

Table 7.3 The average and marginal GHG intensity factors (g CO_{2e}/kWh) for each province of Canada (Farhat and Ugursal, 2010)

Electrical generation characteristics		Canadian provincial GHG EIF (CO_{2e} per kWh)									
		NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Annual $EIF_{Average}$		26	689	191	433	6	199	13	789	921	22
Annual $EIF_{Marginal}$		22	360	6	837			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		9%	4%	6%	6%	4%	6%	12%	6%	4%	3%

Average GHG EIFs are used to estimate the emissions due to electricity consumption of the existing housing stock (base case) while the marginal GHG EIFs are used to estimate the GHG emission variation due to the change in electricity consumption in retrofitted houses.

7.4. Accounting of Renewable Energy from Heat Pump

European Parliament and Council in the Directive 2009/28/EC (EPC-EU, 2009) identified the gross final consumption of energy from renewable resources as the summation of (a) gross final electricity consumption, (b) heating and cooling gross final energy use and (c) gross final energy use for transportation from renewable sources. In accordance to part (b) aerothermal, geothermal and hydrothermal energy of heat pump can be assumed as renewable energy in a case that final gross thermal energy production significantly exceeds the primary energy consumption for the heat pump operations. For this purpose the European Parliament and Council Directive 2009/28/EC introduced Equation (7.11) to define the amount of renewable thermal energy captured by heat pumps.

$$E_{RES}=Q_{usable}\times\left(1-\frac{1}{SPF}\right) \quad (7.11)$$

where E_{RES} is the thermal energy considered from renewable sources (kJ), Q_{usable} is the gross final thermal energy delivered by heat pump (kJ) and *SPF* is the average seasonal performance factor. *SPF* is defined as the ratio of the delivered heat to the electricity consumption of the heat pump. To fulfill the above mentioned criterion (part (b)) the following condition is defined to identify eligible heat pumps:

$$SPF>1.15\times {}^{1}\!/_{\eta} \quad (7.12)$$

where η is the ratio between total gross production of electricity and the primary energy consumption for electricity generation.

Table 7.4 Average seasonal performance factor (SPF) of AWHP retrofits in the CHS and reference efficiency electricity generation and distribution losses in Canada (Asaee *et al.*, 2014)

Province	Fossil fuel contribution (%)	Reference efficiency	1.15×1/η
NF	2.4	1	1.15
NS	90.8	0.35	3.28
PE	63.4	0.57	2.02
NB	63.4	0.57	2.02
QC	0.4	1	1.15
OT	19.1	1	1.15
MB	0.3	1	1.15
SK	78.1	0.41	2.80
AB	95.9	0.32	3.59
BC	3	1	1.15

Asaee *et al.* (2015a) evaluated provincial efficiency of utility electricity generation, inclusive of transmission and distribution losses, from fossil fuels. In each province the electricity generation is from a mixture of fossil fuels and renewable resources. To obtain the reference efficiency that represents the total gross electricity production, the efficiency of electricity generation from fossil fuels is divided by the fossil fuel contribution in the fuel mixture for utility electricity generation. The reference efficiency is therefore in the range of 0 to 1. In the case that the electricity generation exceeds the primary energy consumption due to a vast electricity production from non-fossil fuel sources the reference efficiency value is set to 1. The provincial fossil fuel contributions and reference efficiencies are given in Table 7.4.

7.5. Economic Analysis Based on Tolerable Capital Cost

Accurate estimation of AWHP system capital costs, at residential as well as commercial scale, is difficult because installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, and prevailing labor rates. Therefore the purchase and installation costs of AWHP systems in Canada vary substantially from manufacturer to manufacturer and location to location. Thus, it is not practicable to estimate realistic total investment costs for AWHP systems and to conduct a conventional economic feasibility analysis. Therefore, an alternative approach to conventional economic feasibility analysis is adopted here which involves the calculation of the "tolerable capital cost" (TCC) of the upgrades (Nikoofard *et al.*, 2014a). TCC is the capital cost for an energy saving upgrade that will be recovered based on the annual savings, the number of years allowed for payback, and the estimated annual interest and fuel cost escalation rates. Thus, to estimate the tolerable capital cost of the AWHP upgrade a reverse payback analysis is conducted as follows:

1. The annual fuel and electricity savings for each upgrade is estimated (C$).
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:

$$\text{TCCH}=\begin{cases}\text{ACSH}\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e\\ \text{ACSH}\times n(1+i)^{-1} & \text{for} \quad i=e\end{cases} \tag{7.13}$$

$$\text{ACSH}=\sum_{j=1}^{m}(F\times E)_j \quad (7.14)$$

where:

TCCH	Tolerable capital cost of the retrofit for the house (C$)
n	Acceptable payback period (year)
i	Interest rate (decimal)
e	Fuel cost escalation rate (decimal)
ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
F	Fuel price per unit of each fuel type (C$/unit)
m	Number of different fuels used in a house

The additional maintenance cost of the AWHP system over and above that of the replaced system is assumed to be included in the TCC as a present value of the annual maintenance cost over the lifetime of the AWHP system.

It is not useful or practical to report the TCC for each house in the CSDDRD, or for that matter within the CHS, because from a macro level of interest, data on individual houses have no utility. Thus, the "average tolerable capital cost per house" (ATCCH) is used to evaluate the economic feasibility of the AWHP system retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$\text{ATCCH}=\text{TTCC}/\text{NH} \quad (7.15)$$

where, TTCC is the total tolerable capital cost as a result of the AWHP system upgrade (C$), calculated as follows:

$$\text{TTCC}=\sum_{i=1}^{\text{NH}}\text{TCCH}_{\text{i}} \quad (7.16)$$

NH = number of houses that received the upgrade.

To take into consideration the uncertainty associated with the future of interest and fuel price escalation rates, a sensitivity analysis was conducted. The interest rates used in the analysis are based on the Bank of Canada Prime Rate (BOC, 2015), which was about 1%

in June, 2015. 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.

For each province, fuel prices for residential customers for natural gas, heating oil, electricity and wood were obtained to calculate the energy cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 7.5 (Hydro-Quebec, 2014b; Statistics Canada, 2013).

For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 7.6 are used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada (NEB, 2014) and Energy Escalation Rate Calculator (WBDG, 2014).

Payback periods of six and ten years are used in the sensitivity analysis. Both values are comfortably within the economical lifetime of 15 to 20 years for AWHP systems reported by Natural Resources Canada (NRCan, 2015).

It is likely that an AWHP retrofit would increase the market value of a house. However, the estimation of the increase in market value due to such a retrofit is not straightforward 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.

Table 7.5 Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[a]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	C$/GJ	36.58	45.06	47.08	37.11	21.92	39.72	24.25	42.00	43.19	26.53
Natural gas[b]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	C$/GJ	N/A	N/A	N/A	N/A	12.41	7.99	8.23	7.77	4.62	11.35
Home heating oil[c]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	C$/GJ	29.63	28.42	29.17	30.76	31.25	32.80	30.33	29.37	N/A	33.08
Wood[d]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	C$/GJ	11.20	11.20	11.20	15.69	11.43	13.44	11.65	11.20	22.40	10.75

[a] Hydro-Quebec (Hydro-Quebec, 2014b)

[b] Statistics Canada handbook (Statistics Canada, 2013)

[c] Statistics Canada Handbook (Statistics Canada, 2013)

[d] Local companies

Table 7.6 Real fuel escalation type for each fuel type

	Low	Medium	High
Electricity[a]	2	6	10
Natural gas[b]	2	5	8
Light fuel oil[b]	6	10	14
Mixed wood[c]	3	6	9

[a] National Energy Board of Canada (NEB, 2014)

[b] Energy Escalation Rate Calculator (EERC) (WBDG, 2014)

[c] Equal to interest rate as there is no source for its escalation rate

Table 7.7 CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 7.8 Energy savings and GHG emission reductions for the CHS due to AWHP retrofit

Province	Eligible houses		Total energy saved (PJ)	Average energy saving per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent				
NF	88,207	50	8.3	94	0.59	6,709
NS	205,592	69	17.1	83	-0.04	-173
PE	38,997	87	2.9	74	0.17	4,336
NB	122,070	51	11.4	93	0.14	1,150
QC	385,809	19	24.7	64	1.77	4,579
OT	3,084,282	90	234.1	76	11.79	3,823
MB	243,288	72	17.2	71	1.16	4,781
SK	287,895	91	21.3	74	-0.58	-2,025
AB	970,120	100	65.2	67	-3.47	-3,573
BC	876,761	79	58.3	66	3.62	4,131
Canada	6,303,021	71	460.5		15.16	

Table 7.9 CHREM estimates of annual energy consumption (PJ) with existing (Exist) and AWHP retrofit (AWHPR) in houses eligible (EL) and houses not eligible (N-E) for AWHP retrofit

	Electricity			NG[a]		Oil[a]		Wood			Total		
	N-E	EL						N-E	EL		N-E	EL	
Province		Exist	AWHPR	Exist	AWHPR	Exist	AWHPR		Exist	AWHPR		Exist	AWHPR
NF	10.9	4.3	7.4	0.0	0.0	9.6	0.9	0.6	2.7	0.0	11.5	16.6	8.3
NS	9.1	8.6	15.6	0.0	0.0	22.6	2.2	2.3	3.7	0.0	11.4	34.9	17.8
PE	0.4	1.4	2.7	0.0	0.0	4.0	0.6	0.7	0.8	0.0	1.1	6.2	3.3
NB	12.7	6.0	8.8	0.0	0.0	9.7	2.3	3.9	6.8	0.0	16.6	22.5	11.1
QC	181.7	23.6	24.9	1.0	8.2	30.3	0.0	7.5	2.9	0.0	189.2	57.8	33.1
OT	40.6	96.6	206.5	337.4	40.8	47.4	0.0	0.0	0.0	0.0	40.6	481.4	247.3
MB	12.1	6.8	13.2	33.6	10.0	0.0	0.0	0.0	0.0	0.0	12.1	40.4	23.2
SK	3.1	7.5	16.6	40.2	9.8	0.0	0.0	0.0	0.0	0.0	3.1	47.7	26.4
AB	0.0	28.3	59.7	119.8	23.2	0.0	0.0	0.0	0.0	0.0	0.0	148.1	82.9
BC	23.2	41.4	57.9	83.9	9.5	0.0	0.0	1.7	0.4	0.0	24.9	125.7	67.4
Canada	293.8	224.5	413.3	615.9	101.5	123.6	6.0	16.7	17.3	0.0	310.5	981.3	520.8

[a] Since entire houses with existing oil or NG fired heating system is eligible for AWHP retrofit, NG and oil consumption in not eligible houses is not shown

Table 7.10 Annual energy savings and GHG emission reductions due to AWHP retrofits in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	-3.1	0.0	8.7	2.7	8.3	-0.02	0.00	0.61	0.59
NS	-7.0	0.0	20.4	3.7	17.1	-1.47	0.00	1.43	-0.04
PE	-1.3	0.0	3.4	0.8	2.9	-0.07	0.00	0.24	0.17
NB	-2.8	0.0	7.4	6.8	11.4	-0.38	0.00	0.52	0.14
QC	-1.3	-7.2	30.3	2.9	24.7	0.00	-0.36	2.13	1.77
OT	-109.9	296.6	47.4	0.0	234.1	-6.54	15.00	3.33	11.79
MB	-6.4	23.6	0.0	0.0	17.2	-0.03	1.19	0.00	1.16
SK	-9.1	30.4	0.0	0.0	21.3	-2.12	1.54	0.00	-0.58
AB	-31.4	96.6	0.0	0.0	65.2	-8.35	4.88	0.00	-3.47
BC	-16.5	74.4	0.0	0.4	58.3	-0.14	3.76	0.00	3.62
Canada	-188.8	514.4	117.6	17.3	460.5	-19.12	26.01	8.27	15.16

7.6. Results and Discussion

The CHREM estimates of the current energy consumption and GHG emissions of the CHS are given in Table 7.7. Swan *et al.* (2013) verified the validity of these results by comparing them with other estimates of Canadian residential energy consumption.

Using the criteria given in Section 7.3.2, eligible houses for the AWHP retrofit in CHREM were identified. As shown in Table 7.8, about 71 percent of the houses in CHREM, representing approximately 6.3 million existing houses in the CHS are eligible for the AWHP retrofit. After identifying the eligible houses for the AWHP retrofit, CHREM was updated to reflect the AWHP retrofit in these houses and simulations were carried out to evaluate the energy savings and GHG emissions reduction due to the retrofit. As shown in Table 7.8, results indicate that 460.5 PJ end-use energy and 15.16 Mt of GHG associated emissions would be saved by retrofitting all eligible houses in the CHS by AWHP systems. Also as shown in Table 7.8, the energy savings and GHG emission reductions vary substantially amongst provinces. This is discussed in detail below.

7.6.1. Energy Savings

The existing annual energy consumption and energy consumption with the AWHP retrofit are given in Table 7.9 for each province, disaggregated according to the heating fuel used. As discussed in Section 7.3.2, whereas all houses that use NG or oil are eligible for the retrofit, only a portion of the houses that use electricity and wood are eligible. Thus, the energy consumption of the houses that are not eligible for the retrofit is shown separately in Table 7.9.

Since AWHP compressors use electricity, the electricity use in all houses that receive the AWHP retrofit increase. This increase translates to an increase in the electricity consumption of retrofitted houses by 188.8 PJ (as shown in Table 7.10), or close to 85%, from 224.5 PJ to 413.3 PJ. This represents an increase of about 36% in the current electricity consumption of the CHS (518.3 PJ as shown in Table 7.7 and Table 7.9). The increase in the electrical consumption is beneficial in reducing primary energy consumption in provinces where renewable resources are the main source of electricity generation including NF, QC, MB and BC. However, in provinces that utility electricity generation heavily relies on fossil fuel thermal power plants, AWHP retrofit may not significantly affect primary energy savings.

The average *SPF* and thermal energy from renewable sources of heat pumps (E_{RES} as shown in Equation (7.11)) are given in Table 7.11. The *SPF* is calculated using the average value of *SPF* in individual houses in each province. Comparing the SPF of AWHP and reference efficiencies of electricity generation (given in Table 7.4) based on the European Parliament and Council Directive 2009/28/EC guidelines indicate that heat generation of AWHP can be considered as renewable energy in Canada except in provinces that electricity generation is significantly from fossil fuel resources (NS, NB, PE, SK, and AB). About 91%, 64%, 64%, 78% and 96% of electricity generation is from fossil fuels in NS, NB, PE, SK and AB, respectively. Thus, thermal energy from renewable sources (E_{RES}) is not calculated for theses provinces. It should be noted that E_{RES} only includes the amount of thermal energy captured from the ambient that can be considered as renewable energy. However, in cases that electricity generation is mainly from renewable resources (such as NF, QC, MB and BC) the total gross heat delivered (Q_{usable}) by the heat pump is renewable energy. Results indicate that AWHP capture about 130.9 PJ additional renewable energy, equivalent to 10% of the total existing energy consumption of the CHS (1291.8 PJ as shown in Table 7.7).

Table 7.11 Average seasonal performance factor, thermal energy considered from renewable sources, annual energy savings and GHG emission reductions due to AWHP retrofits in the CHS

Province	*SPF*	E_{RES} (PJ)	Energy Savings (%)	GHG emission reductions (%)
NF	2.04	3.4	30	75
NS	1.87	N/A	37	-1
PE	1.83	N/A	40	44
NB	1.89	N/A	29	5
QC	1.83	10.6	10	69
OT	1.80	90.5	45	41
MB	1.95	5.4	33	66
SK	1.71	N/A	42	-13
AB	1.70	N/A	44	-25
BC	2.59	21	39	78
Canada		130.9	36	23

An AWHP system utilizes an auxiliary heating system that uses NG or oil as fuel source. However, the NG and oil consumption is drastically reduced in eligible houses due to AWHP retrofit. Thus, the current end-use energy consumption of eligible houses (981.3 PJ as shown in Table 7.9) is reduced by about 47% due to AWHP retrofits (520.8 PJ as shown in Table 7.9). However, the primary energy use increases in provinces with relatively low reference efficiency of electricity generation, i.e. in NS, NB, PE, SK and AB.

Annual end-use energy savings due to AWHP upgrade is summarized in Table 7.11. AWHP retrofit yields 36% energy savings in the CHS. The lowest energy savings is associated with QC because of the small penetration level of AWHP system in this province (19% houses in QC are eligible). On the other end of the spectrum, the penetration level of AWHP system is above 90% in OT, SK and AB (as shown in Table 7.8) resulting in more than 40% energy savings in these provinces.

7.6.2. GHG Emissions Reduction

The GHG emission reductions due to AWHP retrofit in all eligible houses based on the energy source in each province are presented in Table 7.10.

As to be expected, GHG emissions associated with electricity use increase due to AWHP retrofit in the CHS. As shown in Table 7.3 the GHG EIF are small in NF and QC where major share of electricity generation is from renewable resources. Thus, the GHG emission variations are negligible despite the increase of electricity consumption in these provinces. The total GHG emission increase (19.12 Mt of CO_{2e}) associated with electricity use is about 75% of national GHG emissions (25.3 Mt of CO_{2e}) associated with electricity use in the CHS. This significant increase of GHG emissions is associated with 36% increase in the electricity use in the CHS as mentioned in the previous section. Close to half of GHG emissions increase (19.12 Mt of CO_{2e}) due to AWHP retrofit in the CHS is from AB (8.35 Mt of CO_{2e}). Thus, AB has the least favourability for the AWHP retrofit from this point of view.

Although AWHP retrofit yields a significant increase of GHG emissions associated with electricity use, close to 86% of GHG emissions associated with onsite fossil fuel consumption is reduced in the CHS. This occurs because of fuel shift from NG and oil as discussed in previous section.

As shown in Table 7.11 AWHP retrofit result in a 23% reduction of GHG emissions in the CHS. While the smallest value of GHG emission reductions occur in NB, overall GHG emissions increase in NS, SK and AB. Unfavourable results of GHG emission variation in NS, SK and AB are in agreement with prior observations regarding the primary energy consumption as discussed in previous section. Since, fossil fuels are the main source of electricity generation in these provinces, AWHP retrofit adds extra emissions. The low value of GHG emission reduction in NB is because of the fuel shift from wood to electricity. As discussed earlier CO_2 emission of wood combustion is considered as a complement of the natural carbon cycle and no GHG emissions is attributed to wood burning heating systems. Since close to 30% of total energy use (39.1 PJ as shown in Table 7.6) of existing houses in NB is supplied from wood (10.7 PJ as shown in Table 7.6) this fuel shift strongly affects the total GHG emissions of eligible houses. As shown in Table 7.9 about 6.8 PJ (equivalent of 17% of total energy use) of energy supply from wood is replaced by electricity in NB. This effect is as to be expected since marginal electricity generation in NB has the highest GHG EIF in the Canadian electricity market as shown in Table 7.6. On the other hand provinces that have a high renewable electricity generation provide substantial GHG emission reductions due to AWHP retrofit.

7.6.3. Economic Analysis

The results of economic analysis for AWHP retrofit using two payback periods, three interest rate scenarios and three fuel escalation rates in each province in the CHS based on the tolerable capital cost are given in Table 7.12.

The operating cost of AWHP system is higher compared to that of the existing systems for space and DHW heating in OT and PR region (excluding MB). Thus TCC is not given for OT, SK and AB provinces in Table 7.12. Also, TCC in MB is fairly small compared other provinces. The higher operating costs in these provinces are due to significantly lower price of NG (8.23, 7.77 and 4.62 C$/GJ as shown in Table 7.5) compared to price of electricity (24.25, 42.00, 43.19 C$/GJ as shown in Table 7.5) in MB, SK and AB, respectively. As shown in Table 7.5 similar to the one in the PR region, the electricity price (39.72 C$/GJ) is much higher than NG price (7.99 C$/GJ) in OT. Thus, TCC for AWHP in OT is not sufficient to justify the initial investment cost in the absence of incentive programs.

Table 7.12 Average TCC per house (C$/house)

Province	Payback (yr)	Interest rate								
		3%			6%			9%		
		Fuel cost escalation rate								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	14,904	17,743	21,196	12,612	14,893	17,656	10,791	12,643	14,875
	6	7,996	8,766	9,613	7,206	7,878	8,615	6,528	7,117	7,763
NS	10	13,540	16,204	19,453	11,419	13,557	16,153	9,739	11,470	13,564
	6	7,035	7,731	8,495	6,331	6,937	7,603	5,728	6,258	6,840
PE	10	8,190	9,778	11,703	6,867	8,136	9,669	5,822	6,846	8,079
	6	4,014	4,394	4,811	3,602	3,933	4,295	3,249	3,539	3,855
NB	10	17,375	20,390	24,017	14,773	17,203	20,112	12,700	14,677	17,034
	6	9,742	10,607	11,553	8,796	9,552	10,377	7,984	8,647	9,369
QC	10	17,296	20,818	25,155	14,701	17,540	21,018	12,634	14,945	17,762
	6	9,667	10,683	11,809	8,728	9,615	10,597	7,921	8,700	9,560
MB	10	819	612	297	703	536	284	610	474	271
	6	501	438	360	454	399	331	413	365	306
BC	10	3,123	3,300	3,447	2,682	2,826	2,947	2,328	2,447	2,546
	6	1,910	1,972	2,031	1,731	1,785	1,837	1,576	1,624	1,670

The major share of space and DHW heating energy is currently supplied from oil in AT and QC regions. Due to comparable price of oil (~30 C$/GJ as shown in Table 7.5) and electricity (~22–45 C$/GJ as shown in Table 7.5) in these provinces, the highest TCC for AWHP retrofit is observed in NF, NS, PE, NB and QC.

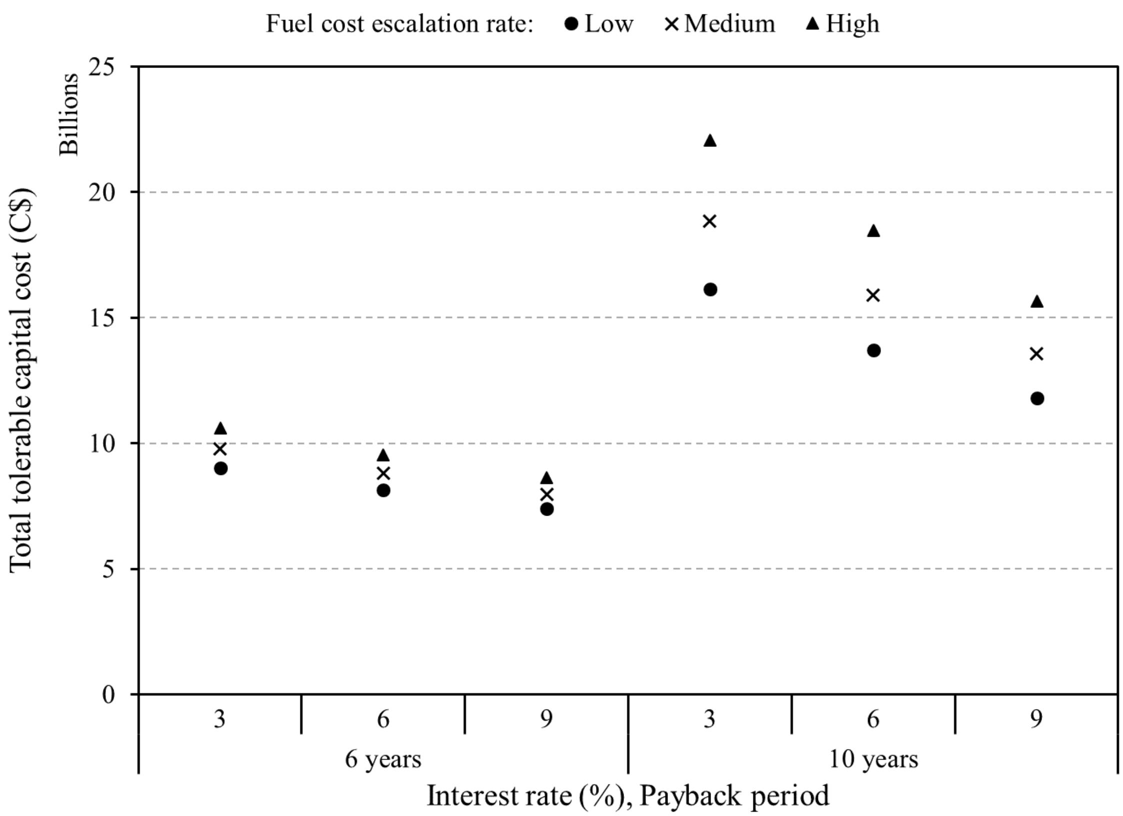

Figure 7.4 Total national excluding PR provinces tolerable capital cost due to air to water heat pump upgrade for different interest rates and fuel cost escalation rates (Low, Medium and High as per Table 7.6).

The high TCC with short payback period may increase a homeowner's willingness to invest in the AWHP retrofit. However, the investment cost might be higher than the TCC in some provinces. In that case incentive programs and subsidies might be helpful if the provincial or federal governments decide to promote the AWHP retrofit in the housing stock. However, the subsidy program might not be the only tool for the government to motivate homeowners for energy retrofits. Tommerup and Svendsen (2006) argue that legislation is an effective and vital part of strategies in this regard, since a rational reaction to traditional market forces is not expected in the energy saving market. The value of TCC per house has less utility for provincial and national decision makers to develop strategies to enhance the penetration level of AWHP retrofit in the housing stock. Thus, TTCC for AWHP retrofit in the CHS is estimated and results for various scenarios are presented in Figure 7.4. Under the most favourable condition (10 years payback period, 3% interest rate and high fuel escalation rate) the total Canadian (excluding OT and PR) homeowners can invest about 22 Billion Canadian Dollars in AWHP retrofit. If the economic conditions varies or the investment cost is higher compared to the TTCC subsidies may cover the shortfall.

7.7. Conclusion

Techno-economic impact of air to water heat pump (AWHP) system on the energy consumption and GHG emissions of the Canadian housing stock (CHS) is presented and discussed. The AWHP system delivers aerothermal energy to the water for space and domestic hot water (DHW) heating purposes. The study was conducted using the Canadian Hybrid Residential End-use Energy and GHG emissions (CHREM) model. A high resolution and versatile whole building performance simulation software, ESP-r, was used to model the AWHP system components (i.e. heat pump, auxiliary boiler, thermal storage tanks, pumps and radiators). CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) which statistically represents the CHS with close to 17,000 unique houses. A selection criteria was defined and houses eligible for the AWHP retrofit were identified in CSDDRD. The AWHP retrofit was introduced into all eligible houses and the simulation was conducted to obtain the energy consumption, GHG emissions and annual energy cost. The results were compared with the base case to evaluate techno-economic impact of AWHP retrofit in the CHS. Tolerable capital cost (TCC) of the retrofit which is the maximum capital cost for an energy saving upgrade based on the annual savings, the number of years allowed for payback, and the estimated annual interest and fuel cost escalation rates.

The results indicate that about 71 percent of the houses in CHREM, representing approximately 6.3 million existing houses in the CHS are eligible for the AWHP retrofit. The AWHP retrofit reduces about 520.8 PJ equivalent of 36 percent end-use energy consumption in the CHS if all of the eligible houses receive the upgrade. The AWHP system retrofit is effective in reducing primary energy consumption in provinces where renewable resources are the main source of electricity generation including NF, QC, MB and BC. Comparing the seasonal performance factor (*SPF*) of AWHP and reference efficiencies of electricity generation based on the European Parliament and Council Directive 2009/28/EC guidelines indicate that heat generation of AWHP can be considered as renewable energy in Canada except in provinces that electricity generation is significantly from fossil fuel resources (NS, NB, PE, SK, and AB). Onsite fossil fuel (i.e. oil and NG) consumption is significantly reduced in the CHS after retrofit. The energy savings cause 15.16 Mt of GHG associated emission reductions in the CHS. Economic analysis indicate that the AWHP system retrofit is not feasible in OT, MB, SK and AB in absence of governmental subsidies and incentive programs.

This study is a part of the efforts to develop strategies, approaches and incentive measure to approach net/near zero energy status for existing Canadian houses by introducing and integrating high efficient and renewable/alternative energy technologies in new construction and existing houses. The project was defined under the Smart Net-Zero Energy Buildings Strategic Research Network (SNEBRN) umbrella to assess the techno-economic feasibility of converting the Canadian housing stock (CHS) into net/near zero energy buildings. Performance assessment of energy retrofit and renewable/alternative energy technologies in existing houses in regional and national scale is necessary to devise feasible strategies and incentive measures.

Chapter 8 Techno-Economic Assessment of Solar Assisted Heat Pump System Retrofit in the Canadian Housing Stock

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Rasoul Asaee is the principal researcher and author of the article. He conducted the research as part of his PhD. Thus, while he received supervision and guidance from his supervisors Drs. Ugursal and Beausoleil-Morrison, he carried out the work, wrote the article, and communicated with the editor of the journal. Minor editorial changes have been made to integrate the article within this dissertation.

8.1. Abstract

The techno-economic feasibility of retrofitting existing Canadian houses with solar assisted heat pump (SAHP) is investigated. The SAHP architecture is adopted from previous studies conducted for the Canadian climate. The system utilizes two thermal storage tanks to store excess solar energy for use later in the day. The control strategy is defined in order to prioritise the use of solar energy for space and domestic hot water heating purposes. Due to economic and technical constraints a series of eligibility criteria are introduced for a house to qualify for the retrofit. A model was built in ESP-r and the retrofit was introduced into all eligible houses in the Canadian Hybrid Residential End-Use Energy and GHG Emissions model. Simulations were conducted for an entire year to estimate the annual energy savings, and GHG emission reductions. Results show that the SAHP system performance is strongly affected by climatic conditions, auxiliary energy sources and fuel mixture for electricity generation. Energy consumption and GHG emission of the Canadian housing stock can be reduced by about 20% if all eligible houses receive the SAHP system retrofit. Economic analysis indicates that the incentive measures will likely be necessary to promote the SAHP system in the Canadian residential market.

8.2. Introduction

Solar energy is one of the main sources of renewable energy for residential applications. Solar thermal energy is used for space heating and cooling as well as domestic hot water (DHW) heating in the residential sector. The non-concentrating liquid cooled thermal collector (e.g. flat plate collector) is the most popular technology to utilize solar energy in buildings. Depending on the geographical location, climatic condition and solar thermal collector installation, water supply temperature from a flat plate collector may vary widely through the year. Thus, traditionally an auxiliary source of energy is integrated into the solar based heating systems to supply energy when solar energy is either not available (i.e. at night) or not sufficient (e.g. on cloudy days) to meet the demand. Integrating solar thermal collectors with a heat pump (HP) system is an energy efficient alternative for this purpose. Heat pumps capture aerothermal, geothermal or hydrothermal energy at the expense of thermodynamic work. Solar thermal collector and HP systems can be combined in different ways. A common method is to deliver the solar thermal energy to the evaporator of the heat pump in a series configuration to enhance the system performance (Hadorn, 2015). In this configuration, efficiency gains compared to standalone solar thermal and HP systems are realized because the high evaporator temperature increases the COP of the HP (Hadorn, 2015). Thus, the solar assisted heat pump (SAHP) system is expected to provide superior performance compared to conventional solar thermal systems such as solar domestic hot water (SDHW) and solar combisystem; however, long term field performance and economic feasibility require in-depth study. To address these issues, numerous studies were conducted, and results reported in the literature.

The International Energy Agency (IEA) Solar Heating and Cooling (SHC) programme launched Task 44 (IEA-SHC, 2016) with the goal to deliver optimized integration of solar thermal and heat pump systems, primarily for single family houses. Several systems were investigated and a series of recommendations were provided for SAHP system design and optimization. According to the survey conducted within the IEA SHC Task 44 most of the market ready SAHP systems are designed to serve both space and DHW heating (Hadorn, 2015). Different system architectures are categorized under four main sections (a) parallel, (b) series, (c) regenerative, and (d) complex. A wide range of measured data was gathered from 50 different systems in seven European countries for one to two years. Simulation results within the IEA SHC Task 44 indicated that solar contribution can be significant to reduce primary energy consumption and greenhouse gas (GHG) emissions. It was concluded that the solar and HP systems will be a part of solutions to fulfill the demands for net zero annual energy balance (Hadorn, 2015).

The performance of SAHP systems in different climatic and operating conditions was studied by several researchers. For example, Chu *et al.* (2014) assessed the feasibility of a SAHP system in a high performance house designed and built for the U.S. Department of Energy's Solar Decathlon 2013 Competition. A numerical model was developed in TRNSYS 17 (TRNSYS, 2013) for this study. Results show that the free energy ratio (the energy not purchased such as solar energy divided by total energy used) of 0.583 can be achieved using SAHP system in Ottawa, Ontario. The study revealed that flat plate collectors provide a superior performance compared to evacuated tube solar collectors for SAHP applications. Impact of heat pump performance, source side and load side input temperatures, solar collector array area and stratifications in the thermal storage tank on the overall performance of the SAHP system were investigated. Bakirci and Yuksel (2011) carried out an experimental study to evaluate the performance of a SAHP system for a residential application in Erzurum, Turkey. Data were collected from an actual system from January to June when the outdoor temperature was in -10.8°C to 14.6°C range. Results indicated that the overall COP of the SAHP system was about 2.9. They concluded that the various parameters including operating conditions, economic viability and environmental impacts may affect the SAHP system selection and design. Thermal storage was found to be a significant component that affects the overall performance of a SAHP system. Liang *et al.* (2011) used a numerical model to study a solar assisted air source heat pump system with flexible operational modes. The impact of solar collector area on the overall performance of the system was investigated. Results show that the COP of the heat pump increased due to increasing solar collector area and solar radiation intensity or sunny days in the heating season. Moreno-Rodríguez *et al.* (2012) developed a mathematical model to determine the operating characteristics of a direct expansion SAHP system. The model predicts the evaporator temperature and energy transfer based on the outdoor temperature, global radiation and wind speed. The model was validated using experimental data. The measured COP was between 1.7 and 2.9 for the load temperature of 51°C. Kong *et al.* (2011) studied a direct expansion SAHP system for DHW heating and used a simulation approach to predict the system performance. The model was validated using experimental measurements. Results show that the solar radiation, ambient temperature and compressor speed have the largest impact on the system performance.

In an extensive effort the Solar Thermal Research Laboratory at the University of Waterloo conducted a series of studies to investigate the solar thermal system performance in Canada. Sterling and Collins (2012) used a numerical model in TRNSYS to compare the energy consumption of a dual tank indirect SAHP system to that of a traditional solar domestic hot water (SDHW) and an electric domestic hot water (DHW) system. An identical load profile and water draw were applied to each system. Results show that the SAHP system provides the lowest energy consumption and operating costs. Wagar (2013) experimentally investigated a single tank indirect SAHP system and used measured data to validate a TRNSYS model. Using the validated model they found that the heat pump capacity should not exceed the capacity of the solar thermal array under moderate solar heating conditions. Temperature limits impose additional restrictions on heat pump operation and limits its solar collection benefits when little solar radiation is available and load temperature exceeds 45°C. Using a small or variable speed heat pump was recommended to increase the cycle time and match the heat input of the solar collector. Using findings of this study, Banister *et al.* (2015; 2015; 2014a, 2014b) built a dual tank SAHP system to create additional modes of operation and decrease the amount of purchased energy. Results show that the system was able to maintain the hot water temperature in the 53-57°C range during 99.9% of the year. The proposed SAHP system configuration showed a superior performance compared to single tank SAHP and SDHW systems.

In a review paper, Chu and Cruickshank (2014) reviewed a series of studies on SAHP system for residential applications. They were not able to identify an optimal system configuration for the Canadian residential sector among the systems reported in the literature. They concluded that integration of solar thermal and heat pump systems provides an opportunity to offset space and DHW heating in the Canadian residential sector. Since the overall energy consumption and environmental footprint of a building is affected by parameters such as climatic condition, building geometry, construction material, occupancy level, occupant behaviour, primary energy source, and heating, ventilation and air conditioning system performance, it is necessary to evaluate the heating system performance in an integrated analysis for an accurate assessment of system performance.

This study is a part of ongoing effort to introduce strategies and incentive measures to convert existing houses across Canada into net/near-net zero energy (NZE) buildings

(SNEBRN, 2012). The techno-economic feasibility of a series of high efficiency and alternative energy technology retrofits including envelope modifications such as glazing and window shading upgrades, as well as installation of solar domestic hot water (SDHW) systems, phase change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling engine (SE) based cogeneration systems, solar combisystem, and air to water heat pump (AWHP) systems have been investigated (Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b, 2017b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d). This study evaluates the techno-economic performance of SAHP system.

8.3. Methodology

This study is focused on large scale retrofit of SAHP systems in existing houses across Canada. Thus, the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM)[1] (Swan, 2010; Swan *et al.*, 2013) is used. CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) (Swan *et al.*, 2009) which statistically represents the CHS with close to 17,000 unique house files. The CSDDRD was developed from the survey data from the EnerGuide for Houses database (SBC, 2006), Statistics Canada and Natural Resources Canada housing surveys (OEE, 2006) and other available housing databases.

CHREM uses a high-resolution building energy simulation program ESP-r (ESRU, 2015) as the simulation engine. ESP-r is an integrated energy modeling software which evaluates the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings. ESP-r has been validated through a vast amount of research results (Strachan *et al.*, 2008) and has been used in many research studies.

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:

- The Canadian Single-Detached & Double/Row Housing Database (Swan *et al.*, 2009),

[1] CHREM was developed through the Solar Building Research Network (SBRN) and was expanded through the Smart Net-zero Energy Building Strategic Research Network (SNEBRN).

- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households (Swan *et al.*, 2011),
- 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 (Farhat and Ugursal, 2010),
- A model to estimate GHG emissions from fossil fuels consumed in households.

The energy savings and GHG emissions reductions associated with any energy efficiency upgrade or renewable/alternative energy technology, such as SAHP systems, can be estimated using CHREM as follows:

(i) Identify houses suitable to receive the upgrade/technology: For SAHP system retrofit, only houses with a basement or a mechanical room and a proper location for collector installation would be suitable. Therefore, such houses has to be identified in the CSDDRD.

(ii) Modify the CHREM to add the upgrade/technology retrofit to the input files of selected houses for use in the ESP-r energy simulations.

(iii) Estimate the energy consumption and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the "base case" (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010). Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

Since its initial development, the modeling capability of CHREM has been gradually expanded, to include PCM thermal energy storage, SDHW heating system, ICE and SE engine based cogeneration, solar combisystem and AWHP system (Asaee *et al.*, 2015a;

Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b, 2017b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

8.3.1. System Configuration

The SAHP system configuration developed by Banister *et al.* (2015) is used in this study. Banister *et al.* investigated the solar thermal system for the Canadian climate and recommended a dual tank configuration to enhance solar energy contribution. As shown in Figure 8.1, the SAHP system is comprised of a flat plate collector array, a float tank, auxiliary heating, a hot water tank, a hydronic heat delivery system and a DHW system. The float tank and the associated three-way valves (valves A, B, C and D shown in Figure 8.1) are included to enable the system to harvest solar energy even during low radiation periods. This is achieved by controlling the flow to the float tank so that tank temperature follows the collector temperature (Banister and Collins, 2015). When the system calls for heat and the float tank temperature is above the hot water tank temperature, the water is circulated directly from the float tank into the hot water tank. As shown in Figure 8.1, a combination of diverging and converting three-way flow valves are used to maintain the DHW temperature. This strategy ensures that the hot water supply temperature remains in the desired range while the DHW water draw varies during a day.

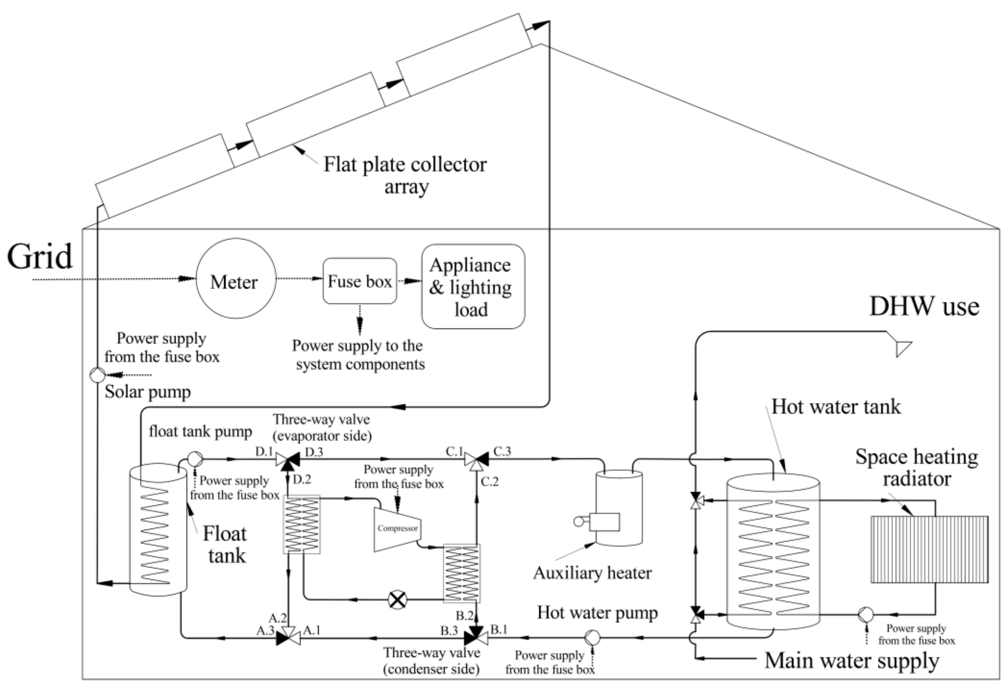

Figure 8.1 Solar assisted heat pump system configuration.

The HP extracts heat from float tank when its temperature is below the hot water tank. This enables the system to capture more solar energy compared to a conventional solar thermal system. If the HP nominal capacity is much larger compared to the thermal capacity of float tank, the float tank temperature will drop in a short time causing instability in the operation of the SAHP (Banister, 2015).

When the SAHP is unable to supply the total heat demand of the building, an auxiliary heating system makes up the shortfall. The three-way converging and diverting flow valves are used to achieve this strategy. When the solar energy exceeds the building load and both storage tanks are charged up to maximum capacity the excess thermal energy is discarded to the environment.

8.3.2. Modeling of the SAHP System

Each system component and building section (including thermal zones, walls, windows and doors) is expressed as a control volume in the ESP-r simulation domain. The conservation of mass and energy equations are solved for each control volume. Conduction, convection and radiation heat transfer modes are considered where applicable. The DHW draw and AL load profiles along with the space heating demand define the building loads in individual houses. A brief discussion of the major components of the SAHP and the control system is presented below.

8.3.2.1. Flat Plate Collector Array

The flat plate collector model used in this work was developed and incorporated into the ESP-r by Thevenard *et al.* (2004). Flat plate collectors are modelled using a second order polynomial equation that defines the collector efficiency as shown in Equation (8.1).

$$\eta = F_R(\tau\alpha)_n - a\frac{\Delta T}{G_T} - b\frac{\Delta T^2}{G_T} \tag{8.1}$$

$$\Delta T = T_{in} - T_{amb} \tag{8.2}$$

where the F_R is the collector heat removal factor, $(\tau\alpha)_n$ is the normal-incidence transmittance–absorptance, and G_T is the solar radiation incident upon the collector. ΔT is the temperature difference between the collector inlet temperature (T_{in}), and the ambient temperature (T_{amb}) as shown in Equation (8.2), which is based on the North-American definition of solar collector efficiency (Duffie and Beckman, 2006). Flow rate and incidence angle corrections in off-test conditions are done using methods discussed in Duffie and Beckman (2006). The flat plate collector data used in the simulations are given in Table 8.1 (Thermo Dynamics Ltd, 2013) and correspond to a typical residential flat plate collector available in Canadian market.

Table 8.1 Parameters of SAHP system components based on the existing heating system capacity

SAHP system components	Parameter	Unit	Value	Reference
Collector weight	M_{coll}	kg	43.5	(Thermo Dynamics Ltd, 2013)
Test flow rate	$\dot{m}$	kg/s	0.059	
Efficiency constant coefficient	$F_R(\tau\alpha)_n$	–	0.689	
Efficiency square coefficient	a	W/m^{2}K	3.8475	
Efficiency quadratic coefficient	b	W/m^{2}K^2	0.01739	
Incidence angle modifier coefficient	b_0	–	0.154	
COP	a_0	–	5.4494	(Banister, 2015; Banister *et al.*, 2014a; Mitsubishi Electric, 2016a)
	a_1	K^{-1}	-0.0836	
	a_2	K^{-2}	9×10^{-5}	
NG fired boiler	η_{ref}	–	0.92	(Viessmann, 2015a)
	T_{ref}	°C	50	
	$(\tan\varphi)_{T>50°C}$	°C^{-1}	-0.15	
	$(\tan\varphi)_{T\leq50°C}$	°C^{-1}	-0.25	
Oil fired boiler	η_{ref}	–	0.85	(Viessmann, 2015b)
	T_{ref}	°C	50	
	$\tan\varphi$	°C^{-1}	-0.15	
Radiator	M_{unit}	kg	49	(Express Radiant Ltd, 2015)
	C_{avg}	J/kgK	1350	
	Q_0	W	967	
	$T_{s,0}$	°C	55	
	$T_{r,0}$	°C	35	
	$T_{env,0}$	°C	21	

8.3.2.2. *Storage Tanks*

The storage tanks are modeled as stratified tanks with immersed helical heat exchangers. The model developed and incorporated into ESP-r by Thevenard and Haddad (2010) is used. The storage tank is divided into 100 control volumes to simulate the stratification. Conservation of mass and energy equations are solved for each control volume, in which the fluid properties are considered to be uniform. The heat transfer inside and through the walls of immersed heat exchangers are assumed to be forced convection and conduction, respectively, while mixed free and forced convection are assumed to govern the heat transfer outside the heat exchangers.

8.3.2.3. *Auxiliary Heating*

The auxiliary heating system is modeled as a condensing boiler where natural gas is available, and non-condensing boiler where heating oil is used. The model was developed and incorporated into ESP-r by Hensen (1991). An efficiency curve is defined for each boiler to determine the instantaneous thermal efficiency based on the return water temperature as shown in Equation (8.3).

$$\eta_b = \left[\eta_{ref} - \tan\varphi \times \left(T_{ref} - T_{ret}\right)\right] \tag{8.3}$$

where η_b is the boiler efficiency, η_{ref} is the full load boiler efficiency at the reference temperature, φ is the slope of the efficiency curve, T_{ref} is the reference temperature, T_{ret} is the return water temperature. The transient status of boiler during the start-up and shutdown is modeled using a multiplier in the efficiency equation in that period. The data used in this study are given in Table 8.1. These data are representative of the commonly used residential boilers in the Canadian market (Viessmann, 2015a, 2015b).

8.3.2.4. *Heat Pump System*

The heat pump system is modeled using a grey-box approach. Instead of modeling individual components of the HP, the behaviour of the HP system is modeled as a whole based on actual performance data. This approach was used for modeling of different energy systems including cogeneration (Ferguson *et al.*, 2009) and air to water heat pump (Kelly and Cockroft, 2011) in ESP-r. Banister *et al.* (2015; 2014a) developed a series of third order polynomial equations for compressor power draw, heat capture and net heat delivery of a water source HP. In this study the second order polynomial Equation (8.4) is used to calculate the COP of the HP.

$$COP=a_0+a_1(T_h-T_c)+a_2(T_h-T_c)^2 \quad (8.4)$$

where the T_h and T_c are the hot side and cold side temperature, respectively. The constant factors (a_0-a_2) are derived using the data reported by Banister *et al.* (2015; 2014a) and performance data published for commercially available water source heat pumps in the Canadian market (Mitsubishi Electric, 2016a). The constant factors are provided in Table 8.1. The COP remains constant for the cold side temperatures greater than or equal to 30°C. The heat supply of HP is calculated based on the COP, return water temperature and flow rate. The power draw of the compressor is then calculated based on the load on the HP and the instantaneous COP of the HP. The heat extraction and heat addition of HP are then added as source terms in the energy balance equations of the evaporator and condenser, respectively.

8.3.2.5. System Sizing

As discussed earlier, the HP enables the SAHP system to extract solar energy at a lower temperature compared to a conventional solar thermal system. Asaee *et al.* (2016b) investigated the impact of solar combisystem retrofit in existing Canadian houses. The results showed that solar energy captured by the solar combisystem is not sufficient to fulfill the thermal energy demand of a house in Canada over a whole year. Thus, this study adds a HP to the system to increase the solar contribution, and uses the same solar array design used in the above mentioned study (Asaee *et al.*, 2016b) for the SAHP system, i.e. solar collectors connected in parallel rows, with each row containing three collectors. The gross and aperture areas of the selected flat plate collector are 2.982 m^2 and 2.870 m^2, respectively, and the number of rows is determined based on the existing heating system capacity and the available roof area of each house. When the desired area for solar collectors is equal to or larger than the total available roof area (facing south, south-east, and south-west), the roof is considered to be totally covered with solar collectors (Asaee *et al.*, 2016b). Also as in the previous study, the hot water tank volume is determined to maintain a storage volume to collector area ratio between 50 to 100 L/m^2. Since the float tank temperature can exceed the hot water tank temperature, its presence is to enhance the overall solar energy utilization of the SAHP. However, since the float tank will occupy space in the building, its volume is limited to 450 litre according to the recommendation of Banister *et al.* (2015; 2015).

8.3.2.6. Hydronic System

The components of the hydronic system are sized based on the nominal capacity of the heating system. Pumping power is calculated using Equations (8.5) and (8.6) (Asaee *et al.*, 2014).

$$P_{el,pump.SH}=90\text{W}+2\times10^{-4}P_{nom,burner} \tag{8.5}$$

$$P_{el,pump.DHW}=49.4\text{W}\times\exp\left(0.0083\,\frac{P_{nom,burner}}{\text{kW}}\right) \tag{8.6}$$

where $P_{el,pump.SH}$ is the pump power for heat delivery to the space, $P_{el,pump.DHW}$ is the pump power for DHW heating loop and $P_{nom,buner}$ is the nominal capacity of auxiliary boiler.

A standard radiator selected from the Express Radiant Ltd product catalogue (Express Radiant Ltd, 2015) is used. CHREM apportions the capacity of a space heating system to each conditioned zone based on volume (Swan, 2010). Thus, the number of radiators installed in each thermal zone is determined based on the ratio of each thermal zone volume to the total building volume.

8.3.3. Control Strategy

The control of the system is accomplished in three modules: (a) collector loop, (b) thermal management, and (c) heat delivery.

The collector loop module includes the flat plate collector array, solar pump and float tank. As discussed earlier, the float tank temperature is not controlled and its temperature follows the collector temperature variations. Hence, when solar energy is available and the float tank has available capacity for thermal energy storage, heat is delivered from the collectors to the tank. To simulate this operation, a control loop was implemented in the simulation model to turn on the solar pump when the collector temperature and float tank temperature difference exceeds 5°C and continue until the temperature difference drops to 1°C. This strategy ensures that the solar pump does not experience rapid ON/OFF cycles.

The thermal management module includes the heat pump, auxiliary boiler, hot water tank and three-way converging and diverging flow valves. This module is the most complex part of the SAHP system control algorithm. The main objective of the SAHP system is to capture as much free renewable energy as possible. Thus, the thermal management control algorithm is designed to prioritize the use of free renewable energy. The control algorithm follows the order below:

1. When the hot water tank is not fully charged (the hot water tank is below 50°C), the system calls for heat,
2. The call for heat signal from the hot water tank initially turns ON the hot water pump,
3. When the float tank temperature is above the hot water tank temperature the system bypasses the HP and circulates water directly from the float tank into the hot water tank. For this purpose the B.2 and D.2 outlet legs of the three-way diverging valves B and D are closed and water is directed through the B.3 and D.3 outlet legs (Figure 8.1),
4. When the float tank temperature is below the hot water tank temperature but it is not fully depleted (float tank temperature is above 2°C), the water is circulated through the HP. For this purpose, the B.3 and D.3 outlet legs of the three-way diverging valves B and D are closed and water is directed through the B.2 and D.2 outlet legs (Figure 8.1). In this state, both the HP and float tank pumps are ON,
5. When the available thermal energy in the float tank is not sufficient (float tank temperature is below 1°C), the system bypasses the float tank by closing the B.3 outlet leg of the three-way diverging valve B and circulates water through the B.2 outlet leg (Figure 8.1). In this state the HP and float tank pump are OFF and the auxiliary boiler supplies heat to the water,
6. When temperature of water that leaves the auxiliary boiler is below the 50°C the auxiliary boiler is turned ON to heat the water to 55°C.
7. The call for heat is terminated as soon as the hot water tank temperature reaches 55°C. The value of control system trigger for each component is presented in Table 8.2.

Table 8.2 Control strategy for SAHP, space heating and DHW supply

Control stage	Actuator	Period		Sensor location	Setpoint	
		start	end		on	off
Collector loop	Solar pump	1 Jan	31 Dec	ΔT between solar floating tank & solar collector	5	1
Thermal management	Hot water pump	1 Jan	31 Dec	Thermal storage tank outlet to zone	50	55
	Three-way valve (evaporator side)	1 Jan	31 Dec	ΔT between hot water tank & float tank	1	0
	Three-way valve (condenser side)	1 Jan	31 Dec	ΔT between hot water tank & float tank	1	0
	HP	1 Jan	31 Dec	float tank	2	1
	Pump HP	1 Jan	31 Dec	float tank	2	1
	Boiler	1 Jan	31 Dec	Boiler outlet	50	55
Heat delivery	DHW Pump	1 Jan	31 Dec	DHW tank	54	56
	DHW tank	1 Jan	31 Dec	DHW draw	--	--
	Radiator pump	17 Sep	3 Jun	Zone main 1	20	22
		4 Jun	16 Sep		0	1*

* The heating system will not turn on due to the low temperature setpoint during the cooling only season

The hydronic system module is designed to control the delivery of the heat from the hot water tank for space and DHW heating. The hydronic heat delivery system supplies heat for space heating. Temperature control is by the main zone thermostat, thus the other zones receive heat only when the main zone calls for it. The space heating pump is triggered when the main zone temperature drops below the thermostat set point (20°C) and deactivates as the main zone temperature exceeds the upper limit of the dead-band temperature (22°C). To simplify the model, the operation of the combination of DHW service valves is simulated as a small fully mixed adiabatic tank held at 55±1°C and DHW draw and equivalent main water supply is applied into this tank, emulating the operation of the valves in a real system.

8.3.4. Eligible Houses

Due to geometrical constraints not all houses in the Canadian housing stock are suitable for a SAHP system retrofit. To retrofit a flat plate collector on an existing house, a suitable roof area is necessary in terms of area and exposure. For residential heating in adverse climates, Iqbal (1979) recommends to use a collector tilt angle of "latitude−10°" in case of 10-20% solar contribution in thermal load supply, and a linear increase to "latitude+15°" for 80% solar contribution. Since major Canadian cities are located in a latitude range of 45-55°, 45° is selected as the collector tilt angle for installation on flat roofs. Also, this tilt angle reduces the chance of snow accumulation on collectors during the winter time. The solar insolation in northern hemisphere is maximum in the south direction. Thus, to be considered eligible for SAHP retrofit, a house should have the required roof area in the south, southeast or southwest direction for collector installation.

Since the SAHP retrofit will require the addition of new mechanical equipment as shown in Figure 8.1, a house needs to have a basement or mechanical room for the installation of this equipment. The presence of a mechanical room is not identified in CHREM. However, since all natural gas or oil fired hydronic and forced air systems require a mechanical room, houses that use such heating systems are considered eligible for SAHP retrofit. Since shading data are not provided in the CSDDRD, the reduction in solar collector performance due to neighbouring obstructions is not considered in this study.

8.3.5. GHG Emission Estimation

The GHG emission are evaluated and reported as "equivalent CO_2" (CO_{2e}) emitted per unit input energy. CO_{2e} is defined by converting GHG emissions from a fossil fuel combustion, such as CH_4 and N_2O, to equivalent CO_2 emission taking into account their global warming potentials as shown in Equation (8.7) (Farhat and Ugursal, 2010; Swan *et al.*, 2013).

$$CO_{2e}=CO_2+25CH_4+298N_2O \quad (8.7)$$

Due to availability of different onsite fuels, various types of energy conversion devices in existing houses and vast differences in the fuel mixture for electricity generation in each province, CHREM estimates the GHG emission of a house by adding the emissions from fossil fuels consumed onsite and the emissions from electricity generation, determined separately for each province.

The GHG emissions due to onsite fossil fuel consumption is determined based on the fuel type and efficiency of the energy conversion device. The GHG emission is updated in each time step using the actual fossil fuel consumption (Swan *et al.*, 2013). The CO_2 emission by wood combustion returns to the atmosphere where the CO_2 that was recently removed by photosynthesis as the tree grew. Hence, this process can be accounted as a stage in natural carbon cycle and thus no GHG emission is reported for the combustion of wood (Farhat and Ugursal, 2010).

Table 8.3 The average and marginal GHG intensity factors (g CO_{2eq}/kWh) for each province of Canada (Farhat and Ugursal, 2010)

Electrical generation characteristics		Canadian provincial GHG EIF (CO_{2e} per kWh)									
		NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Annual $EIF_{Average}$		26	689	191	433	6	199	13	789	921	22
Annual $EIF_{Marginal}$		22	360	6	837			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		9%	4%	6%	6%	4%	6%	12%	6%	4%	3%

The GHG emission associated with electricity use is determined based on the amount of fossil fuel consumption to generate and deliver electricity to a dwelling. For this purpose, the GHG emission intensity factor (EIF) is defined for electricity generation and delivery.

The GHG EIF is defined as the level of CO_{2e} emission for generation and delivery of 1 kWh electricity to the end-user. In Canada electricity generation is under the jurisdiction of provincial utility companies. Thus, provincial GHG EIF is estimated using the primary energy mixture used for electricity generation, efficiency of energy conversion and transmission, and distribution losses. Also, typically utilities consider different types of electricity generation methods during peak and base periods. Thus, different average and marginal GHG EIFs are developed to address electricity generation within the base and peak periods. The provincial average and marginal GHG EIF developed by Farhat and Ugursal (2010) and given in Table 8.3 are used. Average GHG EIFs are used to estimate the emissions due to electricity consumption of the existing housing stock (base case) while the marginal GHG EIFs are used to estimate the GHG emission variation due to the change in electricity consumption in retrofitted houses.

8.3.6. Performance Measures

Dimensionless performance factors are useful to compare the energetic performance of different types of renewable energy systems. Here, four performance factors are used:

- Seasonal performance factor (*SPF*) is the overall energy efficiency of the whole system over a year (or a season) calculated as the ratio of the overall useful energy output to the overall driving energy input (Hadorn, 2015). For a SAHP system the useful energy output is defined as the total thermal energy delivered by the SAHP system for space and DHW heating minus the auxiliary energy, while the energy input is the energy consumption of the HP. Thus, the *SPF* of a SAHP is as shown in Equation (8.8).

$$SPF_{SAHP}=\frac{Q_{SH}+Q_{DHW}}{W_{el,SAHP}+Q_{aux}} \qquad (8.8)$$

- Solar fraction (f_{sol}) is the ratio of delivered solar energy to the total energy demand. In a SAHP system the total energy demand consists of the space and DHW heating demand. Thus, for an SAHP system, f_{sol} is defined as shown in Equation (8.9):

$$f_{sol}=\frac{Q_{Sol}}{Q_{SH}+Q_{DHW}} \qquad (8.9)$$

- Fractional thermal energy saving ($f_{sav,\,therm}$) is an indicator to assess the impact of a specific retrofit option such as solar thermal system in relation to a reference system on thermal energy use (Hadorn, 2015). For an SAHP, this is defined as shown in Equation (8.10):

$$f_{sav,therm}=1-\frac{E_{aux}}{E_{ref}} \qquad (8.10)$$

Existing heating systems in the houses are taken as the reference system.

- Extended fractional energy saving is an indicator to assess the impact of a specific retrofit option such as solar thermal system in relation to a reference system on total auxiliary energy use (Hadorn, 2015). For an ASHP, this is defined as shown in Equation (8.11):

$$f_{\text{sav,ext}} = 1 - \frac{E_{total}}{E_{total,ref}} = 1 - \frac{E_{aux} + \frac{W_{par} + W_{HP}}{\eta_{el}}}{E_{ref} + \frac{W_{par,ref}}{\eta_{el}}} \tag{8.11}$$

Asaee *et al.* (2016b) studied techno-economic performance of solar combisystem retrofit in the CHS. Fractional thermal energy saving and extended fractional energy saving were used to assess the performance of solar combisystem in the Canadian context. To compare the performance of solar combisystem and SAHP system and evaluate the impact of HP on solar thermal system retrofit in existing Canadian houses these parameters are used in this study with the same criteria. The fractional energy savings definition remains the same while power consumption of HP is added to the extended fractional energy saving definition as shown in Equations (8.10) and (8.11).

The value of these parameters are evaluated for individual houses and provincial average are also calculated.

8.3.7. Economic Analysis Methodology

Accurate estimation of SAHP system initial investment is difficult because installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, and prevailing labor rates. Therefore, the purchase and installation costs of SAHP systems in Canada vary substantially from manufacturer to manufacturer and location to location. Thus, it is not practicable to estimate realistic total investment costs for SAHP systems and to conduct a conventional economic feasibility analysis. Therefore, an alternative approach to conventional economic feasibility analysis is adopted here which involves the calculation of the “tolerable capital cost” (TCC) of the upgrades (Nikoofard *et al.*, 2014a). TCC is the capital cost for an energy saving upgrade that will be recovered based on the annual savings, the number of years allowed for payback, and the estimated annual interest and fuel cost escalation rates. Thus, to estimate the tolerable capital cost of the SAHP upgrade a reverse payback analysis is conducted as follows:

1. The annual fuel and electricity savings for each upgrade is estimated (C$).

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:

$$\text{TCCH}=\begin{cases}\text{ACSH}\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e\\ \text{ACSH}\times n(1+i)^{-1} & \text{for} \quad i=e\end{cases} \tag{8.12}$$

$$\text{ACSH}=\sum_{j=1}^{m}(F\times E)_j \tag{8.13}$$

where:

TCCH	Tolerable capital cost of the retrofit for the house (C$)
n	Acceptable payback period (year)
i	Interest rate (decimal)
e	Fuel cost escalation rate (decimal)
ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
F	Fuel price per unit of each fuel type (C$/unit)
m	Number of different fuels used in a house

The additional maintenance cost of the SAHP system over and above that of the replaced system is assumed to be included in the TCC as a present value of the annual maintenance cost over the lifetime of the SAHP system.

It is not useful or practical to report the TCC for each house in the CSDDRD, or for that matter within the CHS, because from a macro level of interest, data on individual houses have no utility. Thus, the “average tolerable capital cost per house” (ATCCH) is used to evaluate the economic feasibility of the SAHP system retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$ATCCH=TTCC/NH \tag{8.14}$$

where, TTCC is the total tolerable capital cost as a result of the SAHP system upgrade (C$), calculated as follows:

$$TTCC=\sum_{i=1}^{NH} TCCH_i \tag{8.15}$$

NH = number of houses that received the upgrade.

To take into consideration the uncertainty associated with the future of interest and fuel price escalation rates, a sensitivity analysis is conducted. The interest rates used in the analysis are based on the Bank of Canada Prime Rate (BOC, 2015), which was about 1% in June, 2016. 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.

For each province, fuel prices for residential customers for natural gas, heating oil, electricity and wood were obtained to calculate the energy cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 8.4 (Hydro-Quebec, 2014b; Statistics Canada, 2013).

For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 8.5 are used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada (NEB, 2014) and Energy Escalation Rate Calculator (WBDG, 2014).

Payback periods of six and ten years are used in the sensitivity analysis. Both values are comfortably within the economical lifetime of 15 to 20 years for SAHP systems.

It is likely that an SAHP retrofit would increase the market value of a house. However, the estimation of the increase in market value due to such a retrofit is not straightforward 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.

Table 8.4 Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[a]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	C$/GJ	36.58	45.06	47.08	37.11	21.92	39.72	24.25	42.00	43.19	26.53
Natural gas[b]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	C$/GJ	N/A	N/A	N/A	N/A	12.41	7.99	8.23	7.77	4.62	11.35
Home heating oil[c]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	C$/GJ	29.63	28.42	29.17	30.76	31.25	32.80	30.33	29.37	N/A	33.08
Wood[d]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	C$/GJ	11.20	11.20	11.20	15.69	11.43	13.44	11.65	11.20	22.40	10.75

[a] Hydro-Quebec (Hydro-Quebec, 2014b)

[b] Statistics Canada handbook (Statistics Canada, 2013)

[c] Statistics Canada Handbook (Statistics Canada, 2013)

[d] Local companies

Table 8.5 Real fuel escalation type for each fuel type

	Low	Medium	High
Electricity[a]	2	6	10
Natural gas[b]	2	5	8
Light fuel oil[b]	6	10	14
Mixed wood[c]	3	6	9

[a] National Energy Board of Canada (NEB, 2014)

[b] Energy Escalation Rate Calculator (EERC) (WBDG, 2014)

[c] Equal to interest rate as there is no source for its escalation rate

8.4. Results and Discussion

The energy consumption and GHG emissions of the CHS in its current state (base case) estimated using CHREM are given in Table 8.6 by energy source and province. The accuracy of the base case estimates of CHREM was validated in Swan *et al.* (2013).

The CSDDRD was examined to identify houses that have proper roof area in desired direction and suitable space for mechanical system installation. The results show that about 37% of existing Canadian houses can satisfy both conditions. Due to different construction characteristics the penetration levels are not the same in all provinces as shown in Table 8.7. The predicted penetration level of SAHP is relatively low in QC. Since the majority of existing houses in QC use baseboard convection electric heating systems, they do not have mechanical rooms. If energy efficiency incentives encourage the homeowners to allocate a space for a mechanical room, the penetration level of SAHP systems in QC would likely increase.

As shown in Table 8.6, energy consumption and GHG emission values vary significantly across Canada. Parameters including fuel availability, cost, house vintage and heating system type influence the choice of energy source in each province. Due to rich hydro-electric sources in NF, QC, MB and BC, electricity prices in these provinces are lower compared to other provinces, and electricity use for space and DHW heating is higher. For example, in QC about 83% of energy demand for residential customer is supplied by electricity. As a result of such fundamental differences between provinces, SAHP system retrofit energy savings and feasibility show substantial differences. Hence, the results are presented below in three sections: energy savings, GHG emission reductions and economic feasibility.

Table 8.6 CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 8.7 Energy savings and GHG emission reductions for the CHS due to SAHP retrofit

Province	Eligible houses		Total energy saved (PJ)	Average energy saving per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent				
NF	60,662	35	5.4	89	0.25	4,057
NS	131,393	44	10.7	81	0.69	5,282
PE	24,175	54	1.9	79	0.11	4,363
NB	72,060	30	7.7	107	0.22	3,036
QC	254,126	13	20.1	79	1.00	3,941
OT	1,608,866	47	131.2	82	6.63	4,120
MB	108,944	32	9.3	85	0.49	4,455
SK	148,106	47	13.8	93	0.64	4,344
AB	508,451	52	41.3	81	1.17	2,293
BC	408,534	37	26.2	64	1.40	3,428
Canada	3,325,316	37	267.6		12.59	

Table 8.8 CHREM estimates of annual energy consumption (PJ) with existing (Exist) and SAHP retrofit (SHPR) in houses eligible (EL) and houses not eligible (N-E) for SAHP retrofit

Province	Electricity			NG			Oil			Wood			Total		
	N-E	EL		N-E	EL		N-E	EL		N-E	EL		N-E	EL	
		Exist	SHPR		Exist	SHPR		Exist	SHPR		Exist	SHPR		Exist	SHPR
NF	12.3	2.9	2.8	0.0	0.0	0.0	2.9	6.7	3.2	1.5	1.8	0.0	16.7	11.4	6.0
NS	12.2	5.5	5.6	0.0	0.0	0.0	8.1	14.5	5.2	4.5	1.5	0.0	24.8	21.5	10.8
PE	0.9	0.9	1.0	0.0	0.0	0.0	1.7	2.3	0.8	1.0	0.5	0.0	3.6	3.7	1.8
NB	15.3	3.4	2.7	0.0	0.0	0.0	4.2	5.5	3.1	6.1	4.6	0.0	25.6	13.5	5.8
QC	189.8	15.5	8.3	0.2	0.8	9.9	9.8	20.5	0.0	8.9	1.5	0.0	208.7	38.3	18.2
OT	87.9	49.3	53.7	162.3	175.1	61.4	25.5	21.9	0.0	0.0	0.0	0.0	275.7	246.3	115.1
MB	15.8	3.1	3.4	19.4	14.2	4.6	0.0	0.0	0.0	0.0	0.0	0.0	35.2	17.3	8.0
SK	6.8	3.8	4.9	20.2	20.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	27.0	23.8	10.0
AB	13.6	14.7	19.4	57.7	62.1	16.1	0.0	0.0	0.0	0.0	0.0	0.0	71.3	76.8	35.5
BC	46.3	18.3	19.8	46.7	37.2	9.5	0.0	0.0	0.0	2.1	0.0	0.0	95.1	55.5	29.3
Canada	400.9	117.4	121.6	306.5	309.4	106.6	52.2	71.4	12.3	24.1	9.9	0.0	783.7	508.1	240.5

Table 8.9 Annual energy savings and GHG emission reductions due to SAHP retrofits in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	0.1	0.0	3.5	1.8	5.4	0.00	0.00	0.25	0.25
NS	-0.1	0.0	9.3	1.5	10.7	0.04	0.00	0.65	0.69
PE	-0.1	0.0	1.5	0.5	1.9	0.00	0.00	0.11	0.11
NB	0.7	0.0	2.4	4.6	7.7	0.05	0.00	0.17	0.22
QC	7.2	-9.1	20.5	1.5	20.1	0.02	-0.46	1.44	1.00
OT	-4.4	113.7	21.9	0.0	131.2	-0.66	5.75	1.54	6.63
MB	-0.3	9.6	0.0	0.0	9.3	0.00	0.49	0.00	0.49
SK	-1.1	14.9	0.0	0.0	13.8	-0.11	0.75	0.00	0.64
AB	-4.7	46.0	0.0	0.0	41.3	-1.16	2.33	0.00	1.17
BC	-1.5	27.7	0.0	0.0	26.2	0.00	1.40	0.00	1.40
Canada	-4.2	202.8	59.1	9.9	267.6	-1.82	10.25	4.16	12.59

Table 8.10 Average seasonal performance factor, solar fraction, fractional thermal energy saving, annual end-use energy savings and GHG emission reductions due to SAHP retrofits in the CHS

Province	Energy Savings (%)	GHG emission reductions (%)	*SPF*	f_{sol} (%)	Fractional thermal energy saving (%)		Extended fractional energy saving (%)	
					SAHP	SCS	SAHP	SCS
NF	19	31	1.7	34	41	34	41	34
NS	23	13	1.8	39	27	23	15	21
PE	26	28	2.9	49	36	31	22	27
NB	20	7	1.8	40	20	18	15	16
QC	8	39	1.7	38	31	23	31	23
OT	25	23	1.7	37	31	27	19	25
MB	18	27	1.6	36	29	24	29	24
SK	27	14	1.8	42	32	28	18	24
AB	28	9	1.9	43	38	33	18	28
BC	17	30	2.3	47	32	27	32	27
Canada	21	19	1.8	40	31	27	21	25

8.4.1. *Energy Savings*

Bulk energy savings and average energy savings per house are presented in Table 8.7. Average annual energy savings per house for all provinces other than NB and BC vary within the range of 79 GJ and 93 GJ due to the differences in the fuel mix and house characteristics. The existing low efficiency heating systems in NB cause a higher energy saving per house for the SAHP system retrofit. In contrast the higher efficiency existing heating systems in BC (compared to existing heating system in other provinces) reduce the amount of energy savings per house in that province. However, the total energy savings differ widely from province to province due to the large differences in the size of the housing stock and number of houses eligible for retrofit.

It is important to consider both values because while the average energy saving per house provides an insight regarding the suitability of the SAHP retrofit, the total energy savings illustrate the size of the opportunity for energy savings. These results are useful in devising national and regional incentive and legislative measures to promote SAHP technologies.

To further clarify the impact of SAHP retrofit, the current energy consumption of eligible and non-eligible houses along with the energy consumption of eligible houses after the SAHP retrofit is presented in Table 8.8 broken down according to energy source and location. As seen from the table, the SAHP retrofit results in a substantial reduction in fossil fuel (i.e. NG and oil) consumption, and complete elimination of wood combustion (since no wood burning auxiliary system is used in the retrofitted houses). Overall, SAHP retrofit in eligible houses reduces the NG consumption of the CHS by 33%, oil consumption by 48% and wood consumption by 29%, and increases electricity consumption by close to 1%. As discussed earlier, a condensing NG boiler is assumed to be the auxiliary heating system where NG is widely available for residential customers. Thus, in QC and OT, oil use is completely eliminated in eligible houses. Table 8.9 shows the magnitude of energy savings in each fuel and each province while Table 8.10 shows the savings in percentage. As shown in Table 8.10, SAHP retrofit of all eligible houses would result in an energy savings of 21% in the entire CHS.

The performance parameters are presented in Table 8.10. The *SPF* of SAHP system is relatively low in the CHS. The free solar energy can be delivered to the building if the supply temperature is above hot water tank temperature (generally 50°C to 55°C) without operating HP system. Solar fraction in all provinces is below 50% which indicates that other energy retrofit measures need to be used in addition to SAHP system to achieve net zero energy status for the existing houses in the CHS.

As shown in Table 8.10, the fractional thermal energy saving of the SAHP system is higher than that of the solar combisystem retrofit in all provinces, indicating that integrating the HP and solar thermal system enhances energetic performance. However, when the electricity use of the HP system is included in the comparison, i.e. the extended fractional energy saving parameters are compared, the solar combisystem is more advantageous as shown in Table 8.10. As discussed earlier electricity generation in Canada is under provincial jurisdiction, and each province has a different fuel mixture for electricity generation based on the available resources. In provinces where there is a significant renewable energy component in the electricity generation, the extended fractional energy saving is higher for the SAHP compared to the solar combisystem. This is due to the lower efficiency of electricity generation from fossil fuels, which is taken into consideration in the definition of extended fractional energy saving as shown in Equation (8.11).

8.4.2. GHG Emission Reduction

One of the main objectives of renewable energy and energy efficiency retrofit measures is to reduce the building's environmental footprint. As shown in Table 8.6, the results of the base case analysis show that the CHS is responsible for 65.3 Mt of CO_{2e} emissions annually. Close to half of the GHG emissions is associated with NG consumption. Hence, it is expected that reducing the demand for thermal energy and replacing the conventional sources of energy with renewable options would shrink the building footprint. As shown in Table 8.9, the SAHP system yields a 19% reduction in the annual GHG emissions of the CHS (equivalent to 12.59 Mt of CO_{2e}). About 80% of that reduction is contributed by the GHG emission reduction associated with NG savings. To illustrate the SAHP system retrofit performance in each province the average GHG emission reduction per house is calculated and presented in Table 8.7. Results show that the houses located in AT region (excluding NB), OT, MB and SK experience higher opportunity for GHG emission reduction compared to other provinces. In AT provinces majority of the existing houses utilize oil based systems for space and DHW heating. Also, most of electricity generation is from fossil fuels except in NF where hydro-electricity is dominant. Thus, replacing existing oil based heating system in AT region and electric based heating system in NS, NB and PE with SAHP system eliminates a major source of GHG emission in buildings. In NB about 10% of the total energy use in existing houses (28.1 PJ) is supplied by wood (3.3 PJ as shown in Table 8.6). The CO_2 emission due to wood burning is considered to be part of the natural carbon cycle and not counted. As a result, the average GHG emission reduction per house in NB is lower compared to other AT provinces. In OT the use of oil in eligible houses is completely eliminated with the retrofit and the NG consumption is significantly reduced. In addition, the GHG EIF for electricity generation is relatively low in OT. Thus, the SAHP retrofit yields a high GHG emission reduction per house in OT. In QC and BC the GHG emission reduction per house is not high because in these provinces many houses utilize electric heating systems, and electricity production is predominantly hydro based. Therefore, although the SAHP system lowers the electricity demand for heating purposes, there is little or no GHG emission reduction. In QC oil consumption has replaced by NG in eligible houses after retrofit. Since GHG EIF of oil is higher compared to NG the total GHG emission reduction is affected by this fuel shift in QC. As a result the GHG emission per house in QC is yet higher compared to BC. Results show the multi-faceted nature of GHG emission in residential sector. As a result an energy saving measure that expected to yield GHG emission reduction may produce unexpected outcomes. Energy modeling and housing stock modeling are the least expensive approaches to measure the impact of large scale modifications in residential sector energy use to prevent unfavorable consequences.

8.4.3. Economic Feasibility

The average TCC per house for three interest rates, three fuel cost escalation rates and two payback periods is presented in Table 8.11 for each province. Results show that the AT and QC region have the highest TCC in Canada. In the AT region, this is due to the relatively high cost of energy (~30C$/GJ for oil and ~36-47 C$/GJ for electricity and absence of NG for residential customers). Thus, the SAHP system provides a reliable opportunity for homeowners to reduce their energy costs. In case that the TCC is not sufficient to cover the investment cost, the difference could be offset by government incentives. In QC relatively inexpensive hydro-electricity is widely available for residential customers. Thus, many houses use electric resistance heaters for space and DHW heating. Introducing HP systems can lower the electricity demand in those houses. Integrating the HP with solar thermal system would increase the overall performance of the system, but due to the relatively higher investment cost of HP compared to solar collectors, it is likely that the SAHP system economic feasibility is less favorable compared to solar combisystem. High cost of electricity (~43 C$/GJ) compared to the relatively cheap NG (~5-8 C$/GJ) in the PR region narrows the TCC margin because the SAHP system replace NG (used by condensing boiler) with electricity (used by HP) as auxiliary source of energy. The average TCC might not provide the required information for government and decision makers. Thus, the total TCC for introducing the SAHP systems into the entire eligible houses across Canada is presented in Figure 8.2.

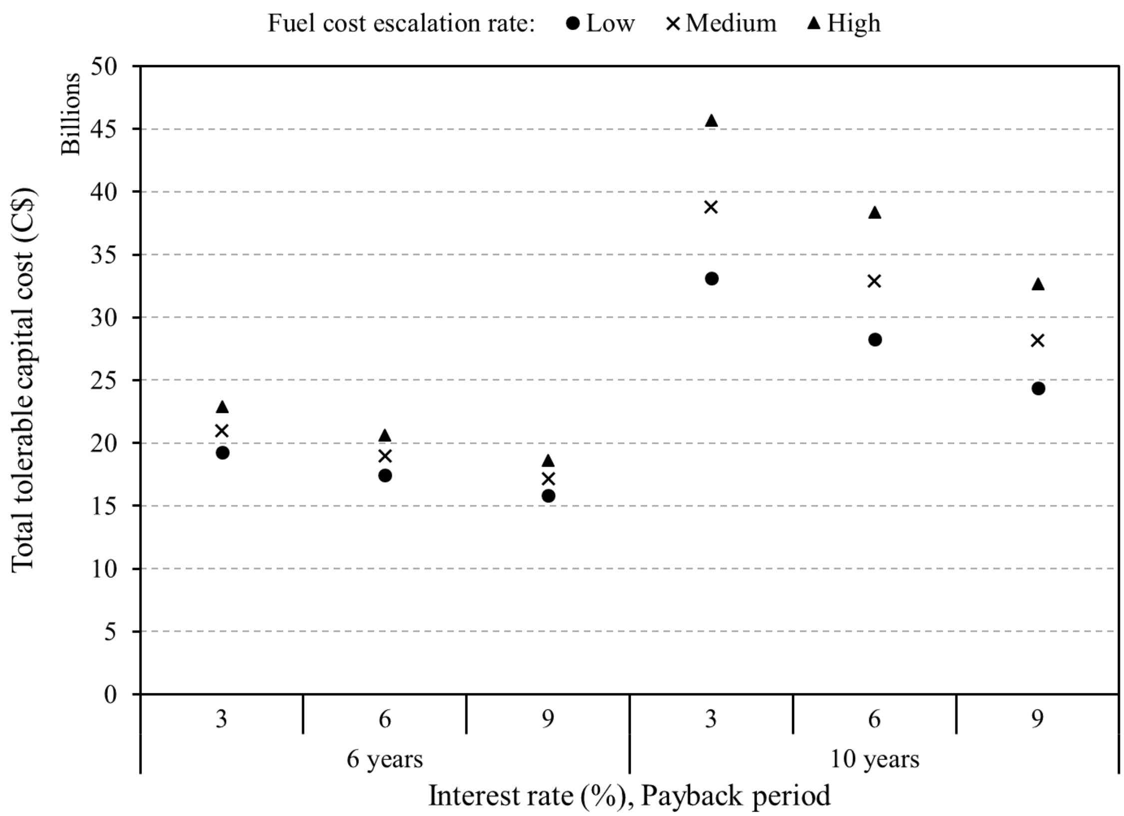

Figure 8.2 Total national tolerable capital cost due to solar assisted heat pump upgrade for different interest rates and fuel cost escalation rates (Low, Medium and High as per Table 8.5).

Table 8.11 Average TCC per house (C$/house)

Province	Payback (yr)	Interest rate 3%			6%			9%		
		Fuel cost escalation rate								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	22,738	27,065	32,350	19,374	22,866	27,110	16,690	19,535	22,977
	6	12,992	14,273	15,685	11,741	12,860	14,092	10,665	11,647	12,727
NS	10	23,219	27,759	33,322	19,765	23,427	27,892	17,011	19,993	23,613
	6	13,154	14,484	15,953	11,883	13,044	14,326	10,790	11,810	12,933
PE	10	20,499	24,451	29,283	17,445	20,631	24,509	15,010	17,604	20,747
	6	11,582	12,735	14,007	10,462	11,469	12,578	9,499	10,382	11,354
NB	10	24,430	28,708	33,877	20,873	24,331	28,490	18,030	20,852	24,231
	6	14,303	15,612	17,050	12,938	14,083	15,337	11,764	12,770	13,870
QC	10	30,244	36,415	44,021	25,755	30,734	36,840	22,175	26,231	31,182
	6	17,195	19,016	21,034	15,536	17,127	18,887	14,110	15,506	17,048
OT	10	9,186	10,712	12,540	7,851	9,084	10,555	6,783	7,789	8,985
	6	5,389	5,856	6,366	4,876	5,284	5,728	4,434	4,792	5,182
MB	10	6,118	6,946	7,906	5,254	5,926	6,702	4,561	5,112	5,745
	6	3,742	4,015	4,309	3,391	3,630	3,887	3,089	3,299	3,524
SK	10	4,364	4,827	5,334	3,748	4,124	4,534	3,253	3,562	3,897
	6	2,669	2,824	2,986	2,419	2,554	2,696	2,203	2,322	2,447
AB	10	170	1	-241	146	9	-185	126	15	-142
	6	104	51	-12	94	48	-7	86	45	-3
BC	10	6,248	7,080	8,040	5,366	6,041	6,817	4,658	5,211	5,845
	6	3,822	4,096	4,391	3,463	3,703	3,961	3,155	3,366	3,592

The amount of investment shows the scale of market for residential customers. Thus, if the CHS moves toward the low energy design the SAHP system manufactures may introduce new products in the Canadian market and more contractors provide related services which can lower the overall system price. It should be noted that if Canadians decide to take retrofits in a short period of time the growing demand may increase the market price. Thus, devising a roadmap for converting existing houses might be helpful to control the market.

8.5. Conclusion

The SAHP retrofit is introduced into existing Canadian houses to reduce energy consumption and GHG emission. The SAHP system include flat plate collectors, float tank, HP, hot water storage tank, a series of three converging and diverging valves, hydronic heat delivery system and DHW heating system. Retrofit is applied to all eligible houses in Canada and assessment is performed from energy saving, GHG emission and economic feasibility perspective. Results can be summarised as below:

- About 37% of existing Canadian houses are eligible for the SAHP system retrofit. Number of eligible houses vary across provinces due to parameters such as vintage, building geometry, existing HVAC systems and population density.
- On average annual energy consumption of an existing house in Canada will reduce about 80-90 GJ due to SAHP system retrofit.
- Fossil fuel consumption in the CHS is substantially lowered while electricity use change is almost negligible. In total about 21% of annual energy consumption in the CHS is reduced if all eligible houses receive SAHP retrofit.
- Solar fraction in all provinces is below 50%, fractional thermal energy saving is higher compared to solar combisystem while the solar combisystem is more efficient from extended fractional energy saving perspective.
- About 19% of GHG emission (equivalent to 12.59 Mt of CO_{2e}) of the CHS is reduced. Major reduction of GHG emission is associated with NG saving.
- Energy saving and GHG emission reduction is strongly affected by climate, auxiliary energy source and fuel mixture for electricity generation.
- Economic feasibility of SAHP retrofit is assessed using tolerable capital cost parameter. Due to varying price of energy in different provinces the tolerable capital

cost of SAHP system changes considerably across Canada. Thus, provincial government might have a radical role to promote SAHP retrofit using incentive measures and proper legislation. Growing demand for such retrofits, if occurs gradually, can help to lower the cost of parts and services for residential customers.

According to the results of the present study integration of HP into solar thermal systems is not sufficient to convert existing Canadian houses into NZEBs. Thus, other energy efficient retrofits such as energy saving measures and seasonal thermal energy storage is likely to be helpful to achieve the NZE status for existing Canadian houses. Further studies are required to assess performance of such options in the Canadian context.

Chapter 9 Techno-Economic Assessment of Photovoltaic (PV) and Building Integrated Photovoltaic/Thermal (BIPV/T) System Retrofit in the Canadian Housing Stock

This section has been submitted for publication to Energy and Buildings.

Rasoul Asaee is the principal researcher and author of the article. He conducted the research as part of his PhD. Also, he modified and used the PV model that was incorporated into the CHREM by Dr. Nikoofard. Thus, while he received supervision and guidance from his supervisors Drs. Ugursal and Beausoleil-Morrison, he carried out the work, wrote the article, and communicated with the editor of the journal. Minor editorial changes have been made to integrate the article within this dissertation.

9.1. Abstract

Techno-economic impact of retrofitting houses in the Canadian housing stock with PV and BIPV/T systems is evaluated using the Canadian Hybrid End-use Energy and Emission Model. Houses with south, south-east and south-west facing roofs are considered eligible for the retrofit since solar irradiation is maximum on south facing surfaces in the northern hemisphere. The PV system is used to produce electricity and supply the electrical demand of the house, with the excess electricity sold to the grid in a net-metering arrangement. The BIPV/T system produces electricity as well as thermal energy to supply the electrical as well as the thermal demands for space and domestic hot water heating. The PV system consists of PV panels installed on the available roof surface while the BIPV/T system adds a heat pump, thermal storage tank, auxiliary heater, domestic hot water heating equipment and hydronic heat delivery system, and replaces the existing heating system in eligible houses. The study predicts the energy savings, GHG emission reductions and tolerable capital costs for regions across Canada. Results indicate that the PV and BIPV/T systems yield 3% and 18% energy savings as well as 5% and 17% GHG emission reductions in the Canadian housing stock, respectively. While the annual electricity use slightly increases, the fossil fuel use of the eligible houses substantially decreases due to BIPV/T system retrofit.

9.2. Introduction

Solar energy is a significant source of renewable energy for residential buildings. Solar energy can be harvested and utilised in buildings by different approaches. Photovoltaics (PV) convert solar energy directly into electricity. PV generated electricity may be used by appliances and lighting or in hybrid systems for space heating and cooling and DHW heating. The electricity generation efficiency of PV systems is affected by PV panel temperature. As the panel temperature increases the electricity generation efficiency decreases due to increasing resistance. To overcome this reduction, PV thermal (PV/T) systems were introduced in 1970's (Kumar and Rosen, 2011). In a PV/T system the panels are cooled using a heat transfer medium. By integrating a PV/T system into the building façade (thus referred to as a BIPV/T system) the captured heat can be used as a source of thermal energy. In a BIPV/T system the PV panels can be connected to a heat pump, in which case the heat transfer fluid pre-heated by the PV panel is directed into the evaporator of the heat pump where the heat is extracted and delivered to the HVAC system. In addition to lowering the panel temperature and increasing PV efficiency, this arrangement increases the performance of the heat pump since the heat pump works with a higher temperature medium (compared to surrounding air) resulting in a higher coefficient of performance (COP). If the heat pump supplies thermal energy for both space and DHW heating, this approach is beneficial during the whole year. Nevertheless, the feasibility of BIPV/T system performance is highly influenced by climatic and geographical conditions as well as building characteristics.

Several authors have focused on the performance of different BIPV/T system configurations in various locations and operating conditions. For example, in one of the early studies, Anderson *et al.* (2009) developed a numerical model for BIPV/T systems and validated its accuracy using experimental results. They showed that a series of parameters can be varied in the design of a BIPV/T collector to maximise performance. Yang and Athienitis (2014) studied a prototype single inlet open loop air-based BIPV/T system in a full scale solar simulator. Experimental results were used to validate a numerical control-volume model for the BIPV/T system. They used the numerical model to estimate the impact of multiple inlets and other means of heat transfer enhancement on the performance of the BIPV/T system. Results of numerical simulations showed that the thermal efficiency may increase by about 5% and electrical efficiency may increase marginally due to using two inlets on a BIPV/T collector. Also, it was found that adding a vertical glazed solar air collector and wire mesh packing in the collector improves the thermal efficiency of system. Hailu *et al.* (2015) studied a two stage variable capacity air source heat pump (ASHP) coupled with a wall integrated BIPV/T system using the TRNSYS software. The COP of the integrated ASHP and BIPV/T system was evaluated and compared to an identical standalone ASHP operating under the same conditions. Results show that the COP was significantly improved for ambient temperatures between -3°C to 10°C. Buonomano *et al.* (2016) (2016) (2016) (2016) developed a numerical model in TRNSYS to evaluate the energy and economic performance of residential BIPV/T systems capable of generating electricity and thermal energy for space and DHW heating in various European climates. Results show that depending on climatic conditions, the BIPV/T system can yield 67-89% primary energy savings, with a payback period between 11 to 20 years. They concluded that a public funding strategy may improve the economic profitability of BIPV/T systems in the European housing market. Lee *et al.* (2014) experimentally studied a BIPV/T system in a test building constructed to achieve zero energy status. The power generation of the BIPV/T system and building load were monitored to evaluate the energy self-sufficiency of the building. Results show that the system was capable of generating enough energy year round to achieve net zero energy status. Kim *et al.* (2015) used a TRNSYS model to study the performance of a BIPV/T system and examine the efficiency of a PV panel on a cold and a warm roof of a low-rise residential building assuming that the BIPV/T back surface temperature is equal to the roof temperature. Results indicated that the BIPV/T system installed on a cold roof has a superior performance compared to a system installed on a warm roof. He *et al.* (2011) compared the performance of PV, conventional solar thermal and PV/T systems under similar operating conditions. The effective areas of the solar thermal and PV/T systems were identical and solar cell covered area of PV/T and PV systems were the same. Results indicated that the thermal efficiency of the conventional solar thermal system was higher compared to that of the PV/T system. However, the primary energy savings due to the PV/T system were considerably higher compared to standalone solar systems. Saadon *et al.* (2016) studied a ventilated PV façade installed in an energy efficient building. The installation enables the BIPV/T system to provide cooling in summer and heat recovery in winter. A numerical model was developed and validated for the simulation of the BIPV/T system during the cooling season. The model was incorporated into TRNSYS and used for an integrated analysis. Results show that the BIPV/T system is a useful technology for net zero energy building design. Yin *et al.* (2013) designed a building integrated solar thermal roofing system to utilize solar energy for electricity and heat generation. The system is comprised of a PV panel augmented with a hydronic cooling system for thermal management of the PV panels. The heated water can be used in the radiant floor heating system. Results show that the BIPV/T system provides significant advantages over the conventional asphalt shingle roof and standalone PV systems.

Kamel *et al.* (2015) designed a full-scale test apparatus of a BIPV/T system integrated with an ASHP and thermal energy storage for a building in Toronto, Canada. The system used 25 PV/T collectors and a concrete slab for thermal energy storage. The preheated air was used in the evaporator of the ASHP to enhance its COP. A numerical approach was used to evaluate the design parameters that may affect heat and electricity generation as well as ASHP COP and power draw. They suggested that the BIPV/T system integrated with an ASHP and thermal storage system might be a suitable technology to approach net zero energy building status. In another study, Kamel and Fung (2014) developed a numerical model in TRNSYS to analyze a BIPV/T system integrated with an air source heat pump (ASHP) in Ontario, Canada. The preheated air from BIPV/T system is used in the evaporator of the ASHP. Their results showed that integrating the BIPV/T system and ASHP reduces the electricity demand of the ASHP due to its enhanced COP. They concluded that the proposed system reduces the annual operating cost and GHG emission. Vuong *et al.* (2015) developed a BIPV/T model in EnergyPlus (NREL, 2016) based on the modeling scheme of BIPV/T systems in TRNSYS. Annual simulations were conducted in both TRNSYS and EnergyPlus and it was concluded that the slight discrepancy in the results was caused by different weather data interpolation methodologies, sky temperature computations, and electrical models used by the two modeling software.

This study investigates a large scale adaption of PV and BIPV/T systems in the Canadian housing stock (CHS) as part of ongoing efforts to identify feasible strategies and incentive measures to approach net zero energy (NZE) status for existing Canadian houses. In earlier studies various high efficiency alternative and renewable energy technologies including envelope modifications, installation of solar domestic hot water (SDHW) systems, phase change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling engine (SE) based cogeneration systems, solar combisystem, air to water heat pump (AWHP) system, and solar assisted heat pump (SAHP) system were investigated (Asaee *et* *al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b; Asaee *et al.*, 2017a; Asaee *et al.*, 2017b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

9.3. Methodology

This study assesses the performance of PV and BIPV/T systems in existing Canadian houses using the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) (Swan, 2010; Swan *et al.*, 2013). CHREM is based on the Canadian Single-Detached Double/Row Database (CSDDRD) (Swan *et al.*, 2009). CSDDRD statistically represents the CHS with close to 17,000 unique houses that were extracted from the latest data available from the EnerGuide for Houses database, Statistics Canada housing surveys and other available housing databases.

A high-resolution building energy simulation program ESP-r (ESRU, 2015) is used as the simulation engine of CHREM. ESP-r is an integrated simulation tool for evaluation of the thermal, visual and acoustic performance as well as energy consumption and GHG emissions of buildings which employs a finite difference control volume approach for energy simulation. ESP-r has been validated through a vast amount of research results (Strachan *et al.*, 2008).

Six components work together in CHREM to predict the end-use energy consumption and GHG emission of the CHS. These components are:

- The Canadian Single-Detached & Double/Row Housing Database (Swan *et al.*, 2009),
- A neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households (Swan *et al.*, 2011),
- 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 (Farhat and Ugursal, 2010),
- A model to estimate GHG emissions from fossil fuels consumed in households.

The energy savings and associated GHG emissions reductions due to any energy efficiency upgrade or renewable/alternative energy technology, such as PV and BIPV/T systems, can be estimated using CHREM as follows:

(i) Identify houses suitable to receive the upgrade/technology: For PV, only houses with suitable roof for panel installation are selected. In addition a house should have a basement or a mechanical room to qualify for BIPV/T system retrofit. Therefore, a filter has designed to select such houses in the CSDDRD.
(ii) Modify the input files of the selected houses to add the upgrade/technology for use in the ESP-r energy simulations.
(iii) Evaluate the energy savings and GHG emissions reductions (or increases) of the CHS with the adopted upgrade/technology by comparing the energy consumption and GHG emissions with the "base case" (i.e. current) values. The change in GHG emissions due to a change in electricity consumption is estimated using the marginal GHG emission intensity factors given by Farhat and Ugursal (2010). Since CSDDRD is representative of the CHS, the CHREM estimates can be extrapolated to the entire CHS using scaling factors (Swan, 2010; Swan *et al.*, 2013).

Since the initial development of CHREM, its modeling capability has been gradually expanded, to include PCM thermal energy storage, SDHW heating system, ICE and SE engine based cogeneration, solar combisystem, AWHP system and SAHP system (Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b; Asaee *et al.*, 2017a; Asaee *et al.*, 2017b; Asaee *et al.*, 2014; Nikoofard *et al.*, 2013, 2014b, 2014c, 2014d).

9.3.1. Numerical Model

In this study first the PV system is simulated in CHREM. A roof-mounted PV module can be modeled in ESP-r: (i) as part of the roof construction, (ii) as a separate zone with a small thickness, attached to the roof. In the former strategy the air gap between the PV and the roof is modeled as one layer of the multi-layer construction. In the latter approach the air gap between top and bottom layers is modeled by an air-flow network. The first approach is simpler and less accurate than the second because of the higher temperatures predicted in the air gap due to neglecting the heat transfer rate increase due to air-flow in the gap. Also, it is less suitable for the modelling of BIPV/T systems because the air flow in the gap between the PV module and the roof is a critical component of the system that delivers thermal energy. Therefore, PV panels are modelled in this work as a separate zone with a narrow air gap above the roof, and the air gap is modelled by an airflow network. (Nikoofard, 2012).

9.3.1.1. PV Array

The current vs. voltage curve (I-V curve) is generally used to characterize a PV system. Power generation of a PV cell can be determined from its operating voltage and current. Mottillo *et al.* (2006) developed and incorporated the PV model into ESP-r based on an equivalent one-diode circuit model (WATSUN-PV model) recommended by Thevenard (2005). The equivalent one-diode circuit is shown in Figure 9.1. The circuit output current, I, is the difference between the light generated current, I_L, and diode current, I_D. The diode current represents the resistance of the cell's junction to current flow (Mottillo *et al.*, 2006).

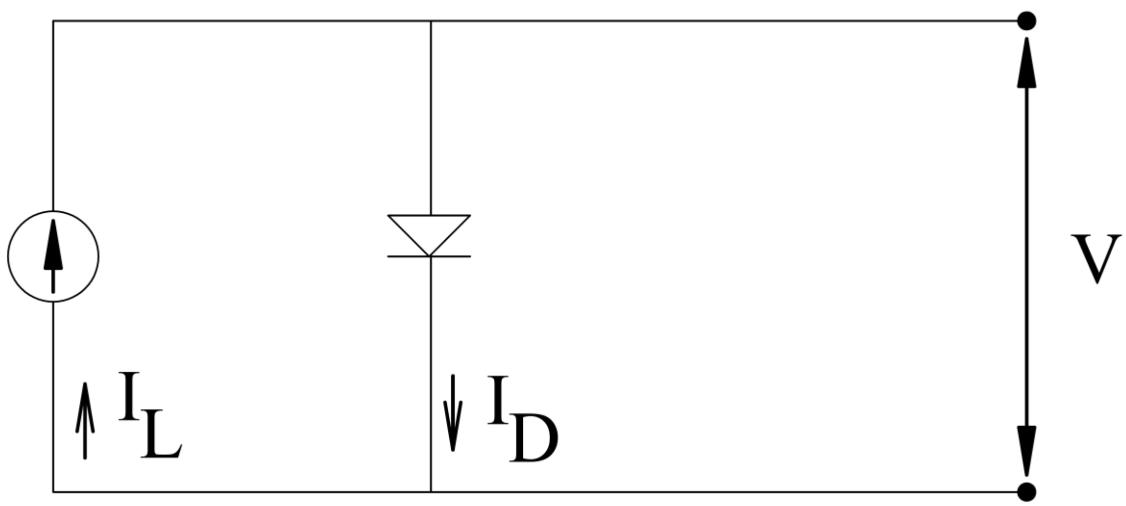

Figure 9.1 The equivalent one-diode circuit.

This model is based on the short circuit current, the open circuit voltage and maximum power point the at the reference conditions. The reference curve is adjusted to match the operating conditions. The equations defining the short circuit current, I_{sc}, and open circuit voltage, V_{oc}, in the WATSUN-PV model are given in Equations (9.1) and (9.2).

$$I_{sc}=I_{sc,ref}\frac{E_{T,eff}}{E_{T,ref}}\left[1+\alpha\left(T_{cell} - T_{cell,ref}\right)\right] \tag{9.1}$$

$$V_{oc}=V_{oc,ref}\left[1\text{-}\gamma\left(T_{cell}\text{ - }T_{cell,ref}\right)\right]\times Max\left\{0,1+\beta\, ln\left(\frac{E_{T,eff}}{E_{T,ref}}\right)\right\} \tag{9.2}$$

where $E_{T,eff}$, is the effective irradiance incident on the surface (W/m^2), T_{cell}, is the cell temperature (°C), and α, β, γ are empirical coefficients. Beam and diffuse solar radiation (inclusive the reflectance of the front surface of the module) are considered in determining the effective irradiance. Reference irradiance and cell temperature are considered to be 1000W/m^2 and 25°C, respectively (Mottillo *et al.*, 2006), and the values of the coefficients are given in Table 9.1 as per Nikoofard (2012).

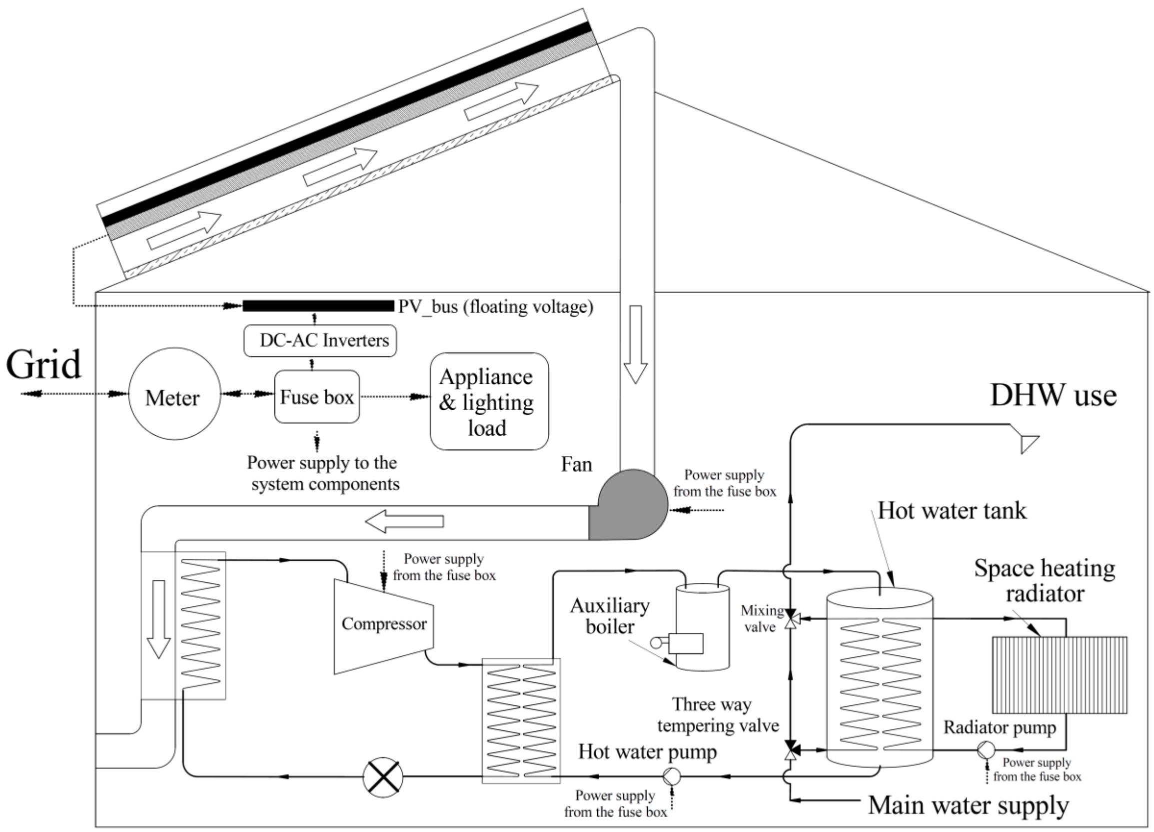

Figure 9.2 A typical house with BIPV/T system retrofit.

Table 9.1 Parameters of BIPV/T system components based on the existing heating system capacity

BIPV/T system components	Parameter	Unit	Existing heating system nominal capacity (kW)			Refs.
			>21	11-16	≤11	
Open circuit voltage at reference	V_{oc}	V	22.1			(Nikoofard, 2012)
Short circuit current at reference	I_{sc}	A	4.8			
Voltage at maximum power point at reference	V_{mpp}	V	17.6			
Current at maximum power point at reference	I_{mpp}	A	4.55			
Reference insolation	H_{ref}	W/m^2	1000			
Reference temperature	-	K	298			
Temperature coefficient of I_{sc}	α	K^{-1}	0.00059			
Temperature coefficient of V_{oc}	γ	K^{-1}	-0.00381			
Empirical coefficient beta used in calculation of V_{oc}	β	-	0.0578			
Number of series connected cells (not panels)	-	-	36			
Number of parallel connected branches	-	-	1			
Number of panels in surface	N	-	10			
Load value	-	V	0			
Miscellaneous loss factor	-	-	0.1			
Efficiency	η	%	11.7			
Invertor nominal power	P_{nom}	W	5000			

BIPV/T system components	Parameter	Unit	Existing heating system nominal capacity (kW)			Refs.
			>21	11-16	≤11	
Idling constant	P_0/P_{nom}	-		0.8975×10^{-5}		
Set-point voltage	U_s	V		3.65		
internal resistance of inverter	R_i	Ω		0.4		
COP of heat pump	a_0	-	5.2202	5.0948	5.6818	(Viessmann, 2016)
	a_1	K^{-1}	-0.077	-0.0583	-0.0864	
	a_2	K^{-2}	4×10^{-4}	3×10^{-4}	5×10^{-4}	
NG fired boiler	$P_{nom,buner}$	kW	19	18	18	(Viessmann, 2015a)
	η_0			0.92		
	T_{ref}	°C		50		
	$(tan\ \varphi)_{T>50°C}$	$°C^{-1}$		-0.15		
	$(tan\ \varphi)_{T\leq50°C}$	$°C^{-1}$		-0.25		
Oil fired boiler	$P_{nom,buner}$	kW	18	11	11	(Viessmann, 2015b)
	η_0			0.85		
	T_{ref}	°C		50		
	$tan\ \varphi$	$°C^{-1}$		-0.15		
Thermal storage tank	V_{store}	USG	400	265	200	
Radiator	M_{unit}	kg		49		(Express Radiant Ltd, 2015)
	C_{avg}	J/kgK		1350		
	Q_0	W		967		
	$T_{s,0}$	°C		55		
	$T_{r,0}$	°C		35		
	$T_{env,0}$	°C		21		

The cell voltage and current at the maximum power point (shown by subscript *mp*) are assumed to be proportional with the short circuit current and open circuit voltage in the WATSUN-PV model. Therefore, the maximum power is defined as:

$$P_{mp}=I_{mp,ref}\times V_{mp,ref}\left(\frac{I_{sc}\times V_{oc}}{I_{sc,ref}\times V_{oc,ref}}\right) \quad (9.3)$$

The PV module surface is represented as a multi-layered construction of several material layers. Individual layers are modeled with one or more nodes. A node within the surface is defined as a special material and represents the location of the PV cells within the structure. Cell temperature is determined by solving the energy balance equation for the special material node.

The power conditioning unit (PCU) model (Ulleberg, 1998) was used to simulate the DC-AC inverter as given in Equation (9.4).

$$\frac{P_{in}}{P_{nom}} = \frac{P_0}{P_{nom}} + \left(1+\frac{U_s}{U_{out}}\right)\frac{P_{out}}{P_{nom}} + \frac{R_i P_{nom}}{U_{out}^2}\left(\frac{P_{out}}{P_{nom}}\right)^2 \qquad (9.4)$$

where P_{in}, is the power input (W), P_{nom}, is the nominal power (W), P_0, is the power loss when there is a voltage across inverter (W), U_s, is the set-point voltage (V), U_{out}, is the voltage output (V), R_i, is the internal resistance of inverter (Ω) and $\frac{P_0}{P_{nom}}$ is collectively named idling constant.

The Crystalline-Silicone type PV modules with ethylene vinyl acetate (EVA) encapsulation, low-iron glass cover and metal back sheet are modelled in CHREM due to their higher efficiency and commercial availability (Nikoofard, 2012).

The number of PV panels for a given roof area is determined as:

$$N_{PV} \leq \frac{H_{ref} \times \eta \times AR}{P_{indv}} \qquad (9.5)$$

where N_{PV}, is the number of PV panels (integer), H_{ref}, is the Reference insolation (W/m^2), η, is the user defined efficiency, AR, is the roof area (m^2) and P_{indv}, is the nominal power of individual module (W). The input data used in modelling the PV modules are given in Table 9.1 (Nikoofard, 2012).

9.3.1.2. Heating System

The preheated outside air exiting the roof integrated PV system is fed into the evaporator of the heat pump as shown in Figure 9.2. The heat pump is modeled as a grey-box component. Under the grey-box modeling strategy the system behaviour is expressed by performance related equations including the power consumption and COP of the heat pump. This strategy has been used for modeling several plant components in ESP-r

(Ferguson *et al.*, 2009; Kelly and Cockroft, 2011). The empirical expressions used for the COP of the heat pump are given in Equation (9.6).

$$COP=\begin{cases} a_0+a_1\left(T_w-T_{sup}\right)+a_2\left(T_w-T_{sup}\right)^2 & -15°C<T_{sup}<35°C \\ a_0+a_1(T_w-35)+a_2(T_w-35)^2 & T_{sup}\geq 35°C \end{cases} \quad (9.6)$$

where T_w, is the water temperature and T_{sup}, is the air supply temperature. The heat pump operation is limited to the supply air temperature above -15°C. At temperatures below -15°C, the heat pump is turned off and the auxiliary boiler supplies heat. The values of the constants are determined using manufacture's data given in Table 9.1 (Viessmann, 2016).

Hot water leaving the condenser of the heat pump is stored in the hot water tank, which is used for energy storage and heat transfer within the hydronic system. Two immersed heat exchangers are considered in the thermal storage tank to serve the space and DHW heating loops. The hot water tank is simulated using a stratified tank model developed and incorporated in ESP-r by Thevenard *et al*. (2010). To model the stratification in the tank the liquid content is divided into a series of control volumes, with each control volume at a uniform temperature determined by the energy balance equation iterated at each time step. Conduction and convection modes of heat transfer are considered for each control volume.

As shown in Figure 9.2, an auxiliary boiler is considered in the system to supply heat when the heat pump energy supply is not enough to satisfy the demand. At each time step, the heat output of the boiler is defined using the boiler efficiency, fuel heating rate, and instantaneous fuel use. The boiler efficiency (HHV for NG and LHV for oil) is defined as a function of the return water temperature as shown in Equation (9.7):

$$\eta_b=\left[\eta_0- \tan\varphi \times\left(T_{ref}- T_{ret}\right)\right] \quad (9.7)$$

where η_b is the boiler efficiency, η_0 is the full load boiler efficiency at the reference temperature, φ is the slope of the efficiency curve, T_{ref} is the reference temperature, and T_{ret} is the return water temperature. The heat output of boiler is added to the energy balance equation as a source term. The boiler output temperature is determined considering the boiler heat supply, water flow rate, and heat loss to the environment. The thermal mass of the boiler is taken into account during the transient operation of the boiler. The auxiliary boiler is assumed to be a condensing boiler where natural gas is available and a non-condensing boiler where natural gas is not available. The boilers are selected among market ready products and the boiler data are given in Table 9.1 (Viessmann, 2015a, 2015b).

A hydronic heat delivery system is used for space heating. In each zone the number of radiators is chosen to satisfy the design heating load based on nominal radiator capacities selected from the Express Radiant Ltd product catalogue (Express Radiant Ltd, 2015). The hot water circulation pump power is estimated using empirical equations that Asaee *et al.* (2016b) used to estimate pump power in space and DHW heating loops as shown in equations (9.8) and (9.9).

$$P_{el,pump.SH}=90\text{W}+2\times10^{-4}P_{nom,burner} \tag{9.8}$$

$$P_{el,pump.DHW}=49.4\text{W}\times\exp\left(0.0083\frac{P_{nom,burner}}{\text{kW}}\right) \tag{9.9}$$

where $P_{el,pump.SH}$ and $P_{el,pump.DHW}$ are the power of the pump operating in the space and DHW heating circuit, respectively. The $P_{nom,burner}$ is the nominal capacity of the auxiliary boiler.

9.3.2. Control Strategy

The details of the BIPV/T system control sensors and actuators are presented in Table 9.2.

Table 9.2 Control strategy for space heating and DHW supply

Control loop	Actuator	Period		Sensor location	Setpoint	
		start	end		on	off
BIPV/T loop	Compressor Fan Hot water pump	1 Jan	31 Dec	Top of the hot water tank in the vicinity of outlet	50	55
	Auxiliary boiler	1 Jan	31 Dec	Boiler outlet	50	55
DHW heating and supply	DHW pump [a]	1 Jan	31 Dec	DHW tank	54	56
	DHW tank [a]	1 Jan	31 Dec	DHW draw	--	--
Space heating	Radiator pump	17 Sep	3 Jun	Zone main 1	20	22
		4 Jun	16 Sep		0	1[b]

[a] To avoid unnecessary complexity in the components and control algorithms of plant simulation using ESP-r, the combination of mixing valve and three way tempering valve are modeled using a fully mixed adiabatic tank and a DHW pump.
[b] The heating system will not turn on due to the low temperature setpoint during the cooling only season.

The system is mainly controlled by space and DHW heating demand. The hot water tank is responsible for heat storage and transfer to the space and DHW heating loops. The desired hot water tank temperature is between 50°C and 55°C. When the temperature of the hot water tank drops below 50°C, the hot water pump turns on and continues to operate until the hot water tank temperature reaches 55°C. When the outlet temperature of the fan is above the cut-out temperature of the heat pump (-15°C), the heat pump turns on to extract heat from the supply air and heats the water. If the temperature of the water leaving the heat pump is below 50°C, the auxiliary boiler turns on to increase the water temperature to 55°C. With this control scheme, the auxiliary heating system is only operated at the BIPV/T system shortfall.

If the main zone temperature drops below the temperature set-point (20°C), a pump supplies hot water from the hot water tank to the space heating radiators. Since the other zones including the basement are slave to the main zone, hot water is supplied into all radiators in the house, until the main zone temperature exceeds the upper temperature threshold (22°C).

The DHW supply temperature is maintained in the range of 55±1°C. To simplify the model, the operation of the combination of DHW service valves is simulated as a small fully mixed adiabatic tank held at 55±1°C and DHW draw and equivalent main water supply is applied into this tank, emulating the operation of the valves in a real system.

9.3.3. Eligible Houses

Since this study is focused on retrofitting existing houses, a series of conditions are considered to identify the houses that can adopt PV and BIPV/T systems with a reasonable cost. Since PV modules are to be installed on roof tops, candidate houses should have a major roof surface facing south-east, south or south-west to maximize incident solar energy. Also, candidate houses should contain a suitable space, such as a basement or mechanical room, to install the BIPV/T system components. Thus, a series of algorithms was developed to select houses in CSDDRD that satisfy both conditions. Since the presence of a mechanical room is not identified in the CSDDRD, houses with heating, ventilation and air conditioning systems that have similar components and likely require a mechanical room were selected.

Due to different construction characteristics of houses across Canada and non-uniform population density, the number of eligible houses varies substantially from province to province. Also, due to additional basement or mechanical room requirement for the BIPV/T system, the number of eligible houses for the PV retrofit is larger compared to the number of eligible houses for BIPV/T system upgrade.

9.3.4. GHG Emission Estimation

The GHG emissions are reported as "equivalent CO_2" (CO_{2e}) emitted per unit input energy. Equivalent carbon dioxide (CO_{2e}) emissions from carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) is determined considering their global warming potential as shown in Equation (9.10) (Farhat and Ugursal, 2010; Swan *et al.*, 2013).

$$CO_{2e}=CO_2+25CH_4+298N_2O \quad (9.10)$$

Equivalent carbon dioxide is determined for each onsite fossil fuel and electricity using GHG emission intensity factor (GHG EIF). The GHG EIF is the level of CO_{2e} emission per unit energy of fuel. The GHG EIF for onsite fossil fuel (i.e. NG and oil) is defined based on the chemical reactions that occur in the combustion of fuel in residential boilers. The emission of CO_2 due to wood combustion is not accounted for in this study because it is assumed that combustion of wood returns to the atmosphere the CO_2 that was recently removed by photosynthesis (Farhat and Ugursal, 2010). Instantaneous GHG emissions due to onsite fuel consumption is calculated in each time step based on the fuel type and efficiency of the energy conversion device (Swan *et al.*, 2013).

Since the electricity generation in Canada is controlled by provincial utilities, the fuel mixture is determined based on the available primary energy sources. Thus, CHREM considers the provincial GHG EIF to evaluate GHG emissions associated with electricity consumption separately for each province due to the vast differences in the fuel mix used, efficiency of energy conversion as well as transmission and distribution losses. The GHG EIF for electricity generation is defined as the level of CO_{2e} emissions for the generation and delivery of one kWh electricity to the end-user. Generally different types of technologies are used for electricity generation during the on-peak period compared to the base load electricity generation. Thus the average and marginal GHG EIFs are used to evaluate the GHG emission during off-peak and on-peak periods, respectively. The provincial average and marginal GHG EIF developed by Farhat and Ugursal (2010) given in Table 9.3 are used.

Table 9.3 The average and marginal GHG intensity factors (g CO_{2eq}/kWh) for each province of Canada (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 $EIF_{Marginal}$		837	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%

9.3.5. Connection of the PV System to the Electrical Grid

Energy storage is an essential part of renewable energy systems. While the hot water tank is a practical option for thermal energy storage for dwellings, electricity storage is a more complicated issue. Onsite electricity storage can be managed using batteries at households. However, the space requirements, initial investment and additional maintenance may decrease the favourability of this option. Grid connected low energy buildings can be considered as an alternative. As shown in Figure 9.2, onsite electricity generation is consumed by the heat pump, fan, pumps and AL operation. If the onsite electricity generation is not sufficient to meet the demand, the required electricity is imported from the grid with the meter recording electricity draw from the grid. When the onsite electricity generation exceeds the electricity demand of the household, the surplus electricity can be exported to the grid. In this case the meter spins backwards and subtracts the value of the exported electricity. This billing strategy is known as net metering and allows residential customers to earn credit for onsite electricity generation. With this strategy, the grid acts as an infinite and lossless electricity storage system for individual houses. The specific policies for net metering is defined by local authorities. Since several parameters can affect the energy market and electricity trade in each jurisdiction, balanced net metering approach is assumed in this study. Under the balanced net metering approach, the onsite electricity generation and grid electricity supply have the same price, GHG EIF and source energy intensity. Net metering is approved by utility companies across Canada for micro scale electricity generation (Alberta Energy, 2016; BC Hydro, 2016; Hydro-Quebec, 2016a; NSP, 2016; OEB, 2016). Whether the electricity grid could support the large electricity export due to widespread PV system adoption is a question that must be investigated in future research.

9.4. Economic Analysis

The price of PV panels has dropped significantly during the last decade. Because of large investments in the solar industry, the cost of PV panels is expected to continue decreasing in the near future (Poissant *et al.*, 2016). Also, the cost of purchase, delivery and installation of BIPV/T system components such as heat pumps, storage tanks and auxiliary heaters are expected to be different in various regions due to economic parameters including market size, population density, geographical area, competitive market conditions, special site requirements and prevailing labor rates. Therefore, the investment cost for PV and BIPV/T system retrofit can vary substantially across the country. Additionally, a solar system retrofit would likely increase the market value of a house. However, the estimation of the increase in market value is affected by factors such as 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 is not considered in this work.

Since a conventional economic feasibility analysis is neither realistic nor practical for the purpose of this study, an alternative approach is adopted here to analyse the economic feasibility of PV and BIPV/T retrofit based on the “tolerable capital cost” (TCC) of the upgrades (Nikoofard *et al.*, 2014a). TCC is the acceptable initial investment for an energy saving upgrade that will be recovered based on the annual cost savings, the number of desired years for payback, and the estimated annual interest of borrowing money and fuel cost escalation rates. The additional maintenance cost of the PV and BIPV/T system over and above that of the replaced system is assumed to be included in the TCC as a present value of the annual maintenance cost over the lifetime of the solar system. The TCC approach has been used in similar studies that evaluated the other renewable and alternative energy technologies for the CHS (Asaee *et al.*, 2015a, 2016b; Asaee *et al.*, 2017a; Asaee *et al.*, 2017b; Nikoofard *et al.*, 2013, 2014b, 2014c).

The TCC is estimated using Equations (9.11) and (9.12).

$$\text{TCCH}=\begin{cases}\text{ACSH}\left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] & \text{for} \quad i\neq e\\ \text{ACSH}\times n(1+i)^{-1} & \text{for} \quad i=e\end{cases} \tag{9.11}$$

$$\text{ACSH}=\sum_{j=1}^{m}(\text{F}\times\text{E})_{j} \tag{9.12}$$

where:

TCCH	Tolerable capital cost of the retrofit for the house (C$)
n	Acceptable payback period (year)
i	Interest rate (decimal)
e	Fuel cost escalation rate (decimal)
ACSH	Annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
E	Energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
F	Fuel price per unit of each fuel type (C$/unit)
m	Number of different fuels used in a house

It is not useful nor practical to report the TCC for each house in the CSDDRD, or for that matter within the CHS, because from a macro level of interest, data on individual houses have no utility. Thus, the "average tolerable capital cost per house" (ATCCH) is used to evaluate the economic feasibility of the SAHP system retrofit. ATCCH is calculated by dividing the total tolerable capital cost by the number of houses:

$$\text{ATCCH}=\text{TTCC}/\text{NH} \tag{9.13}$$

where, TTCC is the total tolerable capital cost as a result of the SAHP system upgrade (C$), calculated as follows:

$$\text{TTCC}=\sum_{i=1}^{\text{NH}}\text{TCCH}_{i} \tag{9.14}$$

NH = number of houses that received the upgrade.

Table 9.4 Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[a]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	C$/GJ	36.58	45.06	47.08	37.11	21.92	39.72	24.25	42.00	43.19	26.53
Natural gas[b]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	C$/GJ	N/A	N/A	N/A	N/A	12.41	7.99	8.23	7.77	4.62	11.35
Home heating oil[c]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	C$/GJ	29.63	28.42	29.17	30.76	31.25	32.80	30.33	29.37	N/A	33.08
Wood[d]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	C$/GJ	11.20	11.20	11.20	15.69	11.43	13.44	11.65	11.20	22.40	10.75

[a] Hydro-Quebec (Hydro-Quebec, 2014b)

[b] Statistics Canada handbook (Statistics Canada, 2013)

[c] Statistics Canada Handbook (Statistics Canada, 2013)

[d] Local companies

Table 9.5 Real fuel escalation type for each fuel type

	Low	Medium	High
Electricity[a]	2	6	10
Natural gas[b]	2	5	8
Light fuel oil[b]	6	10	14
Mixed wood[c]	3	6	9

[a] National Energy Board of Canada (NEB, 2014)

[b] Energy Escalation Rate Calculator (EERC) (WBDG, 2014)

[c] Equal to interest rate as there is no source for its escalation rate

For each province, fuel prices for residential customers for natural gas, heating oil, electricity and wood were obtained to calculate the energy cost savings due to retrofits. The fuel prices that are used in this study are presented in Table 9.4 (Hydro-Quebec, 2014b; Statistics Canada, 2013).

To take into consideration the uncertainty associated with the future of interest and fuel price escalation rates, a sensitivity analysis was conducted. The interest rates used in the analysis are based on the Bank of Canada Prime Rate (BOC, 2015), which was about 1% in June, 2015. 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.

For each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 9.5 are used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada (NEB, 2014) and Energy Escalation Rate Calculator (WBDG, 2014).

Payback periods of six and ten years are used in the sensitivity analysis.

9.5. Results and Discussion

CHREM estimates of the energy consumption and GHG emissions for the current status of the CHS (‘base case’) are presented in Table 9.6. The validity of these estimates was verified earlier (Swan *et al.*, 2013) by comparing them with available statistical data on Canadian energy use. In this study, first the impact of PV retrofit on energy consumption and GHG emissions is investigated. For this purpose, all houses that are eligible for PV retrofit are assumed to receive this retrofit and the energy consumption and GHG emissions are estimated using CHREM. The same approach is used to evaluate the BIPV/T system retrofit for the CHS.

Table 9.6 CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 9.7 PV electricity generation, GHG emission reductions in eligible houses

Province	Eligible houses		Electricity generation (PJ)	Average electricity generation per house (GJ)	Average AL load per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent					
NF	80,588	46	1.0	12	34	0.01	124
NS	127,163	43	1.4	11	34	0.15	1,180
PE	25,795	57	0.3	12	31	0.00	0
NB	103,740	44	1.6	15	29	0.37	3,567
QC	730,955	37	8.9	12	24	0.00	0
OT	1,072,692	31	12.7	12	25	1.70	1,585
MB	115,258	34	1.4	12	23	0.00	0
SK	131,471	42	1.6	12	24	0.11	837
AB	384,813	40	3.9	10	26	0.91	2,365
BC	343,207	31	4.7	14	41	0.02	58
Canada	3,115,683	35	37.5			3.27	

Table 9.8 Energy savings and GHG emission reductions for the CHS due to BIPV/T retrofit

Province	Eligible houses		Total energy saved (PJ)	Average energy saving per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent				
NF	35,707	20	3.9	109	0.18	5,120
NS	84,231	28	8.4	100	0.60	7,128
PE	13,882	31	1.7	122	0.09	6,292
NB	56,288	24	6.5	115	0.27	4,761
QC	115,717	6	10.3	89	0.50	4,351
OT	1,077,900	31	111.5	103	5.43	5,041
MB	96,782	28	9.7	100	0.51	5,224
SK	126,942	40	13.2	104	0.73	5,730
AB	382,336	39	37.5	98	1.30	3,408
BC	279,044	25	24.3	87	1.24	4,440
Canada	2,268,829	25	227.0		10.85	

Table 9.9 CHREM estimates of annual energy consumption (PJ) with existing (Exist) and BIPV/T retrofit (Ret) in houses eligible (EL) and houses not eligible (N-E) for BIPV/T retrofit

	Electricity			NG			Oil			Wood			Total		
	N-E	EL		N-E			N-E			N-E	EL		N-E	EL	
Province		Exist	Ret		Exist	Ret		Exist	Ret		Exist	Ret		Exist	Ret
NF	13.3	1.9	1.6	0.0	0.0	0.0	6.2	3.4	0.8	2.3	1.0	0.0	21.8	6.3	2.4
NS	14.2	3.5	3.6	0.0	0.0	0.0	13.9	8.7	1.3	4.9	1.1	0.0	33.0	13.3	4.9
PE	1.3	0.5	0.5	0.0	0.0	0.0	2.7	1.3	0.2	0.9	0.6	0.0	4.9	2.4	0.7
NB	16.1	2.6	1.9	0.0	0.0	0.0	5.5	4.2	1.1	8.0	2.7	0.0	29.6	9.5	3.0
QC	198.1	7.2	3.9	0.8	0.2	2.4	21.7	8.6	0.0	9.8	0.6	0.0	230.4	16.6	6.3
OT	103.1	34.1	40.2	221.4	116.0	16.0	29.8	17.6	0.0	0.0	0.0	0.0	354.3	167.7	56.2
MB	16.1	2.8	3.1	20.6	13.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	36.7	15.8	6.1
SK	7.2	3.4	3.4	23.7	16.5	3.3	0.0	0.0	0.0	0.0	0.0	0.0	30.9	19.9	6.7
AB	17.1	11.2	14.5	71.8	48.0	7.2	0.0	0.0	0.0	0.0	0.0	0.0	88.9	59.2	21.7
BC	51.5	13.1	13.6	57.0	26.9	2.2	0.0	0.0	0.0	2.0	0.1	0.0	110.5	40.1	15.8
Canada	438.0	80.3	86.3	395.3	220.6	34.1	79.8	43.8	3.4	27.9	6.1	0.0	941.0	350.8	123.8

Table 9.10 Annual energy savings and GHG emission reductions due to BIPV/T retrofit in the CHS

Province	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	0.3	0.0	2.6	1.0	3.9	0.00	0.00	0.18	0.18
NS	-0.1	0.0	7.4	1.1	8.4	0.08	0.00	0.52	0.60
PE	0.0	0.0	1.1	0.6	1.7	0.01	0.00	0.08	0.09
NB	0.7	0.0	3.1	2.7	6.5	0.05	0.00	0.22	0.27
QC	3.3	-2.2	8.6	0.6	10.3	0.01	-0.11	0.60	0.50
OT	-6.1	100.0	17.6	0.0	111.5	-0.86	5.06	1.24	5.43
MB	-0.3	10.0	0.0	0.0	9.7	0.00	0.51	0.00	0.51
SK	0.0	13.2	0.0	0.0	13.2	0.06	0.67	0.00	0.73
AB	-3.3	40.8	0.0	0.0	37.5	-0.76	2.06	0.00	1.30
BC	-0.5	24.7	0.0	0.1	24.3	-0.01	1.25	0.00	1.24
Canada	-6.0	186.5	40.4	6.1	227.0	-1.42	9.43	2.84	10.85

9.5.1. *Energy Saving*

The amount of electricity generated by the PV systems retrofitted in all eligible houses (about 35% of the houses in the CHS) and the associated GHG reductions are presented in Table 9.7. Electricity is used by appliances and lighting (AL), and in some houses additionally for space and DHW heating. Unlike modern, low-energy houses designed to enhance the suitable area for PV panel installation, existing houses were not designed with solar energy utilization in mind, and have limited roof area for PV installation. Thus, the average PV electricity generation per house is considerably low for existing houses. As shown in Table 9.7, the average electricity generation per house is 10-15 GJ per year in the CHS. To provide a comparison, the average per house electricity consumption by appliances and lighting in eligible houses is also presented in Table 9.7. Depending on the province, the average PV electricity generation is about half or less than half of the average AL load per house in the CHS. Thus, a standalone PV retrofit will not be sufficient to convert existing houses into low energy buildings.

As discussed earlier, the BIPV/T system is an alternative approach that combines the benefits of the PV and heat pump systems in a hybrid system. The total energy savings and associated GHG emission reductions with the BIPV/T retrofit is given in Table 9.8. Since the BIPV/T system requires the additional eligibility criterion of a suitable mechanical room in a house, the number of eligible houses for BIPV/T retrofit in the CHS is less than that for PV retrofit, also as shown in Table 9.8. However, the energy savings due to the BIPV/T system retrofit is much higher compared to the electricity generation by PV retrofit although fewer houses are eligible for the BIPV/T retrofit.

As shown in Table 9.8 for each province, the average energy savings per house with the BIPV/T retrofit varies between 90-120 GJ per year, compared to the 10-15 GJ per year of electricity produced per house by the PV retrofit. The significant difference between the PV and BIPV/T retrofit benefits illustrates the importance of space and DHW heating load in the CHS and indicates that efforts to convert existing houses into low energy buildings need to include HVAC system upgrade(s) to be effective.

Estimates of the energy consumption in the CHS including the energy consumption in houses not eligible for the BIPV/T retrofit, and energy consumption before and after the retrofit for eligible houses broken down according to the energy sources used are provided in Table 9.9. As shown in the table, depending on the province, electricity use in eligible houses remains essentially the same (PE and SK), decreases (NF, NB and QC) or increases (NS, OT, MB, AB and BC) after the BIPV/T retrofit. For the entire CHS, electricity consumption increases with the BIPV/T retrofit, indicating that as a whole PV electricity generation is not sufficient for the operation of the heat pumps. However, energy consumption by the eligible houses from every other fuel decreases substantially indicating the overall effectiveness of the BIPV/T system to reduce energy consumption. The 2.2% increase in NG use in QC is because the auxiliary heating with the BIPV/T system is assumed to be from NG rather than the oil used in some existing houses. Thus, all oil consumption by eligible houses is replaced with NG after the BIPV/T retrofit.

Annual energy savings due to BIPV/T system retrofit in the CHS is provided in Table 9.10. Overall, with the BIPV/T system retrofit, the energy consumption of the eligible houses reduce from 350.8 PJ to 123.8 PJ, corresponding to a reduction of 65%. However, due to the low percentage of eligible houses in the CHS for the BIPV/T system retrofit (25% as shown in Table 9.8), the energy savings across the entire CHS is about 18% as shown in Table 9.11. This is about six times more than the savings due to the PV retrofit as shown in the same table.

Table 9.11 Annual energy savings and GHG emission reductions due to BIPV/T and PV retrofits in the CHS

	Energy Savings (%)		GHG emission reductions (%)	
Province	PV	BIPV/T	PV	BIPV/T
NF	4	14	1	23
NS	3	18	3	11
PE	4	23	0	23
NB	4	17	12	9
QC	4	4	0	20
OT	2	21	6	19
MB	3	18	0	29
SK	3	26	2	16
AB	3	25	7	10
BC	3	16	0	27
Canada	3	18	5	17

9.5.2. Reduction of GHG Emissions

The PV and BIPV/T system retrofits not only reduce energy use in the CHS but also replace a portion of the fossil fuel use (including onsite oil and NG as well as offsite fuel use for electricity generation) with more sustainable options. It is assumed here that PV electricity generation only offsets marginal electricity generation. In provinces where marginal electricity generation is mainly from fossil fuels, PV electricity generation translates into a considerable GHG emission reduction as shown in Table 9.7. However, GHG emission reductions due to PV retrofit is negligible in NF, QC, MB and BC where hydroelectricity is largely responsible for all, including marginal, electricity generation. While PE and SK use fossil fuels for base electricity generation, the marginal GHG EIF is relatively low as shown in Table 9.3; thus, the GHG emission reductions in those provinces are also negligible.

The estimates for total and average per house GHG emission reductions due to BIPV/T system retrofit are presented in Table 9.8. Although PV electricity generation offsets the fossil fuel use for marginal electricity generation, the heat pump consumes electricity instead of a fossil fuel for space and DHW heating. Thus, in NF, QC, MB and BC where hydroelectricity is widely available, the BIPV/T system is a favorable option. In Atlantic Provinces where oil is widely used for heating purposes by residential customers and fossil fuels are used for electricity generation, the situation is more complicated. While PV electricity generation is favorable for GHG emission reduction, the heat pump electricity use for heating purposes has an adverse effect on GHG emissions. The most negative impact on GHG emission is predicted in AB where fossil fuels, including coal, are used for electricity generation whereas significantly cleaner NG is mainly used for residential heating purposes.

The GHG emission reductions due to BIPV/T system retrofit by fuel source is provided in Table 9.10. The GHG emissions of fossil fuels are reduced in all provinces. It should be noted that the GHG emissions associated with oil is replaced with GHG emissions due to NG with BIPV/T retrofits in QC. As a result, the GHG emissions due to NG increases in QC while the overall GHG emissions from fossil fuels decrease. Percent GHG emission reductions due to PV and BIPV/T retrofits are presented in Table 9.11. Since the largest GHG EIF is in NB and AB, the largest GHG emission reductions by PV retrofit occur in those provinces. However, due to the large marginal GHG EIF in those provinces, the GHG emission reductions due to BIPV/T retrofit is not significant compared to other provinces. Using heat pumps in place of conventional fossil fuel fired heating systems provides a major benefit to reduce GHG emissions in the provinces where hydro-electricity is the main source of marginal electricity generation.

9.5.3. Economic Feasibility

The results of the economic analysis conducted for three fuel escalation rates, three interest rates and two payback periods (as discussed in Section 9.4) are provided in Table 9.12 and Table 9.13 for the PV and BIPV/T system retrofits. The TCC is highly influenced by the reduction in fossil fuel use and net electricity purchase from the grid, and it varies substantially in the range of 1,250C$ to 7,600C$ for the PV and 550C$ to 43,000 C$ for BIPV/T systems.

The energy savings due to electricity generation is used in the calculation of the TCC for PV systems. As shown in Table 9.12, the TCC is the highest in NB largely because the average electricity generation per house is maximum and the price of electricity is relatively high compared to other provinces. On the other end of the spectrum, the TCC for QC is the lowest in Canada. This is because QC has the lowest price of electricity and the per house electricity generation is close to average amongst all provinces as shown in Table 9.7. While the price of electricity is third highest in AB, the TCC is one of the lowest because AB has the lowest average electricity generation per house.

For BIPV/T systems, TCC is affected by PV electricity generation as well as the change in end-use energy consumption. The significant reduction in oil consumption in AT provinces (i.e. NF, NS, PE and NB) and QC substantially increases the TCC for BIPV/T systems compared to the TCC of PV systems. While the fossil fuel consumption decreases due to BIPV/T retrofit, electricity demand increases as a result of the heat pump operation. Thus, if BIPV/T replaces an inexpensive fossil fuel, i.e. NG, with a relatively higher priced electricity, this results in a low TCC as seen in AB.

Table 9.12 Average TCC per house for PV retrofit (C$/house)

Province	Payback (yr)	Interest rate								
		3%			6%			9%		
		Fuel cost escalation rate								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	4,220	5,032	6,031	3,624	4,283	5,088	3,146	3,685	4,341
	6	2,581	2,845	3,137	2,339	2,570	2,825	2,130	2,333	2,557
NS	10	4,611	5,499	6,590	3,960	4,680	5,560	3,437	4,027	4,743
	6	2,820	3,108	3,427	2,556	2,808	3,086	2,328	2,549	2,794
PE	10	5,090	6,070	7,275	4,371	5,166	6,137	3,795	4,445	5,236
	6	3,113	3,431	3,783	2,821	3,100	3,407	2,570	2,814	3,084
NB	10	5,320	6,345	7,604	4,569	5,400	6,415	3,966	4,646	5,473
	6	3,254	3,587	3,955	2,949	3,240	3,561	2,686	2,942	3,224
QC	10	2,481	2,958	3,545	2,130	2,517	2,991	1,849	2,166	2,552
	6	1,517	1,672	1,844	1,375	1,510	1,660	1,252	1,371	1,503
OT	10	4,371	5,213	6,248	3,754	4,437	5,271	3,259	3,818	4,497
	6	2,674	2,947	3,249	2,423	2,662	2,926	2,207	2,417	2,649
MB	10	2,738	3,265	3,913	2,351	2,779	3,301	2,041	2,391	2,817
	6	1,675	1,846	2,035	1,518	1,667	1,833	1,382	1,514	1,659
SK	10	4,751	5,666	6,791	4,080	4,822	5,729	3,542	4,149	4,888
	6	2,906	3,203	3,532	2,634	2,893	3,180	2,399	2,627	2,879
AB	10	4,069	4,853	5,816	3,495	4,130	4,907	3,034	3,554	4,186
	6	2,489	2,743	3,025	2,256	2,478	2,724	2,054	2,250	2,466
BC	10	3,377	4,027	4,826	2,900	3,427	4,072	2,517	2,949	3,474
	6	2,065	2,276	2,510	1,872	2,056	2,260	1,705	1,867	2,046

Table 9.13 Average TCC per house for BIPV/T retrofit (C$/house)

Province	Payback (yr)	Interest rate 3% Fuel cost escalation rate Low	3% Medium	3% High	6% Low	6% Medium	6% High	9% Low	9% Medium	9% High
NF	10	29,819	35,548	42,555	25,417	30,041	35,670	21,904	25,672	30,238
	6	17,094	18,798	20,680	15,450	16,939	18,580	14,037	15,344	16,782
NS	10	28,598	34,197	41,057	24,342	28,858	34,364	20,949	24,626	29,090
	6	16,192	17,831	19,642	14,627	16,059	17,638	13,282	14,538	15,922
PE	10	30,319	36,070	43,090	25,830	30,470	36,108	22,248	26,029	30,601
	6	17,302	19,002	20,876	15,635	17,120	18,754	14,202	15,505	16,938
NB	10	30,376	35,965	42,766	25,927	30,441	35,909	22,372	26,055	30,494
	6	17,623	19,313	21,173	15,937	17,413	19,035	14,485	15,781	17,204
QC	10	29,940	35,942	43,326	25,511	30,355	36,286	21,978	25,926	30,735
	6	17,112	18,893	20,866	15,465	17,021	18,741	14,048	15,414	16,922
OT	10	10,735	12,479	14,562	9,173	10,583	12,259	7,924	9,075	10,436
	6	6,291	6,823	7,403	5,691	6,156	6,663	5,175	5,583	6,028
MB	10	7,203	8,180	9,312	6,186	6,979	7,894	5,370	6,019	6,766
	6	4,406	4,728	5,074	3,993	4,274	4,577	3,637	3,884	4,150
SK	10	7,508	8,564	9,796	6,448	7,304	8,300	5,597	6,299	7,111
	6	4,592	4,939	5,314	4,162	4,465	4,793	3,790	4,058	4,345
AB	10	1,112	1,089	1,020	955	936	882	829	814	771
	6	680	676	664	617	612	603	562	558	550
BC	10	8,934	10,168	11,603	7,673	8,674	9,833	6,661	7,480	8,427
	6	5,464	5,870	6,308	4,952	5,307	5,690	4,510	4,823	5,159

The low TCC values for PV retrofit indicate that the PV systems will not be considered attractive by Canadian households in the absence of substantial subsidies. The BIPV/T systems are economically more attractive with higher TCC values, but considering the higher capital costs required by these systems, external economic forces such as energy rebates, government subsidies, incentive measures, and legislation (such as Carbon tax that panelizes fossil fuel use) will likely be necessary to promote their wide scale adoption.

9.6. Conclusion

The performance of PV and BIPV/T system retrofits in the CHS was investigated considering energy savings, GHG emission reductions and economic feasibility. It was assumed that the retrofits were applied to all houses that are suitable for the installation without the need for major renovations. The findings are as follows:

- About 35% and 25% of existing houses in the CHS are eligible for PV and BIPV/T retrofits, respectively.
- If all eligible houses adopt PV electricity generation, the energy consumption in the CHS will be reduced by 37.5 PJ per year, which is equivalent to 3% annual energy savings. This will results in 3.27 Mt of CO_{2e} equivalent GHG emission reductions, which is 5% of the annual GHG emissions from the CHS. In NF, QC, MB and BC where utility electricity generation is from renewable resources, the impact of PV retrofit on GHG emission reduction is negligible. While the average per house electricity generation by PV systems is similar in all provinces, the reduction in GHG emissions is not. The highest GHG emission reductions occur in regions where the fuel mixture for marginal electricity generation consists mainly of fossil fuels.
- If all eligible houses in the CHS implement BIPV/T system retrofits, the energy consumption in the CHS will be reduced by 227 PJ per year, which is equivalent to 18% annual energy savings. This will remove 10.85 Mt of CO_{2e} equivalent GHG emissions, which is 17% of the annual GHG emissions from the CHS. The change in total electricity use of the CHS is almost negligible while the 99.9% of the annual energy savings is associated with oil and NG consumption. Since replacing existing fossil fuel fired heating systems with heat pumps may increase the electricity demand of some houses, the associated GHG emissions due to electricity use

increases in OT and AB. The overall impact of BIPV/T system retrofit is favorable from both energy conservation and GHG emission perspectives.

- The majority of energy savings and GHG emission reductions from the BIPV/T system are found to occur from the heat pump and not the PV electricity generation.
- The economic analysis indicates that the BIPV/T system retrofit is more feasible in the AT region and QC where oil consumption for space and DHW heating is significantly reduced. The lowest TCC is predicted in AB where the relatively inexpensive NG use is substituted with electricity.
- Although the maximum suitable roof area for PV panel installation was considered, the standalone PV electricity generation is not sufficient to convert existing houses into NZEBs. On the other hand, the BIPV/T system retrofit can substantially reduce energy consumption and will be a suitable option to be included in the set of potential strategies to be evaluated to achieve near NZE or NZE status for Canadian houses.

Chapter 10 Strategies to Convert Existing Canadian Houses into Net/Near-Net Zero Energy Buildings

10.1. Introduction

A variety of definitions and approaches are given in the literature to define net zero energy buildings, some based on an energy balance conducted at the site, some at the source. Marszal *et al.* (2011), Sartori *et al.* (2012) and Torcellini *et al.* (2006) introduced definitions and frameworks for NZEB analysis taking into consideration the energy balance boundary, period and metrics, as well as energy carriers and grid interaction. Hernandez and Kenny (2010) proposed a methodology for life cycle zero energy building (LC-ZEB) analysis to consider the embodied energy of building components and the energy required for building operation. Srinivasan *et al.* (2012) proposed a definition for NZEB using a renewable energy balance with the goal of enhancing the use of renewable resources in buildings. Pietila *et al.* (2012) defined the zero peak house (ZPH) with the goal to eliminate the building electricity draw from grid during utility peak load periods. In an effort to unify the definition for NZE in the building industry, the US Department of Energy (USDOE) recently conducted a comprehensive consultation process to obtain views and recommendations from the international building energy research community. As a result of this consultation, USDOE published a guide that provides a common definition and measurement methods for NZEB (NIBS, 2015). In the guide, USDOE defines NZEB as "*an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy*". The source energy balance is expressed as:

$$E_{source} = \sum_i E_{use,i} r_{use,i} - \sum_j E_{gen,j} r_{gen,j} \tag{10.1}$$

where $E_{use,i}$ is the energy use of type i, $E_{gen,j}$ is the energy generation of type j, $r_{use,i}$ is the source energy conversion factor of energy use type i and $r_{gen,j}$ is the source energy conversion factor for energy type j.

In the USDOE definition, the building boundary is considered such that it includes all property premises, and the utility connections and the energy import/export occur at the building boundary. All energy use by the building, consisting of the energy use by the HVAC system, DHW heating and AL loads, is considered in the NZE analysis. While the calculation of the primary energy use onsite is straightforward, determining the primary energy use to generate the electricity used onsite is not since electricity supplied by the grid is generated from a multitude of primary energy sources. Similarly, the factors for extraction, processing and transportation of primary fuels are difficult to determine. Therefore, to facilitate source energy calculations, the USDOE provides the national average source energy conversion factors for the US energy market (NIBS, 2015). These factors consider the energy consumed for the extraction, processing and transportation of primary fuels, efficiency of energy conversion in power plants, and transmission and distribution losses, and are given in Table 10.1.

Due to its wide acceptance in the building energy research community, the USDOE definition of NZEB is adopted in this work. As per the definition, and the approach used in the previous chapters of this work, the period used in the net zero balance calculations for both energy and GHG emissions is the calendar year.

The energy carriers used in the Canadian housing stock (CHS) are electricity imported from the grid, onsite electricity generation, NG, oil and wood. Since residential scale net metering is allowed in most jurisdictions in Canada (Alberta Energy, 2016; BC Hydro, 2016; Hydro-Quebec, 2016a; NSP, 2016; OEB, 2016), net metering is assumed to apply to all electricity trade between residential customers and the grid.

Table 10.1 Source energy conversion factors

Energy form	Source energy conversion factor (r)	
	US national average (NIBS, 2015)	Provinces with hydro-electricity
Imported electricity	3.15	0
Exported electricity	3.15	0
Natural gas	1.09	1.09
Oil	1.19	1.19
Other	1.05	1.05

Electricity generation in Canada is by provincial utilities, and the fuel mixture used by each utility is different, based on the availability of primary energy sources, economic factors and dispatch considerations (Farhat and Ugursal, 2010). Thus, determining the national and provincial source energy conversion factors would require a comprehensive evaluation of energy market in Canada and is beyond the scope of this work. Therefore, the values given in Table 10.1, provided by the USDOE are used here for NB, NS, PEI, OT, SK and AB. Since an overwhelming majority of electricity generation in NF, QC, MB and BC is from hydro-electricity, the conversion factor for import/export electricity is considered to be zero in these provinces.

10.2. Retrofit Scenarios

Generally, conversion of a building into a NZEB requires two actions (Sartori *et al.*, 2012): (1) energy demand reduction by increasing energy efficiency, (2) electricity and thermal energy generation to earn credit to achieve NZE balance. The first step can be achieved through envelope modifications and appliance/lighting upgrades in an existing house. Technology retrofit options can be introduced into a house to fulfill the second step.

As presented in the earlier chapters of this work, the techno-economic impact of retrofitting eligible houses in the CHS with internal combustion engine (ICE) and Stirling engine (SE) cogeneration, solar combisystem (SCS), air-water heat pump (AWHP), solar assisted heat pump (SAHP) and building integrated photovoltaic/thermal (BIPV/T) systems was investigated using CHREM (Asaee *et al.*, 2016a; Asaee *et al.*, 2015a; Asaee *et al.*, 2015b; Asaee *et al.*, 2015c, 2016b; Asaee *et al.*, 2017a; Asaee *et al.*, 2017b; Asaee *et al.*, 2014). In this chapter, the feasibility of using a combination of these alternative and renewable energy technology retrofits with energy efficiency retrofits to achieve NZ or near NZ status of eligible houses in the CHS is evaluated. As before, the analysis was conducted using CHREM.

Envelope modifications: Envelope modifications include wall, roof and exposed floor insulation upgrades, window replacement and air-tightness improvement. Increasing the insulation level of external walls generally requires extensive reconstruction and substantial capital expenditure rendering such modifications economically infeasible. Therefore, wall insulation upgrades are not considered in this study. However, ceiling and exposed floor insulation upgrades can be implemented without reconstruction: ceiling insulation can be done using blown-in insulation or by adding layers of batt insulation in an attic, and basement insulation can be done by putting a layer of rigid insulation between the floor and floor covering. Thus, it is assumed in this work that regardless of the existing insulation level, ceiling insulation in all houses eligible for retrofit is upgraded to R-60 and exposed floor insulation is upgraded to R-20. The selected R-values are in close agreement with the energy efficiency requirements of the National Building Code of Canada (Section 9.36) (NRC, 2015) and are similar to the recommended insulation levels for retrofitting existing wood-framed buildings by the ENERGY STAR® program (Energy Star, 2016b, 2016d) for northern US climates.

The impact of window improvement on energy consumption and GHG emission of the CHS was investigated by Nikoofard *et al.* (2013) using a large database of window types in the CHREM that includes single, double and triple glazed windows with low-e coating (clear glass, 0.04, 0.1, 0.2 and 0.4 emissivity) at the innermost glazing layer with air gaps ranging from 6mm to 13mm filled with Air or Argon. Results indicated that changing the existing windows type would result in considerable energy savings and GHG emission reductions in the CHS. Triple glazed windows with 13mm argon-filled gap and low-e coating (emissivity 0.1) yielded the largest energy saving and GHG emission reduction among window retrofit options evaluated. Thus, in this study all windows in houses eligible for retrofit are upgraded to triple glazed windows with 13mm argon-filled gap and low-e coating (emissivity 0.1).

Reducing infiltration by caulking and weather stripping is one of the most effective and economically profitable energy saving measures (Energy Star, 2016c). Modern low energy buildings (such as passive house) are required to consider progressive air-tightness requirements (PHI, 2015). With window replacement and standard caulking/weather stripping measures, it is assumed in this study that the infiltration rate is reduced to 50% of its original value in all houses eligible for retrofit.

Appliance/lighting upgrades: About 20 percent of the AL load in the CHS is associated with lighting (OEE, 2013). On average, approximately 30 light bulbs are used in a Canadian household. In a NZE or near NZE household, high efficient lighting including compact fluorescent lamps (CFLs), and light emitting diodes (LEDs) would be used. According to the US Department of Energy, high efficiency lighting yields more than 75% energy savings compared to traditional incandescent lights (OEERE, 2016). Thus, it is assumed in this work that all low efficiency light bulbs in houses eligible for retrofit are replaced with high efficiency alternatives, reducing the total AL load by 15% (75% reduction in lighting load × 20% of AL load associated with lighting).

About 80 percent of the AL load in the CHS is associated with major (including refrigerator, freezer, dishwasher, clothes washer, clothes dryer and electric range) and minor appliances (OEE, 2013). Over the past two decades, the energy consumption of appliances decreased substantially due to technology improvements (OEE, 2014b). It is customary that high efficient ENERGY STAR® (Energy Star, 2016b) certified devices would be installed in a low energy building. Using the state-of-the art of appliance technologies, the major appliance annual electricity use is roughly about 1700 kWh (Energy Star, 2016a) in a low energy house. This is about 30% of the major appliance load of the average house in CSDDRD (OEE, 2014b; Swan *et al.*, 2009). Considering that the number of minor appliances (such as computers, televisions, DVD, stereo systems and digital cable boxes) are increasing in Canadian households (OEE, 2013), it is assumed in this work that the total appliance load in houses eligible for retrofit will decrease by 60% due to appliance upgrades, translating into a reduction of 48% of the total AL load (60% reduction of major appliance load × 80% of appliance load associated with appliances).

Therefore, it is assumed in this work that a total of 63% reduction in AL load will be achieved in all houses eligible for retrofit (15% reduction due to lighting improvements plus 48% reduction due to appliance improvements).

Phase change material (PCM) thermal storage: Nikoofard *et al.* (Nikoofard *et al.*, 2014c) conducted a techno-economic analysis to evaluate the impact of PCM thermal storage on energy consumption and GHG emissions of the CHS. The PCM thermal storage is added beneath the top layer of first floor of eligible houses, thus the retrofit would have the minimum impact on the building geometry. Results indicated that the PCM thermal storage is a suitable energy efficiency measure in the CHS. Therefore, the PCM thermal storage is selected as one of the energy retrofits considered in this study.

Thus, the techno-economic feasibility of achieving NZE or near NZE status for eligible houses in the CHS is evaluated for the six scenarios shown in Table 10.2.

Table 10.2 Retrofit scenarios considered in this study

<table>
<tr><th>Scenario</th><th colspan="2">Description</th></tr>
<tr><td>Sc. 1 (BIPV/T)</td><td>BIPV/T</td><td rowspan="6">Retrofits common to all scenarios:
• envelope modifications
• appliance/lighting upgrade
• phase change material (PCM) thermal storage</td></tr>
<tr><td>Sc. 2 (SAHP)</td><td>SAHP</td></tr>
<tr><td>Sc. 3 (AWHP)</td><td>AWHP</td></tr>
<tr><td>Sc. 4 (SCS)</td><td>SCS</td></tr>
<tr><td>Sc. 5 (SE)</td><td>SE cogeneration</td></tr>
<tr><td>Sc. 6 (ICE)</td><td>ICE cogeneration</td></tr>
</table>

10.3. Methodology

The methodology used is similar to that used in the studies presented in the earlier chapters of this work, and is shown in Figure 10.1.

The houses eligible for each technology upgrade were selected using the eligibility criteria already developed in the earlier chapters. These are as follows:

- BIPV/T: Presence of major roof surface facing south-east, south or south-west and a suitable space for mechanical system installation (Asaee *et al.*, 2016a).
- SAHP: Presence of major roof surface facing south-east, south or south-west and a suitable space for mechanical system installation (Asaee *et al.*, 2017a).
- AWHP: Presence of a suitable space for mechanical system installation (Asaee *et al.*, 2017b).
- SCS: Presence of major roof surface facing south-east, south or south-west and a suitable space for mechanical system installation (Asaee *et al.*, 2016b).
- SE: Presence of a suitable space for mechanical system installation (Asaee *et al.*, 2015b).
- ICE: Presence of a suitable space for mechanical system installation (Asaee *et al.*, 2015a).
- Phase change material (PCM): Presence of a window on the south, south-east and south-west sides (Nikoofard *et al.*, 2014c).
- Window type upgrade: Presence of single glazed, double, glazed and clear triple glazed windows (Nikoofard *et al.*, 2013).
- Insulation upgrade: Houses with attic are considered for roof insulation upgrade.

The number of houses in the CHS eligible for each scenario is given in Table 10.3.

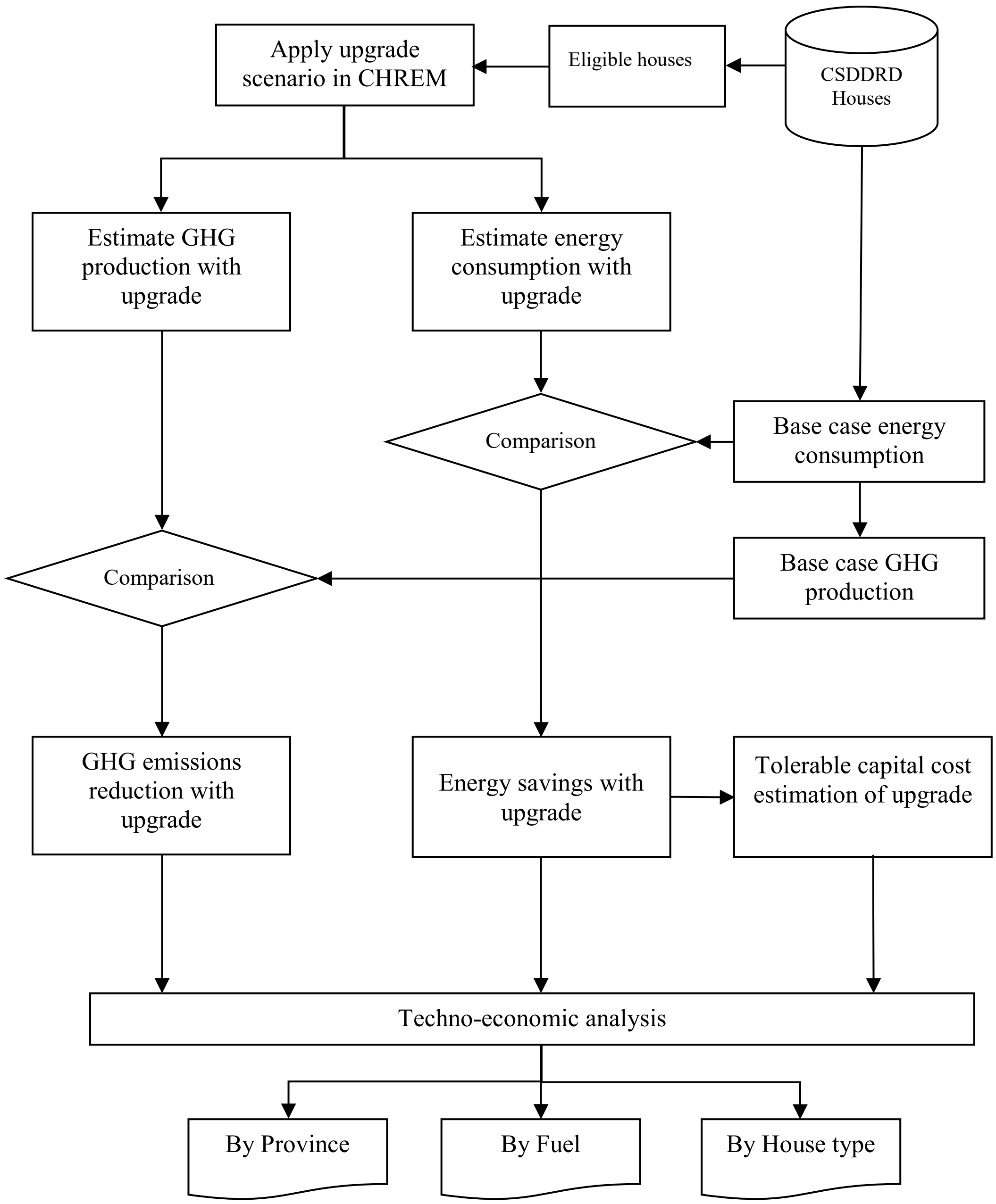

Figure 10.1 Flow diagram of the overall methodology that is used in this study (Asaee *et al.*, 2016d)

Table 10.3 Percent eligible houses for each scenario evaluated

Province	Total houses		Percent eligible houses					
	CHREM	CHS	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	202	174,977	16	31	46	31	46	46
NS	714	298,145	27	42	66	42	66	66
PE	79	44,995	30	51	82	51	82	82
NB	413	238,327	21	27	46	27	46	46
QC	3,680	1,985,444	5	12	18	12	18	18
OT	6,635	3,434,683	29	42	82	42	82	82
MB	937	340,241	27	30	68	30	68	68
SK	202	316,774	37	42	83	42	83	83
AB	2,005	974,773	36	47	92	47	92	92
BC	2,085	1,114,832	22	31	68	31	68	68
Canada	16,952	8,923,191	23	34	65	34	65	65

Once the eligible houses for each upgrade scenario were selected, building energy performance simulations were conducted using ESP-r with 5-minute time step over an entire year to estimate required energy consumption and GHG emissions. The energy consumption and GHG emission values were compared with those for the base case. Also, economic analysis was done for all scenarios using the tolerable capital cost approach used in the previous chapters (Nikoofard *et al.*, 2014a). Energy, emissions and economic analysis results are presented in the following sections.

10.4. Results and Discussion

The CHREM estimates of the annual energy consumption and GHG emission of the CHS by energy source and province are given in Table 10.4. The accuracy of results were verified by comparing the estimates with the available data on energy use in the CHS (Swan *et al.*, 2013).

The savings in the annual end-use energy consumption and the associated reductions in GHG emissions for the entire CHS due to the implementation of the six retrofit scenarios to all eligible houses are given in Table 10.5. To show the potential for energy savings and GHG emission reductions for the entire CHS, the percent energy savings and emission reductions are calculated using Equations (10.2) and (10.3), and the results are given in Table 10.6.

$$EES_{Sc.i} = \frac{EE_{CHS} - (EE_{EL,Sc.i} + EE_{N\text{-}E,Sc.i})}{EE_{CHS}} \quad (10.2)$$

$$GER_{Sc.i} = \frac{GHG_{CHS} - (GHG_{EL,Sc.i} + GHG_{N\text{-}E,Sc.i})}{GHG_{CHS}} \quad (10.3)$$

where subscript *i* denotes the retrofit scenario (*i*=1-6), and

$EES_{sc.i}$	end-use energy savings ratio due to each retrofit scenario (*i*=1-6)
EE_{CHS}	end-use energy consumption of the CHS
$EE_{EL,Sc.i}$	post retrofit end-use energy consumption of eligible houses (*i*=1-6)
$EE_{N\text{-}E,Sc.i}$	end-use energy consumption of houses not eligible for retrofit (*i* =1-6)
$GER_{Sc.i}$	GHG emission reduction ratio due to each retrofit scenario (*i*=1-6)
GHG_{CHS}	GHG emission of the CHS
$GHG_{EL,Sc.i}$	post retrofit GHG emission of eligible houses (*i*=1-6)
$GHG_{N\text{-}E,Sc.i}$	GHG emission of houses not eligible for retrofit (*i*=1-6)

As seen in Table 10.6, the highest energy savings is possible by Sc. 3 (AWHP). Although the number of eligible houses for Sc. 3 (AWHP), Sc. 5 (SE) and Sc. 6 (ICE) are the same as shown in Table 10.3, SC. 3 (AWHP) provides the largest energy savings because the COP of the heat pump is above one and the amount of end-use energy (electricity) used by the heat pump for heating purposes is generally lower compared to the electric resistance heater and fossil fuel based heating systems. While the number of eligible houses for the Sc. 1 (BIPV/T) retrofit is considerably lower compared to that of other retrofit scenarios, the end-use energy savings due to Sc.1 (BIPV/T) is comparable to the savings with Sc. 2 (SAHP) and Sc. 4 (SCS). Thus, amongst active solar technologies, the BIPV/T system retrofit provides the best performance in the CHS. Since OT has the largest house stock in Canada, the annual end-use energy savings are considerably higher in OT compared to other provinces. However, the percent energy savings of different retrofits are in close range across Canada. Number of eligible houses in QC are relatively low due to the wide use of electricity for space heating, and the consequent lack of a mechanical room in many houses. For this reason, QC yields the lowest percent energy savings in the CHS. While the percent energy savings illustrate the performance of retrofit scenarios in every province, the end-use energy savings show the impact of retrofit scenarios on the national energy consumption and can be used for federal level policy making.

Table 10.4 CHREM estimates of annual energy consumption and GHG emissions for the CHS

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 10.5 Savings in annual end-use energy consumption and GHG emission reductions for the CHS due to scenarios 1-6

Province	Energy savings (PJ)						GHG emission reduction (Mt of CO_{2e})					
	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	4.2	8.5	10.9	8.4	8.0	7.3	0.18	0.36	0.57	0.33	0.23	0.05
NS	10.9	15.8	24.0	15.2	17.4	16.1	1.02	1.47	2.00	1.50	1.69	1.77
PE	2.1	2.8	4.1	2.6	3.0	2.8	0.10	0.16	0.28	0.14	0.13	0.07
NB	7.6	10.4	15.3	10.2	12.1	11.0	0.45	0.51	0.37	0.55	0.73	1.09
QC	12.7	27.8	33.9	27.0	24.8	22.1	0.51	1.18	1.70	1.08	0.74	0.23
OT	131.6	181.2	305.2	176.1	221.3	200.4	6.85	9.48	11.97	9.79	13.48	16.57
MB	11.5	12.0	23.0	11.5	17.4	14.9	0.53	0.54	1.22	0.49	0.64	0.19
SK	15.0	17.9	28.4	17.4	22.4	19.8	1.13	1.28	2.03	1.33	1.77	1.76
AB	45.6	58.5	92.0	55.7	69.9	62.4	3.40	4.28	4.49	4.94	7.12	10.42
BC	29.8	42.9	78.5	41.8	56.7	50.5	1.19	1.72	3.42	1.58	1.88	0.96
Canada	271.0	377.7	615.1	366.0	452.9	407.3	15.35	20.98	28.06	21.73	28.40	33.13

Table 10.6 Percent savings in annual end-use energy consumption and GHG emission reductions for the CHS due to scenarios 1-6

Province	Energy savings (%)						GHG emission reduction (%)					
	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	15	30	39	30	28	26	22	46	72	42	29	7
NS	24	34	52	33	38	35	19	27	37	28	31	33
PE	28	38	56	36	41	38	27	41	74	38	34	19
NB	19	27	39	26	31	28	15	16	12	18	24	35
QC	5	11	14	11	10	9	20	46	66	42	29	9
OT	25	35	58	34	42	38	24	33	42	34	47	58
MB	22	23	44	22	33	28	30	31	69	27	36	11
SK	29	35	56	34	44	39	25	29	45	30	39	39
AB	31	39	62	38	47	42	25	31	33	36	52	76
BC	20	28	52	28	38	34	25	37	73	34	40	21
Canada	21	29	48	28	35	32	24	32	43	33	44	51

The GHG emission reductions due to retrofit scenarios indicate that Sc. 6 (ICE), Sc. 5 (SE) and Sc. 3 (AWHP) have the largest effect on the GHG emission of the CHS. The high percentage of eligible houses for Sc. 6 (ICE), Sc. 5 (SE) and Sc. 3 (AWHP) is one of the main reasons for the significantly high GER in the CHS. Since marginal electricity generation in NB and AB relies heavily on fossil fuels, Sc. 3 (AWHP) GER is not close to that of SC. 6 (ICE) and Sc. 5 (SE). Onsite electricity generation with the BIPV/T system offsets a portion of the electricity consumption of the heat pump and provides a high GER among retrofit scenarios. The GER in each province strongly depends on the current status of onsite fossil fuel use and the fuel mixture used by the utility for electricity generation. For example, in AB where fossil fuels are dominant in the fuel mixture for utility electricity generation, retrofit scenarios with onsite electricity generation capability are more favourable for GHG emission reduction.

Since source energy is considered for NZE analysis, the average source energy use intensity and average electricity generation intensity expressed in terms of source energy use by the utility are presented in Table 10.7 for each retrofit scenario. The average source energy intensity (*ASEI*) and the average GHG emission intensity (*AGEI*) in each province are determined using Equations (10.4) and (10.5):

$$ASEI_{Sc.i} = \frac{\sum SEI_{EL,Sc.i} + \sum SEI_{N\text{-}E,Sc.i}}{total\ number\ of\ houses\ in\ the\ province} \quad (10.4)$$

$$AGEI_{Sc.i} = \frac{\sum GEI_{EL,Sc.i} + \sum GEI_{N\text{-}E,Sc.i}}{total\ number\ of\ houses\ in\ the\ province} \quad (10.5)$$

where $SEI_{EL,Sc.i}$ is the source energy intensity of eligible houses, $SEI_{N\text{-}E,Sc.i}$ is the source energy intensity of non-eligible houses, $GEI_{EL,Sc.i}$ is the GHG emission intensity of eligible houses and $GEI_{N\text{-}E,Sc.i}$ is the GHG emission intensity of non-eligible houses for each retrofit scenario (i=1-6).

Due to various types of heating systems and primary energy sources used in the CHS, the ASEI of the CHS (‘base case’) vary in the range of 37-526 kWh/m^2. As discussed earlier, the performance of retrofit options vary substantially amongst provinces. Thus, the impact of individual retrofit scenarios on the ASEI varies substantially in the CHS. Since net metering is assumed in this study, electricity generation of residential customers offsets a portion of the ASEI. As the results given in Table 10.7 show, Sc.6 (ICE) earns the highest credit for onsite electricity generation. As discussed earlier, onsite electricity generation does not reduce source energy in provinces where hydro-electricity is dominant, (i.e. in NF, QC, MB and BC). Therefore, cogeneration technologies are more attractive in provinces that heavily depend on fossil fuel for electricity generation, as shown in Table 10.8 where average net source energy intensities, A-B in Table 10.7, are given for each province.

The average GHG emission intensities associated with energy use and electricity generation are provided in Table 10.9 and average net GHG emission intensity, i.e. A-B in Table 10.9, values are provided in Table 10.10. These results indicate that (i) the performance of the retrofit scenarios on GHG emissions of the CHS strongly depends on the energy sources used and (ii) the GHG emission intensity of the CHS can substantially be reduced by implementing the retrofit scenarios. Due to the large variation in the results from province to province, detailed results on energy consumption, GHG emissions and economic feasibility for each province are presented and discussed below. Suitable paths for converting existing houses into net/near-net zero energy buildings are identified and recommendations to enhance the performance of the technologies evaluated are also provided.

Table 10.7 Average annual source energy use and generation intensity per unit area (kWh/m^2) for the CHS due to scenarios 1-6

Province	Average source energy use intensity (A)							Average onsite electricity generation source energy intensity expressed in terms of source energy used by utility (B)		
	CHS (base case)	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)	Sc. 1 (BIPV/T)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	132	103	74	29	81	86	114	0	0	0
NS	474	399	355	331	353	331	360	12	17	84
PE	478	390	319	301	315	312	341	13	19	87
NB	526	461	440	407	436	402	430	12	14	71
QC	37	30	24	14	26	30	38	0	0	0
OT	348	289	266	236	261	220	256	10	19	96
MB	181	125	128	49	135	113	163	0	0	0
SK	429	350	331	296	328	282	329	21	24	123
AB	326	254	231	190	227	184	227	15	20	111
BC	124	90	82	30	87	75	104	0	0	0

Table 10.8 Annual average net source energy intensity (kWh/m^2) for the CHS due to scenarios 1-6

Province	Average source energy intensity (A-B in Table 10.7)						
	CHS (base case)	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	132	103	74	29	81	86	114
NS	474	387	355	331	353	314	276
PE	478	377	319	301	315	293	254
NB	526	449	440	407	436	388	359
QC	37	30	24	14	26	30	38
OT	348	279	266	236	261	201	160
MB	181	125	128	49	135	113	163
SK	429	329	331	296	328	258	206
AB	326	239	231	190	227	164	116
BC	124	90	82	30	87	75	104

Table 10.9 Average annual GHG emission and reduction intensity due to electricity generation per unit area (kg/m^2) for the CHS due to scenarios 1-6

Province	Average GHG emission intensity associated with energy use (A)							Average reduction in GHG emission intensity due to onsite electricity generation expressed in terms of GHG emission by utility (B)		
	CHS (base case)	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)	Sc. 1 (BIPV/T)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	25	20	15	7	20	19	25	0	0	0
NS	104	85	77	66	88	74	80	1	2	10
PE	54	40	31	18	37	36	42	0	0	0
NB	72	64	62	64	68	59	65	3	4	19
QC	7	5	4	2	5	5	6	0	0	0
OT	41	32	30	24	32	25	31	2	3	13
MB	32	21	23	9	28	20	28	0	0	0
SK	93	73	73	57	83	63	71	2	2	9
AB	73	58	54	49	60	41	48	4	5	30
BC	22	16	15	6	17	14	19	0	0	0

Table 10.10 Annual average net GHG emission intensity (kg/m²) for the CHS due to scenarios 1-6

Provinces	Average GHG emission intensity (A-B in Table 10.9)						
	CHS (base case)	Sc. 1 (BIPV/T)	Sc. 2 (SAHP)	Sc. 3 (AWHP)	Sc. 4 (SCS)	Sc. 5 (SE)	Sc. 6 (ICE)
NF	25	20	15	7	20	19	25
NS	104	84	77	66	88	72	70
PE	54	40	31	18	37	36	42
NB	72	61	62	64	68	55	46
QC	7	5	4	2	5	5	6
OT	41	30	30	24	32	22	18
MB	32	21	23	9	28	20	28
SK	93	71	73	57	83	61	62
AB	73	54	54	49	60	36	18
BC	22	16	15	6	17	14	19

10.4.1. Newfoundland and Labrador

Hydro-electricity (on-peak and off-peak) is widely available in NF (Farhat and Ugursal, 2010). Therefore, source energy and GHG emissions associated with electricity use, and consequently, source energy offset due to onsite electricity generation by residential customers, are negligible as shown in Table 10.7 and Table 10.9. As shown in Table 10.4, electricity has the largest share of housing stock energy use followed by oil and wood. Since electricity generation in NF is free of GHG emissions, and wood is considered to be carbon neutral, oil consumption is solely responsible for the GHG emissions of the housing stock in NF.

The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.11 for each retrofit scenario[1, 2, 3]. The same data are plotted in Figure 10.2 where the size of each circle represents the percentage of eligible houses in each source energy intensity

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[1] Since Table 10.11 is used to present the results in all provinces, its interpretation is discussed here to clarify its contents. The table is organized according to "Source Energy Intensity" ranges. For each retrofit scenario, the first row provides the percentage of houses eligible to receive that particular scenario retrofits corresponding to the given range of source energy intensity. The second row provides the post-retrofit average source energy intensity of the same houses. Thus, for example, Table 10.11 shows that 6% of the houses eligible to receive Scenario 1 retrofits have a source energy intensity between 300-400 kWh/m^2. After these houses receive Scenario 1 retrofits, their average source energy intensity, i.e. post-retrofit average source intensity (PRASEI), drops to 26 kWh/m^2.

[2] The simulation of a few houses was unsuccessful after applying the upgrade scenarios due to simulator instability and out of bounds error production. In those cases, the house was omitted from eligible house pool. As a result, the number of eligible houses may vary for retrofit scenarios that have the same eligibility criteria. For example, ICE and SE cogeneration have the same eligibility criteria but the percentage of houses in the last three energy intensity ranges are slightly different.

[3] The results in Table 10.10 indicate that compared to the houses with existing source energy intensity of 500-600kWh/m^2, houses with existing source energy intensity of 600kWh/m^2 and higher would have a lower average source energy intensity after Sc. 2 (SAHP) and Sc. 4 (SCS) retrofit. This counter-intuitive results occurs due to the relatively small percentage of the eligible houses in those existing source energy intensity ranges which increase the variance of results. Similar results are found in some other provinces and retrofit scenarios as well.

range. Since the source energy associated with electricity consumption is zero in NF, the existing energy intensity of houses is mainly below 500kWh/m^2.

Since the source energy associated with electricity use is zero in NF, retrofit options that include a heat pump system, i.e. Sc. 1 (BIPV/T), Sc. 2 (SAHP) and Sc. 3 (AWHP) are the best options to approach/achieve NZE status for existing houses. As shown in Table 10.11 and Figure 10.2, retrofit scenarios Sc. 1 (BIPV/T) and Sc. 3 (AWHP) are by far the best retrofit options to approach NZE status in the houses eligible for retrofit in NF. As the post-retrofit average source energy intensity numbers show, these will reduce source energy intensity of the vast majority of the eligible houses to less than 30 kWh/m^2 per year. Considering that this energy consumption includes all energy use in a house, i.e. space and DHW heating, appliances and lights, it is clear that the Sc. 1 (BIPV/T) and Sc. 3 (AWHP) retrofits are very effective.

Although Sc. 1 (BIPV/T), Sc. 2 (SAHP) and Sc. 3 (AWHP) retrofitted houses will be very close to NZE status, enough credit to satisfy the net zero energy balance, given in Equation (10.1), will not be achieved with only electricity generation.

Table 10.11 Distribution (%) of existing houses based on existing source energy intensity (kWh/m^2) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Newfoundland and Labrador

Existing source energy intensity (kWh/m^2)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	0	0	3	6	27	64
	PRASEI (kWh/m^2)	-	-	23	26	18	11
Sc. 2 (SAHP)	Eligible houses (%)	2	2	5	16	32	44
	PRASEI (kWh/m^2)	53	140	61	76	61	36
Sc. 3 (AWHP)	Eligible houses (%)	1	2	9	13	28	47
	PRASEI (kWh/m^2)	131	17	33	12	18	15
Sc. 4 (SCS)	Eligible houses (%)	2	2	5	16	32	44
	PRASEI (kWh/m^2)	108	190	92	103	86	54
Sc. 5 (SE)	Eligible houses (%)	1	2	9	14	29	44
	PRASEI (kWh/m^2)	280	261	215	170	146	103
Sc. 6 (ICE)	Eligible houses (%)	1	2	9	12	28	47
	PRASEI (kWh/m^2)	415	432	320	240	219	137

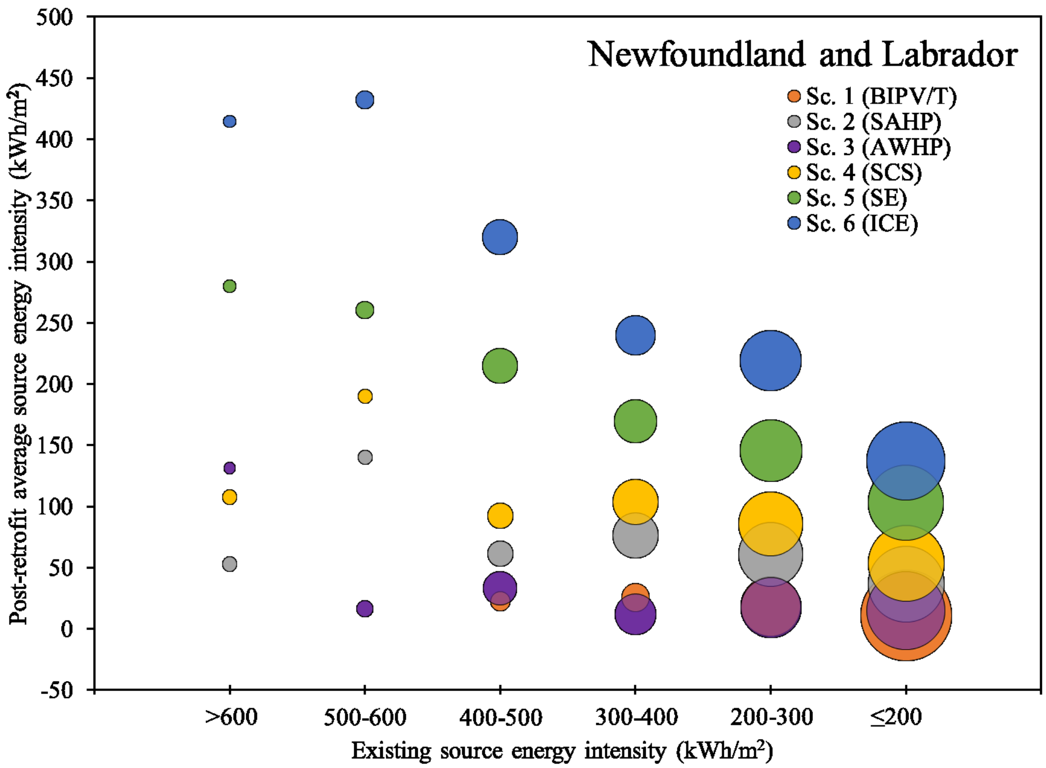

Figure 10.2 Impact of retrofit scenarios on energy intensity of existing houses in NF (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.12 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m^2) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Newfoundland and Labrador

Existing GHG emission intensity (kg/m^2)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	0	3	3	21	48	24
	PRAGEI (kg/m^2)	-	6	6	5	3	3
Sc. 2 (SAHP)	Eligible houses (%)	3	3	8	25	40	21
	PRAGEI (kg/m^2)	23	18	21	15	10	8
Sc. 3 (AWHP)	Eligible houses (%)	2	6	6	22	43	20
	PRAGEI (kg/m^2)	19	9	6	6	5	5
Sc. 4 (SCS)	Eligible houses (%)	3	3	8	25	40	21
	PRAGEI (kg/m^2)	33	25	27	20	14	12
Sc. 5 (SE)	Eligible houses (%)	2	7	7	22	44	18
	PRAGEI (kg/m^2)	67	51	44	33	24	25
Sc. 6 (ICE)	Eligible houses (%)	2	7	5	22	42	21
	PRAGEI (kg/m^2)	104	75	63	48	32	33

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.12 and Figure 10.3 for each retrofit scenario. The retrofit scenarios that include a heat pump substantially reduce the environmental footprint of houses in NF.

Since hydro-electricity is widely available in NF, the GHG emission offset of retrofit scenarios that include cogeneration systems, i.e. Sc. 5 (SE) and Sc. 6 (ICE), is negligible. Thus, cogeneration systems can in fact increase the GHG emission intensity of houses that have low existing GHG emission intensity. Because in the lower ranges of existing GHG emission intensity, electricity is likely used for a portion of heating, replacing existing heating systems with cogeneration may increase the GHG emissions from those houses.

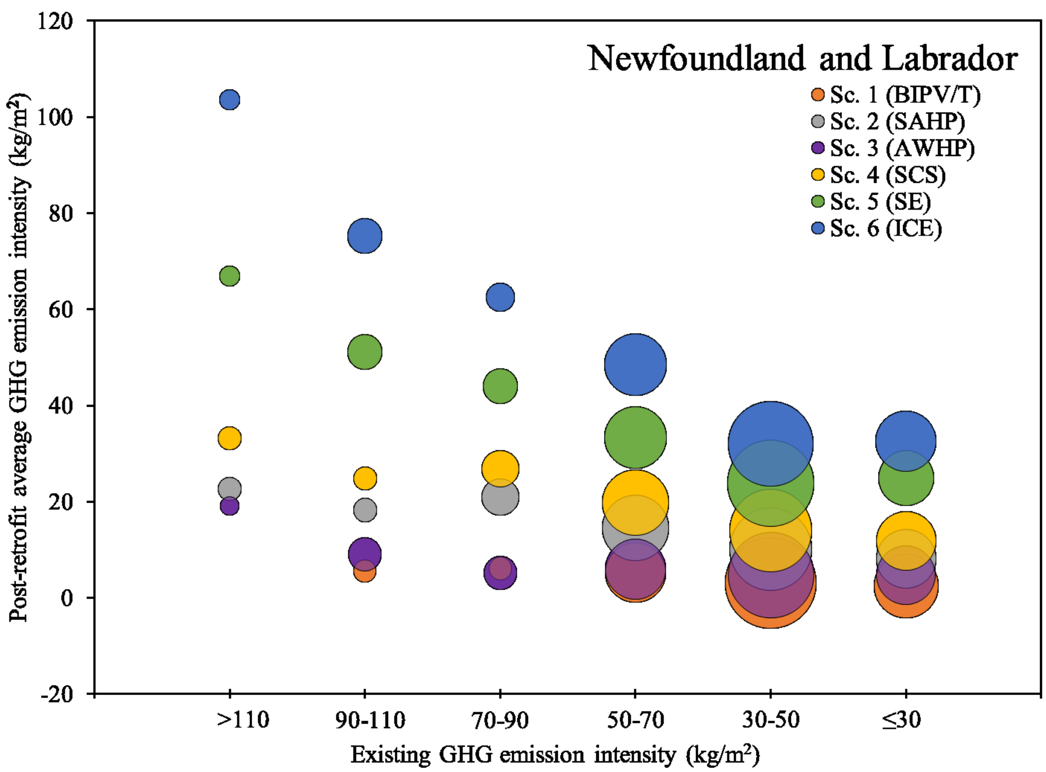

Figure 10.3 Impact of retrofit scenarios on GHG emission intensity of existing houses in NF (Note: the size of the circle is proportional with the number of eligible houses in each category)

From an economic perspective, it is likely that rather than the Sc. 1 (BIPV/T) retrofit, Sc. 3 (AWHP) retrofit may prove to be a more preferable path to converting existing houses into low energy buildings in NF because of the higher initial investment and maintenance costs of the BIPV/T system. As shown in Table 10.13, the TCC of Sc. 1 (BIPV/T) retrofit is about 15% higher than that of Sc. 3 (AWHP). Since this difference is not substantial, it may not be sufficient to cover the additional cost associated with the BIPV/T system. Furthermore, there are many more houses eligible for the AWHP retrofit compared to the BIPV/T retrofit as shown in Table 10.3, making the AWHP retrofit more effective from a provincial perspective.

Table 10.13 Average TCC per house for selected retrofit scenarios in NF

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 3 (AWHP)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	43,485	25,291	38,086	21,734
	Medium	51,884	27,839	45,448	23,911
	High	62,176	30,654	54,458	26,314
6	Low	37,126	22,873	32,447	19,640
	Medium	43,911	25,099	38,387	21,542
	High	52,186	27,556	45,622	23,638
9	Low	32,045	20,792	27,948	17,840
	Medium	37,581	22,747	32,788	19,509
	High	44,299	24,901	38,655	21,346

Overall, it can be concluded from these results that it is technically and economically feasible to upgrade nearly half of all existing houses in NF to achieve near NZE status by making envelope improvements and adding a thermal storage system with AWHP or BIPV/T systems. These upgrades would reduce the end-use energy consumption of the NF housing stock by more than 30% and GHG emissions by about 70%.

Thus, if the objective is to achieve near NZE status for the existing NF housing stock, the focus should be on Sc. 3 (AWHP) and Sc.1 (BIPV/T) retrofits. To choose the more suitable option for a given house, a house specific evaluation will be necessary. Additional actions that can help to fill the gap between the source energy use and onsite electricity generation, and come closer to NZE status include:

1. Using higher insulation levels in the roof and floors, further lowering the infiltration rate to achieve higher air-tightness levels and increasing the thermal energy storage capacity of the PCM system to further lower the thermal energy demand of the building.

2. Using traditional electric resistance heater as auxiliary energy source if there is sufficient capacity in the grid.

Close to half of existing houses in NF are not eligible for Sc. 3 (AWHP) system retrofit as stated in Table 10.3. One of the main obstacles for eligibility is the absence of a mechanical room in the building. If a suitable mechanical room is added inside or outside of the house, the number of eligible houses would increase substantially.

10.4.2. Nova Scotia

Electricity generation in NS is mainly from fossil fuel sources (coal, NG and heavy oil) at base and peak periods. The significant share of coal in the fuel mix causes a large source energy and GHG emission intensity in NS (Farhat and Ugursal, 2010). Oil, electricity and wood are the major sources of residential energy use (in descending order) in NS as shown in Table 10.4. The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.14 for each retrofit scenario. The same data are plotted in Figure 10.4 where the size of each circle represents the percentage of eligible houses in each source energy intensity range.

Table 10.14 Distribution (%) of existing houses based on existing source energy intensity (kWh/m^2) and post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Nova Scotia

Existing source energy intensity (kWh/m^2)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	8	9	27	37	18	1
	PRASEI (kWh/m^2)	223	126	98	70	50	41
Sc. 2 (SAHP)	Eligible houses (%)	10	14	25	35	15	0
	PRASEI (kWh/m^2)	268	188	156	120	93	70
Sc. 3 (AWHP)	Eligible houses (%)	12	12	25	33	17	0
	PRASEI (kWh/m^2)	349	267	221	184	146	100
Sc. 4 (SCS)	Eligible houses (%)	10	14	25	35	15	0
	PRASEI (kWh/m^2)	248	179	149	115	90	67
Sc. 5 (SE)	Eligible houses (%)	12	12	25	33	18	0
	PRASEI (kWh/m^2)	281	215	178	148	118	86
Sc. 6 (ICE)	Eligible houses (%)	12	12	24	34	17	0
	PRASEI (kWh/m^2)	188	139	128	104	84	67

Due to the large share of fossil fuels, including onsite oil consumption for heating and off-site fossil fuel use for electricity generation, the existing source energy intensity of NS houses are mainly above 200kWh/m^2, and all retrofit scenarios yield a considerable source energy intensity reduction. While Sc. 1 (BIPV/T) system retrofit provides the lowest average source energy intensity among retrofit scenarios, Sc. 3 (AWHP) retrofit provides the highest. Since both systems use heat pump technology for space and DHW heating, the difference is due to the onsite electricity generation capacity of the BIPV/T system. Also, the heat pump has a better performance in the BIPV/T system as the evaporator operates with air supplied from the PV panels which provides a higher temperature air compared to the ambient. Due to the significant magnitude of the onsite electricity generation, Sc. 6 (ICE) cogeneration results in the second lowest average source energy intensity. Sc. 5 (SE) cogeneration system has a lower electricity generation capacity compared to Sc. 6 (ICE) cogeneration system, therefore offering a smaller potential for source energy offset. Thus, Sc. 1 (BIPV/T) and Sc. 6 (ICE) are the best retrofit scenarios to convert eligible houses into near NZEB in NS.

Amongst all retrofit scenarios evaluated here, the only scenario that can achieve net zero (NZ) status in NS is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity with no source energy consumption. It is possible to convert 12 percent of eligible houses in NS to NZEBs with the Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses will approach but not achieve NZE status.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.15 and Figure 10.5 for each retrofit scenario. Majority of houses in NS have a considerable GHG emission intensity (50kg/m^2 and higher). Retrofit scenarios that use active solar systems, i.e. Sc. 1 (BIPV/T), Sc. 3 (AWHP) and Sc. 4 (SCS), yield the largest GHG emission intensity reduction in existing houses. Sc. 6 (ICE) retrofit in eligible houses is less effective from GHG emission intensity reduction point of view compared to the source energy intensity reduction.

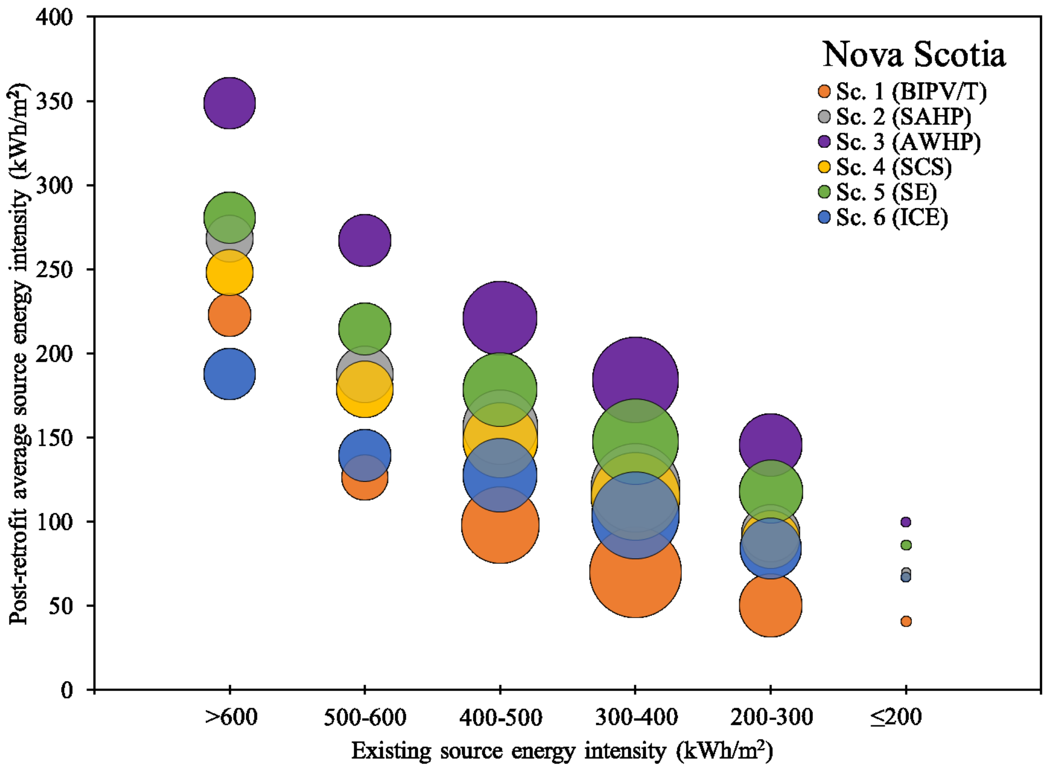

Figure 10.4 Impact of retrofit scenarios on energy intensity of existing houses in NS (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.15 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m²) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Nova Scotia

Existing GHG emission intensity (kg/m²)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	19	21	34	24	2	0
	PRAGEI (kg/m²)	27	20	14	12	15	-
Sc. 2 (SAHP)	Eligible houses (%)	26	21	30	20	3	0
	PRAGEI (kg/m²)	45	34	28	22	25	-
Sc. 3 (AWHP)	Eligible houses (%)	23	22	30	21	4	0
	PRAGEI (kg/m²)	50	38	32	27	29	-
Sc. 4 (SCS)	Eligible houses (%)	25	21	30	21	3	0
	PRAGEI (kg/m²)	45	34	28	22	26	-
Sc. 5 (SE)	Eligible houses (%)	23	21	30	22	4	0
	PRAGEI (kg/m²)	58	44	37	31	35	
Sc. 6 (ICE)	Eligible houses (%)	23	21	30	22	4	0
	PRAGEI (kg/m²)	57	42	35	29	33	-

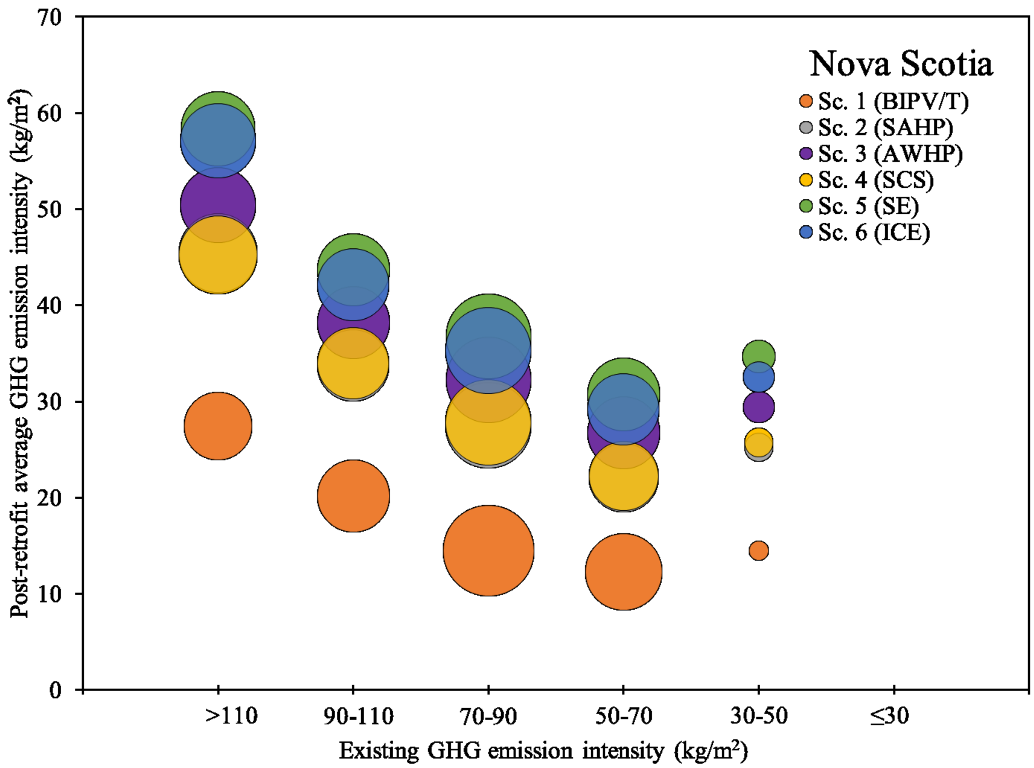

Figure 10.5 Impact of retrofit scenarios on GHG emission intensity of existing houses in NS (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.16 Average TCC per house for selected retrofit scenarios in NS

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 6 (ICE)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	43,255	25,005	28,739	17,374
	Medium	51,691	27,543	34,192	19,117
	High	62,037	30,350	40,876	21,044
6	Low	36,904	22,608	24,647	15,737
	Medium	43,717	24,826	29,064	17,261
	High	52,032	27,275	34,451	18,944
9	Low	31,833	20,547	21,366	14,327
	Medium	37,388	22,494	24,980	15,667
	High	44,136	24,641	29,363	17,144

Provincial authorities in NS have announced plans to increase the capacity of renewable electricity generation using solar, tidal and wind resources (NSDE, 2015). Therefore, lower GHG EIF for utility electricity generation can be expected in future. In that case, the solar thermal system retrofit scenarios (i.e. SCS and SAHP) would gain more attention in NS.

As shown in Table 10.16, the TCC for Sc. 6 (ICE) is about 70 percent of the TCC for Sc. 1 (BIPV/T), making the Sc. 1 (BIPV/T) retrofit scenario the most suitable path to approach NZE status for eligible houses in NS. However, due to low number of eligible houses for Sc. 1 (BIPV/T), Sc. 6 (ICE) is a more effective retrofit is NS from provincial point of view.

As shown in Table 10.3 about 70 percent of existing houses cannot qualify for the Sc. 1 (BIPV/T) retrofit. Non-eligible houses for Sc. 1 (BIPV/T) are likely not qualified for retrofit due to lack of a mechanical room and/or suitable roof area for PV panel installation. Any changes in roof geometry require major reconstruction and is not a realistic approach. Thus, Sc. 6 (ICE) retrofit should be pursued as an alternative scenario for eligible houses in NS.

Potential strategies to promote energy conservation and NZE penetration in housing stock of NS include:

1. Reducing household electricity consumption to reduce both source energy consumption and GHG emissions of houses is necessary. Such approaches include rebates on ENERGY STAR® devices, advanced lighting controls and occupant education on energy efficiency.
2. Introducing further energy efficiency measures (increase insulation level and air-tightness) to decrease heating demand of houses and shrink oil consumption.
3. Promote solar thermal systems for space and DHW heating.
4. Reduction of source energy consumption and GHG emission intensity of electricity supplied by the grid.

10.4.3. Prince Edward Island

Majority of the electricity demand of PE is imported from NB at peak periods (Farhat and Ugursal, 2010), thus onsite electricity generation will offset the non-renewable electricity generation in NB. Therefore, the source energy average conversion factors (provided in Table 10.1) are used for NZE analysis. Similar to NS, oil, electricity and wood are the sources of energy used by residential customers in PE. The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.17 for each retrofit scenario. The same data are plotted in Figure 10.6 where the size of each circle represents the percentage of eligible houses in each source energy intensity range. Sc. 1 (BIPV/T) retrofit is the best strategy by a wide margin to reduce source energy intensity of eligible houses in PE. The average source energy intensity with Sc. 6 (ICE) and solar thermal system retrofits, i.e. Sc. 2 (SAHP) and Sc. 4 (SCS), in a close range follow Sc. 1 (BIPV/T) retrofit. Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZ status in PE is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity with no source energy consumption. It is possible to convert 5 percent of eligible houses in PE to NZEBs with the Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses will approach but not achieve NZE status.

Table 10.17 Distribution (%) of existing houses based on existing source energy intensity (kWh/m^2) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Prince Edward Island

Existing source energy intensity (kWh/m^2)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	21	13	17	25	25	0
	PRASEI (kWh/m^2)	184	177	107	61	32	-
Sc. 2 (SAHP)	Eligible houses (%)	30	10	18	25	15	3
	PRASEI (kWh/m^2)	256	200	142	122	92	66
Sc. 3 (AWHP)	Eligible houses (%)	20	8	17	31	23	2
	PRASEI (kWh/m^2)	348	248	208	191	156	108
Sc. 4 (SCS)	Eligible houses (%)	30	10	18	25	15	3
	PRASEI (kWh/m^2)	248	187	137	117	89	63
Sc. 5 (SE)	Eligible houses (%)	19	9	17	31	22	2
	PRASEI (kWh/m^2)	310	201	165	153	124	88
Sc. 6 (ICE)	Eligible houses (%)	20	8	17	29	24	2
	PRASEI (kWh/m^2)	265	132	122	105	80	55

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.18 and Figure 10.7 for each retrofit scenario. While very low PRAGEI can be achieved in the majority of eligible houses in PE by Sc. 1 (BIPV/T) retrofit scenario, Sc. 5 (SE) and Sc. 6 (ICE) cogeneration retrofits are the least favorable options from the GHG emissions perspective. Although Sc. 1 (BIPV/T) provides the closest to net zero emission (NZEm), since about 70 percent of the PE houses are not eligible for Sc. 1 (BIPV/T) retrofit, Sc. 6 (ICE) should also be considered to devise strategies to promote net zero emission building (NZEmB) in PE.

As shown in Table 10.3, close to 80 percent of existing houses can qualify for Sc. 6 (ICE) retrofit, making Sc. 6 (ICE) very effective retrofit from the province point of view. If onsite electricity generation can offset the non-renewable electricity in NB, Sc. 6 (ICE) will become a more attractive option. Also, biomass fuels can help to achieve lower GHG emission intensity in houses with Sc. 6 (ICE) retrofit.

As shown in Table 10.19, the TCC for Sc. 6 (ICE) is about 70 percent of TCC for Sc. 1 (BIPV/T). Thus, Sc. 1 (BIPV/T) is likely more attractive economically. However, due to the different system components of ICE and BIPV/T systems, comparing the initial investment and maintenance costs of those systems is not straightforward. Therefore, a house specific analysis is necessary to select the most appropriate scenario for a given house.

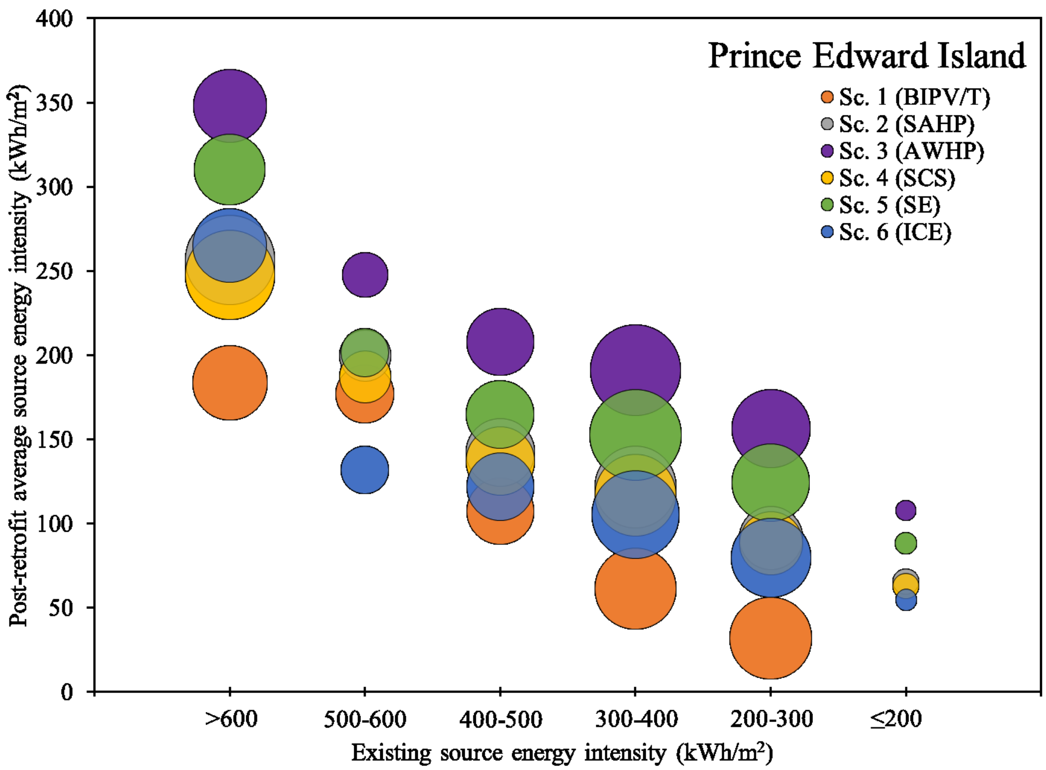

Figure 10.6 Impact of retrofit scenarios on energy intensity of existing houses in PE (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.18 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m^2) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Prince Edward Island

Existing GHG emission intensity (kg/m^2)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	0	8	17	29	33	13
	PRAGEI (kg/m^2)	-	15	6	4	3	4
Sc. 2 (SAHP)	Eligible houses (%)	3	15	20	28	25	10
	PRAGEI (kg/m^2)	20	20	20	13	11	14
Sc. 3 (AWHP)	Eligible houses (%)	2	9	14	37	29	9
	PRAGEI (kg/m^2)	38	28	17	9	7	8
Sc. 4 (SCS)	Eligible houses (%)	3	15	20	28	25	10
	PRAGEI (kg/m^2)	26	25	26	15	14	18
Sc. 5 (SE)	Eligible houses (%)	2	9	14	41	24	10
	PRAGEI (kg/m^2)	54	45	39	27	25	29
Sc. 6 (ICE)	Eligible houses (%)	2	8	15	37	27	10
	PRAGEI (kg/m^2)	66	58	54	36	31	41

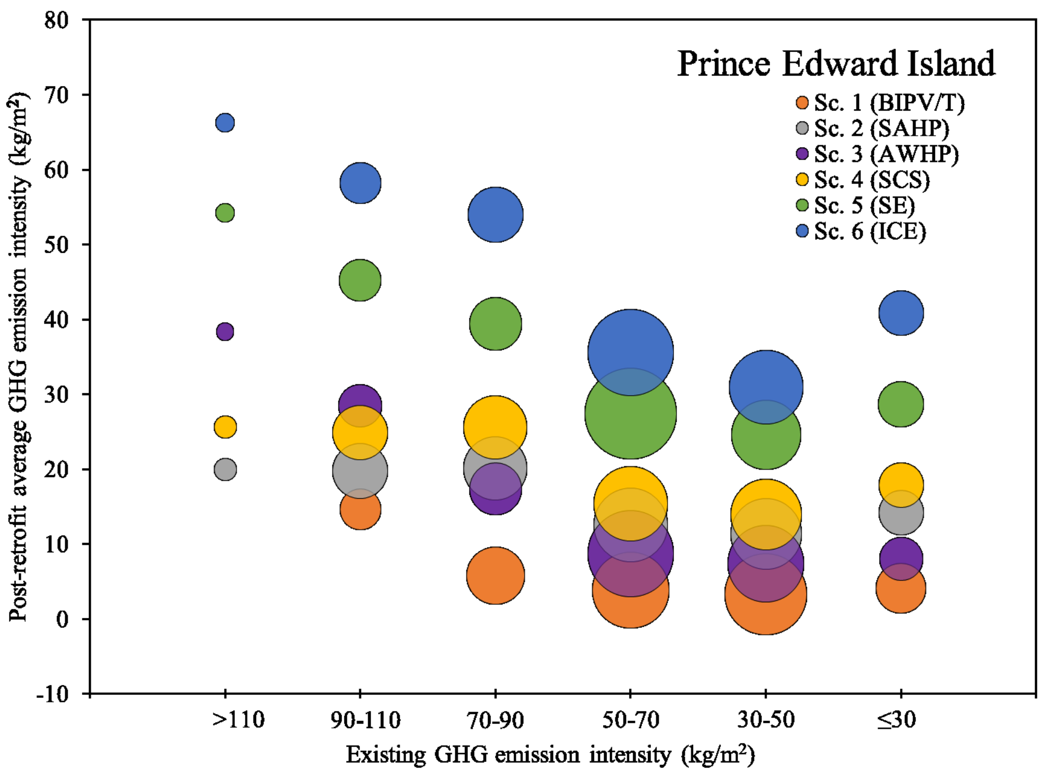

Figure 10.7 Impact of retrofit scenarios on GHG emission intensity of existing houses in PE (Note: the size of the circle is proportional with the number of eligible houses in each category)

Overall, from source energy, GHG emissions and TCC perspective, Sc. 1 (BIPV/T) is the most suitable retrofit for eligible houses in PE. Using higher insulation levels in the roof and floors, further lowering the infiltration rate to achieve higher air-tightness levels and increasing the thermal energy storage capacity of the PCM system to further lower the thermal energy demand of the building are additional steps that can help eligible houses in PE to achieve closer to NZE status.

Table 10.19 Average TCC per house for selected retrofit scenarios in PE

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 6 (ICE)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	41,264	23,865	26,604	16,032
	Medium	49,142	26,237	31,618	17,628
	High	58,776	28,854	37,756	19,392
6	Low	35,208	21,578	22,808	14,520
	Medium	41,570	23,650	26,868	15,916
	High	49,313	25,934	31,814	17,456
9	Low	30,371	19,611	19,765	13,217
	Medium	35,559	21,430	23,085	14,444
	High	41,843	23,432	27,110	15,795

10.4.4. New Brunswick

A mixture of primary energy sources are used for electricity generation in NB. Coal and oil are the main sources of energy for marginal electricity generation which cause relatively high source energy and GHG emission intensities for marginal electricity generation (Farhat and Ugursal, 2010). As shown in Table 10.4, electricity, wood and oil are the sources of energy use in the housing stock of NB. The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.20 for each retrofit scenario. The same data are plotted in Figure 10.8 where the size of each circle represents the percentage of eligible houses in each source energy intensity range. As shown in Table 10.20, existing source energy intensity of all eligible houses are above 200kWh/m^2. Thus, energy retrofits are necessary and can be very effective in NB. The lowest PRASEI in eligible houses is predicted for Sc. 1 (BIPV/T) followed by Sc. 6 (ICE) retrofit scenario.

Table 10.20 Distribution (%) of existing houses based on existing source energy intensity (kWh/m²) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario New Brunswick

Existing source energy intensity (kWh/m²)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	12	20	33	30	6	0
	PRASEI (kWh/m²)	173	126	83	46	37	-
Sc. 2 (SAHP)	Eligible houses (%)	16	19	30	31	4	0
	PRASEI (kWh/m²)	223	169	143	106	92	-
Sc. 3 (AWHP)	Eligible houses (%)	18	18	31	30	3	0
	PRASEI (kWh/m²)	339	254	220	175	155	-
Sc. 4 (SCS)	Eligible houses (%)	16	19	31	31	4	0
	PRASEI (kWh/m²)	213	161	136	103	89	-
Sc. 5 (SE)	Eligible houses (%)	18	19	32	29	3	0
	PRASEI (kWh/m²)	269	202	173	142	116	-
Sc. 6 (ICE)	Eligible houses (%)	18	18	30	30	3	0
	PRASEI (kWh/m²)	160	133	113	98	83	-

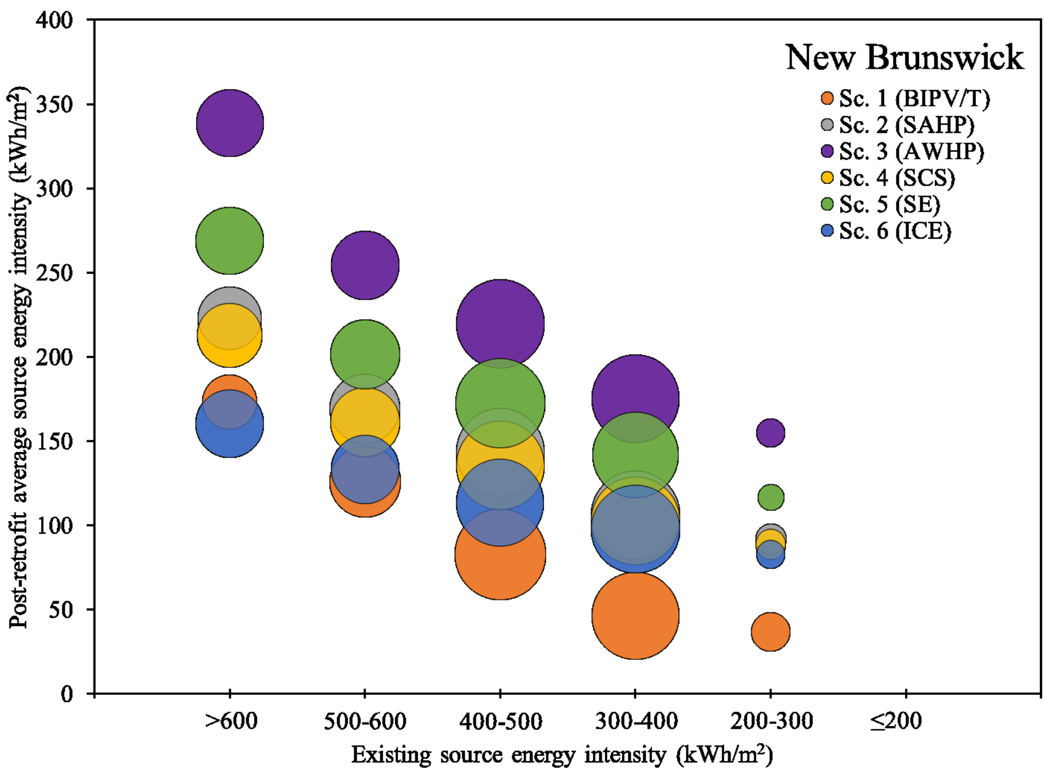

Figure 10.8 Impact of retrofit scenarios on energy intensity of existing houses in NB (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.21 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m²) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in New Brunswick

Existing GHG emission intensity (kg/m²)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	3	12	27	26	27	6
	PRAGEI (kg/m²)	40	29	16	4	12	0
Sc. 2 (SAHP)	Eligible houses (%)	6	9	23	24	31	7
	PRAGEI (kg/m²)	45	36	29	21	28	21
Sc. 3 (AWHP)	Eligible houses (%)	9	11	23	25	24	8
	PRAGEI (kg/m²)	86	57	52	41	52	43
Sc. 4 (SCS)	Eligible houses (%)	5	10	23	23	31	8
	PRAGEI (kg/m²)	41	31	27	20	26	23
Sc. 5 (SE)	Eligible houses (%)	9	12	24	24	23	8
	PRAGEI (kg/m²)	53	36	32	26	32	26
Sc. 6 (ICE)	Eligible houses (%)	9	11	22	25	24	8
	PRAGEI (kg/m²)	14	13	13	12	10	6

The significant difference between the PRASEI of Sc. 1 (BIPV/T) and Sc. 6 (ICE) indicate that the former is the first choice for houses that qualify for both retrofit scenarios. As shown in Table 10.3, close to 80 percent and 55 percent of houses are not eligible for Sc. 1 (BIPV/T) and Sc. 6 (ICE) in NB, respectively. It is likely that many more houses can obtain the requirement for retrofit scenarios by constructing a mechanical room. As a result both retrofit scenarios, i.e. Sc. (BIPV/T) and Sc. 6 (ICE), should be considered for further evaluation to determine the best strategy to achieve near NZE status in a given house in NB. Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZ status in NB is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity with no source energy consumption. It is possible to convert 11 percent of eligible houses in NB to NZEBs with the Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses will approach but not achieve NZE status.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.21 and Figure 10.9 for each retrofit scenario. The GHG EIF for marginal electricity is about twice its value at off-peak period in NB (Farhat and Ugursal, 2010). While onsite electricity generation can help to reduce the GHG emission intensity of eligible houses substantially, the additional electricity demand due to the retrofit can strongly affect the associated GHG emissions. Therefore, Sc. 1 (BIPV/T) and Sc. 6 (ICE) yield the lowest PRAGEI in eligible houses for retrofit in NB. All eligible houses would reach PRAGEI of less than 15 kg/m^2 with Sc. 6 (ICE) retrofit.

As shown in Table 10.4, about 30 percent of the current energy use is supplied by wood in the housing stock of NB. Using wood in highly efficient heating devices and innovative solutions such as external combustion SE micro cogeneration system can help to reduce the GHG emissions of the houses in NB. The additional electricity generated by the utility is currently exported to NS, PE, QC and New England (Farhat and Ugursal, 2010). Thus, it can be expected that the micro cogeneration systems can easily integrate into the electricity market of NB.

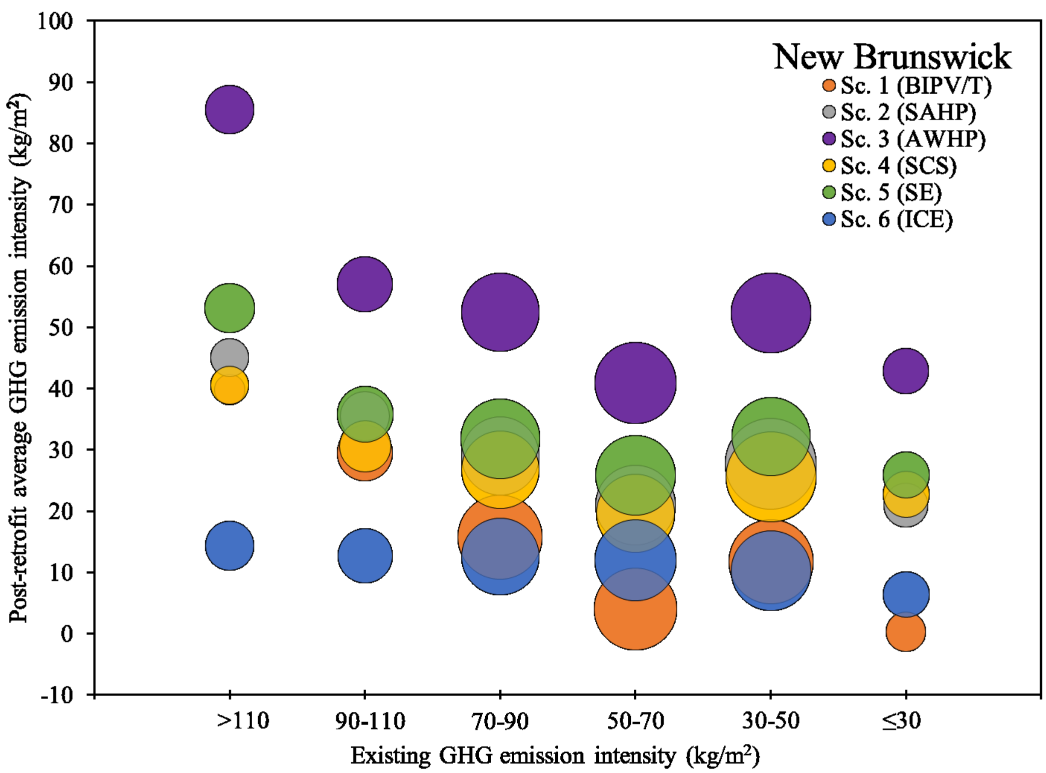

Figure 10.9 Impact of retrofit scenarios on GHG emission intensity of existing houses in NB (Note: the size of the circle is proportional with the number of eligible houses in each category)

Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZEm status in NB is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity which offsets the GHG emissions of a household. It is possible to convert 26 percent of eligible houses in NB to NZEmBs with the Sc. 1 (BIPV/T) retrofit. Although none of the eligible houses could achieve NZEm status with the Sc. 6 (ICE) retrofit, the average source energy and GHG emission intensity of eligible houses reduce substantially with the Sc. 6 (ICE) retrofit.

From the economic perspective Sc. 1 (BIPV/T) retrofit scenario is superior to Sc. 6 (ICE), as shown in Table 10.22, since the TCC of Sc. 6 (ICE) is about half of that for Sc. 1 (BIPV/T). Whether the TCC is sufficient to cover the costs of Sc. 1 (BIPV/T) retrofit is a question that can be answered with a house specific evaluation. However, the large percent of non-eligible houses for Sc. 1 (BIPV/T) results in a small market share for BIPV/T system in NB. Given the low TCC for Sc. 6 (ICE), a percentage of the eligible houses can face difficulties to adopt retrofit scenario. To promote the retrofit scenarios subsidies will likely be necessary. Higher subsidies will be required for non-eligible houses to build a mechanical room and adopt the retrofit scenarios.

Table 10.22 Average TCC per house for selected retrofit scenarios in NB

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 6 (ICE)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	42,166	24,632	23,629	14,710
	Medium	50,056	27,039	27,678	16,068
	High	59,684	29,694	32,579	17,561
6	Low	36,018	22,281	20,336	13,340
	Medium	42,394	24,385	23,624	14,528
	High	50,137	26,701	27,584	15,833
9	Low	31,104	20,257	17,689	12,158
	Medium	36,307	22,105	20,385	13,203
	High	42,596	24,137	23,616	14,349

Overall, it can be concluded that the Sc. 1 (BIPV/T) and Sc. 6 (ICE) can be very effective to convert eligible houses to NZEB and near NZEB in NB. Further improvement of energy efficiency in houses, devising regulations to purchase onsite electricity generation by micro cogeneration devices to encourage homeowners for Sc. 6 (ICE) retrofit, energy incentives and subsidies to economically justify the construction of mechanical room in non-eligible houses are a series of additional steps that can be considered for conversion of existing houses into near NZEB.

10.4.5. Quebec

While NG is widely available in QC, NG consumption in residential sector is very low. As shown in Table 10.4, energy needs of households in QC are mainly supplied with electricity followed by oil and wood. Since electrical heating systems are generally installed in the living area, a mechanical room does not exist in majority of the houses. As a result, over 80 percent of houses are not eligible for any retrofit scenario. As shown in Table 10.3, QC has a large population with the second largest housing stock in Canada. Thus, identifying paths to enhance energy conservation in households can have a substantial impact on the energy use of the CHS. Close to 99 percent of electricity generation in QC is from renewable resources (Hydro-Quebec, 2016b). Thus, the source energy use for electricity generation is negligible and source energy conversion factor for provinces with hydro-electricity given in Table 10.1 are used for NZE analysis.

The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.23 for each retrofit scenario. The same data are plotted in Figure 10.10 where the size of each circle represents the percentage of eligible houses in each source energy intensity range. Since the hydro-electricity is widely available and existing heating systems in eligible houses use oil, the PRASEI trend for retrofit scenarios in QC is similar to that of NF. As discussed for houses in NF, the retrofit scenarios that use a heat pump, i.e. Sc. 1 (BIPV/T) and Sc. 3 (AWHP), are the best choice to achieve near NZE status for eligible houses. Although onsite electricity generation provides no source energy credit for eligible houses, Sc. 1 (BIPV/T) has a better performance compared to Sc. 3 (AWHP) because of higher temperature supply to the evaporator of the heat pump. The PRASEI is less than 30 kWh/m^2 in over than 95 percent of eligible houses with Sc. 1 (BIPV/T) and Sc. 3 (AWHP) retrofit scenarios. Therefore, both retrofit scenarios would be very effective in eligible houses as the PRASEI represents the total energy use of households.

Table 10.23 Distribution (%) of existing houses based on existing source energy intensity (kWh/m²) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Quebec

Existing source energy intensity (kWh/m²)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	1	1	4	6	21	69
	PRASEI (kWh/m²)	51	34	32	22	17	13
Sc. 2 (SAHP)	Eligible houses (%)	0	1	3	7	25	63
	PRASEI (kWh/m²)	178	138	82	77	51	34
Sc. 3 (AWHP)	Eligible houses (%)	1	1	2	7	24	65
	PRASEI (kWh/m²)	93	44	50	32	28	22
Sc. 4 (SCS)	Eligible houses (%)	0	1	3	7	25	63
	PRASEI (kWh/m²)	227	172	110	101	69	47
Sc. 5 (SE)	Eligible houses (%)	1	1	2	7	24	64
	PRASEI (kWh/m²)	308	258	209	157	125	97
Sc. 6 (ICE)	Eligible houses (%)	1	1	2	7	25	63
	PRASEI (kWh/m²)	488	418	319	239	184	132

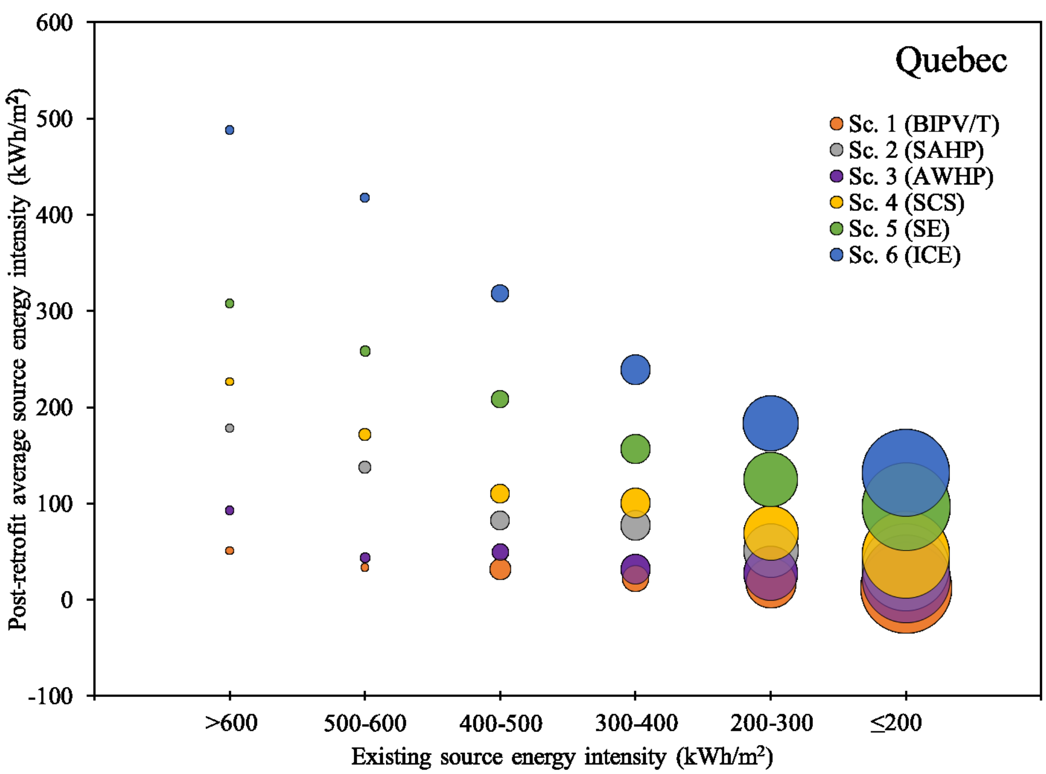

Figure 10.10 Impact of retrofit scenarios on energy intensity of existing houses in QC (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.24 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m^2) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Quebec

Existing GHG emission intensity (kg/m^2)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	1	4	3	10	35	47
	PRAGEI (kg/m^2)	1	0	1	1	0	1
Sc. 2 (SAHP)	Eligible houses (%)	1	2	5	15	31	45
	PRAGEI (kg/m^2)	26	16	13	10	6	6
Sc. 3 (AWHP)	Eligible houses (%)	1	2	4	15	33	45
	PRAGEI (kg/m^2)	12	9	6	6	4	4
Sc. 4 (SCS)	Eligible houses (%)	1	2	5	15	31	45
	PRAGEI (kg/m^2)	32	21	17	14	9	8
Sc. 5 (SE)	Eligible houses (%)	1	2	4	14	34	44
	PRAGEI (kg/m^2)	48	37	27	23	18	16
Sc. 6 (ICE)	Eligible houses (%)	1	2	4	15	33	44
	PRAGEI (kg/m^2)	78	56	42	34	24	22

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.24 and Figure 10.11 for each retrofit scenario. The GHG emission intensity of existing houses is substantially reduced with retrofit scenarios. The PRAGEI due to Sc. 1 (BIPV/T) retrofit scenario is close to zero and PRAEGI due to Sc. 3 (AWHP) is less than 10 kg/m^2 in majority of the eligible houses in QC. Thus, Sc. 1 (BIPV/T) and Sc. 3 (AWHP) retrofits are the best strategies to be considered in QC. The NG fired auxiliary heating system can be replaced with a conventional electric resistance heater to further reduce the GHG emission intensity of households if there is enough capacity in the grid. While Sc. 1 (BIPV/T) and Sc. 3 (AWHP) retrofit scenarios are very effective to achieve near NZEm status for eligible houses, the savings cannot be translated into a large energy savings and reduction of GHG emissions in the housing stock of QC because more than 80% of the houses in QC are not suitable for retrofits due to the lack of mechanical rooms. Construction of mechanical rooms should be encouraged to achieve higher energy savings in QC.

The TCC for selected retrofit scenarios are presented in Table 10.25. As discussed earlier, Sc. 1 (BIPV/T) requires a higher initial investment and maintenance than the Sc. 3 (AWHP) retrofit. Thus, from an economic perspective Sc. 3 (AWHP) retrofit scenario is likely a more suitable option. A house specific study is necessary to select the suitable retrofit scenario for individual houses.

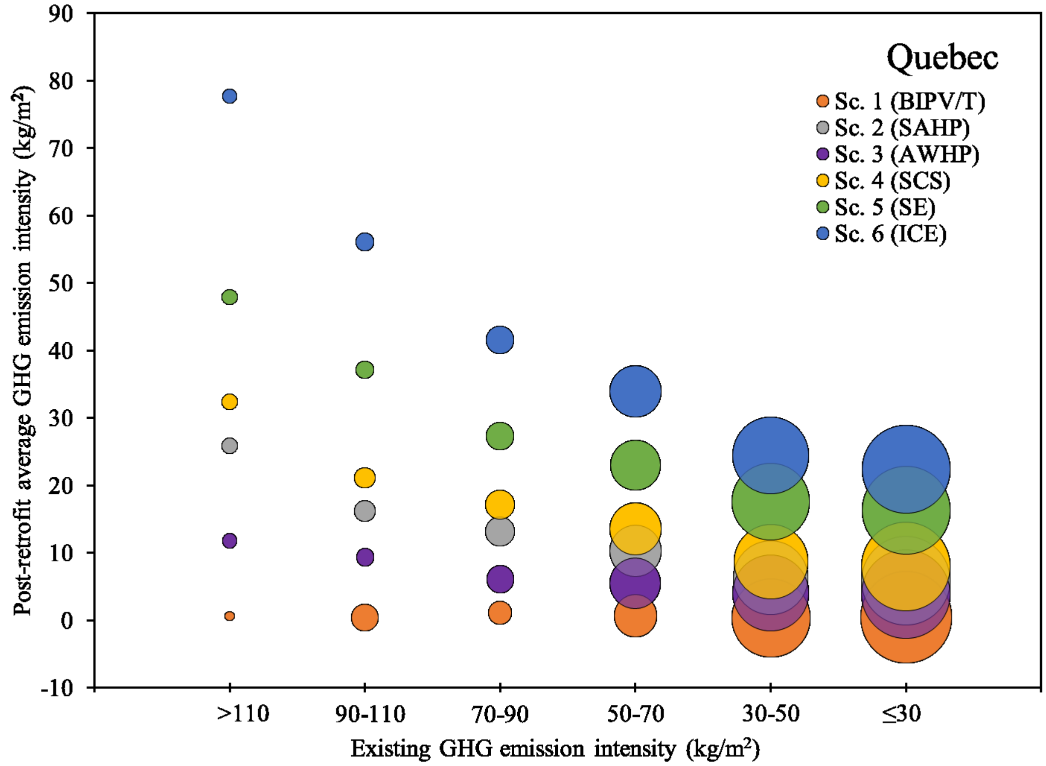

Figure 10.11 Impact of retrofit scenarios on GHG emission intensity of existing houses in QC (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.25 Average TCC per house for selected retrofit scenarios in QC

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T) 10 year Payback	Sc. 1 (BIPV/T) 6 year Payback	Sc. 3 (AWHP) 10 year Payback	Sc. 3 (AWHP) 6 year Payback
3	Low	34,857	20,141	30,932	17,677
	Medium	41,731	22,208	37,077	19,500
	High	50,174	24,496	44,628	21,517
6	Low	29,738	18,210	26,356	15,975
	Medium	35,289	20,017	31,315	17,567
	High	42,074	22,013	37,379	19,326
9	Low	25,650	16,549	22,705	14,511
	Medium	30,176	18,135	26,747	15,909
	High	35,682	19,885	31,664	17,451

10.4.6. Ontario

The largest housing stock in Canada is in OT with about 38 percent of the houses in the CHS, as shown in Table 10.3. NG is widely available for residential customers and is the major source of energy for space and DHW heating, as shown in Table 10.4.

The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.26 for each retrofit scenario. The same data are plotted in Figure 10.12 where the size of each circle represents the percentage of eligible houses in each source energy intensity range.

Table 10.26 Distribution (%) of existing houses based on existing source energy intensity (kWh/m²) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Ontario

Existing source energy intensity (kWh/m²)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	3	5	13	32	37	10
	PRASEI (kWh/m²)	209	167	130	93	59	37
Sc. 2 (SAHP)	Eligible houses (%)	2	4	11	29	41	13
	PRASEI (kWh/m²)	237	197	162	126	95	70
Sc. 3 (AWHP)	Eligible houses (%)	3	4	12	29	40	12
	PRASEI (kWh/m²)	352	295	250	197	149	109
Sc. 4 (SCS)	Eligible houses (%)	3	4	11	29	41	13
	PRASEI (kWh/m²)	220	181	150	116	87	62
Sc. 5 (SE)	Eligible houses (%)	3	4	12	29	40	12
	PRASEI (kWh/m²)	269	208	177	142	109	80
Sc. 6 (ICE)	Eligible houses (%)	3	4	13	29	40	12
	PRASEI (kWh/m²)	142	111	101	85	67	46

The lowest PRASEI is predicted for Sc. 6 (ICE) and Sc. 1 (BIPV/T) retrofit scenarios in the eligible houses of OT. Sc. 6 (ICE) provides a better performance in houses with high existing source energy intensity. As shown in Table 10.3, close to 80 percent of the existing houses can qualify for Sc. 6 (ICE) and 30 percent for Sc. 1 (BIPV/T) retrofit. Thus, the considerable penetration of Sc. 6 (ICE) in the housing stock of OT, results in a significant energy savings in the CHS. The detailed techno-economic analysis (presented in Chapter 3) showed that introducing the ICE cogeneration system retrofit in all eligible houses in OT would convert the entire housing stock into a net electricity exporter (Asaee *et al.*, 2015a).

Thus, a widely implemented Sc.6 (ICE) retrofit would have a significant effect on the electricity market. Also, because of the large scale of the housing stock a large demand for a specific technology in a short period can result in higher costs of equipment and services due to shortage of supply. To avoid such circumstances and to balance the supply and demand, alternative paths should be considered to convert existing houses into near NZEBs in short period of time. That would also reduce the risk of substantial changes in the energy supply and demand that can affect other sectors in the province. In conclusion, it is recommended that Sc. 1 (BIPV/T) and Sc. 6 (ICE) retrofit scenarios be considered for eligible houses in OT. If all houses that qualify for both retrofit scenarios adopt Sc. 1 (BIPV/T), the market share for both technologies would be better balanced.

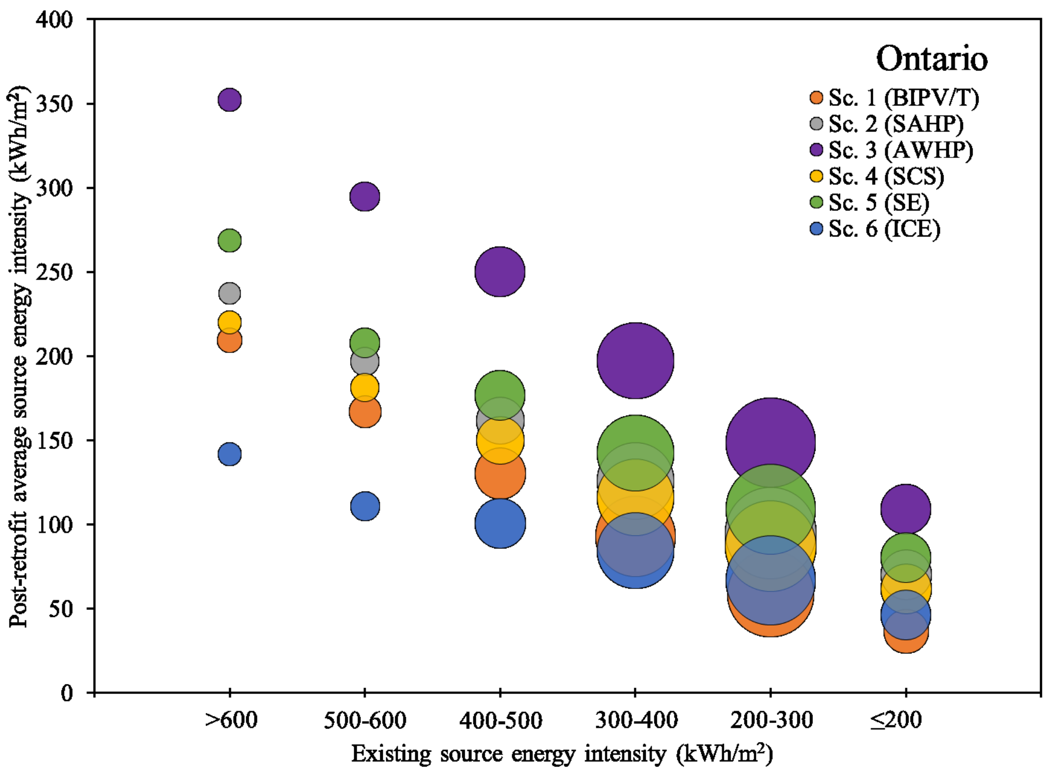

Figure 10.12 Impact of retrofit scenarios on energy intensity of existing houses in OT (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.27 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m^2) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Ontario

Existing GHG emission intensity (kg/m^2)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	1	1	5	17	52	24
	PRAGEI (kg/m^2)	23	20	16	11	6	3
Sc. 2 (SAHP)	Eligible houses (%)	1	1	4	15	52	28
	PRAGEI (kg/m^2)	31	28	24	18	12	9
Sc. 3 (AWHP)	Eligible houses (%)	1	1	4	16	50	28
	PRAGEI (kg/m^2)	47	40	35	29	20	14
Sc. 4 (SCS)	Eligible houses (%)	1	1	4	15	52	28
	PRAGEI (kg/m^2)	31	27	23	18	12	8
Sc. 5 (SE)	Eligible houses (%)	1	1	4	16	50	28
	PRAGEI (kg/m^2)	43	33	28	23	17	12
Sc. 6 (ICE)	Eligible houses (%)	1	1	4	16	49	28
	PRAGEI (kg/m^2)	26	21	18	15	11	8

Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZ status in OT is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity with no source energy consumption. It is possible to convert 9 percent of eligible houses in OT to NZEBs with Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses will approach but not achieve NZE status.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.27 and Figure 10.13 for each retrofit scenario. Since NG is widely used for heating purposes by households and the GHG EIF of electricity generation in OT is relatively low, the existing GHG emission intensity of majority of houses is below $50kg/m^2$. Four retrofit scenario including Sc. 1 (BIPV/T), Sc. 2 (SAHP), Sc. 4 (SCS) and Sc. 6 (ICE) yield the PRAGEI of less than $20kg/m^2$ in close to 95 percent of eligible houses in OT. The GHG EIF of marginal electricity generation is about twice the GHG EIF for average electricity. As a result, the additional electricity consumption of retrofit options that utilize a heat pump reduces their favourability from the GHG emission reduction point of view. On the other hand, onsite electricity generation can offset a large portion of household GHG emissions. If all eligible houses receive Sc. 1 (BIPV/T) and Sc. 6 (ICE) retrofit, close to 70 percent of GHG emissions associated with household energy use in OT will be eliminated.

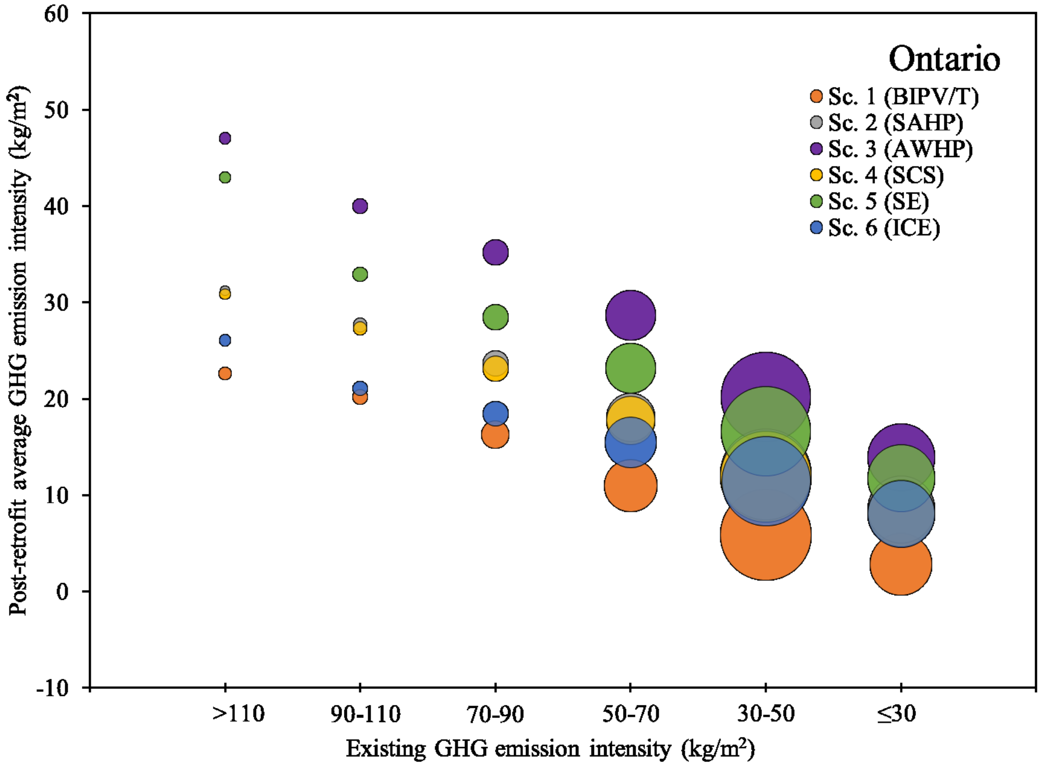

Figure 10.13 Impact of retrofit scenarios on GHG emission intensity of existing houses in OT (Note: the size of the circle is proportional with the number of eligible houses in each category)

Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZEm status in OT is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity which offset GHG emission of household. It is possible to convert 16 percent of eligible houses in OT to NZEmBs with the Sc. 1 (BIPV/T) retrofit. Although none of the eligible houses could achieve NZEm status with the Sc. 6 (ICE) retrofit, the average source energy and GHG emission intensity of eligible houses is substantially reduced with Sc. 6 (ICE) retrofit.

As shown in Table 10.28, the TCC for Sc. 1 (BIPV/T) is about 75 percent of the TCC for the Sc. 6 (ICE) in OT. The larger TCC and the number of eligible houses along with the low PRASEI endorse Sc. 6 (ICE) as the best strategy to convert eligible houses to near NZEB in OT. A province wide demand for renewable/alternative energy technologies such as ICE cogeneration and BIPV/T in OT can attract manufacturers to introduce new products in the Canadian market and increase affordability of such technologies in Canada.

Table 10.28 Average TCC per house for selected retrofit scenarios in OT

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 6 (ICE)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	19,136	11,415	24,462	14,693
	Medium	22,463	12,459	29,167	16,183
	High	26,484	13,605	34,943	17,832
6	Low	16,386	10,334	20,963	13,306
	Medium	19,078	11,247	24,773	14,609
	High	22,317	12,248	29,425	16,048
9	Low	14,183	9,404	18,160	12,111
	Medium	16,383	10,206	21,274	13,256
	High	19,018	11,084	25,059	14,518

10.4.7. Manitoba

Electricity generation in MB is mainly from hydro energy (Farhat and Ugursal, 2010). As shown in Table 10.4, the housing stock in MB uses about twice as much NG energy compared with electricity. The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.29 for each retrofit scenario. The same data are plotted in Figure 10.14 where the size of each circle represents the percentage of eligible houses in each source energy intensity range.

The lowest PRASEI for eligible houses is achieved with the Sc. 1 (BIPV/T) retrofit. Since zero source energy consumption is associated with electricity use, the retrofit options which use heat pump technology, i.e. Sc. 1 (BIPV/T), Sc. 2 (SAHP) and Sc. 3 (AWHP), provide the highest source energy intensity reduction among retrofit scenarios. Also, onsite electricity generation provides no credit to offset source energy of households in MB. As a result Sc. 6 (ICE) and Sc. 5 (SE) retrofits are not attractive options for eligible houses in MB. Auxiliary system in all retrofit scenarios use NG for heat supply when the main system cannot fulfill the thermal energy demand of a house. Thus, zero source energy intensity is not achieved in eligible houses with any retrofit scenario.

Table 10.29 Distribution (%) of existing houses based on existing source energy intensity (kWh/m²) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Manitoba

Existing source energy intensity (kWh/m²)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	0	1	5	18	36	39
	PRASEI (kWh/m²)	23	67	66	53	38	24
Sc. 2 (SAHP)	Eligible houses (%)	1	0	5	18	32	44
	PRASEI (kWh/m²)	59	-	131	99	65	38
Sc. 3 (AWHP)	Eligible houses (%)	1	1	6	18	34	40
	PRASEI (kWh/m²)	138	115	91	75	57	42
Sc. 4 (SCS)	Eligible houses (%)	1	0	5	18	32	44
	PRASEI (kWh/m²)	104	-	164	127	88	56
Sc. 5 (SE)	Eligible houses (%)	1	1	6	17	34	41
	PRASEI (kWh/m²)	299	283	234	190	144	104
Sc. 6 (ICE)	Eligible houses (%)	1	1	6	17	34	41
	PRASEI (kWh/m²)	462	451	367	296	217	152

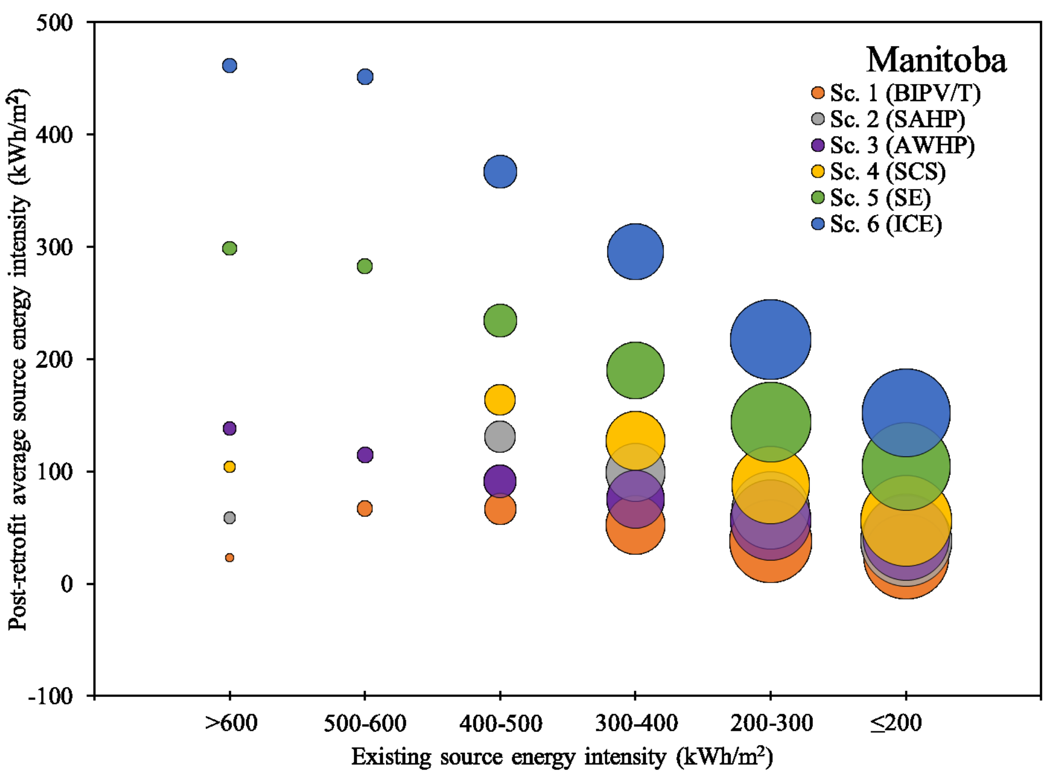

Figure 10.14 Impact of retrofit scenarios on energy intensity of existing houses in MB (Note: the size of the circle is proportional with the number of eligible houses in each category)

Replacing NG fired auxiliary heating systems with conventional electric resistance heaters for space and DHW heating can help to approach NZE status for existing houses if there is enough capacity in the grid. The only path to achieve net zero source energy houses is the completely abandon fossil fuels in households. Sc. 1 (BIPV/T) provides a clear superiority from the source energy perspective amongst retrofit scenarios. Between Sc. 2 (SAHP) and Sc. 3 (AWHP), the latter is preferable due to the lower complexity of the system and the similar PRASEI achieved in eligible houses. Also, close to 70 percent of the houses are eligible for Sc. 3 (AWHP). Thus, Sc. 1 (BIPV/T) and Sc. 3 (AWHP) are recommended for conversion of eligible houses into near NZEB in MB.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.30 and Figure 10.15 for each retrofit scenario. Because of the wide availability of hydro-electricity, the existing GHG emission intensity of houses is mainly below 50kg/m^2. The PRAGEI of eligible houses with Sc. 1 (BIPV/T) retrofit scenario is very close to zero and retrofitted houses achieve near zero emission status in MB. The PRAGEI of eligible houses with Sc. 2 (SAHP) and Sc. 3 (AWHP) are below 17 kg/m^2 in majority of eligible houses. Given the PRASEI and PRAGEI, Sc. 1 (BIPV/T) is the primary option for conversion of a given house to near NZEm building in MB.

The results of TCC analysis for Sc. 1 (BIPV/T) and Sc. 3 (AWHP) retrofits are given in Table 10.31. The TCC for Sc. 3 (AWHP) is about 60 percent of that for Sc. 1 (BIPV/T). Thus, from the economic perspective Sc. 1 (BIPV/T) is likely to be more preferable compared to Sc. 3 (AWHP) for retrofit eligible houses in MB. However, the TCC for both retrofit scenarios are relatively low and they will likely fail to provide a sufficient economic justification in the absence of subsidy programs. The same additional steps for energy efficiency recommended for NF can be applied to the eligible houses in MB as well.

Table 10.30 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m^2) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Manitoba

Existing GHG emission intensity (kg/m^2)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	0	1	6	20	50	23
	PRAGEI (kg/m^2)	-	6	1	1	1	0
Sc. 2 (SAHP)	Eligible houses (%)	0	0	4	19	48	28
	PRAGEI (kg/m^2)	10	11	23	17	10	6
Sc. 3 (AWHP)	Eligible houses (%)	1	1	5	20	49	25
	PRAGEI (kg/m^2)	25	20	16	13	9	7
Sc. 4 (SCS)	Eligible houses (%)	0	0	4	19	48	28
	PRAGEI (kg/m^2)	20	16	29	22	14	9
Sc. 5 (SE)	Eligible houses (%)	1	1	5	19	49	25
	PRAGEI (kg/m^2)	54	47	41	32	23	16
Sc. 6 (ICE)	Eligible houses (%)	1	1	6	19	49	25
	PRAGEI (kg/m^2)	84	71	64	49	34	23

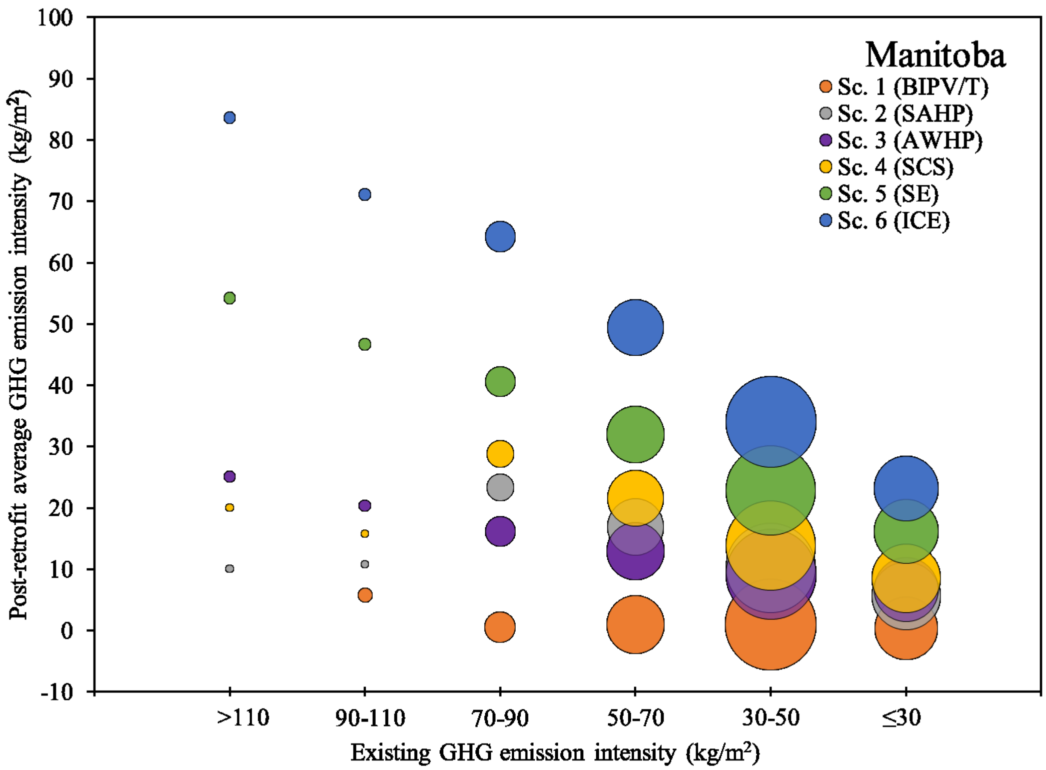

Figure 10.15 Impact of retrofit scenarios on GHG emission intensity of existing houses in MB (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.31 Average TCC per house for selected retrofit scenarios in MB

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 3 (AWHP)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	11,824	7,233	7,032	4,301
	Medium	13,654	7,831	7,973	4,612
	High	15,828	8,484	9,062	4,945
6	Low	10,155	6,554	6,039	3,898
	Medium	11,639	7,078	6,803	4,169
	High	13,395	7,648	7,683	4,461
9	Low	8,815	5,970	5,242	3,550
	Medium	10,030	6,430	5,868	3,789
	High	11,462	6,931	6,586	4,045

10.4.8. Saskatchewan

Average electricity generation in SK relies heavily on fossil fuels including coal, oil and NG. As shown in Table 10.4, NG is the dominant source of energy for the housing stock in SK. The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.32 for each retrofit scenario. The same data are plotted in Figure 10.16 where the size of each circle represents the percentage of eligible houses in each source energy intensity range. Sc. 6 (ICE) system provides the lowest PRASEI in eligible houses in SK. Since close to 80 percent of the existing houses are eligible for Sc. 6 (ICE), the savings due to this retrofit scenario translate into a significant source energy conservation in the province. Considering that NG is currently extensively used in eligible houses in SK, Sc. 6 (ICE) retrofit would not require a major NG distribution and infrastructure modification.

Prairies provinces benefit a relatively high sunshine hours in the Canadian context (Nikoofard, 2012). Thus, retrofit scenarios that use an active solar technology, i.e. Sc. 1 (BIPV/T), Sc. 2 (SAHP) and Sc. 4 (SCS), provide a considerable reduction in source energy intensity of eligible houses. The PRASEI with Sc. 1 (BIPV/T), Sc. 2 (SAHP) and Sc. 4 (SCS) are the second lowest in eligible houses in SK. Percent eligible houses for those retrofit scenarios are fairly close. Thus, the Sc. 1 (BIPV/T) retrofit is the second most favorable option because of the capability of onsite electricity generation.

Table 10.32 Distribution (%) of existing houses based on existing source energy intensity (kWh/m²) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Saskatchewan

Existing source energy intensity (kWh/m²)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	4	7	16	31	38	4
	PRASEI (kWh/m²)	207	183	159	105	76	58
Sc. 2 (SAHP)	Eligible houses (%)	6	9	18	29	34	4
	PRASEI (kWh/m²)	219	192	176	122	91	83
Sc. 3 (AWHP)	Eligible houses (%)	6	11	14	32	33	4
	PRASEI (kWh/m²)	324	290	254	203	154	122
Sc. 4 (SCS)	Eligible houses (%)	6	10	18	30	33	4
	PRASEI (kWh/m²)	207	178	164	116	86	80
Sc. 5 (SE)	Eligible houses (%)	6	11	14	32	33	4
	PRASEI (kWh/m²)	251	214	185	151	119	92
Sc. 6 (ICE)	Eligible houses (%)	6	11	14	32	34	4
	PRASEI (kWh/m²)	132	116	103	84	72	54

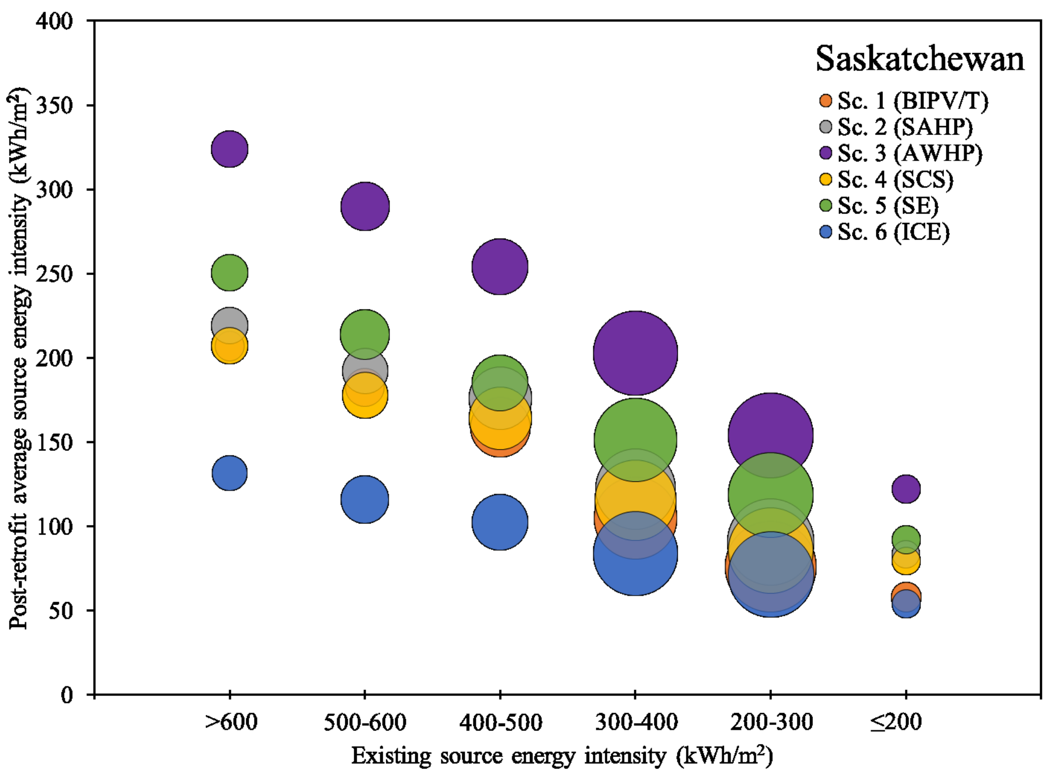

Figure 10.16 Impact of retrofit scenarios on energy intensity of existing houses in SK (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.33 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m²) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Saskatchewan

Existing GHG emission intensity (kg/m²)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	7	14	20	45	15	0
	PRAGEI (kg/m²)	24	20	15	8	7	-
Sc. 2 (SAHP)	Eligible houses (%)	8	14	22	41	14	0
	PRAGEI (kg/m²)	43	36	30	22	17	-
Sc. 3 (AWHP)	Eligible houses (%)	10	12	25	40	13	0
	PRAGEI (kg/m²)	49	38	33	26	20	-
Sc. 4 (SCS)	Eligible houses (%)	8	14	23	40	14	0
	PRAGEI (kg/m²)	43	36	30	22	17	-
Sc. 5 (SE)	Eligible houses (%)	11	12	24	39	14	0
	PRAGEI (kg/m²)	56	43	38	30	23	-
Sc. 6 (ICE)	Eligible houses (%)	10	12	25	40	14	0
	PRAGEI (kg/m²)	56	44	37	29	23	-

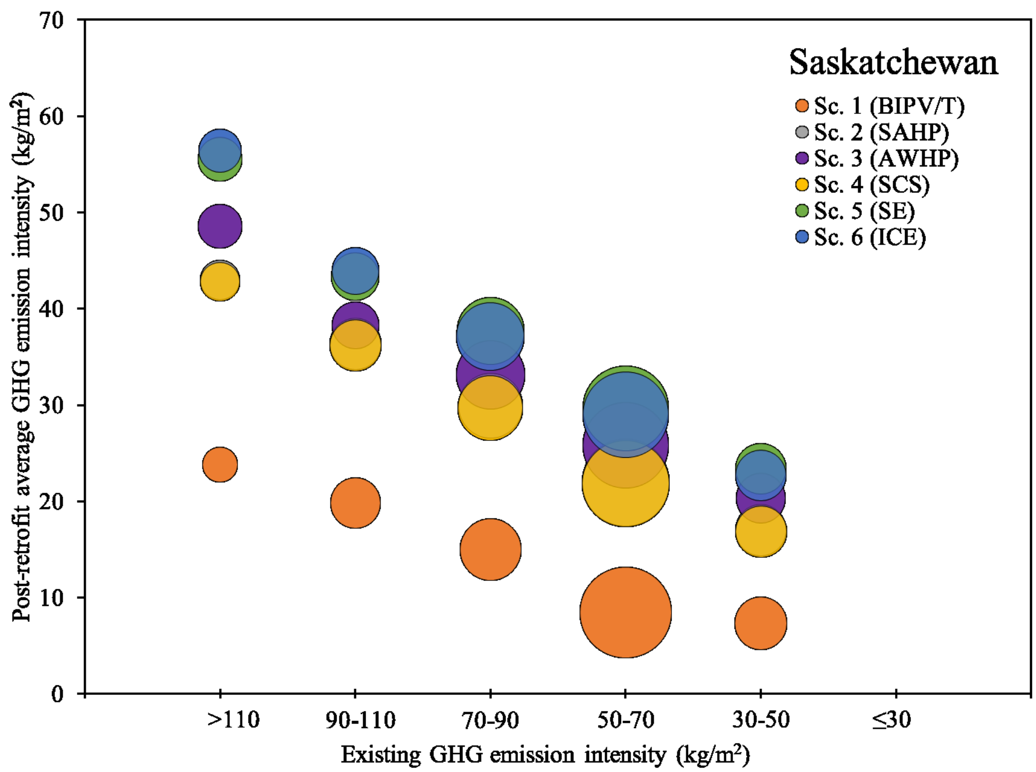

Figure 10.17 Impact of retrofit scenarios on GHG emission intensity of existing houses in SK (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.34 Average TCC per house for selected retrofit scenarios in SK

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 6 (ICE)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	14,857	9,087	20,288	12,410
	Medium	17,285	9,880	24,067	13,637
	High	20,199	10,748	28,691	14,993
6	Low	12,759	8,235	17,424	11,246
	Medium	14,729	8,929	20,487	12,319
	High	17,080	9,687	24,216	13,504
9	Low	11,076	7,501	15,125	10,243
	Medium	12,689	8,111	17,633	11,187
	High	14,605	8,776	20,670	12,226

Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZ status in SK is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity with no source energy consumption. It is possible to convert 25 percent of eligible houses in SK to NZEBs with the Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses will approach but not achieve NZE status.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.33 and Figure 10.17 for each retrofit scenario. Due to the high GHG EIF of average electricity generation in SK, the existing GHG emission intensity of households is relatively high. Thus, retrofit options can be very effective in reducing the GHG emission intensity of eligible houses. The PRAGEI with Sc. 1 (BIPV/T) retrofit scenario is less than 25 kg/m^2 in all eligible houses. Other retrofit scenarios also substantially reduce the GHG emission intensity of eligible houses as shown in Table 10.33. A well-established network of residential micro cogeneration systems would be a suitable alternative for coal thermal power plants used for electricity generation. Under that circumstances, Sc. 6 (ICE) electricity generation would offset average GHG emissions by the utility rather than marginal GHG emissions, and the GHG emission intensity of eligible houses would reach lower values.

As shown in Table 10.34, Sc. 6 (ICE) is the more economically attractive option compared to Sc. 1 (BIPV/T). The TCC for Sc. 1 (BIPV/T) is about 70 percent of TCC for Sc. 6 (ICE) in eligible houses. While Sc. 1 (BIPV/T) provides a better performance from GHG emission perspective, the low PRASEI, the large number of eligible houses and the high TCC benefit Sc. 6 (ICE). Since, the TCC is likely not sufficient to cover initial investment costs of Sc. 1 (BIPV/T) subsidies will likely be necessary, and house specific analysis will be needed to evaluate the superior retrofit scenario for a given house.

10.4.9. Alberta

Alberta has the largest housing population in the Prairies region as shown in Table 10.3. According to Table 10.4, NG is the dominant source of energy use and GHG emissions in the housing stock of AB. Coal and NG are the main primary energy sources for electricity generation resulting in the high source energy and GHG energy intensity for marginal and average electricity generation in AB (Farhat and Ugursal, 2010).

The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.35 for each retrofit scenario. The same data are plotted in Figure 10.18 where the size of each circle represents the percentage of eligible houses in each source energy intensity range. Because of the dominant fossil fuel use in AB, more than 97 percent of the eligible houses currently have a source energy intensity above 200kWh/m^2. High source energy intensity and large size of housing stock illustrate the importance of energy conservation programs in AB. As discussed earlier, due to the high sunshine hours, solar systems provide a suitable energy performance in the Prairies. Onsite electricity generation makes Sc. 1 (BIPV/T) and Sc. 6 (ICE) the most attractive retrofit scenarios in eligible houses in AB from the source energy perspective. About 88 percent of houses are eligible for Sc. 6 (ICE) and 36 percent eligible for Sc. 1 (BIPV/T), making these retrofits very effective from a provincial point of view. Thus, a potential path to convert eligible houses into near NZEBs should consider one of those retrofit scenarios. NG is currently used by households across the province and Sc. 6 (ICE) is likely to have a low impact on the NG distribution system.

Amongst all retrofit scenarios evaluated here, the only scenario that can achieve NZ status in AB is Sc. 1 (BIPV/T) since this scenario involves the use of a BIPV/T system that produces onsite electricity with no source energy consumption. It is possible to convert 13 percent of eligible houses in AB to NZEBs with the Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses will approach but not achieve NZE status.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.36 and Figure 10.19 for each retrofit scenario. The GHG emission intensity of the majority of the eligible houses is in the 50-110 kg/m^2 range prior to any retrofit. The GHG emission offset effect of onsite electricity generation is substantial in eligible houses in AB; therefore, the PRAGEI of all eligible houses reduce to lower than 20 kg/m^2 with Sc. 6 (ICE) retrofit. Sc. 6 (ICE) retrofit provides the lowest PRAGEI in eligible houses in AB. The second lowest PRAGEI is with Sc. 1 (BIPV/T), but its magnitude is about twice as much higher.

Amongst all retrofit scenarios evaluated here, Sc. 1 (BIPV/T) and Sc. 6 (ICE) scenarios can achieve NZEm status in AB since these scenarios involve the use of a BIPV/T and ICE cogeneration systems that produce onsite electricity which offset the GHG emissions of households. It is possible to convert 11 percent and 6 percent of eligible houses in AB to NZEmBs with the Sc. 1 (BIPV/T) and Sc. 6 (ICE) retrofits. Although the percent eligible houses that can achieve NZEm status with Sc. 6 (ICE) is smaller compared to Sc. 1 (BIPV/T), the large number of eligible houses for Sc. 6 (ICE) retrofit make this scenario the most effective retrofit from GHG emission reduction in eligible houses in AB.

Table 10.35 Distribution (%) of existing houses based on existing source energy intensity (kWh/m^2) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in Alberta

Existing source energy intensity (kWh/m^2)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	2	4	10	37	44	3
	PRASEI (kWh/m^2)	236	173	130	89	63	32
Sc. 2 (SAHP)	Eligible houses (%)	2	3	12	34	46	3
	PRASEI (kWh/m^2)	238	207	165	126	98	70
Sc. 3 (AWHP)	Eligible houses (%)	2	3	11	37	45	2
	PRASEI (kWh/m^2)	329	282	234	186	147	112
Sc. 4 (SCS)	Eligible houses (%)	2	3	12	34	46	3
	PRASEI (kWh/m^2)	223	193	153	117	92	67
Sc. 5 (SE)	Eligible houses (%)	2	3	11	37	45	2
	PRASEI (kWh/m^2)	278	224	185	148	117	89
Sc. 6 (ICE)	Eligible houses (%)	2	3	10	37	45	3
	PRASEI (kWh/m^2)	170	132	110	91	71	53

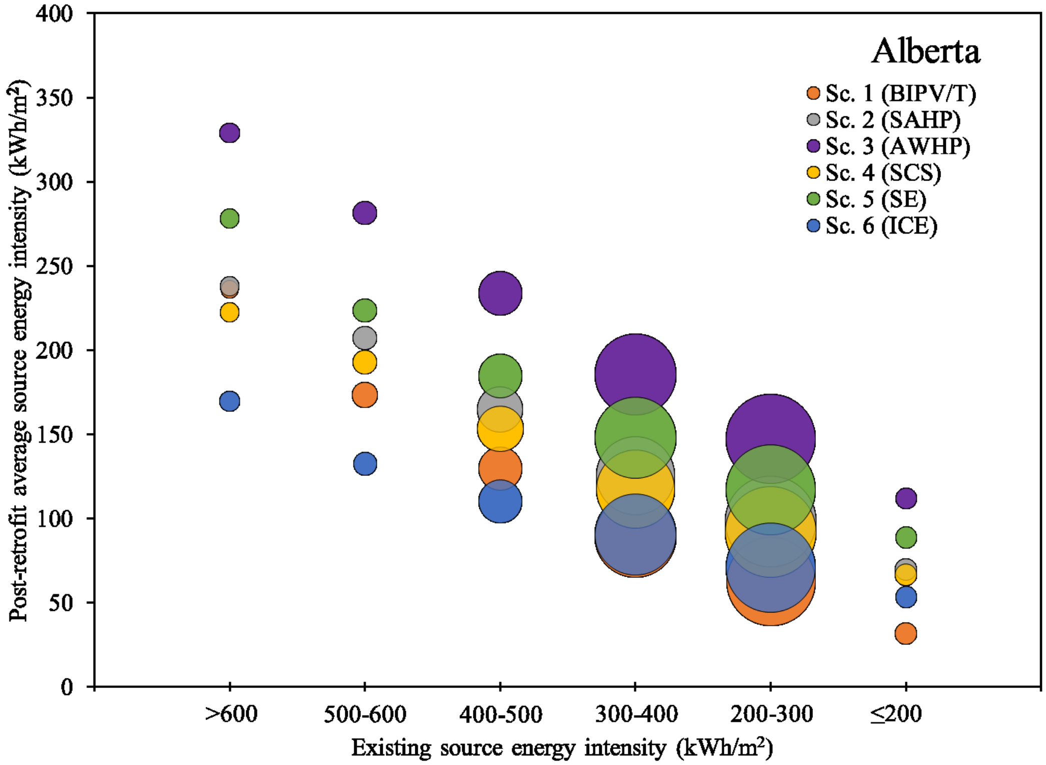

Figure 10.18 Impact of retrofit scenarios on energy intensity of existing houses in AB (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.36 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m²) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in Alberta

Existing GHG emission intensity (kg/m²)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	6	8	32	46	8	0
	PRAGEI (kg/m²)	47	31	23	16	11	-
Sc. 2 (SAHP)	Eligible houses (%)	6	9	29	47	8	0
	PRAGEI (kg/m²)	55	43	34	27	21	-
Sc. 3 (AWHP)	Eligible houses (%)	6	9	30	47	8	0
	PRAGEI (kg/m²)	76	61	50	41	32	-
Sc. 4 (SCS)	Eligible houses (%)	6	9	29	47	8	0
	PRAGEI (kg/m²)	48	37	30	23	18	-
Sc. 5 (SE)	Eligible houses (%)	6	9	30	47	8	0
	PRAGEI (kg/m²)	52	40	33	26	20	-
Sc. 6 (ICE)	Eligible houses (%)	6	9	30	47	8	0
	PRAGEI (kg/m²)	19	14	12	8	5	-

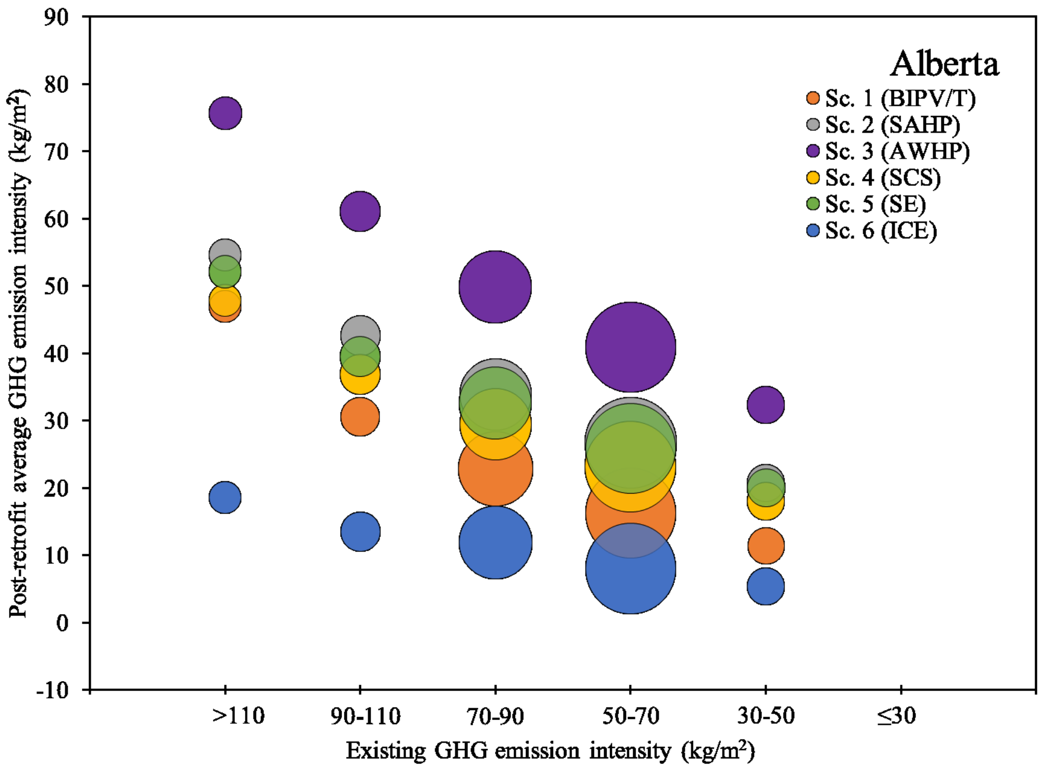

Figure 10.19 Impact of retrofit scenarios on GHG emission intensity of existing houses in AB (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.37 Average TCC per house for selected retrofit scenarios in AB

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 6 (ICE)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	10,462	6,399	18,738	11,461
	Medium	12,220	6,973	22,279	12,611
	High	14,338	7,601	26,622	13,883
6	Low	8,985	5,799	16,092	10,386
	Medium	10,410	6,301	18,963	11,392
	High	12,120	6,850	22,466	12,503
9	Low	7,800	5,282	13,969	9,460
	Medium	8,967	5,723	16,320	10,344
	High	10,360	6,205	19,172	11,319

As shown in Table 10.37, the TCC for Sc. 1 (BIPV/T) is about 55 percent of the TCC for Sc. 6 (ICE) in eligible houses in AB. The TCC for Sc. 1 (BIPV/T) is likely not sufficient to cover the initial investment for the retrofit. Therefore, due to better performance of Sc. 6 (ICE) in reduction of GHG emission intensity of eligible houses in addition to the higher TCC and number of eligible houses compared to Sc. 1 (BIPV/T) and similar PRASEI of both retrofit scenarios, Sc. 6 (ICE) is recommended for retrofit in all eligible houses in AB.

10.4.10. British Columbia

Vancouver (capital and largest municipality in BC) has the lowest HDD among major Canadian cities (Asaee *et al.*, 2015c). NG and electricity are the main sources of energy use BC households. The significant part of electricity is supplied from hydro power plants, while NG is occasionally used for marginal electricity generation (Farhat and Ugursal, 2010). Thus, the source energy conversion factor for provinces with dominant hydro-electricity generation (provided in Table 10.1) is used for NZE analysis. The distribution of eligible houses based on their existing source energy intensity and the average source energy intensity of the same houses after retrofit are given in Table 10.38 for each retrofit scenario. The same data are plotted in Figure 10.20 where the size of each circle represents the percentage of eligible houses in each source energy intensity range. Due to the wide availability of NG and hydro-electricity, the existing source energy intensity of dwellings are mainly below 300kWh/m^2. The lowest PRASEI in eligible houses is obtained by retrofit scenarios that include heat pump technology, i.e. Sc. 1 (BIPV/T), Sc. 2 (SAHP) and Sc. 3 (AWHP). While Sc. 1 (BIPV/T) retrofits significantly reduce the source energy intensity of retrofitted houses, the fulfilment of NZE balance requirement, presented in Equation (10.1), is not possible due to lack of credit for onsite electricity generation. Sc. 3 (AWHP) and Sc. 2 (SAHP) provide a very close PRASEI in all eligible houses. Although the majority of eligible houses achieve near NZE status with Sc. 1 (BIPV/T), all electric systems that use heat pump and electric resistance auxiliary heating system is a likely alternative to convert eligible houses into NZEB in BC.

Table 10.38 Distribution (%) of existing houses based on existing source energy intensity (kWh/m^2) and the post-retrofit average source energy intensity (PRASEI) of the same houses with each retrofit scenario in British Columbia

Existing source energy intensity (kWh/m^2)		>600	500-600	400-500	300-400	200-300	≤200
Sc. 1 (BIPV/T)	Eligible houses (%)	0	0	0	5	16	78
	PRASEI (kWh/m^2)	13	41	26	18	13	6
Sc. 2 (SAHP)	Eligible houses (%)	0	0	0	2	15	82
	PRASEI (kWh/m^2)	72	103	92	50	37	16
Sc. 3 (AWHP)	Eligible houses (%)	0	0	0	3	16	80
	PRASEI (kWh/m^2)	120	90	35	53	30	15
Sc. 4 (SCS)	Eligible houses (%)	0	0	0	2	15	82
	PRASEI (kWh/m^2)	120	141	118	75	58	31
Sc. 5 (SE)	Eligible houses (%)	0	0	0	3	17	79
	PRASEI (kWh/m^2)	246	235	190	151	116	70
Sc. 6 (ICE)	Eligible houses (%)	0	0	0	3	17	79
	PRASEI (kWh/m^2)	371	365	284	231	178	109

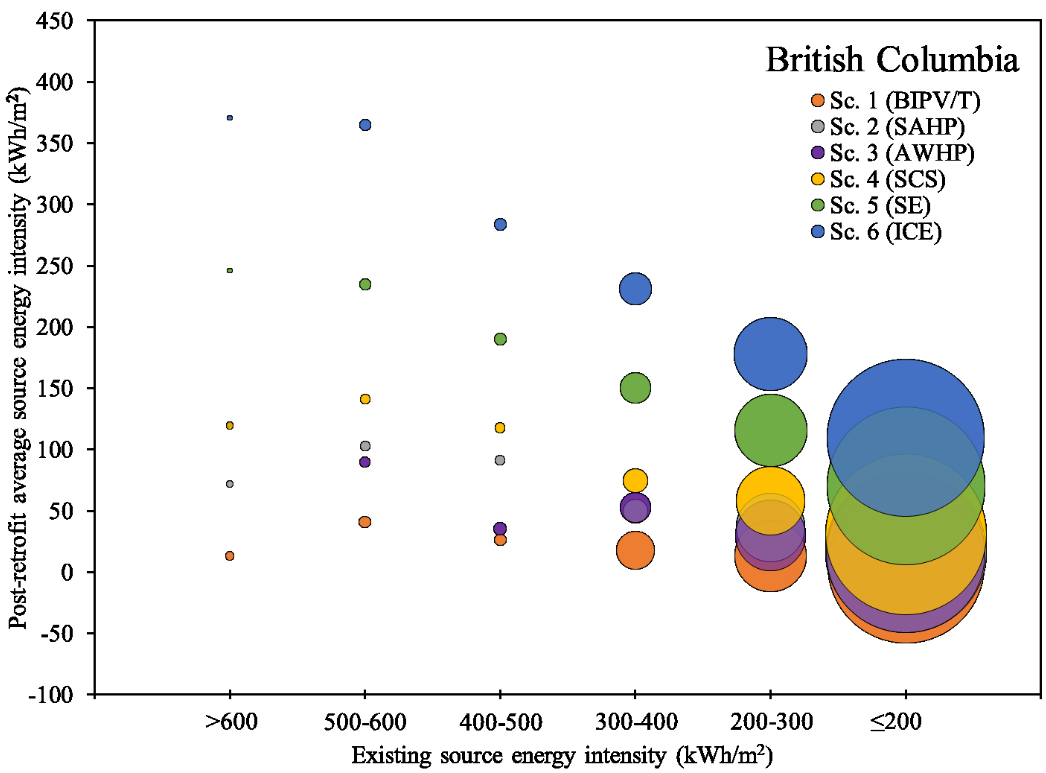

Figure 10.20 Impact of retrofit scenarios on energy intensity of existing houses in BC (Note: the size of the circle is proportional with the number of eligible houses in each category)

Table 10.39 Distribution (%) of existing houses based on existing GHG emission intensity (kg/m²) and the post-retrofit average GHG emission intensity (PRAGEI) of the same houses with each retrofit scenario in British Columbia

Existing GHG emission intensity (kg/m²)		>110	90-110	70-90	50-70	30-50	≤30
Sc. 1 (BIPV/T)	Eligible houses (%)	0	0	0	6	30	64
	PRAGEI (kg/m²)	2	2	2	2	1	1
Sc. 2 (SAHP)	Eligible houses (%)	0	0	0	3	28	68
	PRAGEI (kg/m²)	14	19	16	9	6	3
Sc. 3 (AWHP)	Eligible houses (%)	0	0	0	4	28	67
	PRAGEI (kg/m²)	22	17	11	10	6	3
Sc. 4 (SCS)	Eligible houses (%)	0	0	0	3	29	68
	PRAGEI (kg/m²)	21	25	20	13	9	5
Sc. 5 (SE)	Eligible houses (%)	0	0	0	4	29	65
	PRAGEI (kg/m²)	42	40	31	25	18	11
Sc. 6 (ICE)	Eligible houses (%)	0	0	0	4	30	65
	PRAGEI (kg/m²)	61	60	43	38	27	17

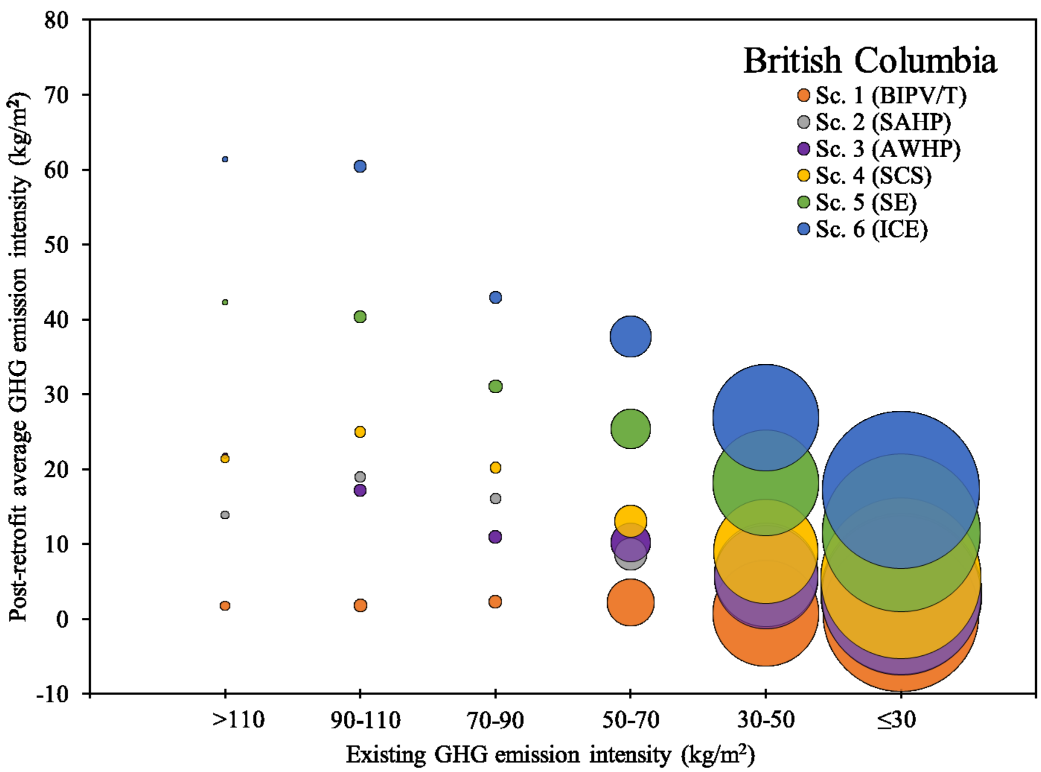

Figure 10.21 Impact of retrofit scenarios on GHG emission intensity of existing houses in BC (Note: the size of the circle is proportional with the number of eligible houses in each category)

Sc. 1 (BIPV/T) is the primary retrofit scenario for eligible houses in BC. Due to the lower complexity of Sc. 3 (AWHP) compared to Sc. 2 (SAHP), the former is recommended as the second retrofit option. Also, larger number of houses are eligible for Sc. 3 (AWHP) scenario compared to Sc. 2 (SAHP). If all eligible houses receive the recommended retrofit scenarios, i.e. Sc. 1 (BIPV/T) and Sc. 3 (AWHP), the source energy intensity of houses would be less than 30kWh/m^2 in BC.

The distribution of eligible houses based on their existing GHG emission intensity and the average GHG intensity of the same houses after retrofit are given in Table 10.39 and Figure 10.21 for each retrofit scenario. Retrofit scenarios that use solar thermal, i.e. Sc. 2 (SAHP) and Sc. 4 (SCS), and heat pump systems, i.e. Sc. 1 (BIPV/T) and Sc. 3 (AWHP), reduce the GHG emission intensity of houses to considerably low ranges (less than 10 kg/m^2). Among investigated retrofit scenarios Sc. 5 (SE) and Sc. 6 (ICE) are the least effective retrofit options to reduce GHG emission intensity of eligible houses in BC.

Existing GHG emission intensity in housing stock of BC is mainly below 50kg/m^2. The PRAGEI with Sc. 1 (BIPV/T) retrofit is largely reduced. It is possible to convert 5 percent of eligible houses in BC to NZEm buildings with the Sc. 1 (BIPV/T) retrofit. The rest of the eligible houses for Sc. 1 (BIPV/T) and eligible houses with Sc. 2 (SAHP), Sc. 3 (AWHP) and Sc. 4 (SCS) reach near NZEm status. To increase the number of NZEm building in BC, conventional electric resistance can be used to eliminate GHG emissions associated with NG consumption of auxiliary heating systems in eligible houses. However, NG is an inexpensive, reliable and relatively low emission source of energy that can be used by residential customers. Since the level of PRASEI and PRAGEI achieved with Sc. 1 (BIPV/T) and Sc. 3 (AWHP) are relatively low, limited use of NG for auxiliary heating purposes can be an acceptable option for near NZEm houses.

The TCC for Sc. 1 (BIPV/T) and Sc. 3 (AWHP) retrofit scenarios are provided in Table 10.40. Results indicate that that the TCC of Sc. 3 (AWHP) is about 80 percent of that for Sc. 1 (BIPV/T). However, due to the lower investment and maintenance cost and large number of houses eligible for Sc. 3 (AWHP) retrofit, it is likely a more effective option from a provincial perspective. House specific analysis should be conducted for a given house to select the best retrofit choice to achieve NZE status.

Table 10.40 Average TCC per house for selected retrofit scenarios in BC

Interest rate (%)	Fuel cost escalation rate	Sc. 1 (BIPV/T)		Sc. 3 (AWHP)	
		10 year Payback	6 year Payback	10 year Payback	6 year Payback
3	Low	17,044	10,425	13,237	8,096
	Medium	19,812	11,329	15,302	8,771
	High	23,129	12,317	17,758	9,508
6	Low	14,637	9,447	11,368	7,337
	Medium	16,882	10,238	13,042	7,928
	High	19,560	11,102	15,026	8,571
9	Low	12,706	8,604	9,868	6,682
	Medium	14,544	9,300	11,239	7,202
	High	16,727	10,058	12,857	7,767

10.5. Conclusion

An overview of strategies to achieve near NZE status for Canadian houses with six retrofit scenarios are presented in this section. All retrofit scenarios include energy efficiency measures, appliance and lighting upgrades and phase change material thermal storage. In addition, each retrofit scenario includes one renewable/alternative energy technology upgrade, i.e. BIPV/T, SAHP, AWHP, SCS, and cogeneration with SE and ICE. Eligible houses that satisfy all the required conditions for a given retrofit measure are included in the individual retrofit scenario. CHREM was used for the analysis and all eligible houses were upgraded to evaluate the impact of each retrofit scenario on the energy savings and GHG emissions reduction of the CHS as well as post-retrofit source energy and GHG emission intensity of eligible houses. The definition for NZEB provided in the US Department of Energy guideline was used for the analysis. The post-retrofit source energy intensity was selected as the indicator to identify the most suitable retrofit scenarios to convert Canadian houses to NZEB and near NZEB. Due to the significant variations in housing stock characteristics and energy source options in Canadian provinces, two best retrofit scenarios were selected for each province. The TCC was estimated for the selected retrofit scenarios for three interest rates, three fuel cost escalation rates and two payback periods.

A summary of the results of the two retrofit scenarios that produce the lowest source energy intensity in the eligible houses in the CHS are provided in Table 10.41 and Table 10.42. An overview of findings are as follows:

- Sc. 1 (BIPV/T) results in the lowest PRASEI in the eligible houses of AT provinces, QC, MB and BC and the second lowest PRASEI in the eligible houses of OT, SK and AB.
- Sc. 6 (ICE) results in the lowest PRASEI in the eligible houses of OT, SK and AB and the second lowest PRASEI in the eligible houses of AT provinces excluding NF. In NF, QC, MB and BC where hydro-electricity is widely used, Sc. 3 (AWHP) results in the second lowest PRASEI in the eligible houses.
- The end-use energy savings in the housing stock of the provinces vary in the range of 5% to 39% and 14% to 44% with the first combination and second combination of retrofit scenarios, respectively. The number of eligible houses is larger for the second set of retrofit scenarios in AT provinces, QC, MB and BC, resulting in a larger end-use energy savings for the second set of retrofit scenarios in those provinces.
- For the same reason, the reduction in the ASEI of the entire housing stock is larger for the second set of retrofit scenarios in all provinces except OT, SK and AB.
- Over 75% reduction in source energy intensity of the eligible houses can be achieved with retrofit scenarios. Thus, the retrofits are very effective to achieve near NZE status for eligible Canadian houses. In addition, about 5% to 25% of eligible houses fulfilled the NZE balance in provinces where hydro-electricity is not dominant. Where hydro-electricity generation is dominant, onsite electricity generation cannot offset the source energy consumption of the houses.
- Retrofit scenarios result in 13% to 76% reduction of the GHG emissions of the housing stock in the provinces of Canada. Over 80% reduction in the average GHG emission intensity of the majority of eligible houses can be achieved, making the retrofit scenarios the suitable paths for Canadian houses to achieve near NZEm status. About 5% to 26% of the eligible houses achieve NZEm status with retrofit scenarios in NB, OT, AB and BC.

- The TCC is highest in eastern Canada including AT provinces, QC and OT. The significant reliance on fossil fuels for electricity generation and residential heating purposes along with the high TCC, over 40,000C$ for the first set of retrofit scenarios and over 23,000C$ for the second set, indicate that AT houses should be the primary focus of a large scale potential energy conservation program in Canada.
- Summary results of the both sets of retrofit scenarios for the CHS is presented in Table 10.43. The results indicate that retrofit scenarios yield about 28% of energy savings in the CHS. While both sets of retrofit scenarios result in a 76% reduction in the average source energy intensity in the eligible houses, the first and second sets result in a reduction of 47% and 31% of the ASEI of the CHS.
- The two sets of scenarios convert 0.2% and 1.7% of the CHS to NZEB, respectively. Since Sc. 1 (BIPV/T) has a high performance to achieve NZE status and it is included in second set of retrofit scenarios for OT and AB, which have a large number of houses, the percent NZE achieved is higher for the second set compared to the first one.
- The first set of retrofit scenarios yield over 50% reduction of GHG emissions in the CHS. Since the housing stock is responsible for a considerable percentage of GHG emissions in Canada, retrofit scenarios are very effective to reduce national GHG emissions and can be significantly important to help Canada to achieve its international commitments to reduce GHG emissions.
- The average GHG emission intensity of eligible houses decreases by more than 75% due to the two sets of retrofit scenarios and between 0.9% and 2.2% of the housing stock can be converted to NZEm buildings by the first and second set of retrofit scenarios, respectively.
- On average, a Canadian household can invest about 24,000C$ and 18,000C$ on the first and second set of retrofit scenarios, under the assumed economic conditions. Such level of investment would go a long way to pay for the retrofits.
- Given the energy savings and GHG emission reductions, the retrofit scenarios are highly effective for the CHS. Since 50% of the CHS is eligible for the first set of retrofit scenarios, construction of a mechanical room in non-eligible houses would

increase the eligibility of the remaining houses and should be encouraged for larger energy savings and GHG emission reductions.

– This study provides guidelines in macro scale and house specific analysis is necessary to select the best solution for a given house.

One of the main objectives of this dissertation was to propose strategies and approaches to facilitate conversion of Canadian houses into NZEB. Based on the findings of this work the following strategy recommendations are made:

1. If the primary objective is to convert as many houses as possible to near NZEB in the CHS, the first set of retrofit scenarios in OT, SK and AB and the second set of retrofit scenarios in other provinces should be promoted. With this approach about 63% of the CHS (5.6 Million Canadian houses) will achieve lower source energy and GHG emissions intensity compared to the base case.
2. If the primary objective is to achieve the highest end-use energy savings in the CHS, retrofit Sc. 3 (AWHP) should be promoted in all provinces. With this approach about 48% end-use energy savings (equivalent to 615 PJ per year) will be achieved.
3. If the primary objective is to achieve the lowest average source energy intensity in the CHS, the first set of retrofit scenarios in OT, SK and AB and the second set of retrofit scenarios in other provinces should be promoted. With this approach the lowest and highest ASEI of the provincial housing stock will be 14 kWh/m^2 in QC and 359 kWh/m^2 in NB.
4. If the primary objective is to achieve the lowest average source energy intensity in the eligible houses, the first set of retrofit scenarios should be promoted in all provinces. With this approach the lowest and highest PRASEI in the eligible houses will be 8 kWh/m^2 in BC and 102 kWh/m^2 in PE. The PRASEI of all eligible houses in Canada will reduce to 73 kWh/m^2 which translates to 76% reduction in source energy intensity of about half of the CHS.
5. If the primary objective is to convert as many houses as possible to the NZEB, Sc. 1 (BIPV/T) should be promoted in all provinces. With this approach about 1.8% of the CHS will achieve the NZE status.
6. If the primary objective is to achieve the highest GHG emission reductions in the CHS, the first set of retrofit scenarios in OT, SK and AB and the second set of

retrofit scenarios in other provinces should be promoted. With this approach about 60% of the GHG emissions of the CHS (equivalent to 39 Mt of CO_{2e}) will be reduced.

7. If the primary objective is to achieve the lowest GHG emissions intensity in the eligible houses, the first set of retrofit scenarios should be promoted in all provinces. With this approach the average source energy intensity of about half of the CHS will reduce to 11 kg/m^2.
8. If the primary objective is to convert as many houses as possible to the NZEm buildings, Sc. 1 (BIPV/T) should be promoted in the CHS. With this approach about 2.5% of the CHS will achieve the NZEm status.
9. If the primary objective is to achieve the highest tolerable capital cost in the CHS, the first set of retrofit scenarios should be promoted in all provinces. With this approach the TCC varies between 44,000 C$ and 12,000 C$ in provinces and the average TCC for a Canadian household will be 24,000 C$. If the investment costs exceed the TCC, subsidies and incentives can cover the shortfall.
10. If the primary objective is to promote retrofit scenarios with the least amount of incentives, the focus should be on AT provinces, QC and OT. Since estimation of the investment costs for each retrofit scenario in provinces is not feasible, the amount of incentives cannot be estimated and providing recommendations regarding the best approach to achieve NZE and near NZE status for all eligible houses with minimum amount of incentives in the CHS is not practicable. However, due to significantly higher TCC for the same retrofit scenario in eastern Canada, the amount of incentives would be lower in AT provinces, QC and OT. The eligible houses in these provinces represent 39% of the CHS.
11. If the primary objective is to increase the percentage of the eligible houses by providing incentives for construction of a mechanical room, the focus should be on QC, NF and NB where the highest percentage of the eligible houses are currently 18%, 46% and 46%, respectively.

Table 10.41 Summary results for each province of the retrofit scenario that results in the lowest post-retrofit source energy intensity in eligible houses

Province			NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Retrofit scenario			Sc. 1 (BIPV/T)	Sc. 1 (BIPV/T)	Sc. 1 (BIPV/T)	Sc. 1 (BIPV/T)	Sc. 1 (BIPV/T)	Sc. 6 (ICE)	Sc. 1 (BIPV/T)	Sc. 6 (ICE)	Sc. 6 (ICE)	Sc. 1 (BIPV/T)
Eligible houses		%	16	27	30	21	5	82	27	83	92	22
Energy												
Entire housing stock												
Current end-use energy consumption (Base case)	Elec	PJ	15.2	17.7	1.8	18.7	205.3	137.2	18.9	10.6	28.3	64.6
	NG	PJ	0	0	0	0	1	337.4	33.6	40.2	119.8	83.9
	Oil	PJ	9.6	22.6	4	9.7	30.3	47.4	0	0	0	0
	Wood	PJ	3.3	6	1.5	10.7	10.4	0	0	0	0	2.1
	Total	PJ	28.1	46.3	7.3	39.1	247	522	52.5	50.8	148.1	150.6
Current ASEI		kWh/m^2	132	474	478	526	37	348	181	429	326	124
Post retrofit end-use energy consumption	Elec	PJ	14.1	15.7	1.5	17.0	200.2	7.2	17.6	-0.7	-8.7	57.6
	NG	PJ	0.0	0.0	0.0	0.0	1.8	309.8	23.4	31.7	94.4	61.3
	Oil	PJ	7.2	14.8	2.8	6.2	22.5	4.6	0.0	0.0	0.0	0.0
	Wood	PJ	2.6	4.9	0.9	8.3	9.8	0.0	0.0	0.0	0.0	2.0
	Total	PJ	23.9	35.4	5.2	31.5	234.3	321.6	41.0	31.0	85.7	120.8
Post retrofit ASEI		kWh/m^2	103	387	377	449	30	160	125	206	116	90
End-use energy savings		PJ	4.2	10.9	2.1	7.6	12.7	200.4	11.5	19.8	62.4	29.8
		%	15	24	29	19	5	38	22	39	42	20
Source energy intensity reduction		kWh/m^2	29	87	101	77	7	188	56	223	210	34
		%	22	18	21	15	19	54	31	52	64	27

Province		NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Eligible houses											
ASEI	kWh/m^2	195	418	434	455	148	318	243	366	325	161
PRASEI	kWh/m^2	14	92	102	88	15	78	37	87	86	8
Reduction in ASEI	%	93	78	76	81	90	75	85	76	74	95
NZE achieved in											
Eligible houses	%	–	12	5	11	–	–	–	–	–	–
All housing stock	%	–	3.2	1.5	2.3	–	–	–	–	–	–
GHG Emissions											
Base case	Mt of CO_{2e}	0.8	5.4	0.4	3.1	2.6	28.6	1.8	4.5	13.6	4.7
Post retrofit	Mt of CO_{2e}	0.6	4.4	0.3	2.7	2.1	12	1.3	2.7	3.2	3.5
Reduction	Mt of CO_{2e}	0.2	1.0	0.1	0.4	0.5	16.6	0.5	1.8	10.4	1.2
Reduction	%	25	19	25	13	19	58	28	40	76	26
Average GHG emission intensity of the housing stock											
Base case	kg/m^2	25	104	54	72	7	41	32	93	73	22
Post retrofit	kg/m^2	20	84	40	61	5	18	21	62	18	16
Reduction	%	20	19	26	15	29	56	34	33	75	27
Average GHG emission intensity of eligible houses											
AGEI	kg/m^2	37	91	52	65	30	41	41	74	73	29
PRAGEI	kg/m^2	4	18	5	13	1	12	1	35	10	1
Reduction	%	89	80	90	80	97	71	98	53	86	97
NZEm achieved in											
Eligible houses	%	–	–	–	26	–	–	–	–	6	5
All housing stock	%	–	–	–	5.5	–	–	–	–	5.5	1.1
Economic feasibility											
TCC (C$)[a]		43,911	43,717	41,570	42,394	35,289	24,773	11,639	20,487	18,963	16,882

[a] The TCC for 10 years payback period, 6% interest rate and medium fuel cost escalation rate

Table 10.42 Summary results for each province of the retrofit scenario that results in the second lowest post-retrofit source energy intensity in eligible houses

Province			NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Retrofit scenario			Sc. 3 (AWHP)	Sc. 6 (ICE)	Sc. 6 (ICE)	Sc. 6 (ICE)	Sc. 3 (AWHP)	Sc. 1 (BIPV/T)	Sc. 3 (AWHP)	Sc. 1 (BIPV/T)	Sc. 1 (BIPV/T)	Sc. 3 (AWHP)
Eligible houses		%	46	66	82	46	18	29	68	37	36	65
Energy												
Entire housing stock												
Current end-use energy consumption (Base case)	Elec	PJ	15.2	17.7	1.8	18.7	205.3	137.2	18.9	10.6	28.3	64.6
	NG	PJ	0	0	0	0	1	337.4	33.6	40.2	119.8	83.9
	Oil	PJ	9.6	22.6	4	9.7	30.3	47.4	0	0	0	0
	Wood	PJ	3.3	6	1.5	10.7	10.4	0	0	0	0	2.1
	Total	PJ	28.1	46.3	7.3	39.1	247	522	52.5	50.8	148.1	150.6
Current ASEI		kWh/m^2	132	474	478	526	37	348	181	429	326	124
Post retrofit end-use energy consumption	Elec	PJ	14.7	7.5	0.3	11.6	196.7	123.1	19.8	8.7	23.4	52.7
	NG	PJ	0.0	0.0	0.0	0.0	5.4	236.7	9.7	27.1	79.1	17.8
	Oil	PJ	1.5	20.3	3.5	12.2	3.3	30.5	0.0	0.0	0.0	0.0
	Wood	PJ	0.9	2.5	0.7	4.3	7.7	0.0	0.0	0.0	0.0	1.7
	Total	PJ	17.2	30.2	4.5	28.1	213.1	390.4	29.5	35.8	102.5	72.1
Post retrofit ASEI		kWh/m^2	29	276	254	359	14	279	49	329	239	30
End-use energy savings		PJ	10.9	16.1	2.8	11	33.9	131.6	23	15	45.6	78.5
		%	39	35	38	28	14	25	44	30	31	52
Source energy intensity reduction		kWh/m^2	103	198	224	167	23	69	132	100	87	94
		%	78	42	47	32	62	20	73	23	27	76

Province		NF	NS	PE	NB	QC	OT	MB	SK	AB	BC
Eligible houses											
ASEI	kWh/m^2	242	434	437	488	156	329	247	349	326	156
PRASEI	kWh/m^2	18	120	136	120	25	87	57	114	86	19
Reduction in ASEI	%	93	72	69	75	84	74	77	67	74	88
NZE achieved in											
Eligible houses	%	–	–	–	–	–	9	–	25	13	–
All housing stock	%	–	–	–	–	–	2.61	–	9.25	4.68	–
GHG Emissions											
Base case	Mt of CO_{2e}	0.8	5.4	0.4	3.1	2.6	28.6	1.8	4.5	13.6	4.7
Post retrofit	Mt of CO_{2e}	0.2	3.6	0.3	2	0.9	21.7	0.6	3.4	10.2	1.3
Reduction	Mt of CO_{2e}	0.6	1.8	0.1	1.1	1.7	6.9	1.2	1.1	3.4	3.4
Reduction	%	75	33	25	35	65	24	67	24	25	72
Average GHG emission intensity of the housing stock											
Base case	kg/m^2	25	104	54	72	7	41	32	93	73	22
Post retrofit	kg/m^2	7	70	42	46	2	30	9	71	54	6
Reduction	%	72	33	22	36	71	27	72	24	26	73
Average GHG emission intensity of eligible houses											
AGEI	kg/m^2	45	93	56	69	32	42	42	72	73	28
PRAGEI	kg/m^2	6	40	40	12	4	7	10	12	21	4
Reduction	%	87	57	29	83	88	83	76	83	71	86
NZEm achieved in											
Eligible houses	%	–	–	–	–	–	15	–	–	11	–
All housing stock	%	–	–	–	–	–	4.4	–	–	4.0	–
Economic feasibility											
TCC (C$)[a]		38,387	29,064	26,868	23,624	31,315	19,078	6,803	14,729	10,410	13,042

[a] The TCC for 10 years payback period, 6% interest rate and medium fuel cost escalation rate

Table 10.43 Summary results of the best and second best combination of retrofit scenarios for the CHS

Retrofit scenario			Best combination	2nd Best combination
Eligible houses		%	50	37
Energy				
Entire housing stock				
Current end-use energy consumption (Base case)	Electricity	PJ	518	
	NG	PJ	616	
	Oil	PJ	124	
	Wood	PJ	34	
	Total	PJ	1292	
Current ASEI		kWh/m^2	250	
Post retrofit end-use energy consumption	Electricity	PJ	322	459
	NG	PJ	522	376
	Oil	PJ	58	71
	Wood	PJ	29	18
	Total	PJ	930	923
Post retrofit ASEI		kWh/m^2	133	173
End-use energy savings		PJ	361	368
		%	28	29
Source energy intensity reduction		kWh/m^2	117	77
		%	47	31
Eligible houses	ASEI	kWh/m^2	309	275
	PRASEI	kWh/m^2	73	65
	Reduction	%	76	76
NZE achieved in	Eligible houses	%	0.4	4.5
	All housing stock	%	0.2	1.7
GHG Emissions				
Base case		Mt of CO_{2e}	65	
Post retrofit		Mt of CO_{2e}	32	44
Reduction		Mt of CO_{2e}	33	21
Reduction		%	51	32
Average GHG emission intensity of the housing stock	Base case	kg/m^2	39	
	Post retrofit	kg/m^2	20	26
	Reduction	%	49	33
Average GHG emission intensity of eligible houses	AGEI	kg/m^2	49	47
	PRAGEI	kg/m^2	11	11
	Reduction	%	76	77
NZEm achieved in	Eligible houses	%	1.8	6
	All housing stock	%	0.9	2.2
Economic feasibility				
TCC [a]		C$	23,637	18,319

[a] The TCC for 10 years payback period, 6% interest rate and medium fuel cost escalation rate

Chapter 11 Conclusion

Net zero energy building (NZEB) is a viable alternative for conventional housing. The design and construction of a NZEB require extensive knowledge and understanding of the performance of energy efficiency measures and renewable/alternative energy technologies in a given climate and geographical location. In addition, building geometry, construction materials, occupancy and the fuel mix used affect strategies to convert existing houses into NZEB. Canada has numerous regions with unique fuel mix and housing stock conditions. This dissertation provides strategies to facilitate a massive conversion of Canadian houses into NZEB and near NZEB.

11.1. Summary of Contributions

This work aims to enhance the state of knowledge on the options and types of technologies, as well as strategies and policy tools that could be used to achieve NZE and near NZE status for houses in the different regions of Canada. This dissertation had three inter-connected objectives:

i. Expansion of CHREM to include capability to model technologies required to achieve NZE status, including internal combustion engine and Stirling engine cogeneration, solar combisystem, solar-assisted heat pump, air to water heat pump and building integrated photovoltaic and thermal (BIPV/T) systems.
ii. Techno-economic analysis for each individual technology retrofit.
iii. Development of feasible approaches, policies and strategies to achieve, encourage and support the conversion of existing Canadian houses into NZE and near NZE buildings.

All objectives of this work were achieved as summarized below:

i. Selected renewable/alternative energy technology retrofits were added to the CHREM (Sections 3.3, 4.3, 6.4, 7.3, 8.3 and 9.3).
ii. The techno-economic analysis was completed for all technology retrofits using various performance indicators for energy savings, GHG emission reductions and economic feasibility (Sections 3.5, 4.4, 6.6, 7.6, 8.4 and 9.5).
iii. Retrofit scenarios were developed based on the results of techno-economic analysis and their impact on energy consumption and GHG emissions of the CHS as well as

source energy and GHG emission intensity of Canadian houses was investigated. The strategies and recommendations to promote, support and encourage NZEB in the CHS was provided (Sections 10.2, 10.3, 10.4 and 10.5).

In addition to achieving the objectives of this work, the following contributions were made to the state of the knowledge:

1. Explicit plant models were developed in ESP-r for each retrofit technology. Individual plant components were modeled as separate control volumes and conservation of mass and energy equations were solved for each control volume (Sections 2.5, 3.3.1, 4.3.2, 5.5, 6.4, 7.3.1, 8.3.2 and 9.3.1).
2. Eligibility criteria were defined based on the specific requirements of each retrofit technology to avoid major reconstruction that can be unrealistic/impracticable for existing houses (Sections 3.3.2, 4.3.3, 6.4.7, 7.3.2, 8.3.4 and 9.3.3).
3. Algorithms were developed to identify the eligible houses and adapt the individual renewable/alternative energy technology retrofits to the houses based on the building size, heating requirement and available energy sources.
4. Control algorithms were developed in ESP-r for each technology retrofit to control the operation of the plant system components and space and DHW heating (Sections 2.5, 5.5.5, 6.4, 7.3.1.7, 8.3.3 and 9.3.2).
5. A model for the ICE cogeneration system was developed for Canadian houses based on the cogeneration system architecture used in the IEA/ECBCS Annex 42 subtask B (Kelly and Beausoleil-Morrison, 2007). The system consists of a cogeneration engine, thermal storage tank, auxiliary heater and hydronic system for space and DHW heating. The system is controlled with a thermal load following scheme (Section 2.5).
6. A case study was conducted with a representative house in five major cities of Canada to identify the impact of key parameters on the performance of the ICE cogeneration retrofit (Section 2.7).
7. The primary energy saving (PES) index, introduced in the European Parliament and Council published in Directive 2004/8/EC, was adapted to be used for evaluation of cogeneration systems in Canadian houses as an alternative to the existing heating systems and most efficient heating systems in the market. Two scenarios for utility

electricity generation including the current technology and best technology in the market were introduced to estimate the PES for cogeneration system retrofits in Canadian houses (Section 2.6.1).

8. GHG emission reduction (GER) index was introduced based on the same approach used for the PES index to evaluate the performance of cogeneration systems from an environmental perspective (Section 2.6.2).
9. The ICE and SE cogeneration system retrofit models were added into the CHREM to evaluate their impact on energy consumption and GHG emissions in the CHS. The PES and GER indices were modified to evaluate the performance of cogeneration systems at the housing stock level (Chapter 3 and Chapter 4).
10. The architecture of a solar combisystem adopted from the IEA SHC Task 26 system 6 (Weiss, 2003) was modified to fit in Canadian houses. The solar combisystem includes an array of flat plate collectors, solar storage tank, hot water tank, auxiliary heating system, DHW heating and hydronic heat delivery system (Sections 5.5 and 6.4).
11. A case study analysis was conducted for the solar combisystem using a very detailed plant model in TRNSYS to investigate the impact of key parameters on the performance of the solar combisystem. Based on the results of the preliminary analysis the solar combisystem model was developed for the CHS (Chapter 5 and Chapter 6).
12. Fractional thermal energy savings and extended fractional energy savings concept were adapted to be used for the analysis of solar thermal systems at the housing stock level (Section 6.5).
13. A model for the air to water heat pump system which include heat pump, thermal storage tank, auxiliary boiler and hydronic system was developed for Canadian houses. The system is capable to supply heat for space and DHW heating (Section 7.3).
14. The seasonal performance factor (SPF) and the European Parliament and Council methodology for accounting of renewable energy from heat pump systems published in Directive 2009/28/EC, was adopted and modified to evaluate the

amount of renewable energy delivered by air to water heat pump systems in the CHS (Section 7.4).

15. The solar assisted heat pump system architecture developed for a house in Ontario (Banister, 2015) was adopted and modified to be used in the CHS. The solar array design used in solar combisystem retrofit was used for the solar assisted heat pump system. A sophisticated control algorithm was used to prioritize the renewable energy use in the system (Section 8.3).
16. Several indicators including solar fraction, seasonal performance factor, fractional thermal energy saving and extended fractional energy saving were modified to be used for analysis of solar assisted heat pump system at the housing stock level (Section 8.3.6).
17. The BIPV/T system model was developed for Canadian houses and the model was incorporated into the CHREM to evaluate the impact of BIPV/T system retrofit in the CHS (Section 9.3).
18. Post processing algorithms were developed for the big data analysis of the batch simulation results.
19. Six retrofit scenarios were developed as potential and practical paths to achieve near NZE status for Canadian houses. The retrofit scenarios include energy efficiency measures, i.e. envelope modification and appliance/lighting upgrade, energy storage, phase change material (PCM) thermal storage, and renewable/alternative energy technology retrofits, i.e. ICE and SE cogeneration, SCS, AWHP, SAHP and BIPV/T. The NZEB definition was adopted from the US Department of Energy guide (NIBS, 2015) that provides a common definition and measurement methods for NZEB (Sections 10.2 and 10.3).
20. The source energy and GHG emission intensity of all houses in the CHS and post retrofit source energy and GHG emission intensity of eligible houses were estimated. Since reporting the results of individual houses was not practical and have no utility for the macro scale nature of this analysis, the post retrofit average source energy intensity of eligible houses was used as the indicator to assess the performance of retrofit scenarios to achieve near NZE status for Canadian houses (Section 10.4).

21. Suitable strategies for the conversion of Canadian houses into the NZE and near NZE buildings were developed based on the techno-economic results of retrofit scenarios. Impact of those strategies on energy savings and reduction of GHG emissions of the CHS and their economic feasibility was estimated (Section 10.5).

11.2. Specific Findings and Results

In this work, first the energy savings, GHG emission reductions and economic implications of six renewable/alternative energy technology retrofits were evaluated. Based on the results of these analyses, six retrofit scenarios were developed to achieve NZE and near NZE status for Canadian houses, and these scenarios were similarly evaluated. The key findings of each study are summarised in the following sections.

11.2.1. Techno-Economic Analysis for Alternative/Renewable Energy Technologies in the CHS

The summary results for each renewable/alternative energy technology retrofit in each province are provided in Table 11.1.

As shown in Table 11.1, the energy savings vary significantly depending on the technology and province. The highest and lowest percent energy savings are 45% and 3%, associated with air to water heat pump retrofit in OT and ICE cogeneration retrofit in QC, respectively. The variation in the percent reduction of GHG emissions are even larger with 37% increase in NF with ICE cogeneration retrofit and 78% decrease with AWHP retrofit in BC. The economic feasibility of renewable/alternative energy technology retrofits is strongly affected by energy savings and cost of energy.

The most suitable renewable/alternative energy technology retrofit for each province can be identified using the results provided in Table 11.1 depending on the desired point of view, i.e. the percent eligible houses, energy savings, GHG emissions reduction or economic feasibility. This information can be used to devise an energy plan for each province.

Table 11.1 Summary results of techno-economic performance of selected renewable/alternative energy technology retrofit in each province of Canada

Technology	Percent eligible houses	Energy savings		GHG emission reductions		Average TCC per house (C$)
		PJ	%	Mt of CO_{2e}	%	
			Newfoundland and Labrador			
ICE	50	3.2	11	-0.29	-37	5,887
SE	50	4.3	15	0.01	1	9,540
SCS	35	5.0	18	0.18	23	20,783
AWHP	50	8.3	30	0.59	75	14,893
SAHP	35	5.4	19	0.25	31	22,866
BIPV/T	20	3.9	14	0.18	23	30,041
			Nova Scotia			
ICE	69	6.5	14	0.65	12	11,446
SE	69	8.9	19	0.55	10	11,122
SCS	44	9.6	21	0.66	12	21,409
AWHP	69	17.1	37	-0.04	-1	13,557
SAHP	44	10.7	23	0.62	12	23,427
BIPV/T	28	8.4	18	0.60	11	28,858
			Prince Edward Island			
ICE	87	1.5	21	-0.05	-12	12,247
SE	87	1.9	26	0.05	13	11,453
SCS	54	1.7	23	0.08	22	18,412
AWHP	87	2.9	40	0.17	44	8,136
SAHP	54	1.9	26	0.11	28	20,631
BIPV/T	31	1.7	23	0.09	23	30,470
			New Brunswick			
ICE	51	5.3	14	0.96	31	4,344
SE	51	6.8	17	0.30	10	8,382
SCS	30	7.0	18	0.24	8	21,003
AWHP	51	11.4	29	0.14	5	17,203
SAHP	30	7.7	20	0.25	8	24,331
BIPV/T	24	6.5	17	0.27	9	30,441
			Quebec			
ICE	19	7.7	3	-0.63	-25	28,493
SE	19	11.5	5	0.23	9	26,271
SCS	13	18.3	7	0.84	33	30,460
AWHP	19	24.7	10	1.77	69	17,540
SAHP	13	20.1	8	1.00	39	30,734
BIPV/T	6	10.3	4	0.50	20	30,355

Technology	Percent eligible houses	Energy savings		GHG emission reductions		Average TCC per house (C$)
		PJ	%	Mt of CO_{2e}	%	
			Ontario			
ICE	90	86.4	17	14.33	50	20,966
SE	90	120.3	23	8.81	31	10,923
SCS	47	121.5	23	6.61	23	10,359
AWHP	90	234.1	45	11.79	41	–
SAHP	47	131.2	25	7.03	25	9,084
BIPV/T	31	111.5	21	5.43	19	10,583
			Manitoba			
ICE	72	6.8	13	-0.31	-17	10,201
SE	72	11.1	21	0.35	20	4,962
SCS	32	8.4	16	0.40	23	6,303
AWHP	72	17.2	33	1.16	66	536
SAHP	32	9.3	18	0.49	27	5,926
BIPV/T	28	9.7	18	0.51	29	6,979
			Saskatchewan			
ICE	91	10.6	21	0.67	15	16,740
SE	91	13.9	27	0.64	14	5,632
SCS	47	12.7	25	0.62	14	5,363
AWHP	91	21.3	42	-0.58	-13	–
SAHP	47	13.8	27	0.53	12	4,124
BIPV/T	40	13.2	26	0.73	16	7,304
			Alberta			
ICE	100	27.0	18	8.37	61	15,602
SE	100	38.4	26	2.68	20	3,360
SCS	52	37.6	25	1.56	11	1,935
AWHP	100	65.2	44	-3.47	-25	–
SAHP	52	41.3	28	1.08	8	9
BIPV/T	39	37.5	25	1.30	10	936
			British Columbia			
ICE	79	17.9	12	-0.63	-13	7,693
SE	79	28.2	19	1.03	22	4,448
SCS	37	24.2	16	1.19	26	6,369
AWHP	79	58.3	39	3.62	78	2,826
SAHP	37	26.2	17	1.40	30	6,041
BIPV/T	25	24.3	16	1.24	27	8,674

11.2.2. Strategies to Convert Canadian Houses into NZE and Near NZE Buildings

The summary results of each retrofit scenario for each province are provided in Table 11.2. A summary of findings are as follows:

- Energy savings and GHG emission reductions due to retrofit scenarios vary significantly for retrofit scenarios and are affected by the percentage of eligible houses. The lowest and highest energy savings are 5% due to Sc. 1 (BIPV/T) in QC and 62% due to Sc. 3 (AWHP) in AB, respectively. The lowest and highest GHG emissions reduction are 7% due to Sc. 6 (ICE) in NF and 76% due to Sc. 6 (ICE) in AB, respectively.
- About 78% reduction in average source energy intensity (ASEI) is achieved in NF with Sc. 3 (AWHP) and 75% reduction in average GHG emissions intensity (AGEI) is achieved in AB with Sc. 6 (ICE).
- Due to the wide range of energy savings and GHG emission reductions as well as source energy and GHG emission intensity reductions, the most suitable retrofit scenarios for each province need to be identified based on the desired point of view.
- Thus, to achieve the lowest post retrofit average source energy intensity (PRASEI) in the eligible houses, Sc. 1 (BIPV/T) is the best retrofit scenario in AT provinces, QC, MB and BC. Sc. 6 (ICE) is the best retrofit scenario in OT, SK and AB.
- The second best retrofit is Sc. 3 (AWHP) in provinces where hydro-electricity is largely available, i.e. NF, QC, MB and BC, Sc. 1 (BIPV/T) in OT, SK and AB and Sc. 6 (ICE) in NS, NB and PE.
- Economic feasibility of retrofit scenarios are higher in eastern Canada, i.e. AT provinces, QC and OT.
- Proposed strategies can be used to devise national codes and regulations to promote energy conservation in the households.
- House specific analysis can help to identify the best practices to achieve NZE status in a given house.

Table 11.2 Summary results for each province of retrofit scenarios to convert Canadian houses into NZE and near NZE buildings

Retrofit scenario	Percent eligible houses	Energy savings		ASEI reduction		GHG emission reductions		AGEI reduction		Average TCC per house
		PJ	%	kWh/m^2	%	Mt	%	kg/m^2	%	(C$)
				Newfoundland and Labrador						
Sc. 1 (BIPV/T)	16	4.2	15	29	22	0.18	22	5	20	43,911
Sc. 2 (SAHP)	31	8.5	30	58	44	0.36	46	10	40	37,191
Sc. 3 (AWHP)	46	10.9	39	103	78	0.57	72	18	72	38,387
Sc. 4 (SCS)	31	8.4	30	51	39	0.33	42	5	20	36,608
Sc. 5 (SE)	46	8	28	46	35	0.23	29	6	24	29,654
Sc. 6 (ICE)	46	7.3	26	18	14	0.05	7	0	0	26,732
				Nova Scotia						
Sc. 1 (BIPV/T)	27	10.9	24	87	18	1.02	19	20	19	43,717
Sc. 2 (SAHP)	42	15.8	34	119	25	1.47	27	27	26	34,071
Sc. 3 (AWHP)	66	24	52	143	30	2	37	38	37	34,766
Sc. 4 (SCS)	42	15.2	33	121	26	1.5	28	16	15	33,380
Sc. 5 (SE)	66	17.4	38	160	34	1.69	31	32	31	29,339
Sc. 6 (ICE)	66	16.1	35	198	42	1.77	33	34	33	29,064
				Prince Edward Island						
Sc. 1 (BIPV/T)	30	2.1	28	101	21	0.1	27	14	26	41,570
Sc. 2 (SAHP)	51	2.8	38	159	33	0.16	41	23	43	32,176
Sc. 3 (AWHP)	82	4.1	56	177	37	0.28	74	36	67	30,704
Sc. 4 (SCS)	51	2.6	36	163	34	0.14	38	17	31	30,618
Sc. 5 (SE)	82	3	41	185	39	0.13	34	18	33	26,419
Sc. 6 (ICE)	82	2.8	38	224	47	0.07	19	12	22	26,868
				New Brunswick						
Sc. 1 (BIPV/T)	21	7.6	19	77	15	0.45	15	11	15	42,394
Sc. 2 (SAHP)	27	10.4	27	86	16	0.51	16	10	14	35,249
Sc. 3 (AWHP)	46	15.3	39	119	23	0.37	12	8	11	35,443
Sc. 4 (SCS)	27	10.2	26	90	17	0.55	18	4	6	33,812
Sc. 5 (SE)	46	12.1	31	138	26	0.73	24	17	24	26,938
Sc. 6 (ICE)	46	11	28	167	32	1.09	35	26	36	23,624
				Quebec						
Sc. 1 (BIPV/T)	5	12.7	5	7	19	0.51	20	2	29	35,289
Sc. 2 (SAHP)	12	27.8	11	13	35	1.18	46	3	43	32,999
Sc. 3 (AWHP)	18	33.9	14	23	62	1.7	66	5	71	31,315
Sc. 4 (SCS)	12	27	11	11	30	1.08	42	2	29	32,998
Sc. 5 (SE)	18	24.8	10	7	19	0.74	29	2	29	31,681
Sc. 6 (ICE)	18	22.1	9	-1	-3	0.23	9	1	14	33,082

Retrofit scenario	Percent eligible houses	Energy savings		ASEI reduction		GHG emission reductions		AGEI reduction		Average TCC per house
		PJ	%	kWh/m^2	%	Mt	%	kg/m^2	%	(C$)
				Ontario						
Sc. 1 (BIPV/T)	29	131.6	25	69	20	6.85	24	11	27	19,078
Sc. 2 (SAHP)	42	181.2	35	82	24	9.48	33	11	27	16,100
Sc. 3 (AWHP)	82	305.2	58	112	32	11.97	42	17	41	10,252
Sc. 4 (SCS)	42	176.1	34	87	25	9.79	34	9	22	17,096
Sc. 5 (SE)	82	221.3	42	147	42	13.48	47	19	46	18,066
Sc. 6 (ICE)	82	200.4	38	188	54	16.57	58	23	56	24,773
				Manitoba						
Sc. 1 (BIPV/T)	27	11.5	22	56	31	0.53	30	11	34	11,639
Sc. 2 (SAHP)	30	12	23	53	29	0.54	31	9	28	9,372
Sc. 3 (AWHP)	68	23	44	132	73	1.22	69	23	72	6,803
Sc. 4 (SCS)	30	11.5	22	46	25	0.49	27	4	13	9,863
Sc. 5 (SE)	68	17.4	33	68	38	0.64	36	12	38	9,448
Sc. 6 (ICE)	68	14.9	28	18	10	0.19	11	4	13	13,147
				Saskatchewan						
Sc. 1 (BIPV/T)	37	15	29	100	23	1.13	25	22	24	14,729
Sc. 2 (SAHP)	42	17.9	35	98	23	1.28	29	20	22	11,571
Sc. 3 (AWHP)	83	28.4	56	133	31	2.03	45	36	39	5,354
Sc. 4 (SCS)	42	17.4	34	101	24	1.33	30	10	11	13,035
Sc. 5 (SE)	83	22.4	44	171	40	1.77	39	32	34	12,653
Sc. 6 (ICE)	83	19.8	39	223	52	1.76	39	31	33	20,487
				Alberta						
Sc. 1 (BIPV/T)	36	45.6	31	87	27	3.4	25	19	26	10,410
Sc. 2 (SAHP)	47	58.5	39	95	29	4.28	31	19	26	8,765
Sc. 3 (AWHP)	92	92	62	136	42	4.49	33	24	33	2,873
Sc. 4 (SCS)	47	55.7	38	99	30	4.94	36	13	18	10,187
Sc. 5 (SE)	92	69.9	47	162	50	7.12	52	37	51	10,649
Sc. 6 (ICE)	92	62.4	42	210	64	10.42	76	55	75	18,963
				British Columbia						
Sc. 1 (BIPV/T)	22	29.8	20	34	27	1.19	25	6	27	16,882
Sc. 2 (SAHP)	31	42.9	28	42	34	1.72	37	7	32	14,389
Sc. 3 (AWHP)	68	78.5	52	94	76	3.42	73	16	73	13,042
Sc. 4 (SCS)	31	41.8	28	37	30	1.58	34	5	23	14,942
Sc. 5 (SE)	68	56.7	38	49	40	1.88	40	8	36	13,045
Sc. 6 (ICE)	68	50.5	34	20	16	0.96	21	3	14	15,091

11.3. Recommendations for Future Work

CHREM was expanded and used in this work to analyse the performance of energy efficiency and renewable/alternative energy technologies in the Canadian housing stock and to identify retrofit scenarios to convert Canadian houses into NZE and near NZE buildings. As discussed earlier CHREM consists of six components including: (i) the Canadian Single-Detached & Double/Row Housing Database, (ii) a neural network model of the appliances and lighting (AL) and DHW energy consumption of Canadian households, (iii) a set of AL and DHW load profiles representing the usage profiles in Canadian households, (iv) a model to estimate GHG emissions from electricity generation in each province of Canada and for each month of the year, (v) a high resolution energy simulation software, i.e. ESP-r, and (vi) a model to estimate GHG emissions from fossil fuels consumed in households. Among those the first four components require continuous upgrade to reflect the up-to-date state of the CHS and maintain CHREM as a current tool for energy analysis at the housing stock level. CHREM is a valuable asset for the building energy research community of Canada and its maintenance is highly encouraged. Maintenance of CHREM includes following steps:

- Extensive statistical data from energy surveys was used to develop the housing database and the neural network model of AL and DHW load as well as the AL and DHW usage profiles. Data from recent housing energy surveys should be used to update these components.
- The GHG emission intensity factors were developed using detailed data on electricity generation and distribution in each province. Since utility companies change the primary energy mix they use to reduce GHG emissions and to increase the percentage of renewable energies for electricity generation, the GHG emission intensity factors should be regularly updated. The micro-electricity generation such as ICE and PV electricity generation, can be a potential new extension to the GHG emission estimation model.
- ESP-r, the simulation engine of CHREM, is a sophisticated high-resolution building performance simulation software. While the building modeling in ESP-r is very well developed, the plant modeling capability of ESP-r is not sufficiently advanced. Since, ESP-r is an open source software and its developers' community is limited

to highly educated volunteers, its development is a slow process and cannot keep up with the pace of renewable/alternative energy technologies. Thus, reliance only on ESP-r for energy simulation would be a disadvantage for CHREM. Also, ESP-r has a very steep learning curve that makes it very difficult to use for anyone except those who are willing to dedicate hundreds of hours to become fluent in ESP-r modeling. While effort to develop an ESP-r/TRNSYS co-simulation platform (Beausoleil-Morrison *et al.*, 2012; Beausoleil-Morrison *et al.*, 2014) for CHREM at the early stages of this work to address the shortcomings of the plant models of ESP-r, was successful, several obstacles for co-simulation on a computer cluster, which is necessary for the operation of CHREM, made the co-simulator impractical to me. Thus finding solutions to enhance the simulation capability of CHREM for emerging technologies need to be investigated. Also, transporting CHREM to a more user-friendly building simulation platform such as EnergyPlus™ (NREL, 2016) need to be investigated. EnergyPlus is an open-source cross-platform building performance simulation software and uses text based input/output files which makes it a suitable candidate as the simulation engine for CHREM.

This work was the first step to identify suitable and commercially available renewable/alternative energy technology retrofits for the housing stock in each province. Further studies are required to evaluate the performance of emerging technologies and provide guidelines to update building codes and regulations. Also, further improvements can be made to the selected technologies to optimise the operation of those technologies in each province. Future studies should focus on the housing stock in each province to provide optimised solutions and determine the realistic market share for retrofit scenarios.

As discussed earlier the source energy conversion factors was adopted from the US Department of Energy guideline for NZEB. To develop source energy conversion factors for the provinces of Canada extensive information on efficiency of extraction, processing, transportation, conversion and distribution processes for each energy sources is required. The electricity and energy markets in Canada are diversified and the efficiency of electricity generation varies from province to province. Also, electricity generation in Canada is by provincial utilities, and the fuel mixture used by each utility is different, based on the availability of primary energy sources, economic factors and dispatch considerations.

Therefore, a comprehensive analysis is required to develop source energy conversion factors for Canadian provinces.

Canada is committed to substantially reduce its GHG emissions. The impact of economic measures such as Carbon tax and cap and trade programs that aim to limit the GHG emissions on the feasibility of retrofit scenarios is complex and requires an in depth study.

Net metering was adopted in this work for billing micro-electricity generation in households. The effects of other approaches including micro feed-in tariff and net metering with weighting factors for source energy, GHG emissions and energy cost need to be investigated.

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